Climate II

(Winter 2020/2021)

6th lecture:

Biogeochemical Cycles

(turnover times and circulation of biochemical tracers: carbon, nitrogen, sulfur, phosphorus)

Gerrit Lohmann, Martin Werner

Tuesday, 10:00-11:45

(sometimes shorter, but with some exercises)

https://paleodyn.uni-bremen.de/study/climate2020_21.html

Repetition

The last glacial maximum (LGM)

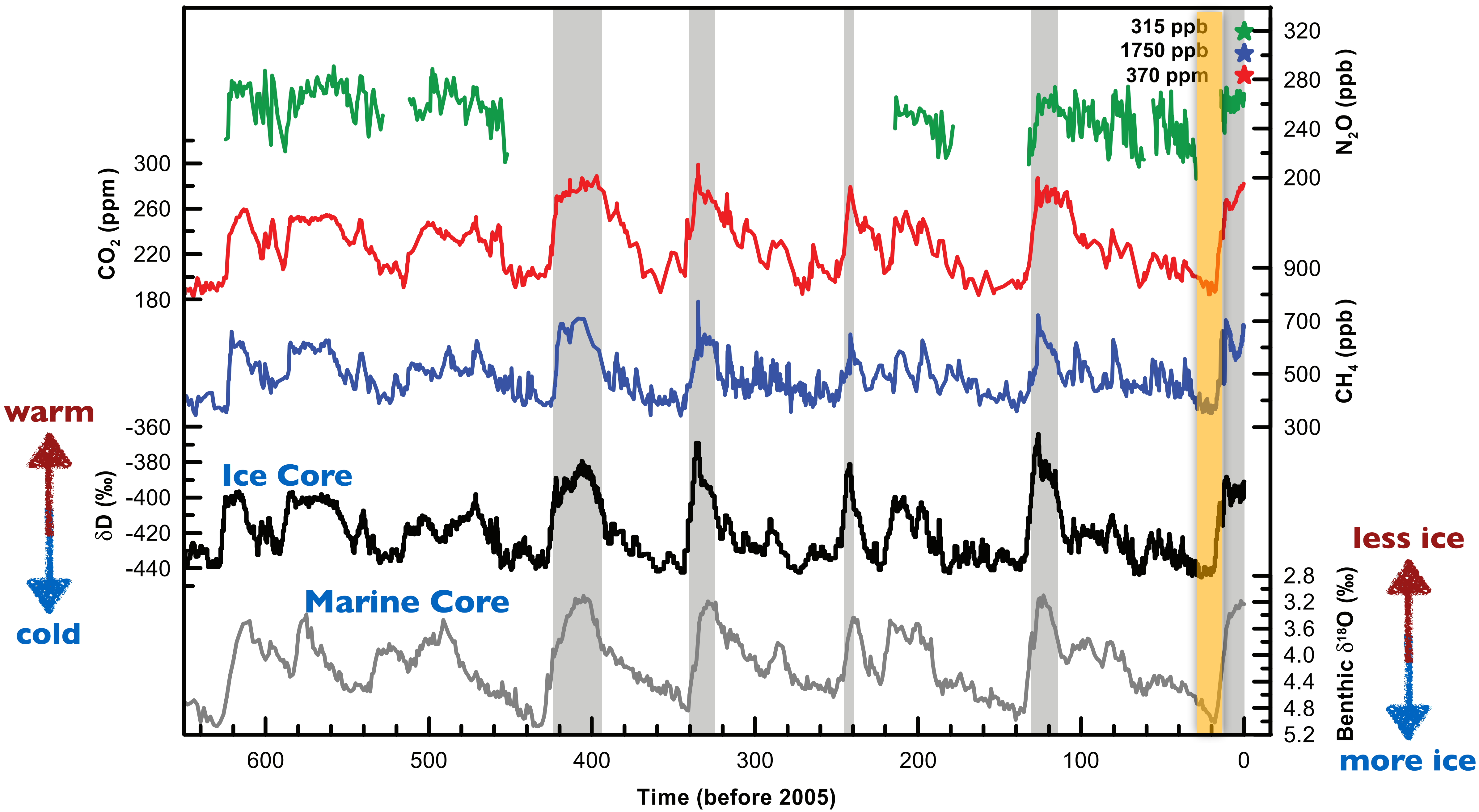


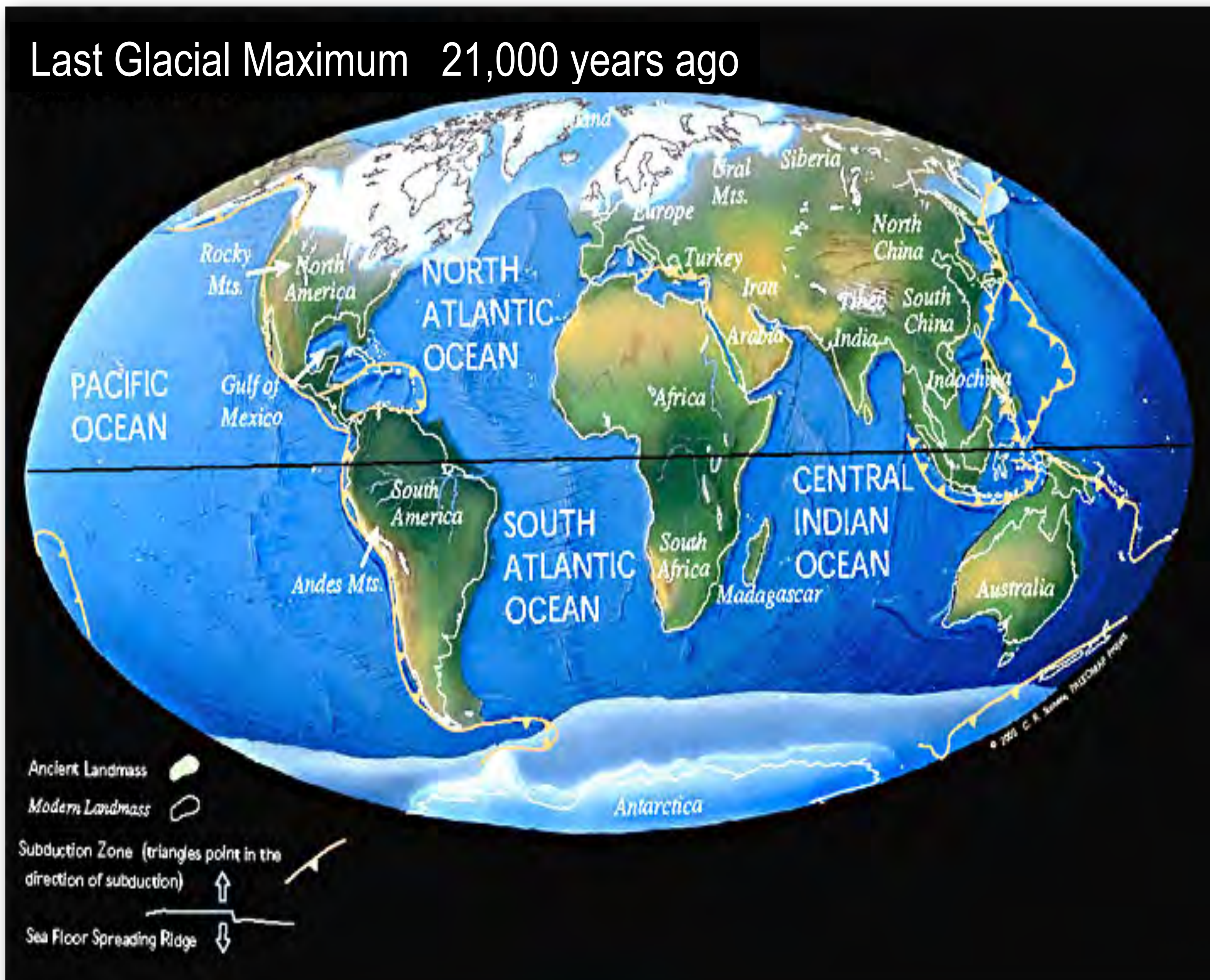
Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit et al., 1999; Indermühle et al., 2000; EPICA community members, 2004; Spahni et al., 2005; Siegenthaler et al., 2005a,b). The shading indicates the last interglacial warm periods. Interglacial periods also existed prior to 450 ka, but these were apparently colder than the typical interglacials of the latest Quaternary. The length of the current interglacial is not unusual in the context of the last 650 kyr. The stack of 57 globally distributed benthic $\delta^{18}O$ marine records (dark grey), a proxy for global ice volume fluctuations (Lisiecki and Raymo, 2005), is displayed for comparison with the ice core data. Downward trends in the benthic $\delta^{18}O$ curve reflect increasing ice volumes on land. Note that the shaded vertical bars are based on the ice core age model (EPICA community members, 2004), and that the marine record is plotted on its original time scale based on tuning to the orbital parameters (Lisiecki and Raymo, 2005). The stars and labels indicate atmospheric concentrations at year 2000.*

IPCC, 2007

Repetition

Overview: the last glacial maximum

- approx. 21,000 years before present (end of the last glacial period)
- CO_2 and other greenhouse gases were much lower than during warm interglacials
- North America and Eurasia were covered by large ice sheets
- sea level was lower by approx. 108m



Repetition

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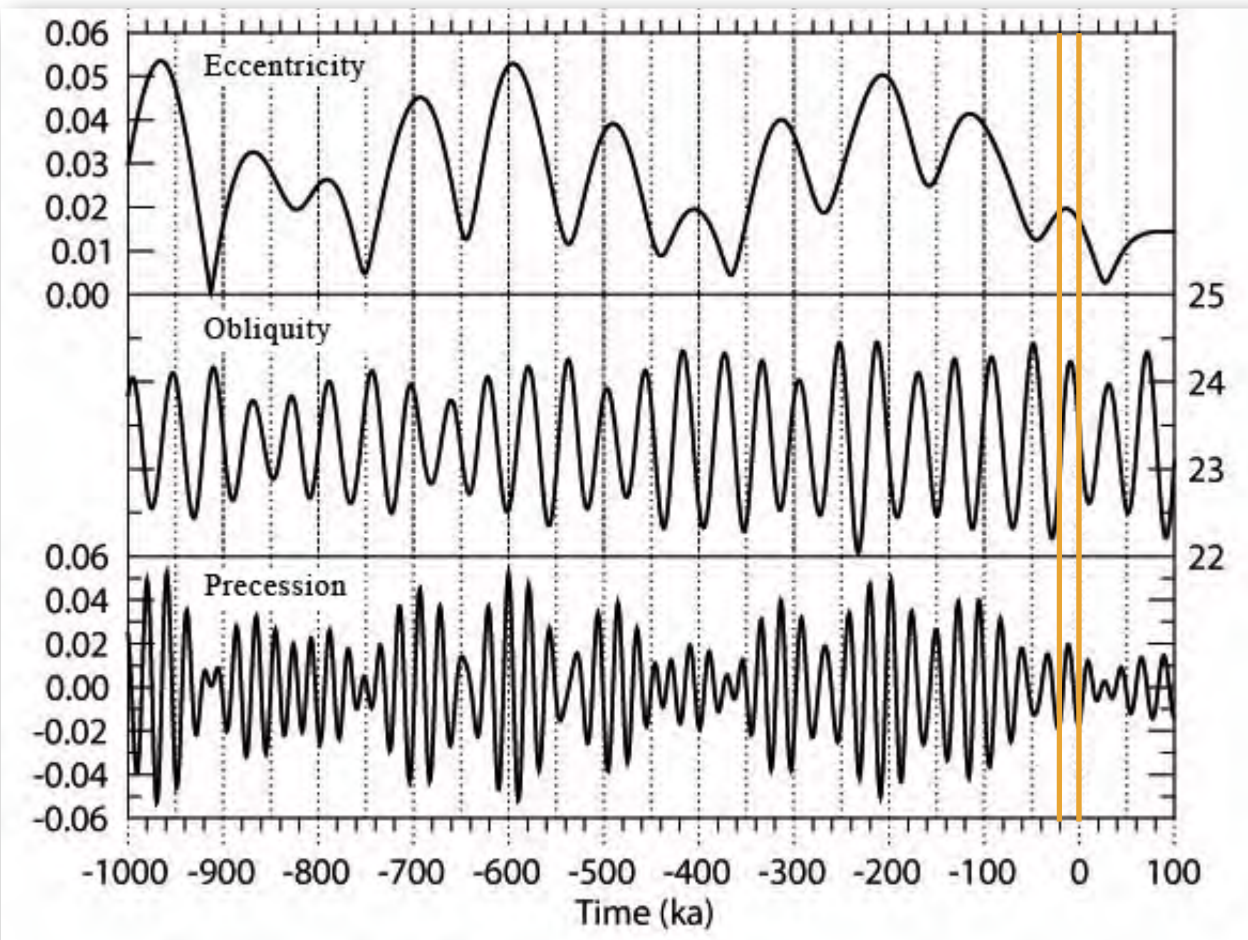
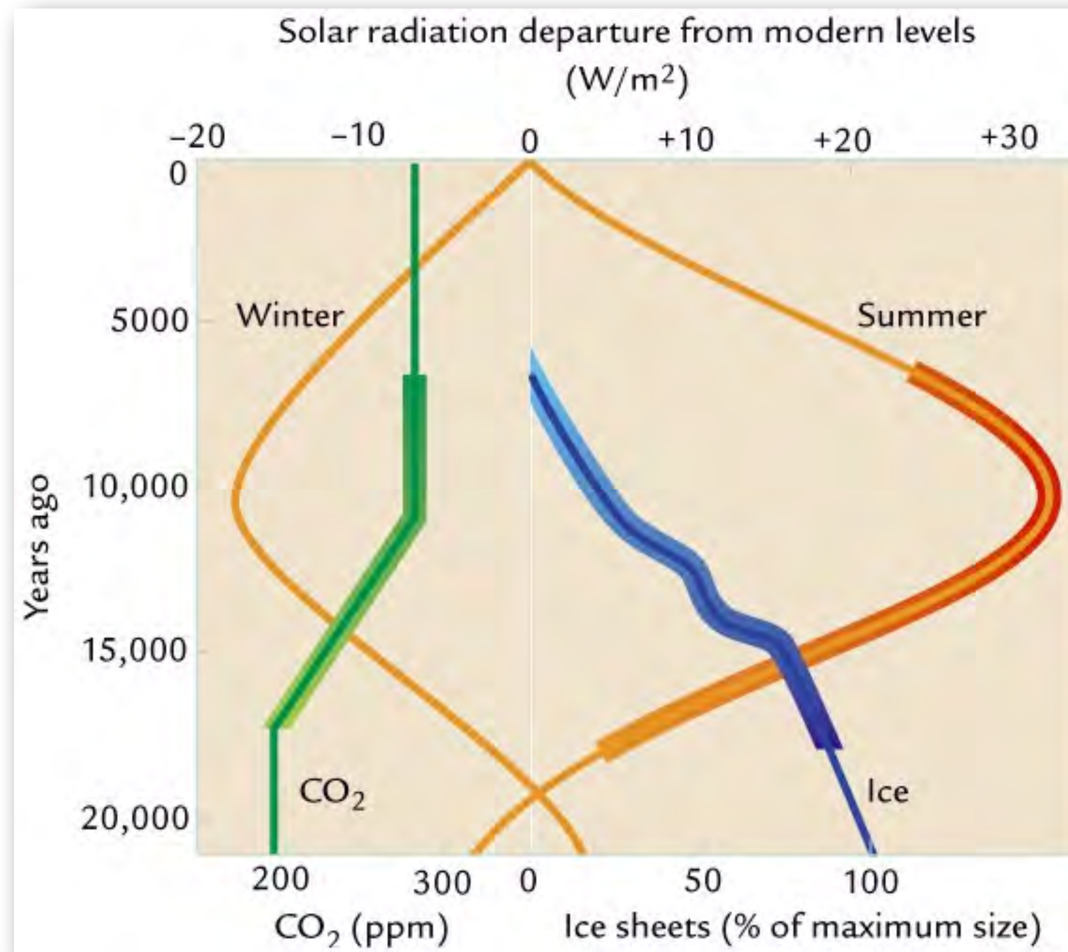
- CO_2 and other greenhouse gases were much lower than during warm interglacials
- North America and Eurasia were covered by large ice sheets
- sea level was lower by approx. 108m
- incoming solar insolation was comparable to present-day



