Climate System II
(Winter 2021/2022)

8th lecture:
Dust and Vegetation
(glacial dust increase, iron fertilisation, radiative forcing, vegetation and aridity)

Gerrit Lohmann, Martin Werner

Tuesday, 10:00-11:45

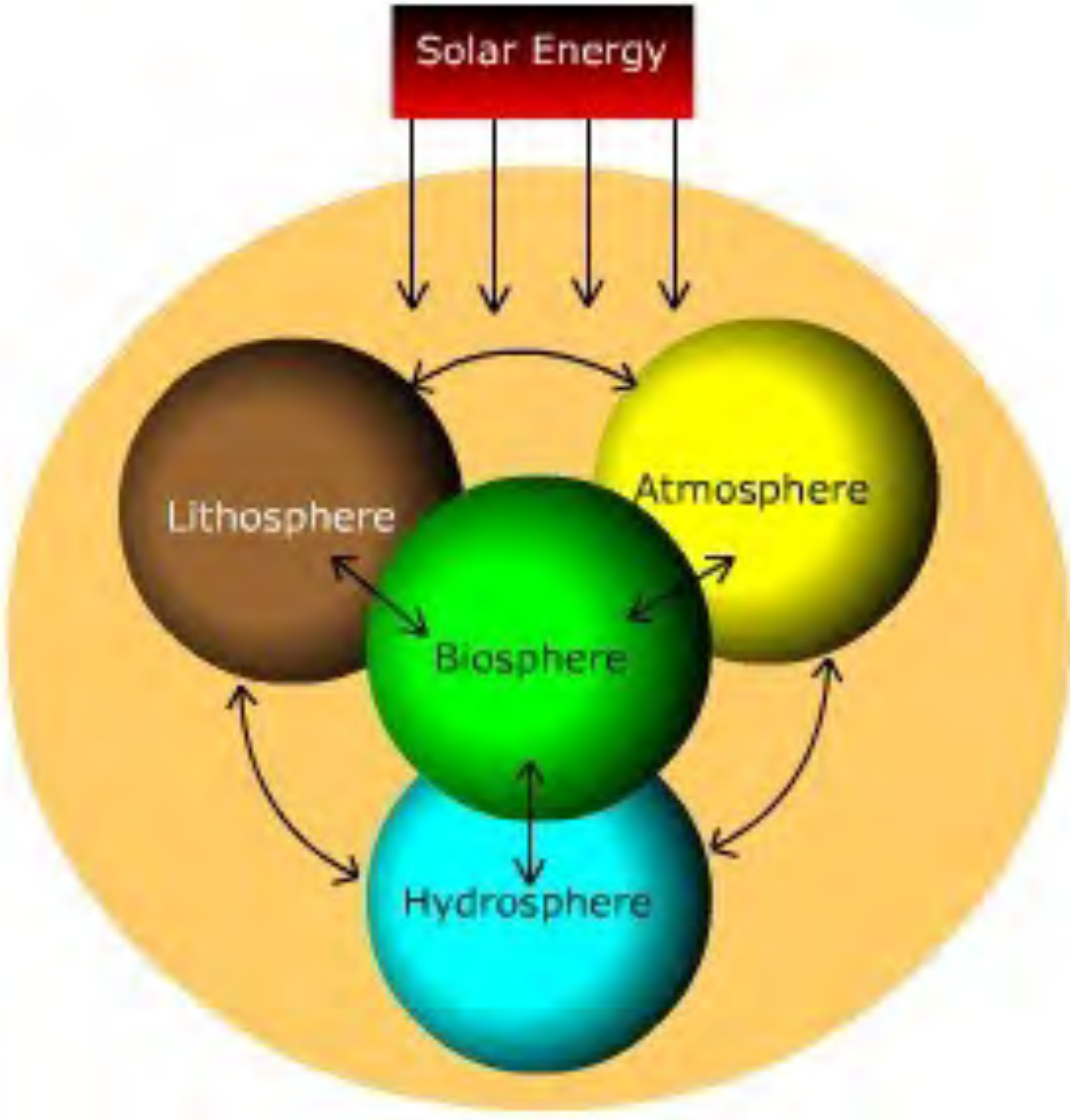
(sometimes shorter, but then with some exercises)

https://paleodyn.uni-bremen.de/study/climate2021_22.html

Repetition

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



Repetition

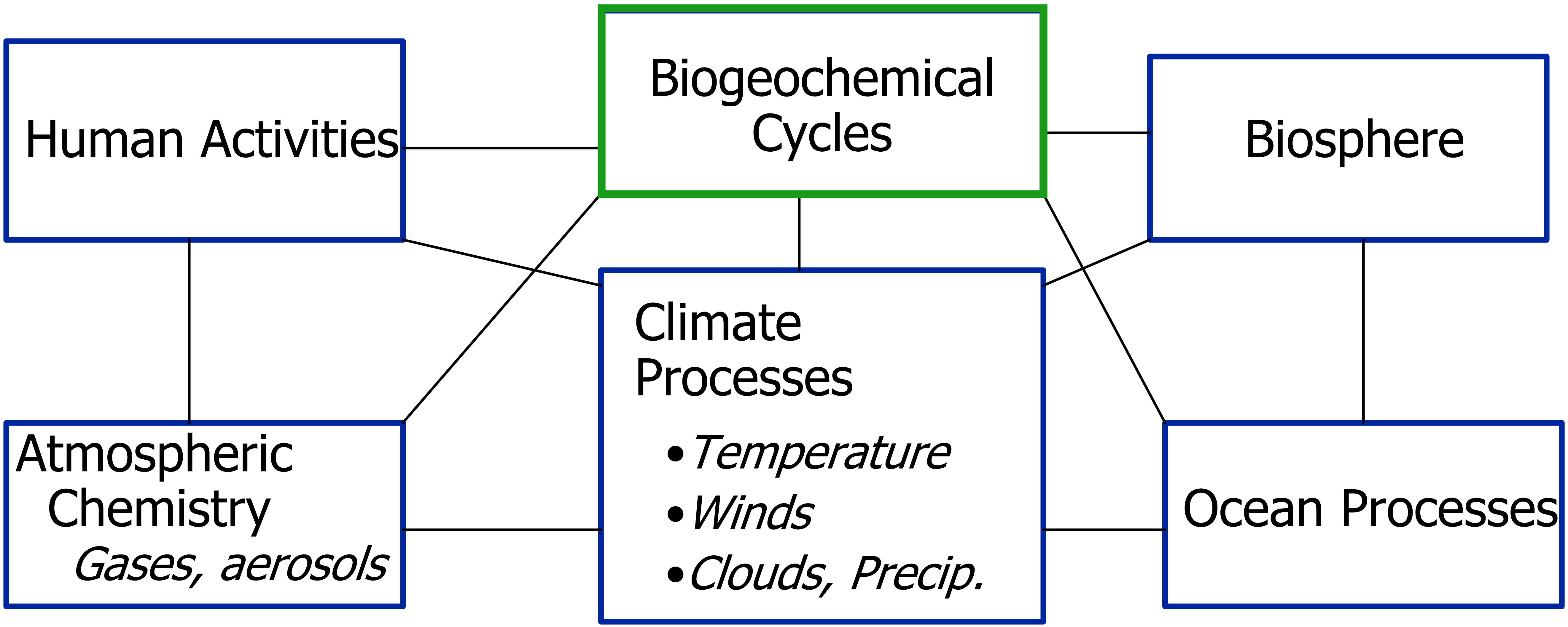
Biogeochemical cycles - key elements

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**

Repetition

Biogeochemical cycles in climate research



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