(http://www.elic.ucl.ac.be/textbook/chapter5_node12.xml, calculated from Berger, 1978)



(from Ruddiman, 2008)

Climate of the LGM - key information from ice cores

Repetition

LGM climate in Greenland & Antarctica - summary

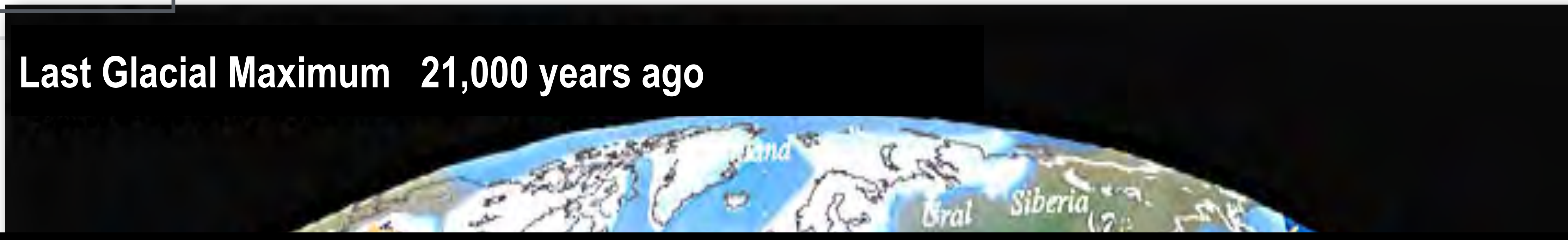
- **temperature difference** between LGM and present-day:
  - **strong cooling on Greenland**: -20…-23°C (from $\delta^{18}O$ and other methods), **medium cooling on Antarctica**: -5…-12°C (from δD)

- **precipitation rate** during LGM: reduced by ca. 40-70%

- **greenhouse gases (CO_2, CH_4) at minimum level during the LGM** (e.g. CO2: pre-industrial: 280ppm, LGM: 180ppm)

- extrem strong **correlation between T_{Surf} (local change) and CO_2 & CH_4 (global change)**, eben for smaller scale variations

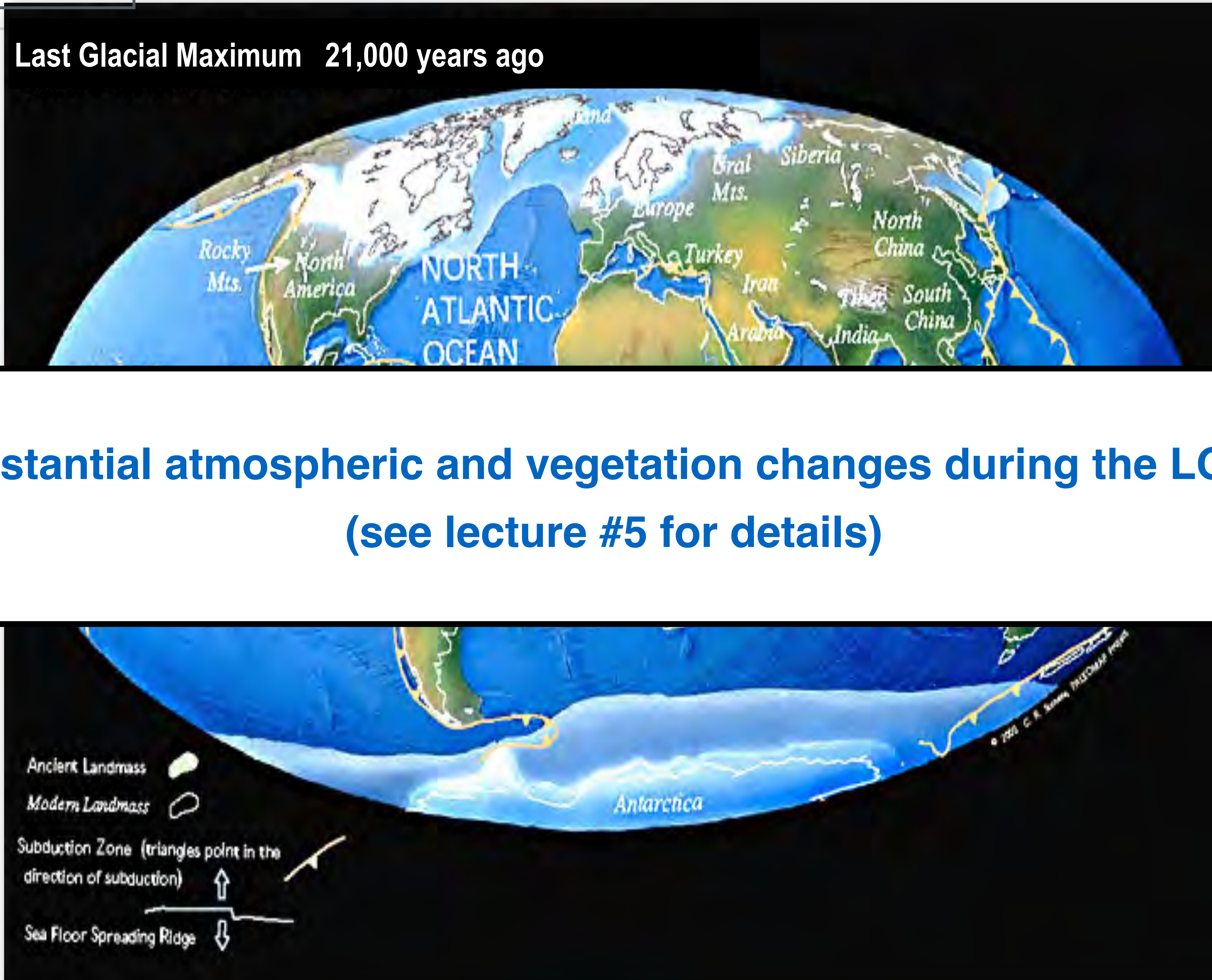
- temperature changes and **global ice volume** correlate well, too



How cold were the oceans and the tropics?

- the LGM cooling in the tropics was „medium-small“, between -1…-3°C
- MARGO data suggests even a slight warming in some tropical regions
  - *this warming is still under discussion*
    (e.g., such warming can’t be reproduced by climate models)
- land-based estimate show in some regions a cooling of up to -5°C

Repetition



Substantial atmospheric and vegetation changes during the LGM…

(see lecture #5 for details)

Repetition

The last glacial maximum (LGM)

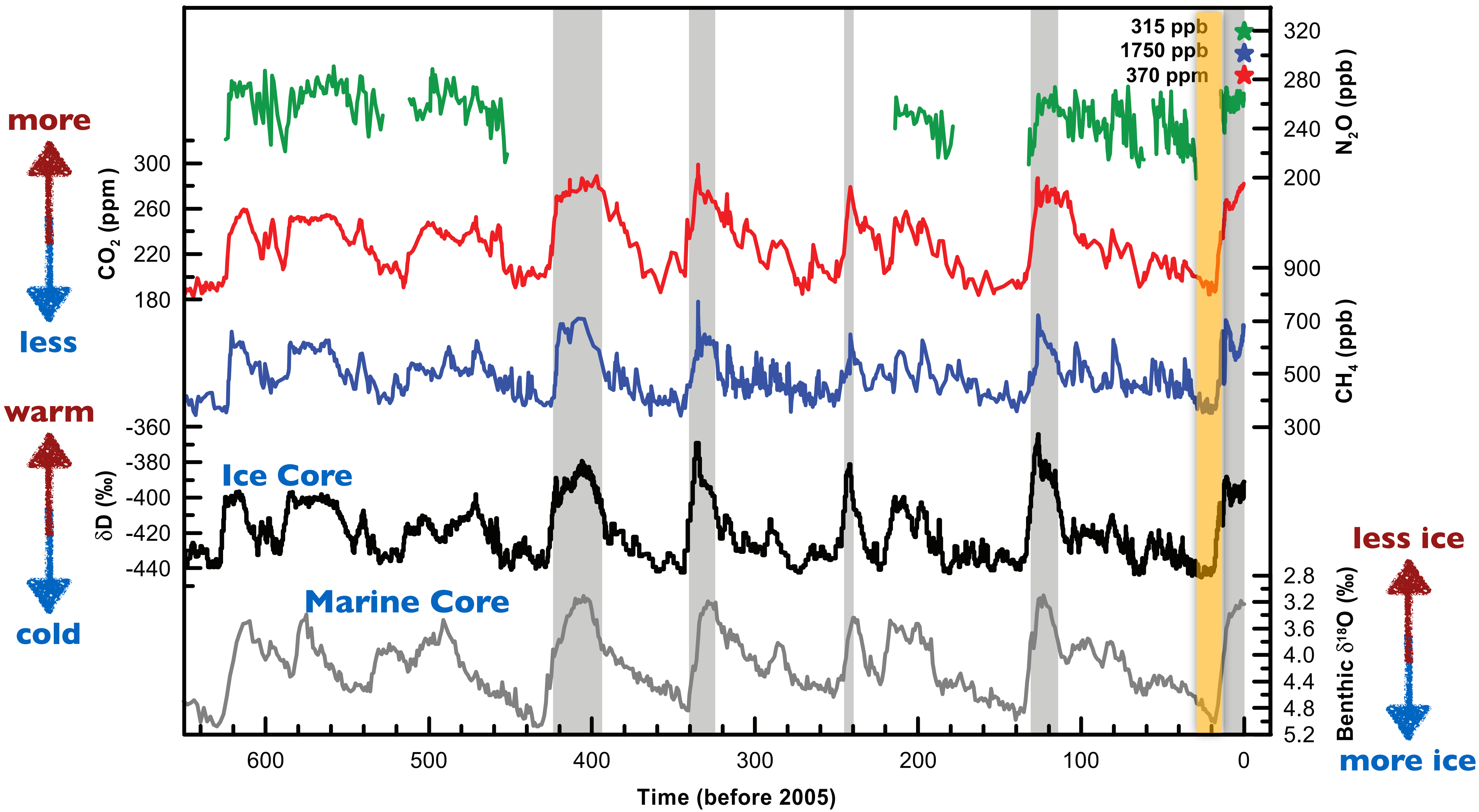


Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit et al., 1999; Indermühle et al., 2000; EPICA community members, 2004; Spahni et al., 2005; Siegenthaler et al., 2005a,b). The shading indicates the last interglacial warm periods. Interglacial periods also existed prior to 450 ka, but these were apparently colder than the typical interglacials of the latest Quaternary. The length of the current interglacial is not unusual in the context of the last 650 kyr. The stack of 57 globally distributed benthic $\delta^{18}O$ marine records (dark grey), a proxy for global ice volume fluctuations (Lisiecki and Raymo, 2005), is displayed for comparison with the ice core data. Downward trends in the benthic $\delta^{18}O$ curve reflect increasing ice volumes on land. Note that the shaded vertical bars are based on the ice core age model (EPICA community members, 2004), and that the marine record is plotted on its original time scale based on tuning to the orbital parameters (Lisiecki and Raymo, 2005). The stars and labels indicate atmospheric concentrations at year 2000.*