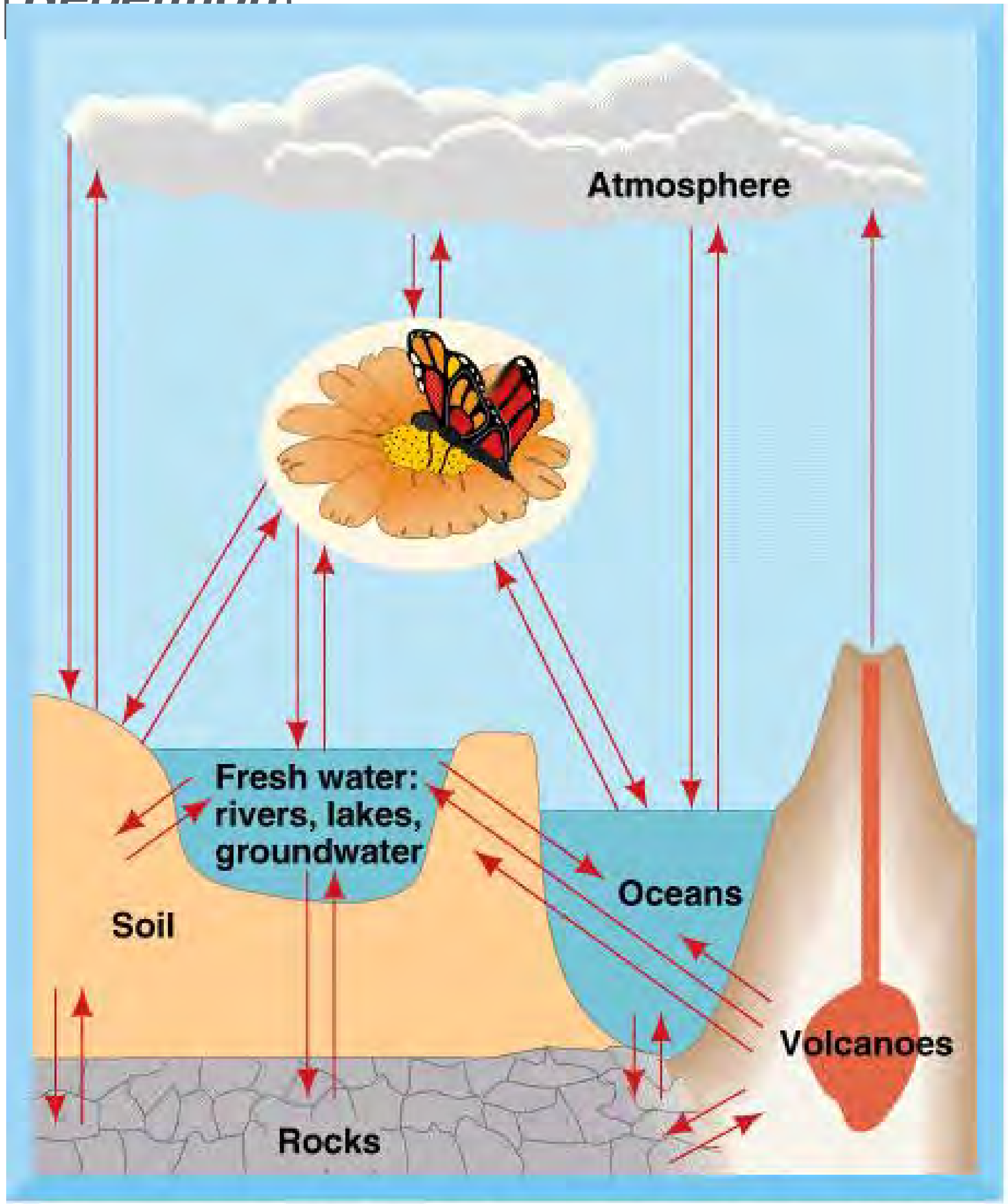
Repetition

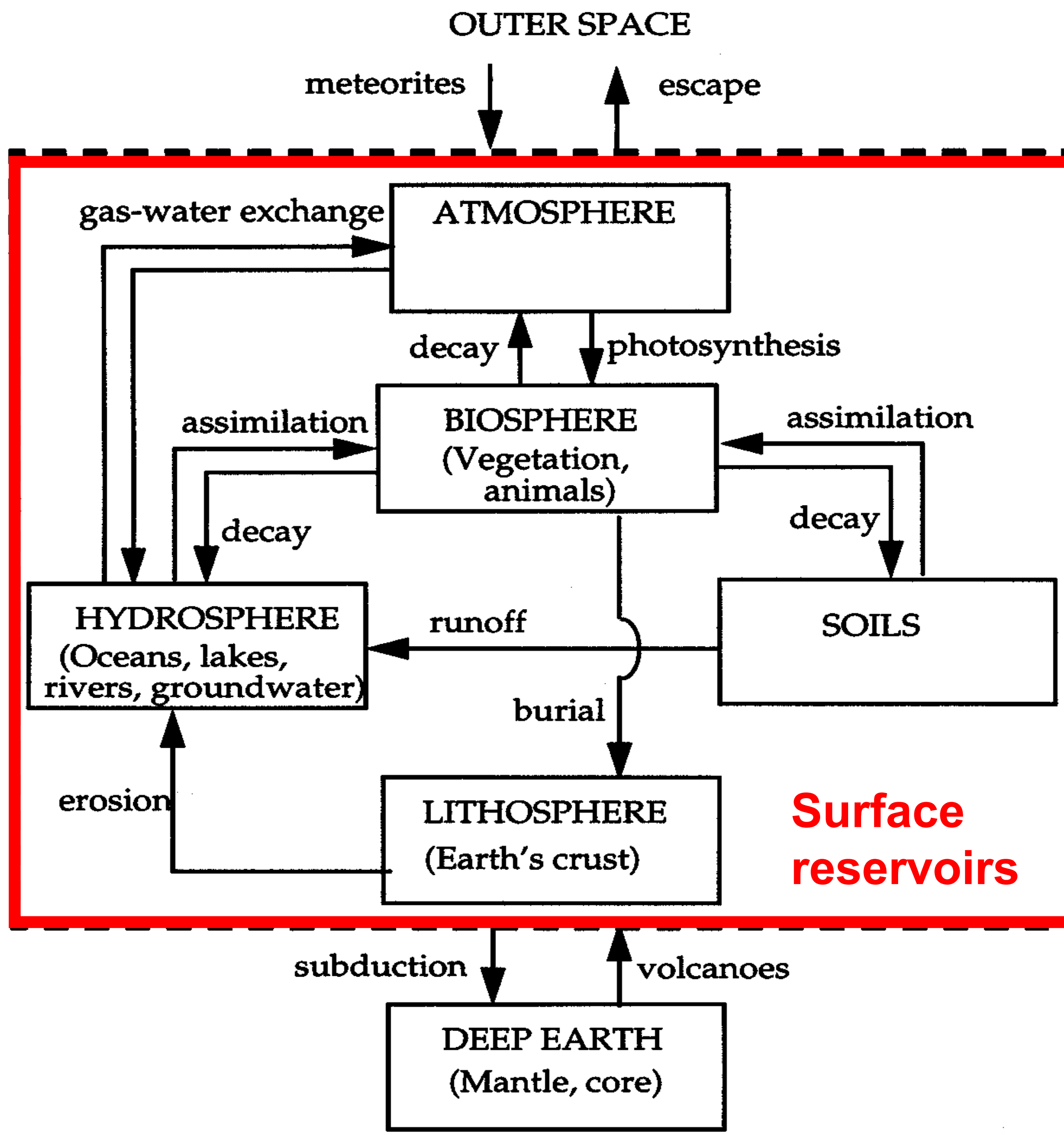
Biogeochemical cycles: Common features of all key elements

- **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***

Repetition

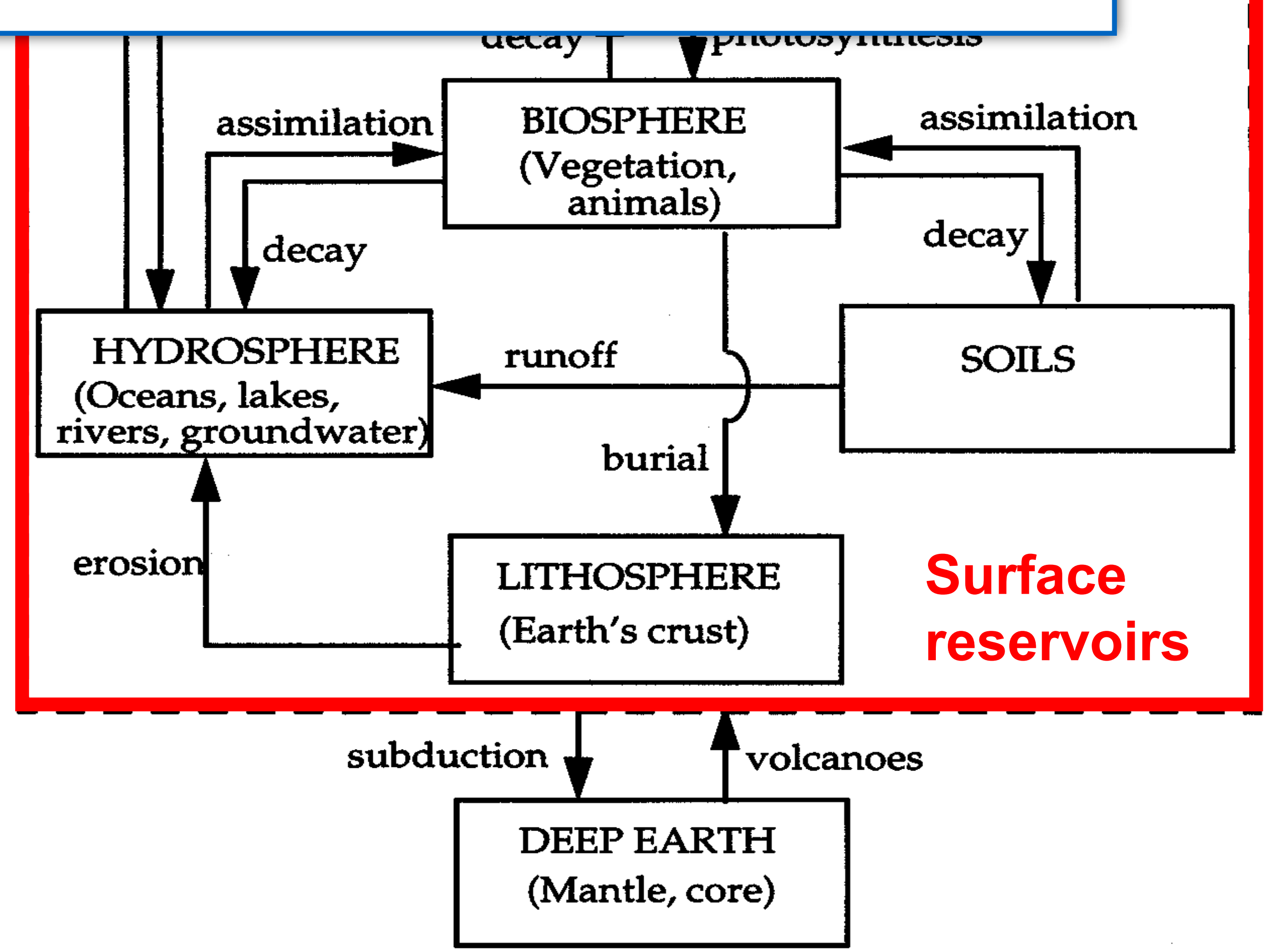

Atmosphere
Fresh water: rivers, lakes, groundwater
Oceans
Soil
Volcanoes
Rocks


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)