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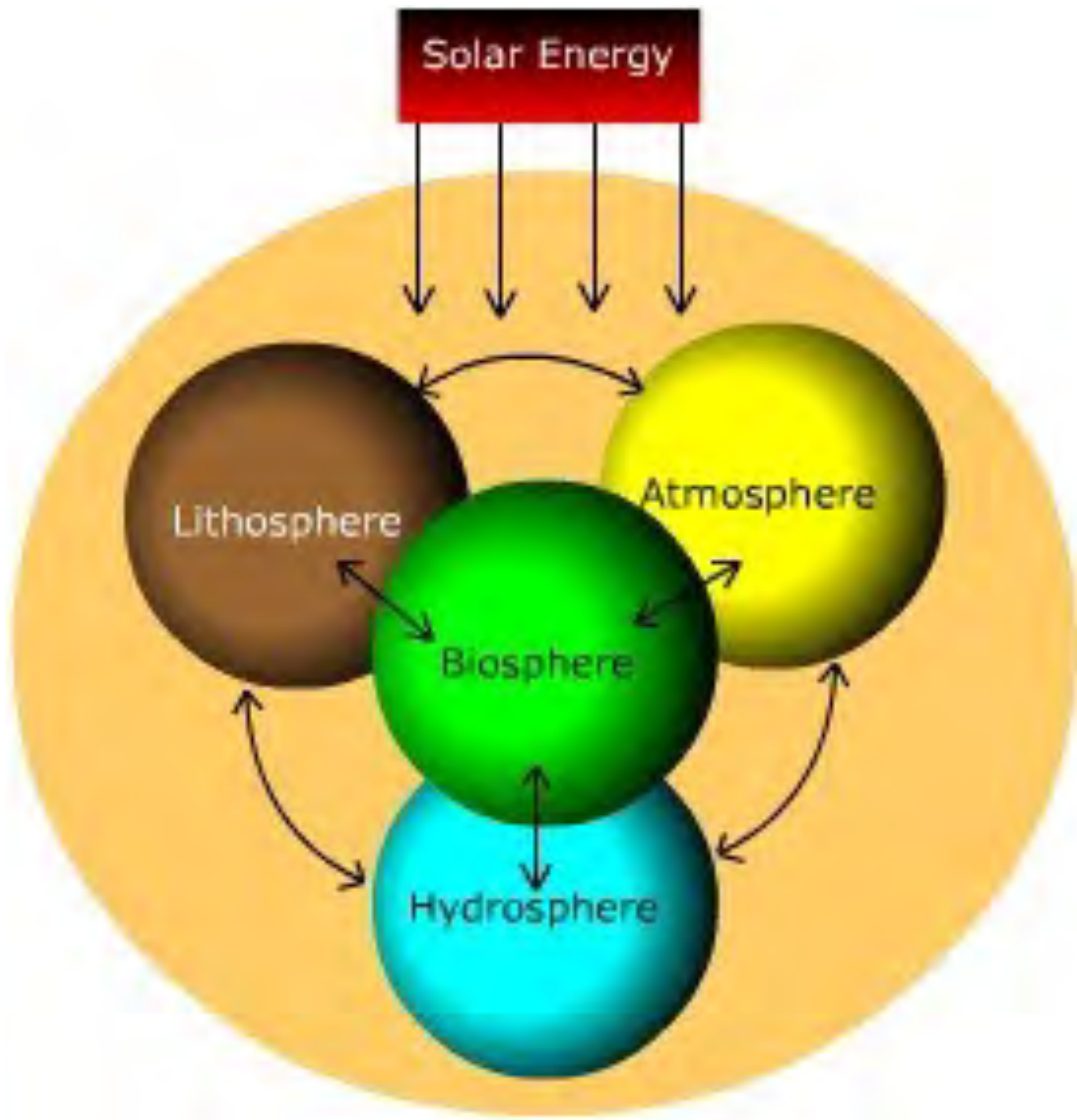
What are biogeochemical cycles?

- Earth system has four parts
  - *atmosphere*
  - *hydrosphere*
  - *lithosphere*
  - *biosphere*
- Biogeochemical cycles
  - *The chemical interactions (cycles) that exist between the atmosphere, hydrosphere, lithosphere, and biosphere*
- Abiotic (physio-chemical) and biotic processes drive these cycles

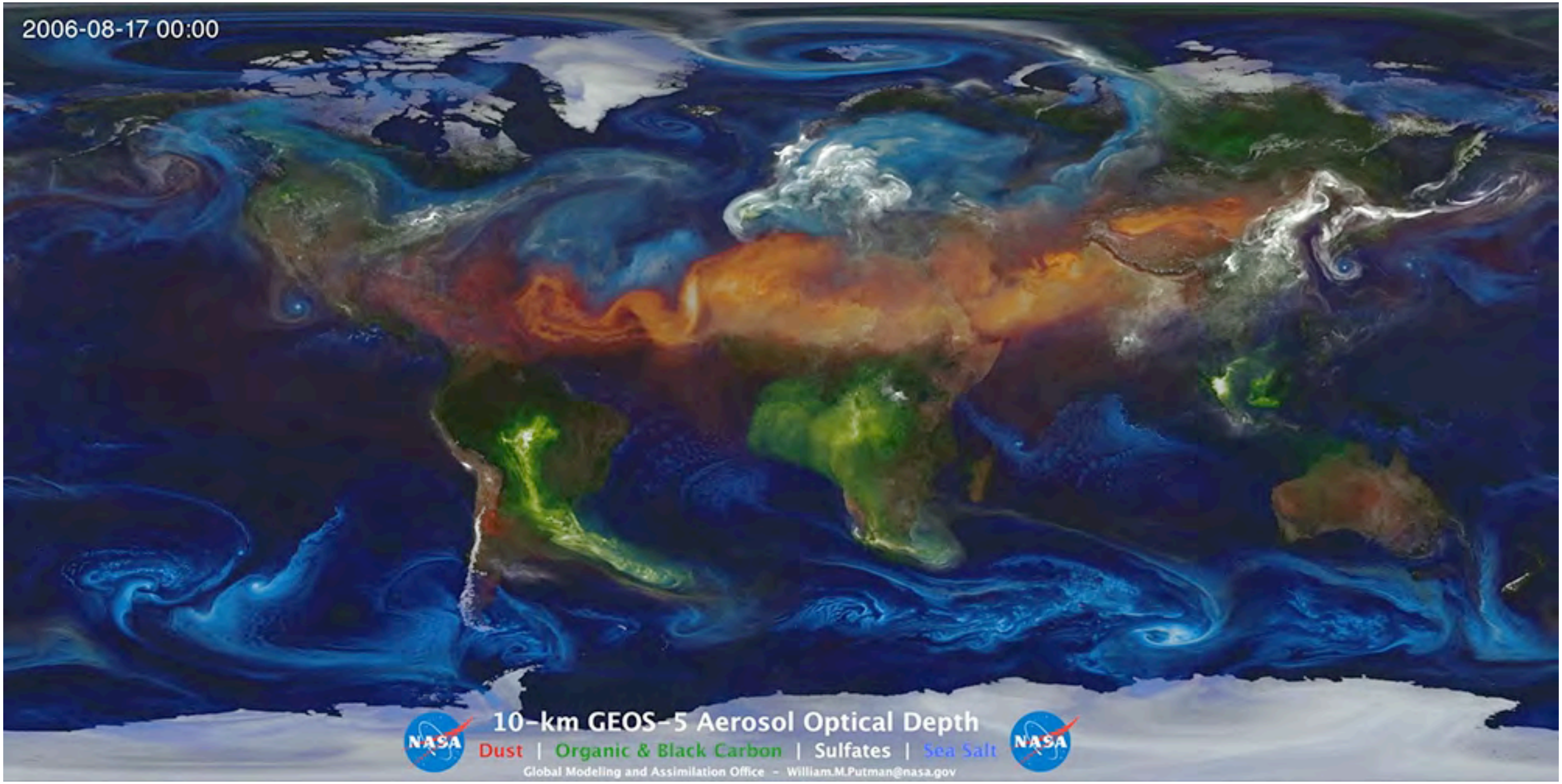


Biogeochemical cycles - key elements

Six nutrient elements make up 95% of the biomass mass on earth and form the biochemical foundation for life.

- **Carbon (CO_2, CH_4, CO)**
- **Nitrogen (N_2O, NO, NO_2, NH_3)**
- **Sulfur (SO_2, COS, H_2S, H_2SO_4)**
- **Phosphorous**
- **Hydrogen**
- **Oxygen**
- **Water**

Transport of dust and biogeochemical aerosols



Animation 1. Aerosol optical thickness of black and organic carbon (green), dust (red-orange), sulfates (white), and sea salt (blue) from a 10 km resolution GEOS-5 "nature run" using the GOCART model. The animation shows the emission and transport of key tropospheric aerosols from August 17, 2006 to April 10, 2007.

(http://gmao.gsfc.nasa.gov/research/aerosol/modeling/nr1_movie/)

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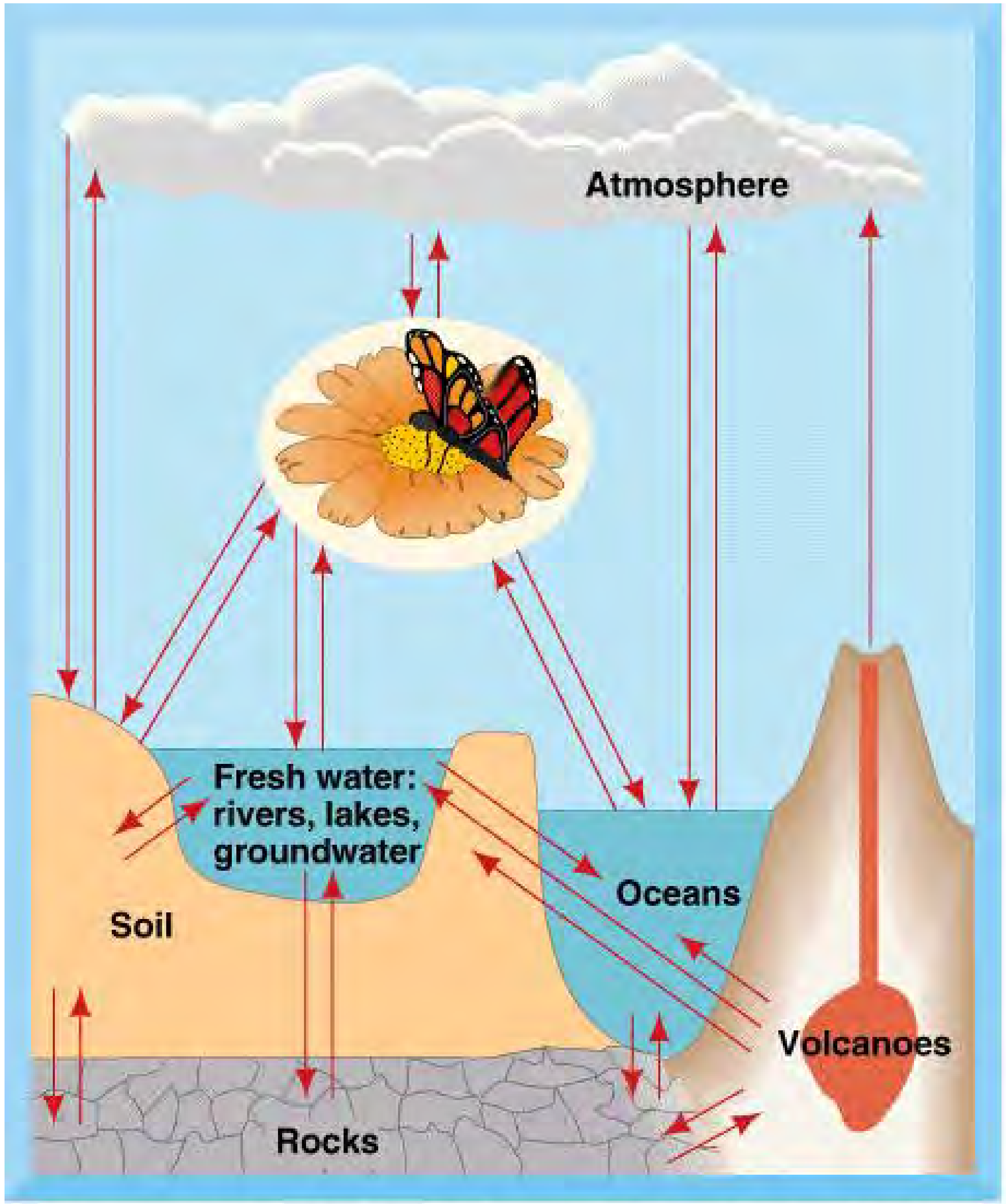
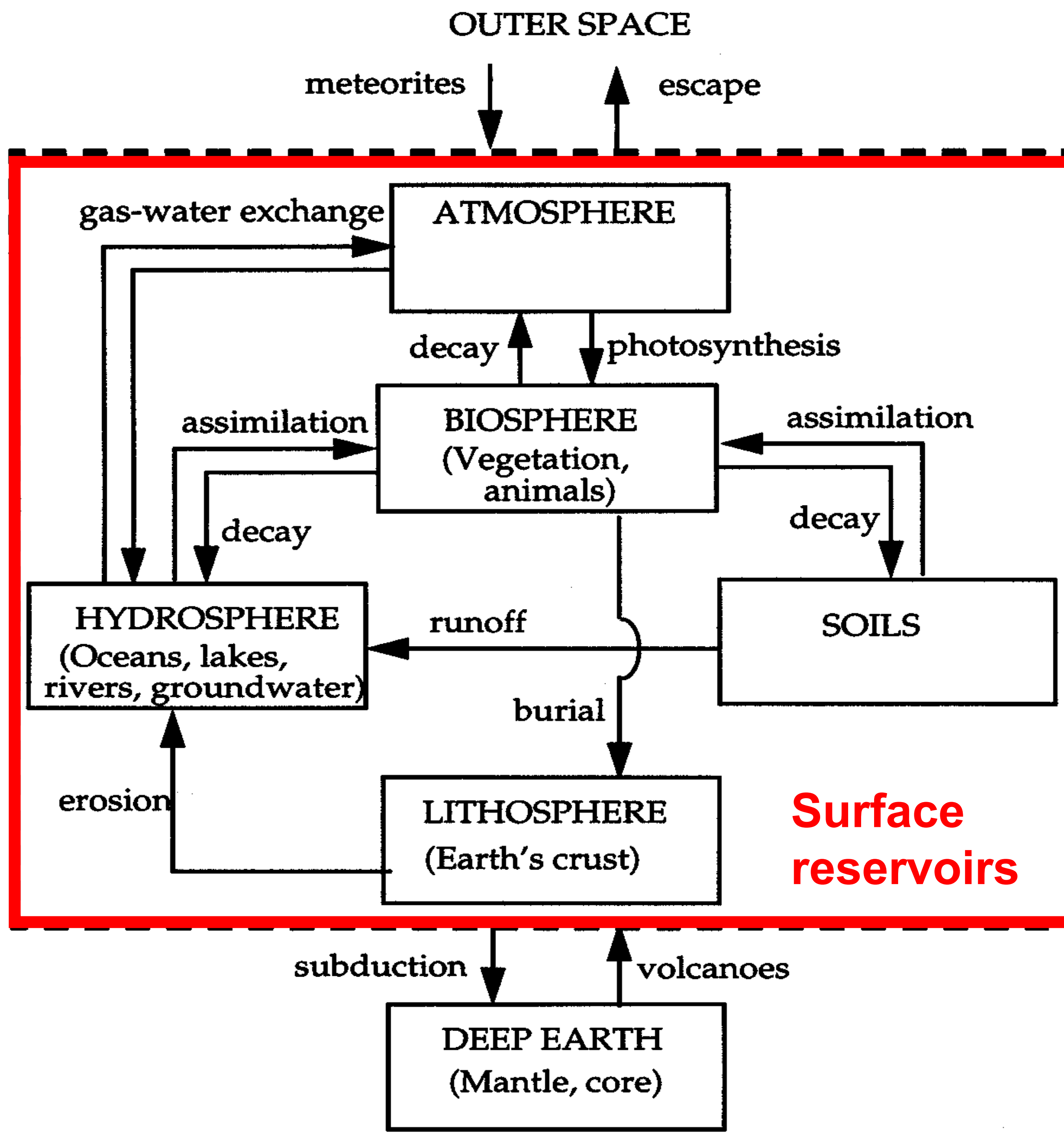
Biogeochemical cycles: Common features of all key elements

- **each element typically occurs in all four parts of the Earth System**
  (e.g. water, carbon, nitrogen, etc.)

- **each biogeochemical cycle can be described by**
  - ***pools***
  - ***fluxes in and out of pools***
  - ***chemical or biochemical transformations***

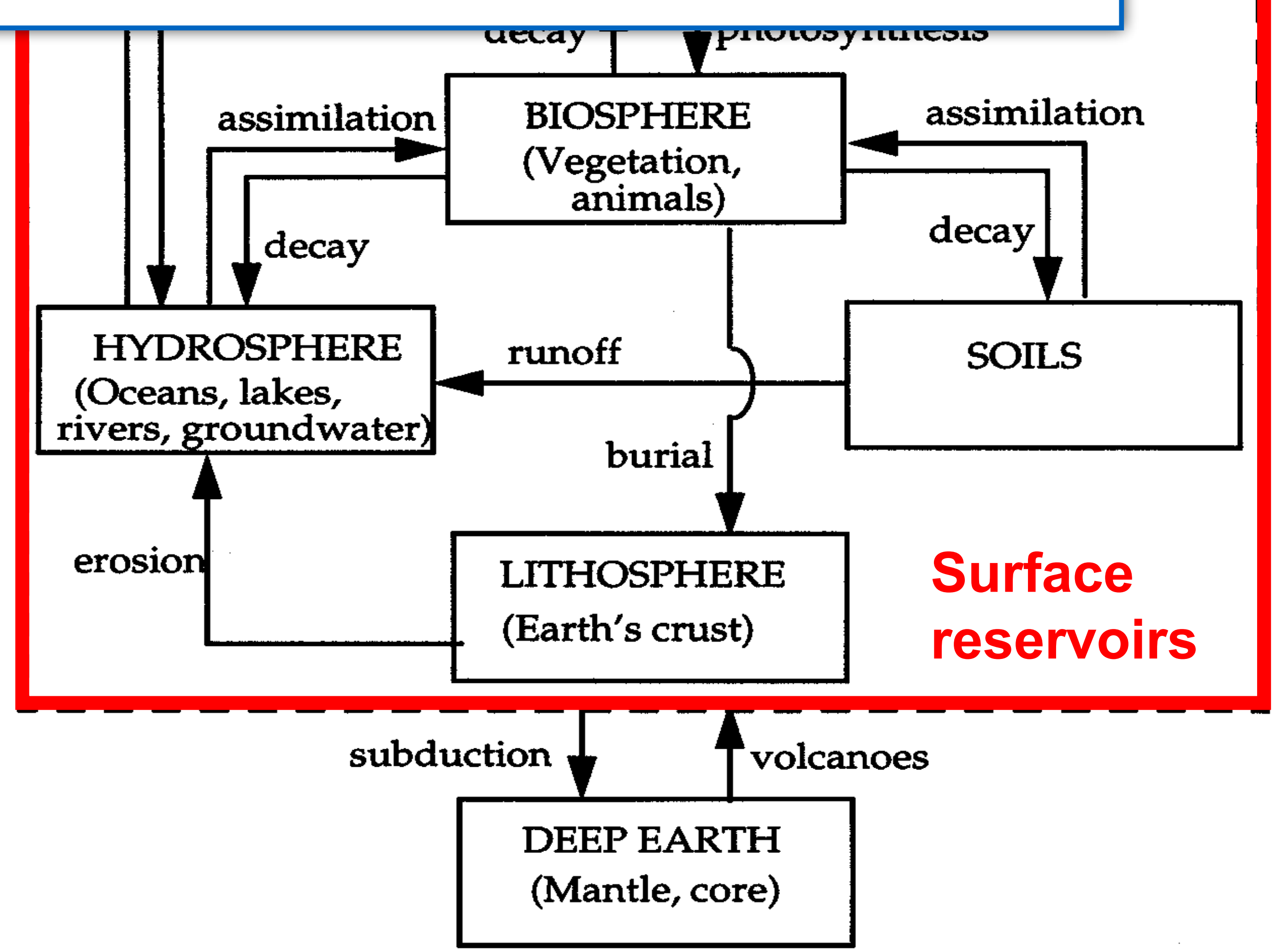

Atmosphere
Fresh water:
rivers, lakes,
groundwater
Oceans
Soil
Volcanoes
Rocks


OUTER SPACE
meteorites
escape
gas-water exchange
ATMOSPHERE
decay
photosynthesis
assimilation
BIOSPHERE
(Vegetation,
animals)
assimilation
decay
decay
HYDROSPHERE
(Oceans, lakes,
rivers, groundwater)
runoff
SOILS
burial
erosion
LITHOSPHERE
(Earth's crust)
Surface
reservoirs
subduction
volcanoes
DEEP EARTH
(Mantle, core)

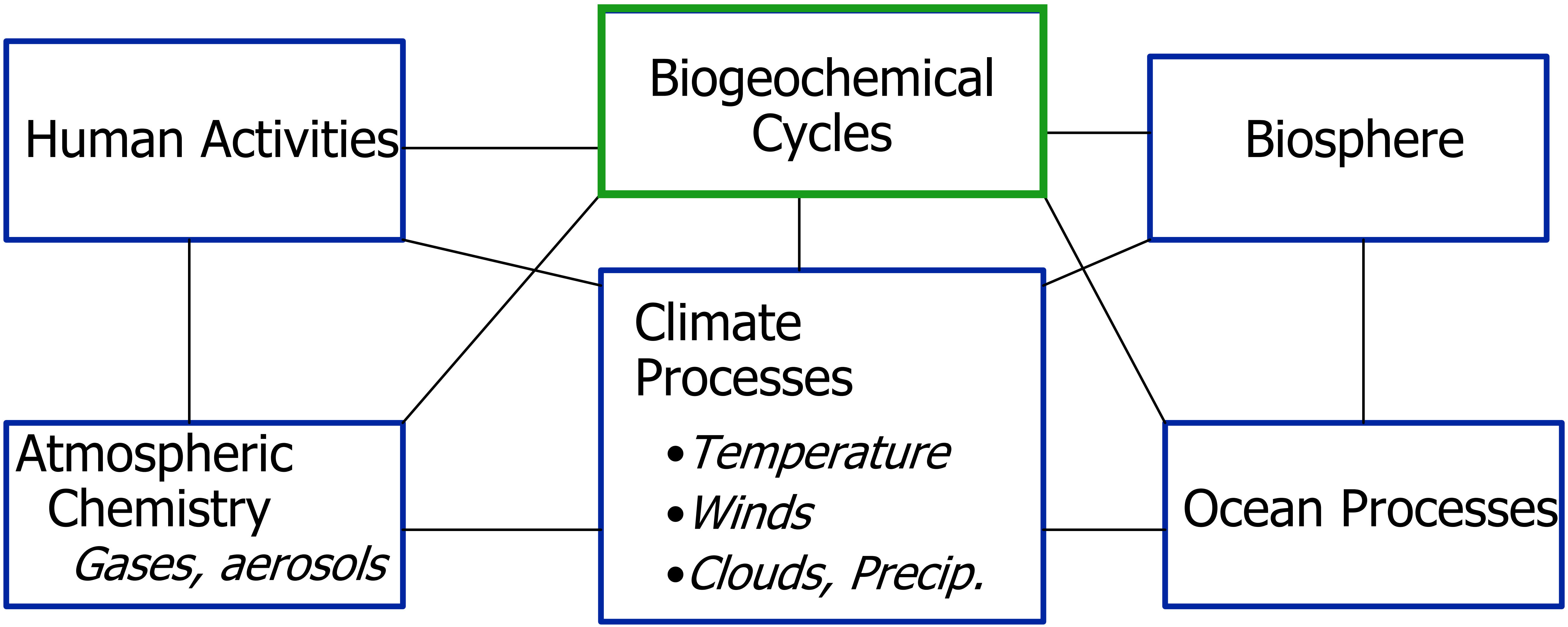
definition

turnover time τ is the size of a reservoir A, divided by the sum of all fluxes into (or out of) it $\sum F$, $\tau = A/\sum F$

- if there are only fluxes out of the reservoir, τ is how long it takes until the reservoir is empty
- if fluxes are balanced, τ is how long it takes until $1/e$-th of the original molecules is still in the reservoir



Biogeochemical cycles in climate research



Biogeochemical cycles are a key element for understanding our past and present climate!

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- Hydrogen
- Oxygen
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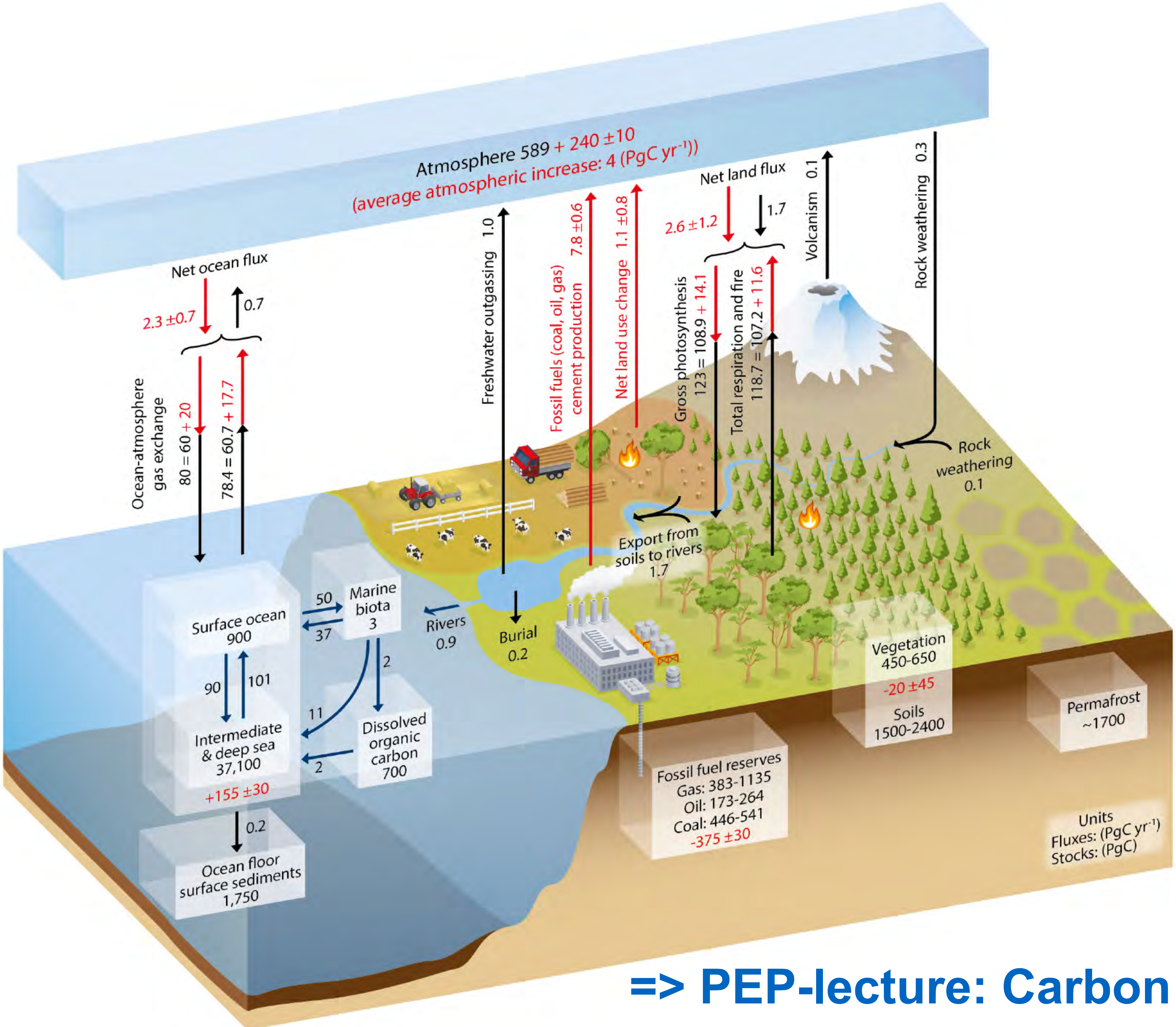
The global carbon cycle