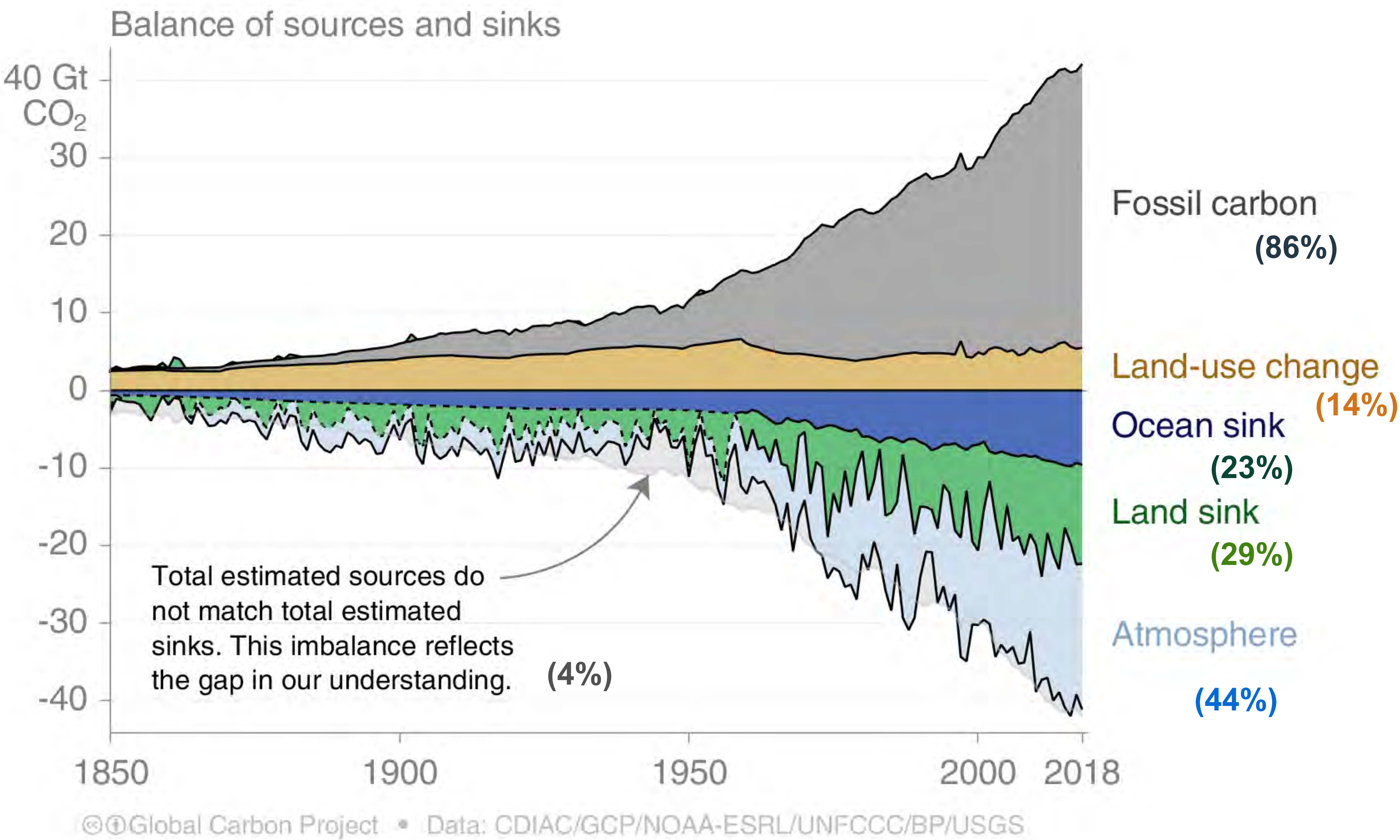
definition

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



CO_2 sources and sinks



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

(percentage for years 2009-2018)