=> PEP-lecture: Carbon Cycle

CO_2 sources and sinks

CO_2 sources

34.7 $GtCO_2$/yr
86%

14%
5.5 $GtCO_2$/yr

CO_2 sinks

17.9 $GtCO_2$/yr
44%

29%
11.5 $GtCO_2$/yr

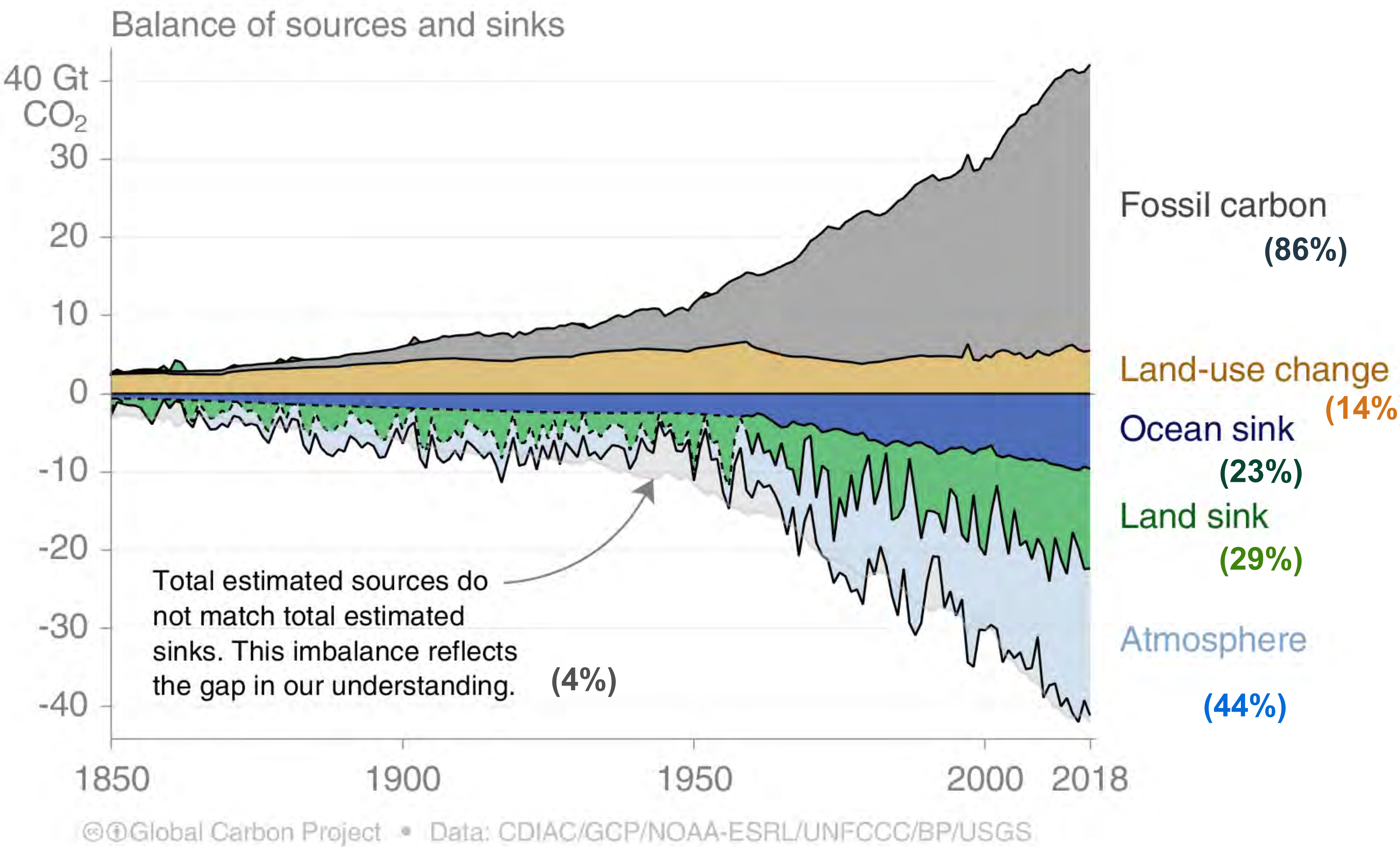
23%
9.2 $GtCO_2$/yr

CO_2 sources minus sinks: 4% 1.6 $GtCO_2$/yr

(all numbers for period 2009-2018)

[https://www.globalcarbonproject.org/carbonbudget/19/presentation.htm]

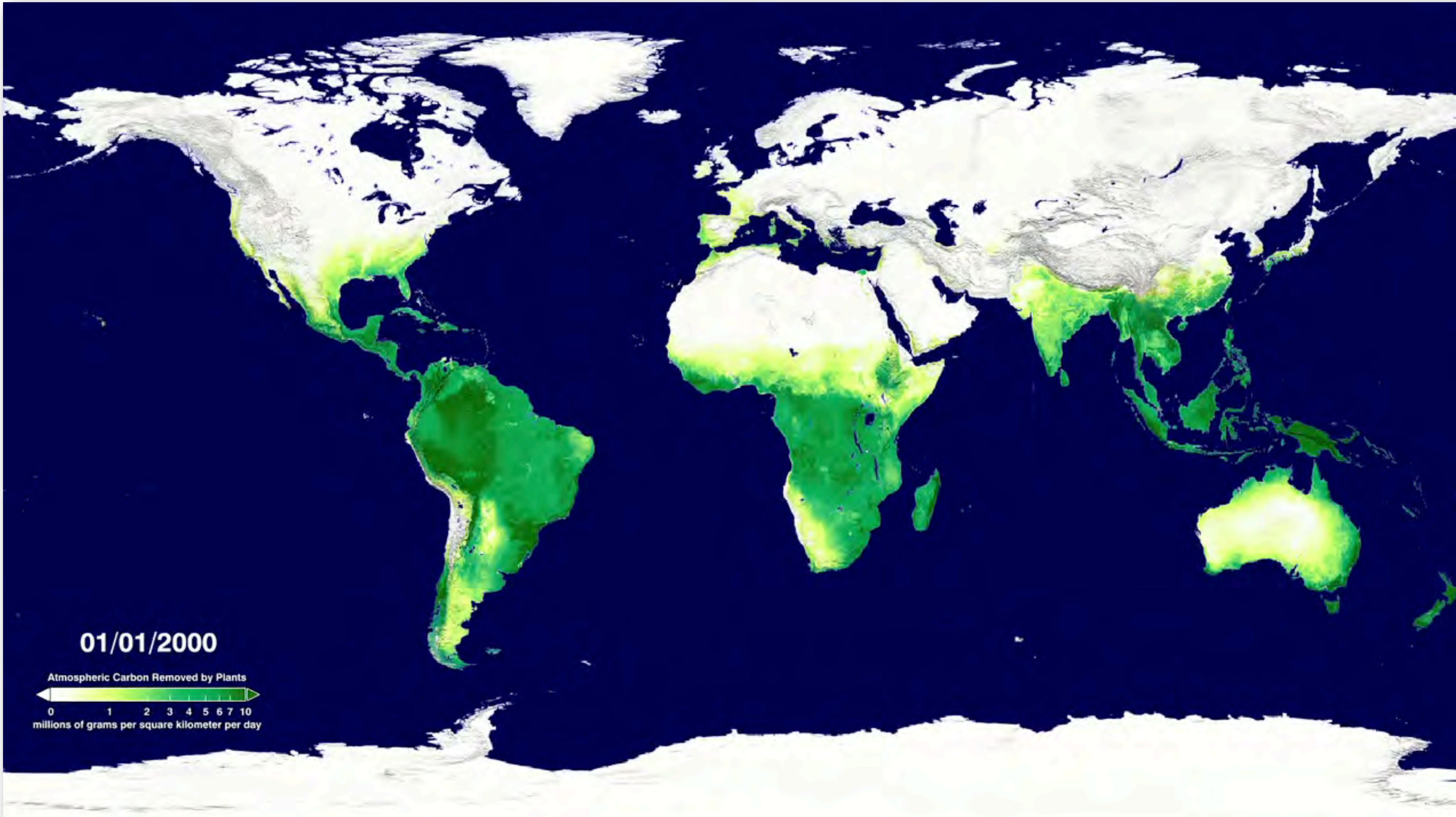
CO_2 sources and sinks



[[https://www.globalcarbonproject.org/carbonbudget/19/presentation.htm]]

(percentage for years 2009-2018)

Atmospheric carbon removed by plants



[http://svs.gsfc.nasa.gov/Gallery/index.html]

Carbon isotopes

- Relative abundance
  - ^{12}C 98.89 % stable
  - ^{13}C 1.11 % stable
  - ^{14}C 1×10^{-10} % half-life=5276 years
- ^{12}C and ^{13}C are stable isotopes
- ^{14}C is called radiocarbon
  - Formed by cosmic radiation ($^{14}N + {}^{1}n \rightarrow {}^{14}C + {}^{1}p$)
  - Also formed in nuclear explosions

Carbon isotopes

C^{12} and C^{13}

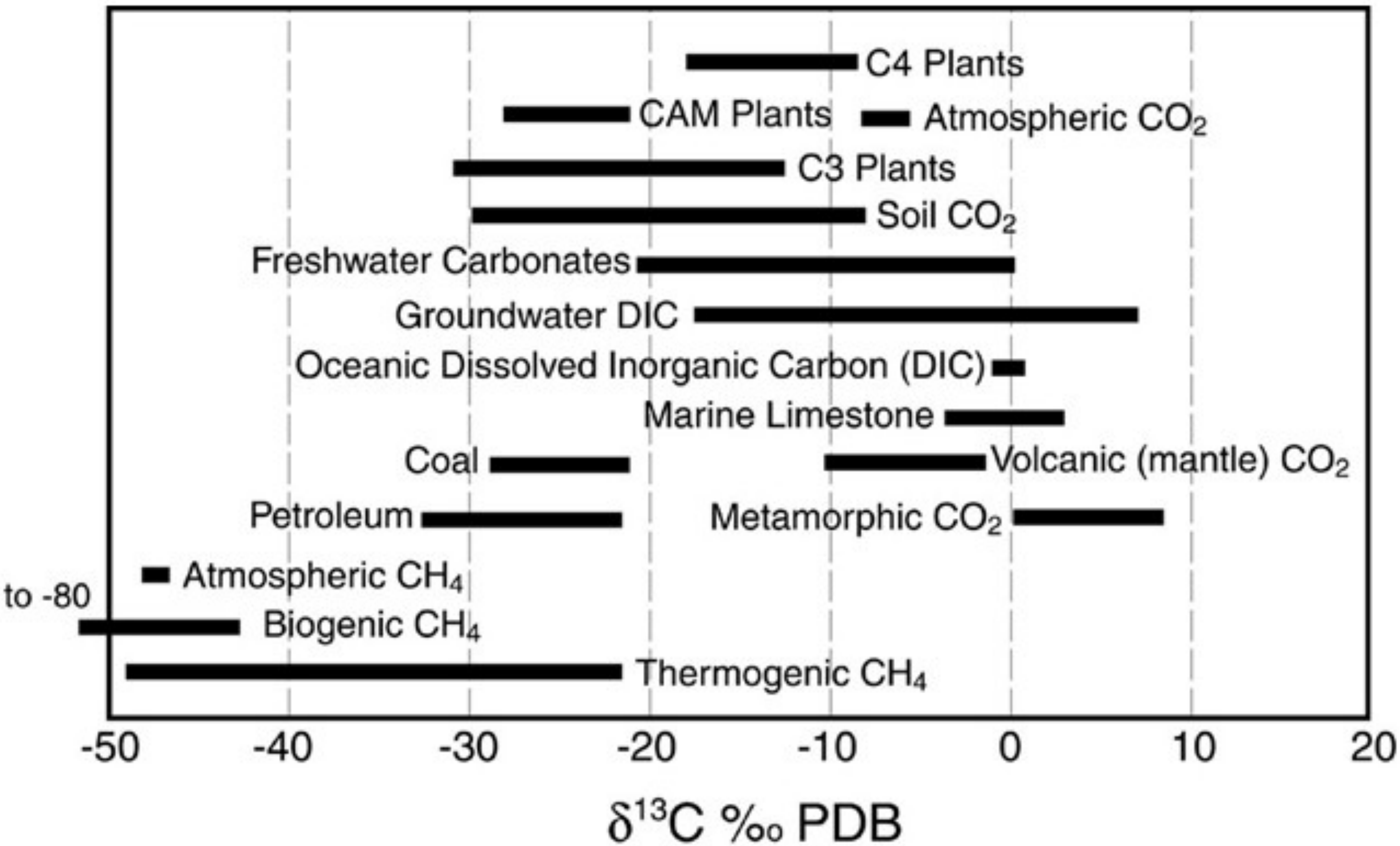
There are two stable isotopes of carbon; (there is also an unstable isotope of carbon, C^{14}!!).

The lighter isotope of carbon is preferentially used by plants in photosynthesis.

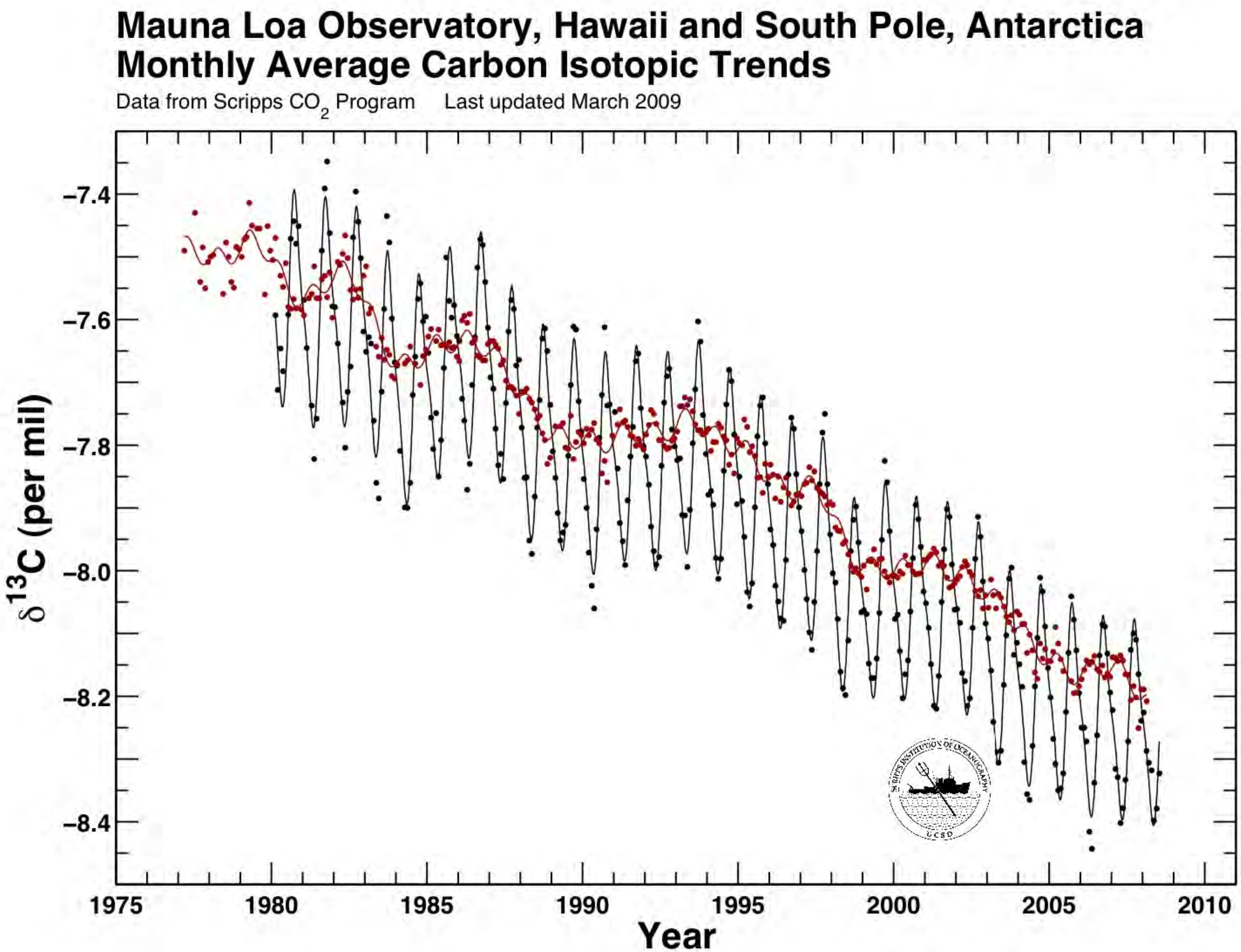
Therefore, if you have an atmosphere with fixed amounts of C^{12} and C^{13}, the removal of C^{12} into organic material will leave behind an atmosphere enriched in C^{13}.

One way to study why atmospheric CO_2 levels might be fluctuating is to study what the C^{12} and C^{13} ratios are, as plants will be enriched in C^{12} relative to C^{13} and the atmosphere the opposite.

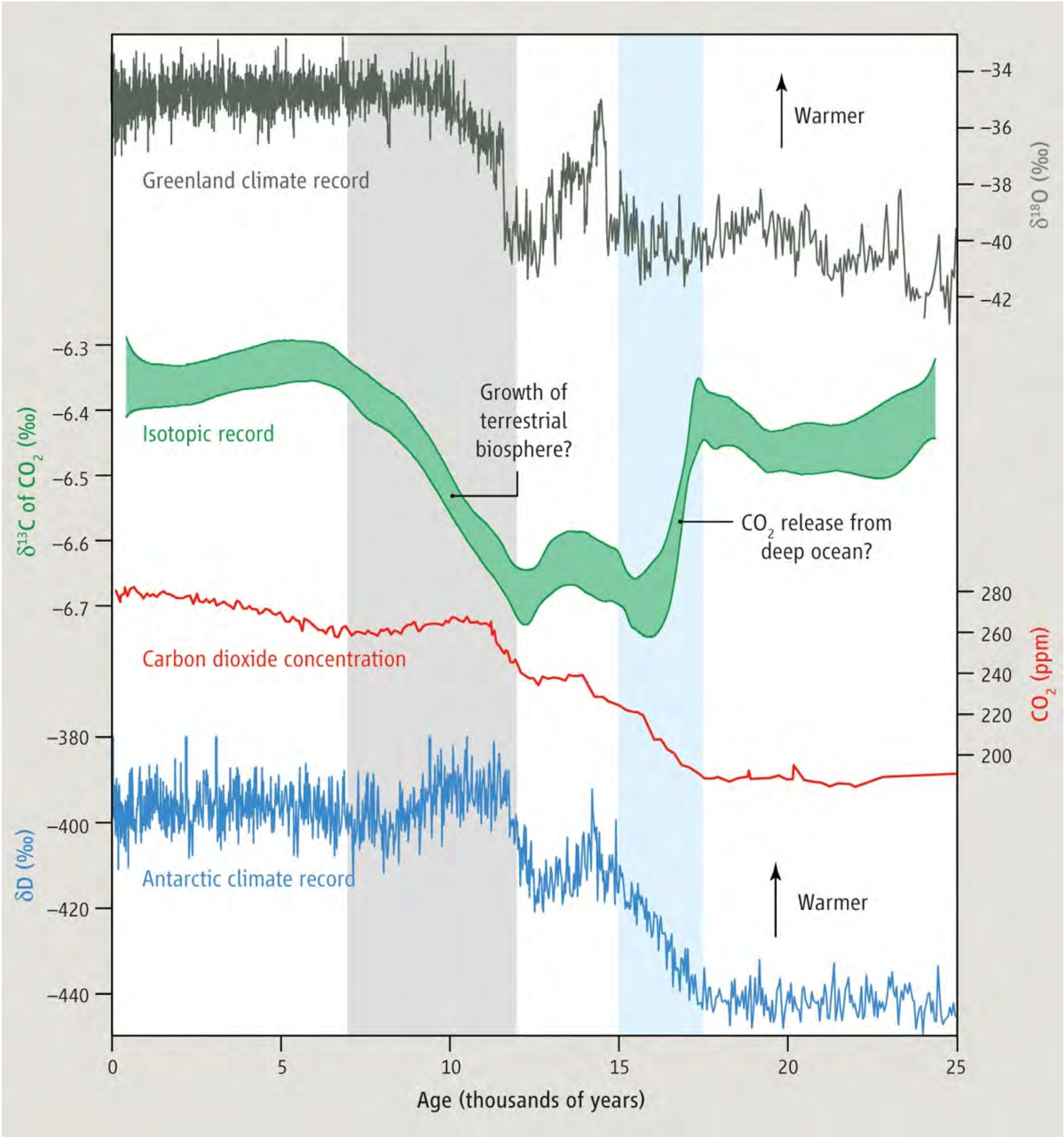
Variations of ^{13}C in different carbon pools



Variations of ^{13}C due to fossil fuel burning



Variations of ^{13}C since the last glacial maximum (LGM)



[Brook, The Ice Age Carbon Puzzle, Science, 2012]

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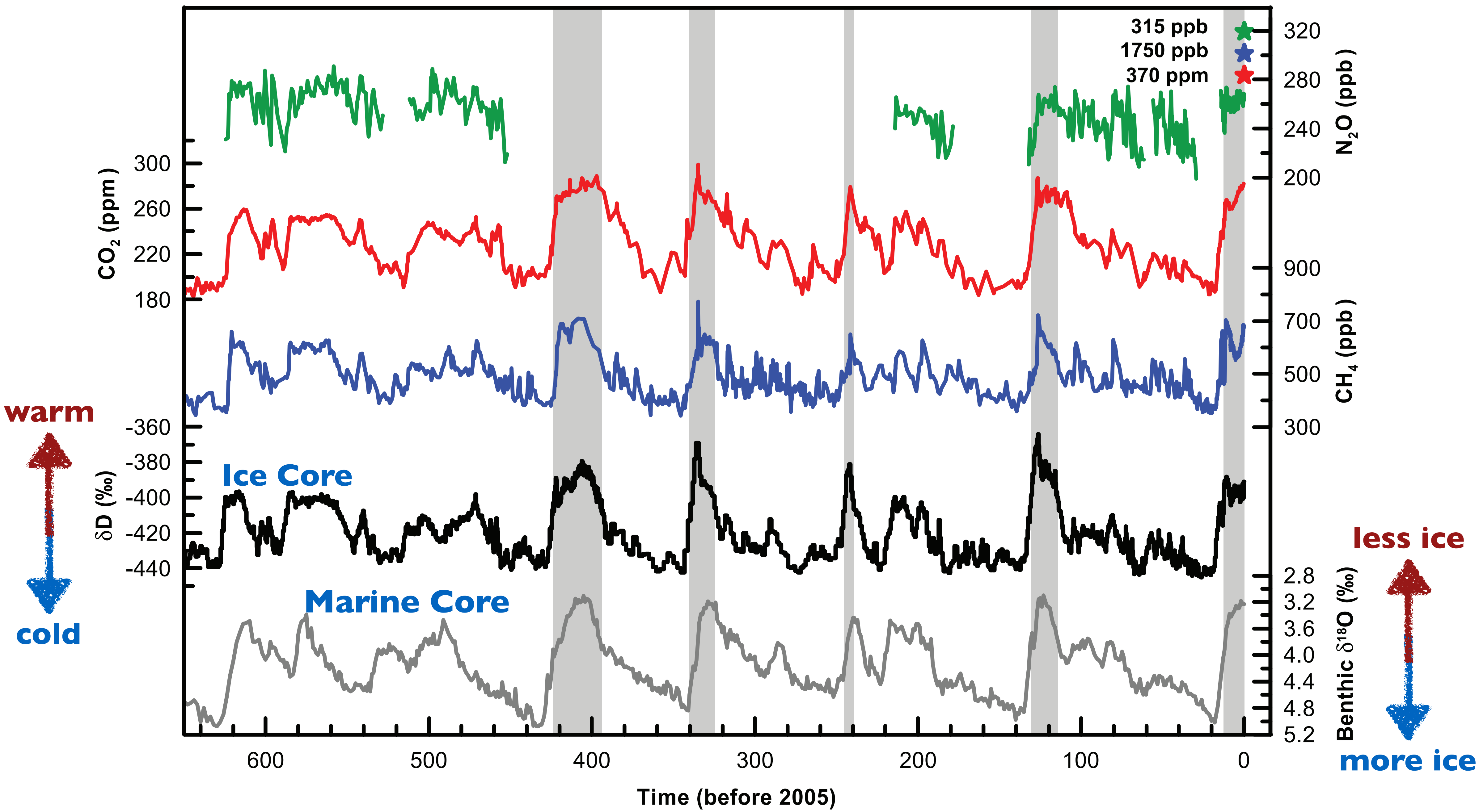
Nitrogen cycle: key points

- **Nitrogen is in the atmosphere as N_2 (78%)**
  - ***NO, $N_2$0, NO_2 - other gases of nitrogen***
- **N_2 is an inert gas and cannot be used by plants or animals**
- **N_2 can be converted to a usable form via**
  - ***Lightening***
  - ***N-fixing micro-organisms (free living, assoc. with plant)***
  - ***Industrial process (energy intensive)***
- **Nitrogen is easily converted & lost from biological systems (e.g., fire)**
- **N_2O is the 3rd most important greenhouse gas**

REMEMBER: Climate change on orbital time scales



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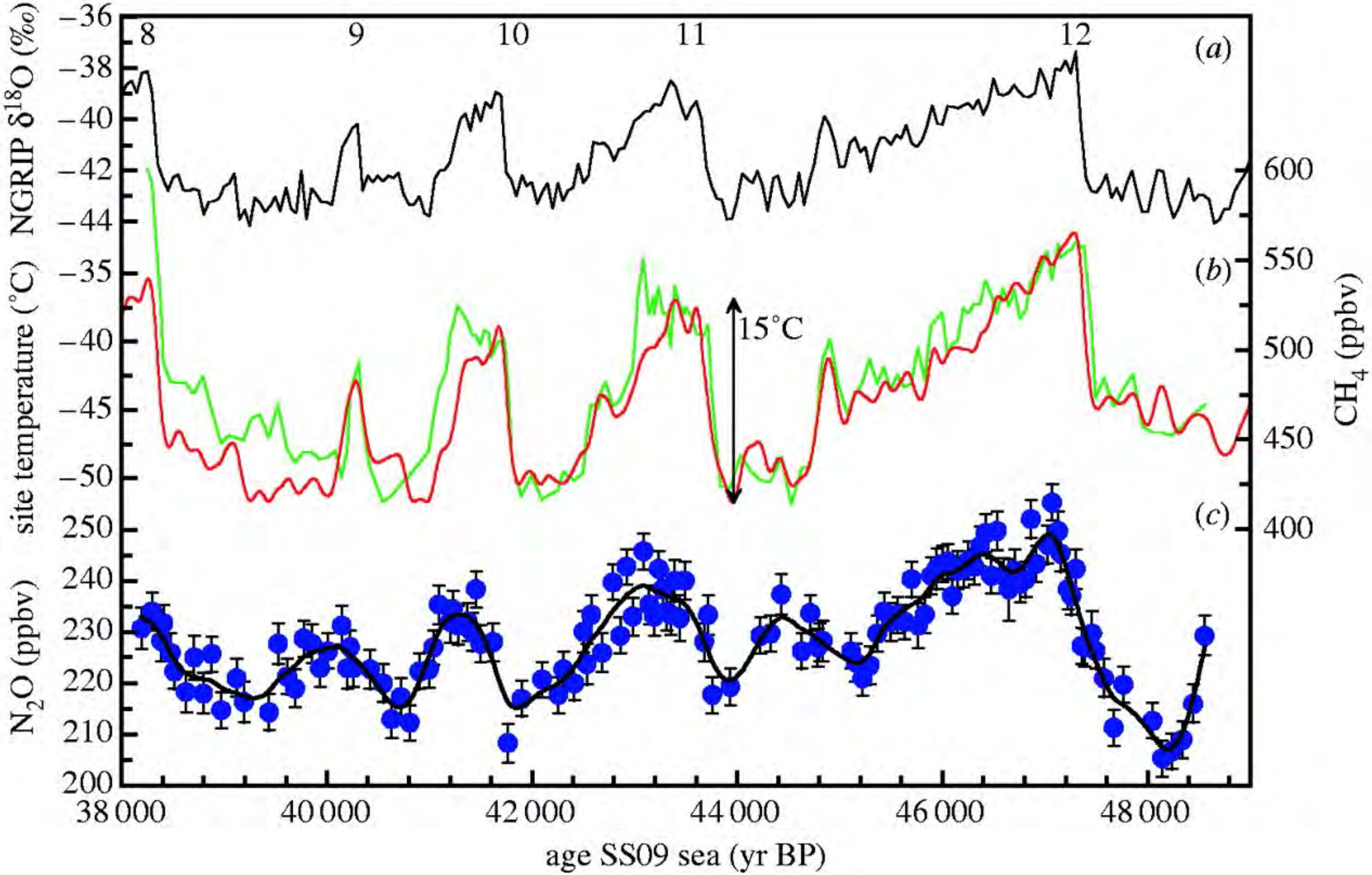
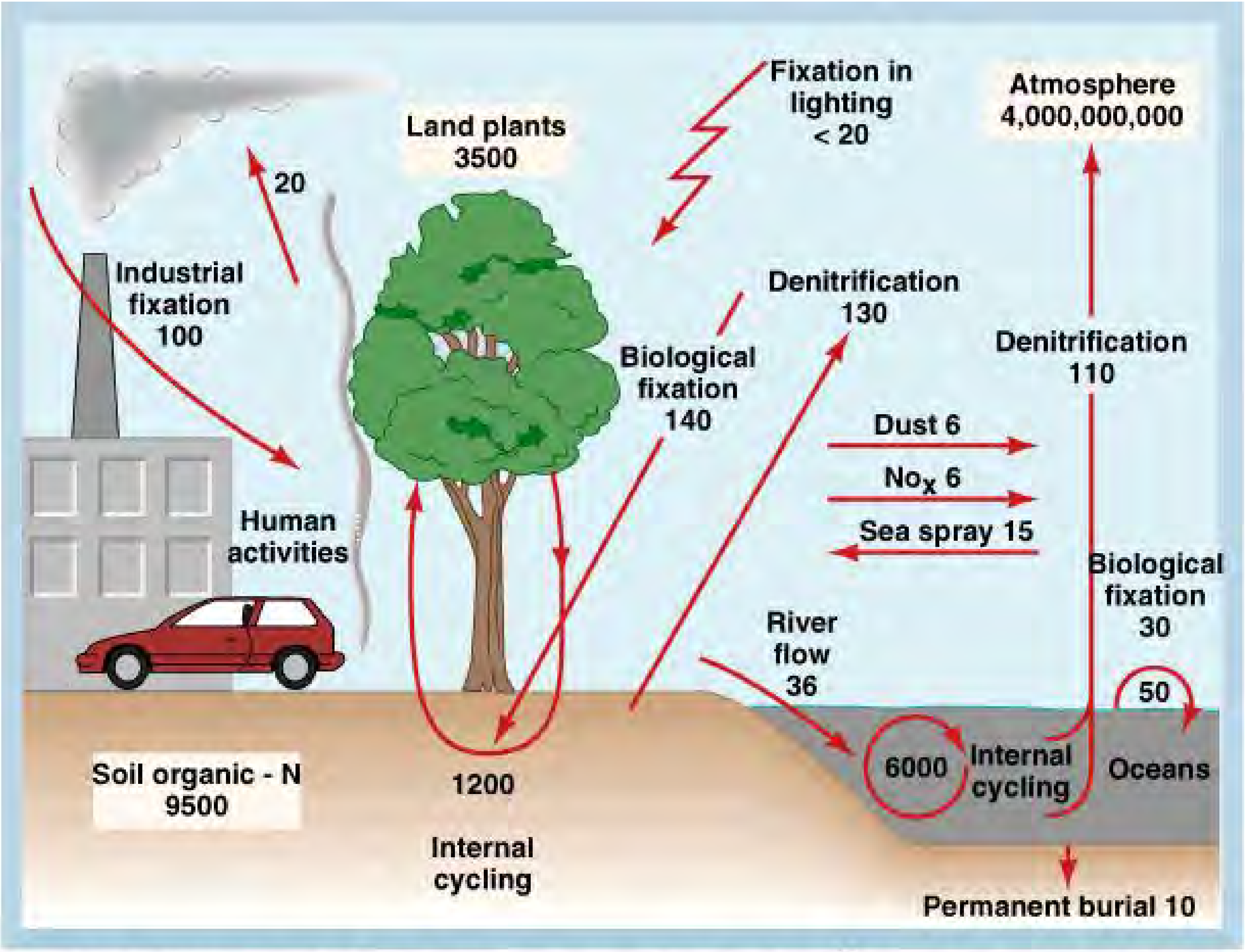
IPCC, 2007