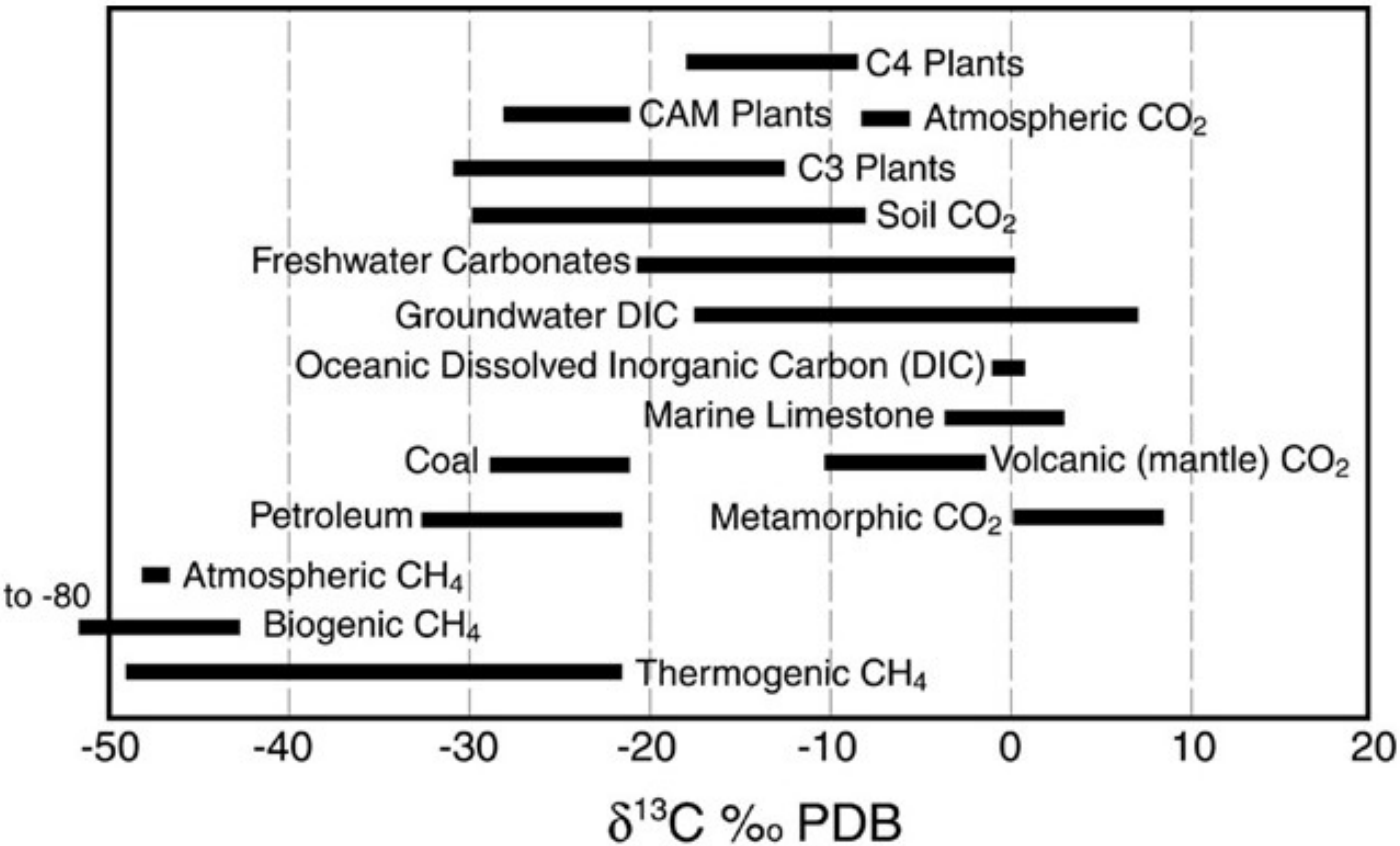
Carbon isotopes

- **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

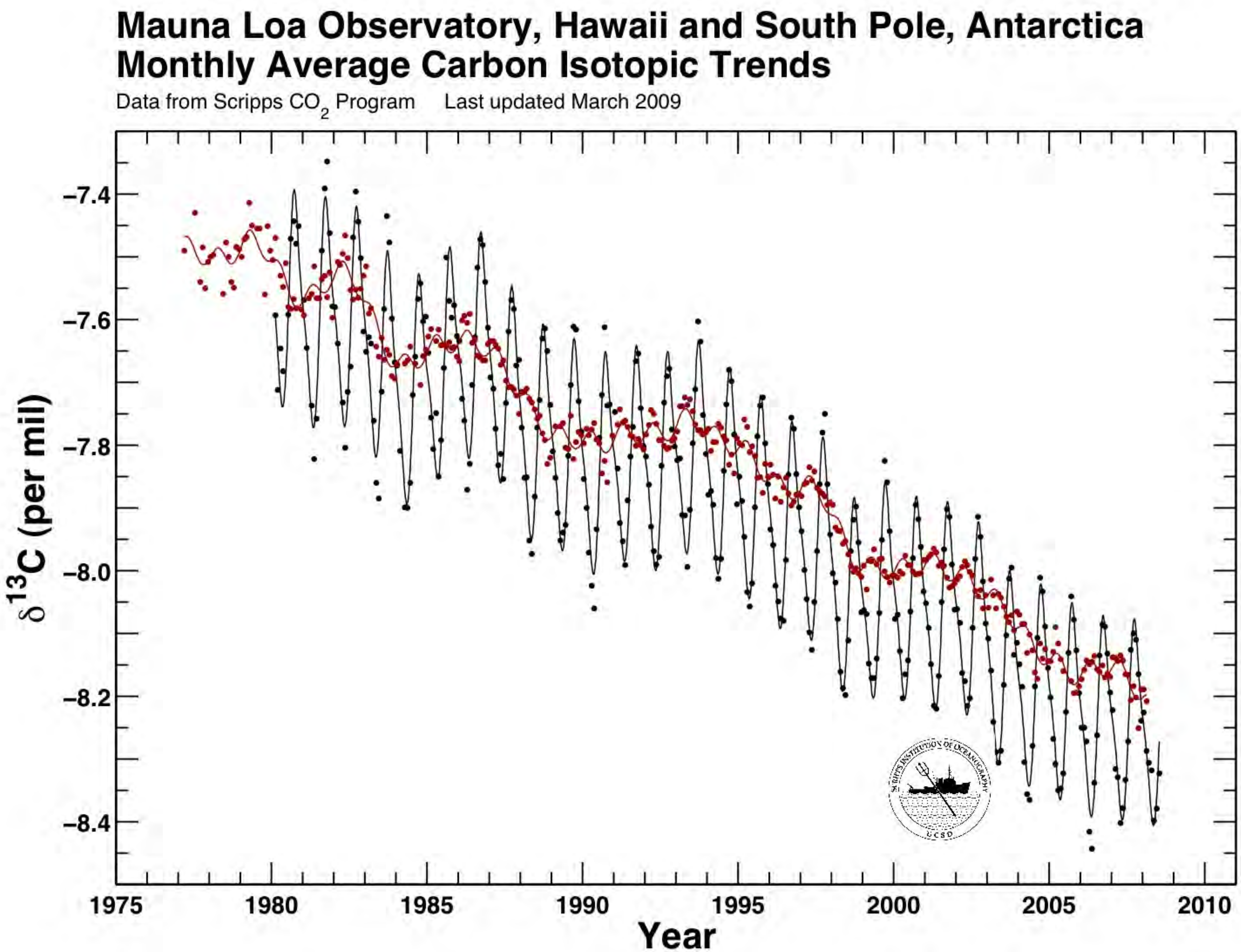
- ***During photosynthesis, plants preferentially uptake ^{12}C***