Oxygen isotope (North Greenland Ice Core Project Members 2004), temperature (red; Huber et al. 2006), CH4 (green) and N2O (Flückiger et al. 2004) data from NorthGRIP, Greenland over the period of 38–49 kyr BP on the SS09_sea time-scale (Johnsen et al. 2001).



Eric Wolff, and Renato Spahni Phil. Trans. R. Soc. A 2007;365:1775-1792

The global nitrogen cycle



The global nitrogen cycle. Pools (□)and annual (→) flux in $10^{12}gN_2$. Note that the industrial fixation of nitrogen is nearly equal to the global biological fixation. (*SOURCE:* Data from Söderlund, and T. Rosswall, 1982 , O. Hutzinger (ed.), *The Handbook of Environmental Chemistry*, Vol 1, Pt. B., Springer-Verlag New York, Inc., New York).

Nitrous Oxide (N_2O) Budget

Table 4.4. Global Nitrous Oxide Budget (Tg(N)/yr)

Ref:	Mosier++(1998b) Kroeze++(1999)		Olivier++ (1998)		SAR	/ TAR
Base year :	1994		1990		1980 /	90s
Sources						
Ocean	3.0	*1-5*	3.6	*2.8-5.7*	3	
Atmos.(NH_3 oxid.)	0.6	*0.3-1.2*	0.6	*0.3-1.2*		
Tropical Soils						
Wet Forest	3.0	*2.2-3.7*			3	
Dry Savannas	1.0	*0.5-2.0*			1	
Temperate Soils						
Forests	1.0	*0.1-2.0*			1	
Grasslands	1.0	*0.5-2.0*			1	
All Soils			6.6	*3.3-9.9*		
Natural Subtotal	**9.6**	*4.6-15.9*	**10.8**	*6.4-16.8*	**9**	
Agricultural Soils	4.2	*0.6-14.8*	1.9	*0.7-4.3*	3.5	
Biomass Burning	0.5	*0.2-1.0*	0.5	*0.2-0.8*	0.5	
Industrial Sources	1.3	*0.7-1.8*	0.7	*0.2-1.1*	1.3	
Cattle and Feedlots	2.1	*0.6-3.1*	1.0	*0.2-2.0*	0.4	
Anthrop. Subtotal	**8.1**	*2.1-20.7*	**4.1**	*1.3-7.7*	**5.7**	**6.9**
Total Sources	**17.7**	*6.7-36.6*	**14.9**	*7.7-24.5*	**14.7**	
Imbalance (trend)	3.9	*3.1-4.7*			3.9	3.8
Total sinks (strat.)	12.3	*9-16*			12.3	12.6
Implied Total Source	**16.2**				**16.2**	**16.4**

- TAR anthropogenic N_2O emissions from SRES year-2000.

  SAR budget not in balance: sources ≠ sink + imbalance.

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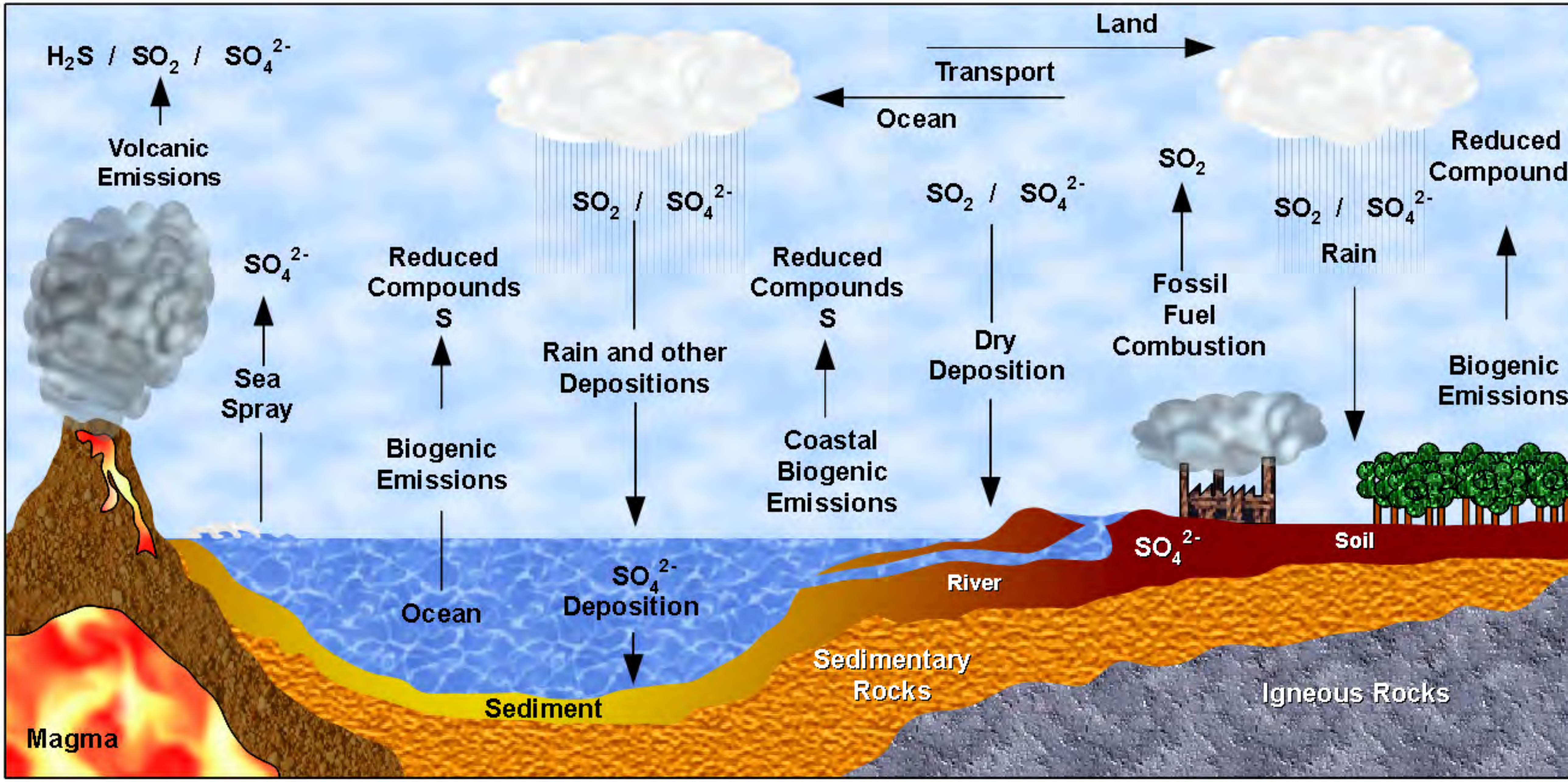
The importance of sulfur cycling

- **Sulfur, along with carbon, hydrogen, oxygen, nitrogen, and phosphorus, is one of the major constituents of living tissue.**
- **While this element is essential to life, it is also relatively abundant.**
- **It is therefore an** essential **plant nutrient, but not ordinarily a** limiting **plant nutrient.**
- **Plants take up SO_4^{2-} by reduction and incorporation into amino acids. It is released in many forms during decomposition.**

The global sulfur cycle



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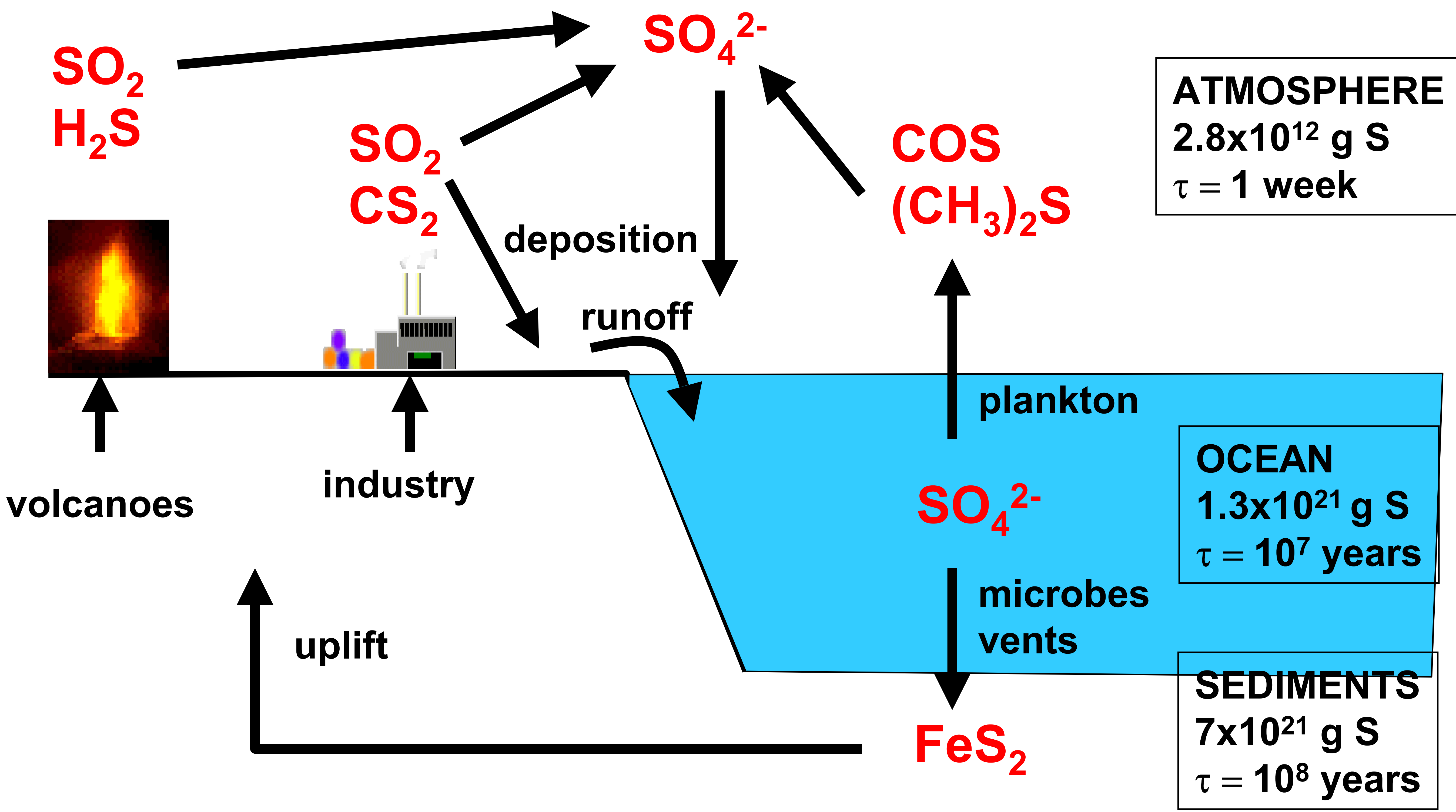