  => the atmosphere will become enriched in ^{13}C

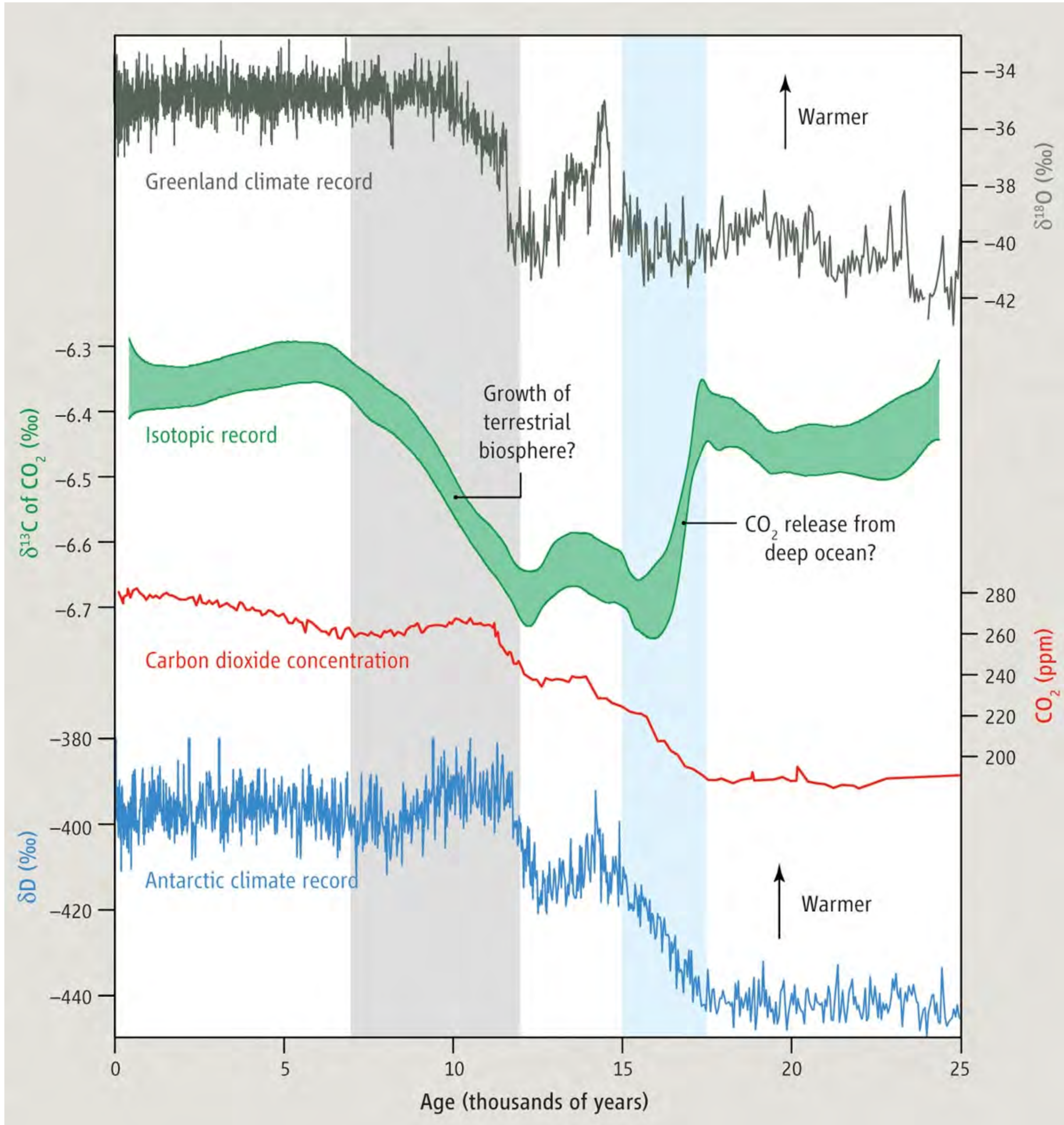
Variations of ^{13}C in different carbon pools



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



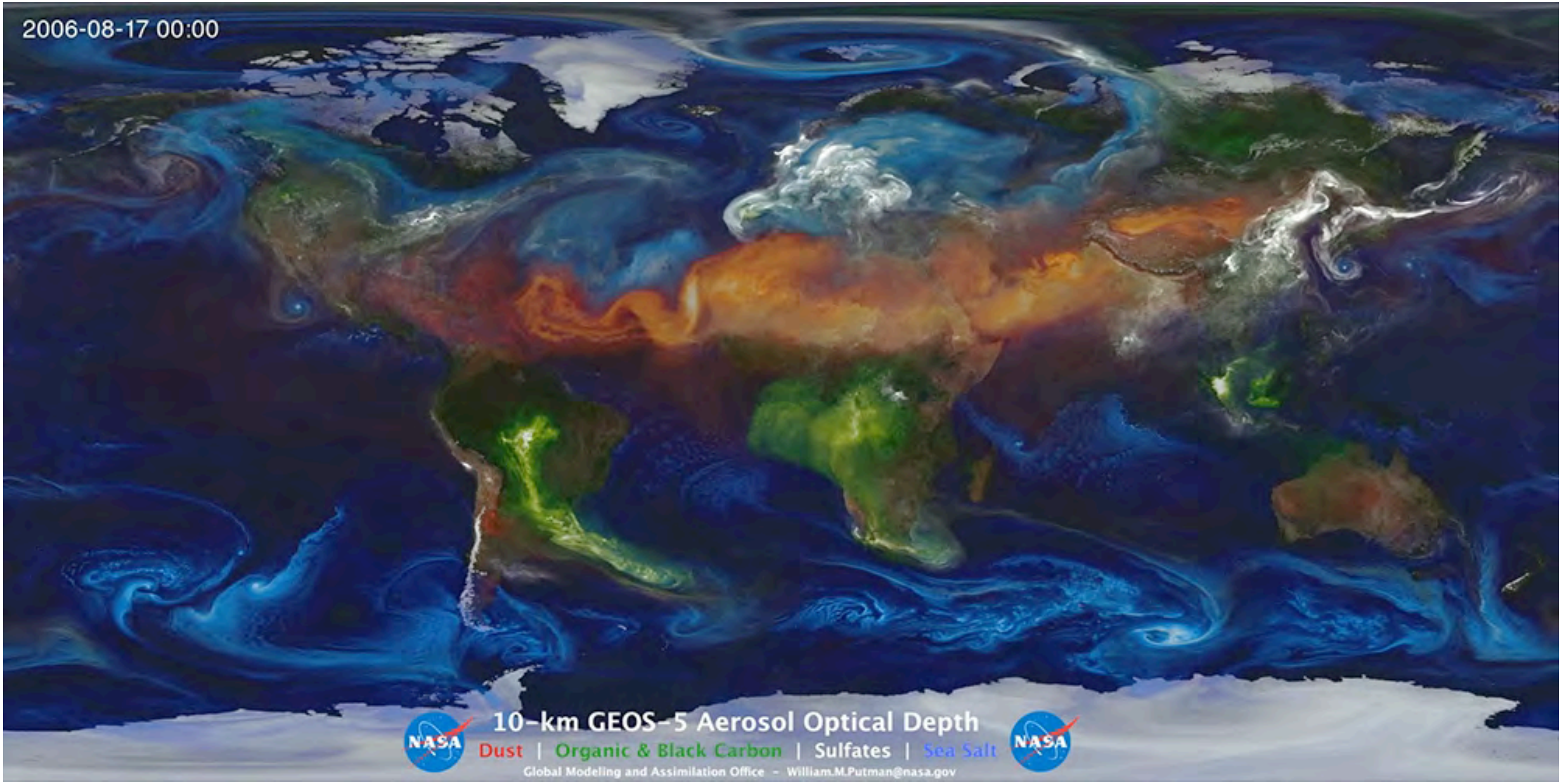
Variations of ^{13}C since the last glacial maximum (LGM)



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

Repetition

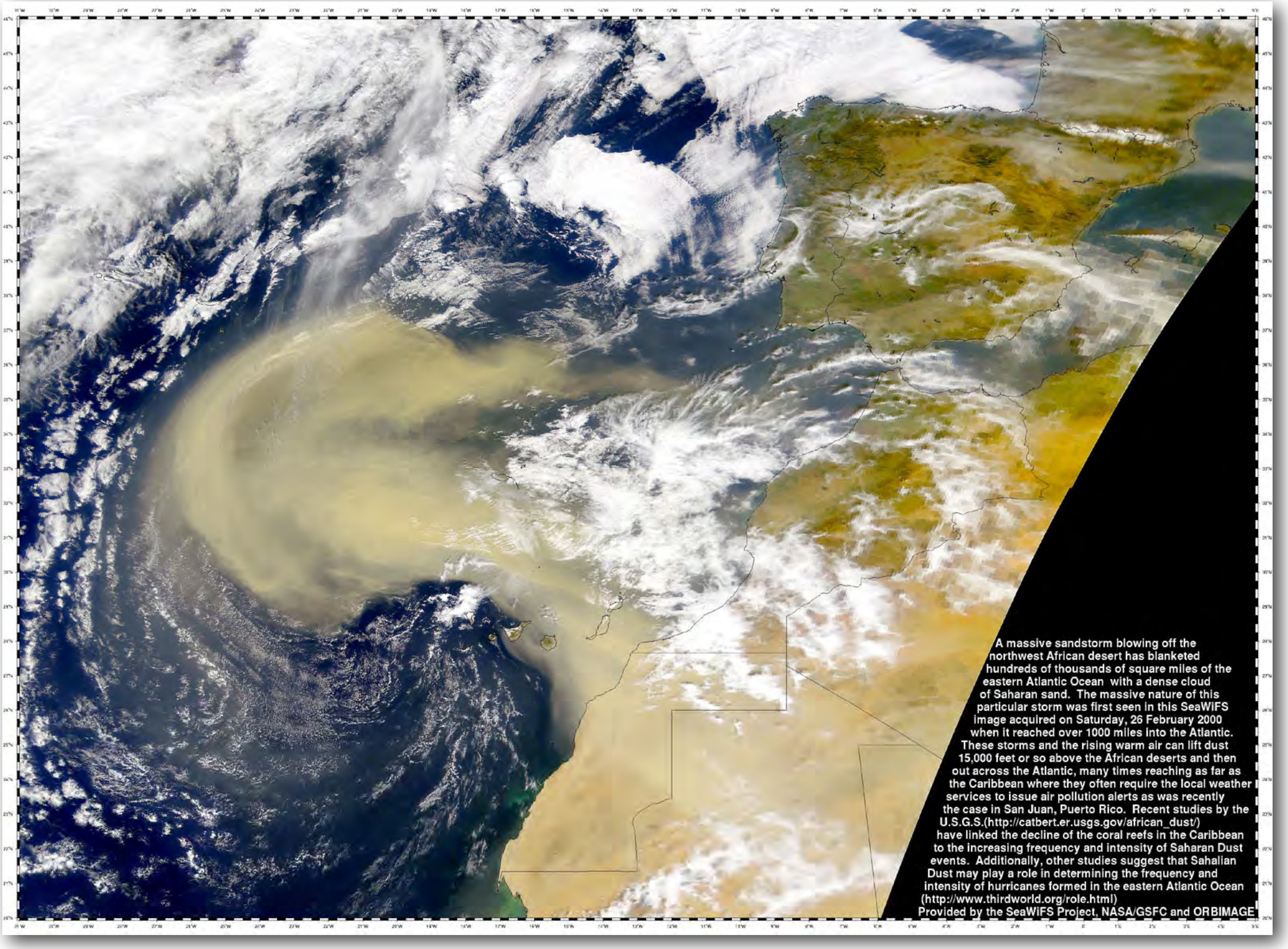
Transport of dust and biogeochemical aerosols



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/)