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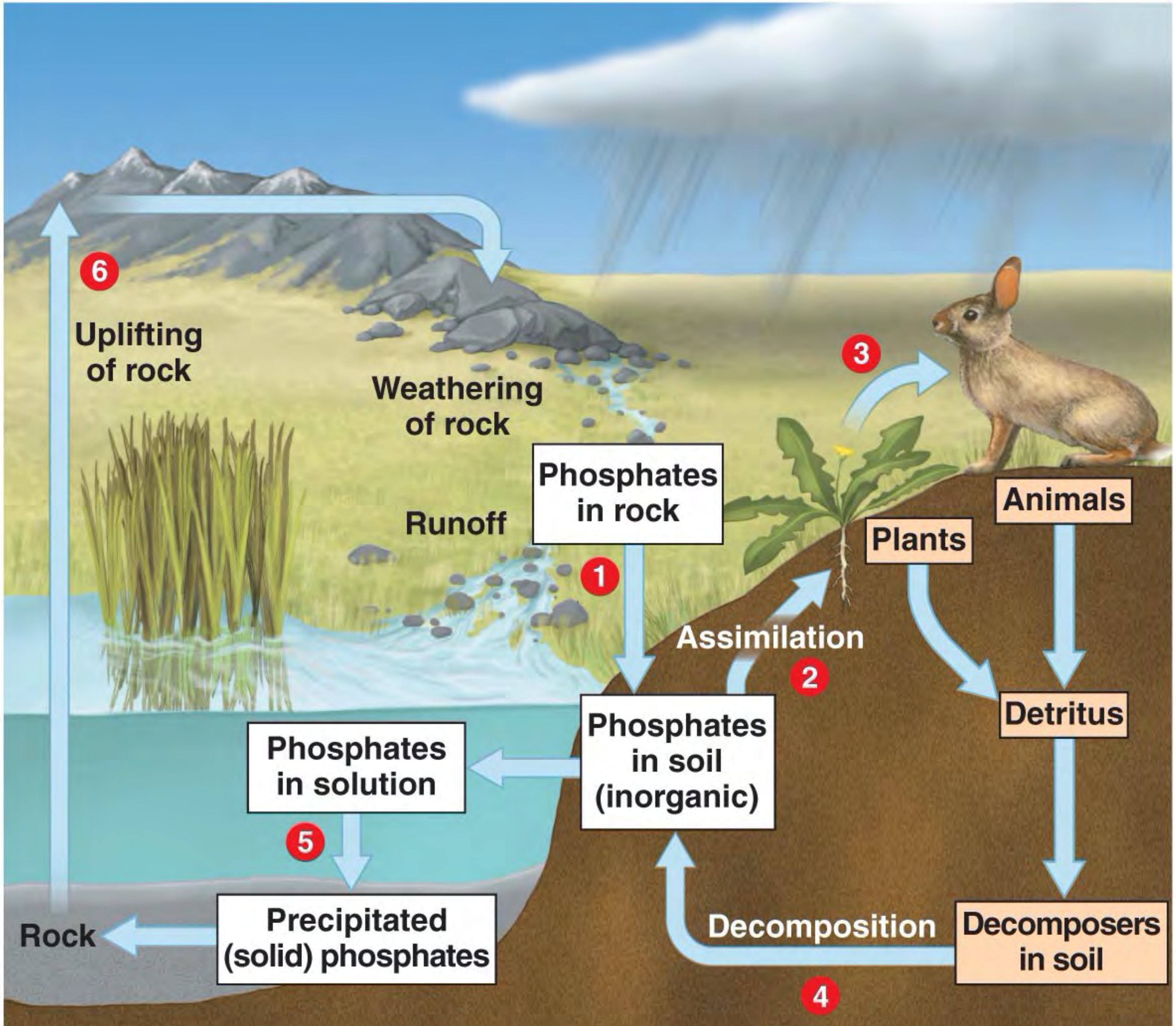
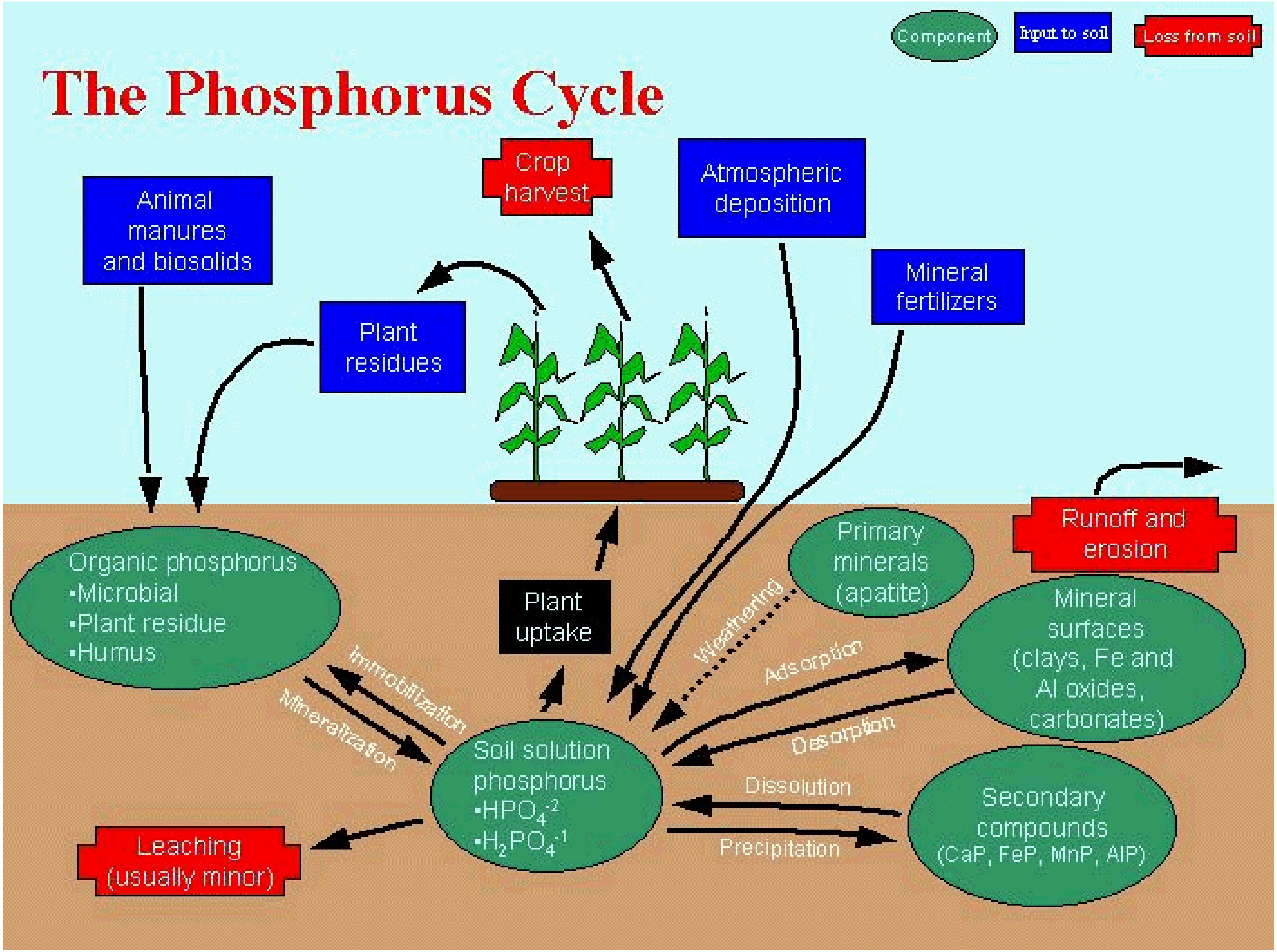
The phosphorus cycle

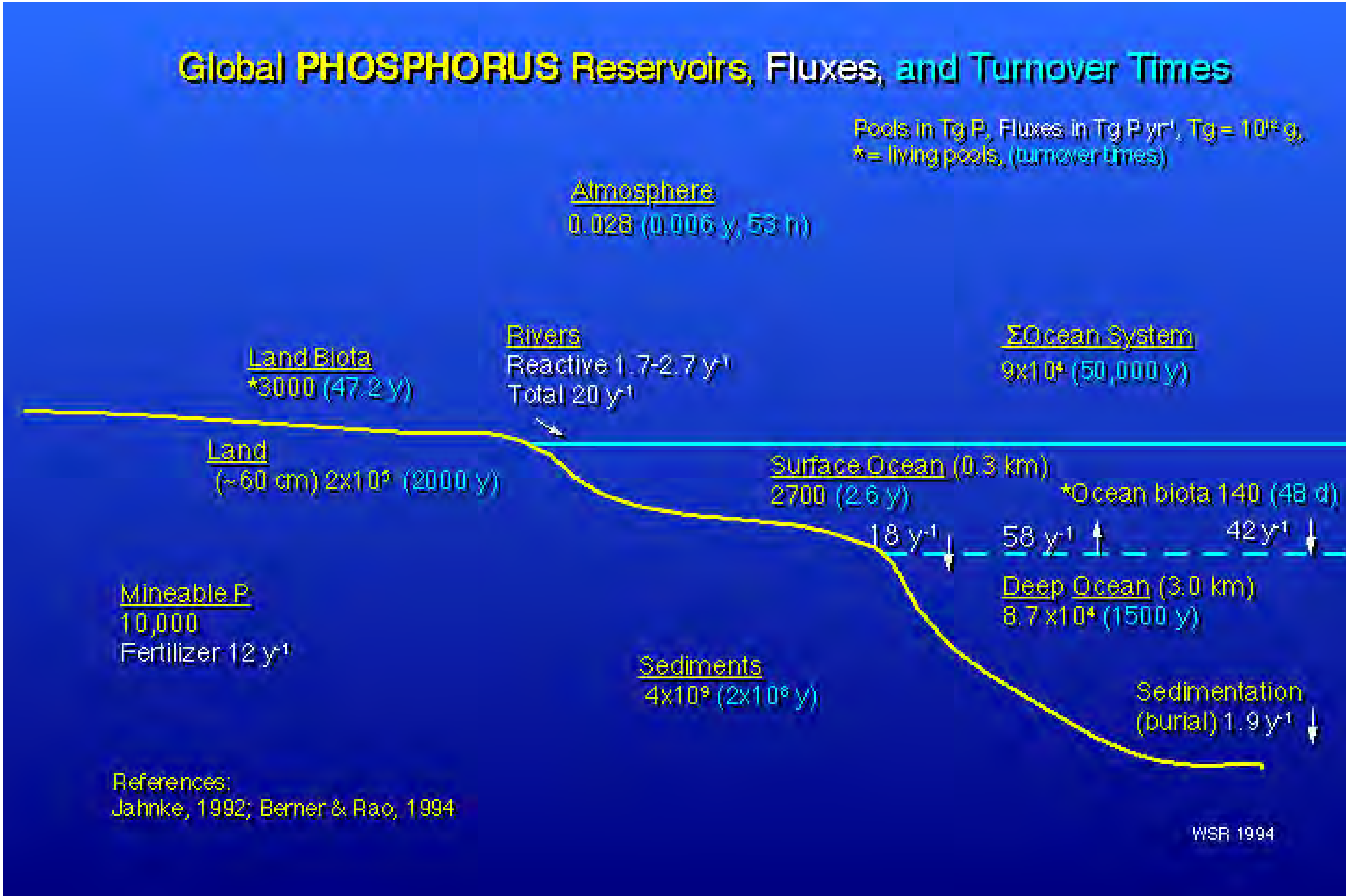
- The phosphorus cycle has no atmospheric component
- The phosphorous cycle is largely restricted to solid and liquid phases.
- Unlike N cycle, major source of reactive P is not through microbial reactions
- Only 10% of P from rivers to oceans is available to marine biota; rest tied to soil and deposited quickly
- The major sink is burial in marine sediments. Marine phosphorite deposits are mined and reintroduced to the cycle by man's activities. The phosphorus biomass reservoirs are derived from the carbon cycle and C:P ratios.

The phosphorus cycle





Component
Input to soil
Loss from soil
The Phosphorus Cycle
Crop harvest
Atmospheric deposition
Animal manures and biosolids
Mineral fertilizers
Plant residues
Runoff and erosion
Primary minerals (apatite)
Organic phosphorus
•Microbial
•Plant residue
•Humus
Plant uptake
Weathering
Mineral surfaces (clays, Fe and Al oxides, carbonates)
Immobilization
Mineralization
Adsorption
Desorption
Soil solution phosphorus
•HPO_4^{-2}
•$H_2PO_4^{-1}$
Dissolution
Secondary compounds (CaP, FeP, MnP, AlP)
Leaching (usually minor)
Precipitation


Global PHOSPHORUS Reservoirs, Fluxes, and Turnover Times
Pools in Tg P, Fluxes in Tg P yr-1, Tg = 10^12 g,
*= living pools, (turnover times)
Atmosphere
0.028 (0.006 y, 53 h)
Land Biota
*3000 (47.2 y)
Rivers
Reactive 1.7-2.7 y-1
Total 20 y-1
ΣOcean System
9x10^4 (50,000 y)
Land
(~60 cm) 2x10^5 (2000 y)
Surface Ocean (0.3 km)
2700 (2.6 y)
*Ocean biota 140 (48 d)
18 y-1
58 y-1
42 y-1
Mineable P
10,000
Fertilizer 12 y-1
Deep Ocean (3.0 km)
8.7 x10^4 (1500 y)
Sediments
4x10^9 (2x10^8 y)
Sedimentation
(burial) 1.9 y-1
References:
Jahnke, 1992; Berner & Rao, 1994
WSR 1994

Global Phosphorus Reservoirs and Turnover Times

	10^{12} g P	Turnover time
Sediments	4×10^{9}	2×10^{8} y
Land	2×10^{5}	2000 y
Deep Ocean	8.7×10^{4}	1500 y
Terrestrial biota	3000	~50 y
Surface ocean	2700	2.6 y
Atmosphere	0.028	days

Biogeochemical cycles - key elements

Six nutrient elements make up 95% of the biomass mass on earth and form the biochemical foundation for life.

- **Carbon (CO_2, CH_4, CO)**
- **Nitrogen (N_2O, NO, NO_2, NH_3)**
- **Sulfur (SO_2, COS, H_2S, H_2SO_4)**
- **Phosphorous**
- **Hydrogen**
- **Oxygen**
- **Water**

Climate II

(Winter 2020/2021)

6th lecture:

Biogeochemical Cycles

(turnover times and circulation of biochemical tracers: carbon, nitrogen, sulfur, phosphorus)

End of lecture.

Slides available at:

https://paleodyn.uni-bremen.de/study/climate2020_21.html