Dust in the climate system

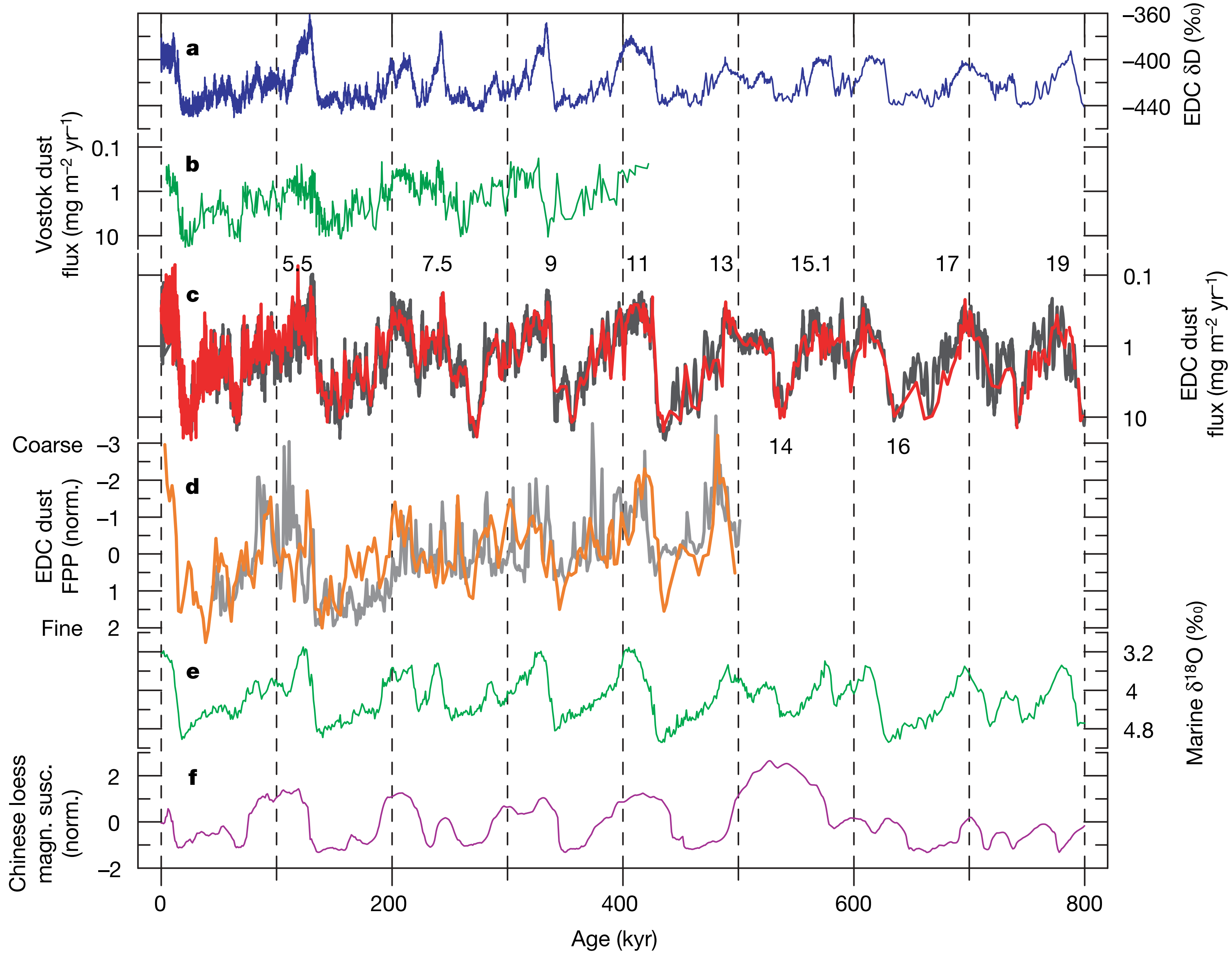


Dust depositions on glacial-interglacial time scales

Dust—climate couplings over the past 800,000 years from the EPICA Dome C ice core

Vol 452|3 April 2008|**doi:10.1038/nature06763**

F. Lambert[1,2], B. Delmonte[3], J. R. Petit[4], M. Bigler[1,5], P. R. Kaufmann[1,2], M. A. Hutterli[6], T. F. Stocker[1,2], U. Ruth[7], J. P. Steffensen[5] & V. Maggi[3]



temperature

dust

ice volume

Figure 1 | EDC dust data in comparison with other climatic indicators. **a**, Stable isotope (δD) record from the EPICA Dome C (EDC) ice core[8] back to Marine Isotopic Stage 20 (EDC3 timescale) showing Quaternary temperature variations in Antarctica. **b**, Vostok dust flux record (Coulter counter) plotted on its original timescale[11]. **c**, EDC dust flux records. Red and grey lines represent, respectively, Coulter counter (55-cm to 6-m resolution) and laser-scattering data (55-cm mean). Numbers indicate Marine Isotopic Stages. Note that the vertical extent of the scales of **b** and **c** is larger than for the other records. **d**, EDC dust size data expressed as FPP (see Methods). The orange and grey curves represent measurements by Coulter counter (2-kyr mean) and laser (1-kyr mean), respectively. **e**, Marine sediment δ^{18}O stack[18], giving the pattern of global ice volume. **f**, Magnetic susceptibility stack record for Chinese loess[17] (normalized).

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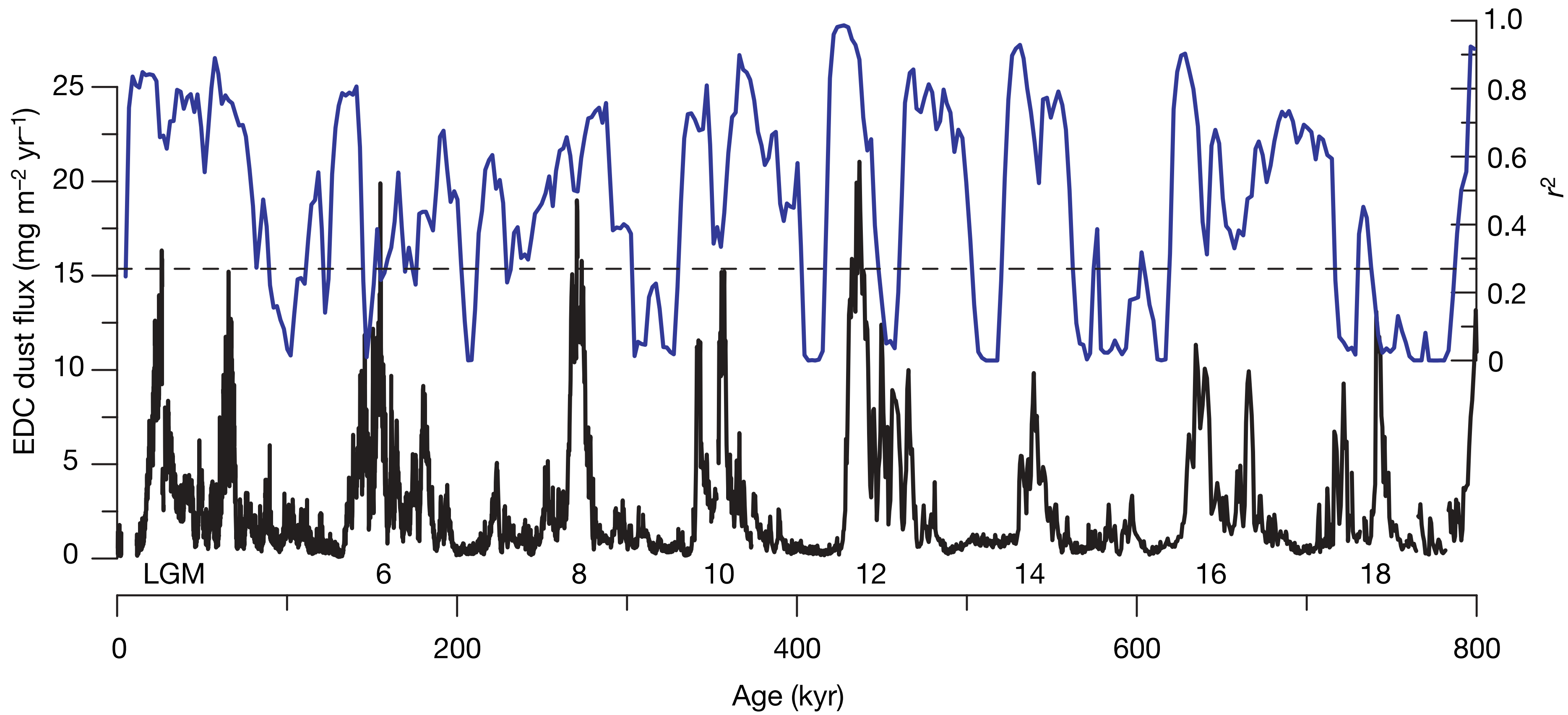

Figure 2 | EDC correlation between dust and temperature. Linear plot of dust flux (black) and the coefficient of determination r^2 (blue) between the high-pass filtered values (18-kyr cut-off) of both the δD and the logarithmic values of dust flux. The correlation was determined using 2-kyr mean values in both records and a gliding 22-kyr window. Correlations above $r^2 = 0.27$ (dashed line) are significant at a 95% confidence level. Numbers indicate the marine isotopic glacial stages.

- strong correlation between dust and temperature changes

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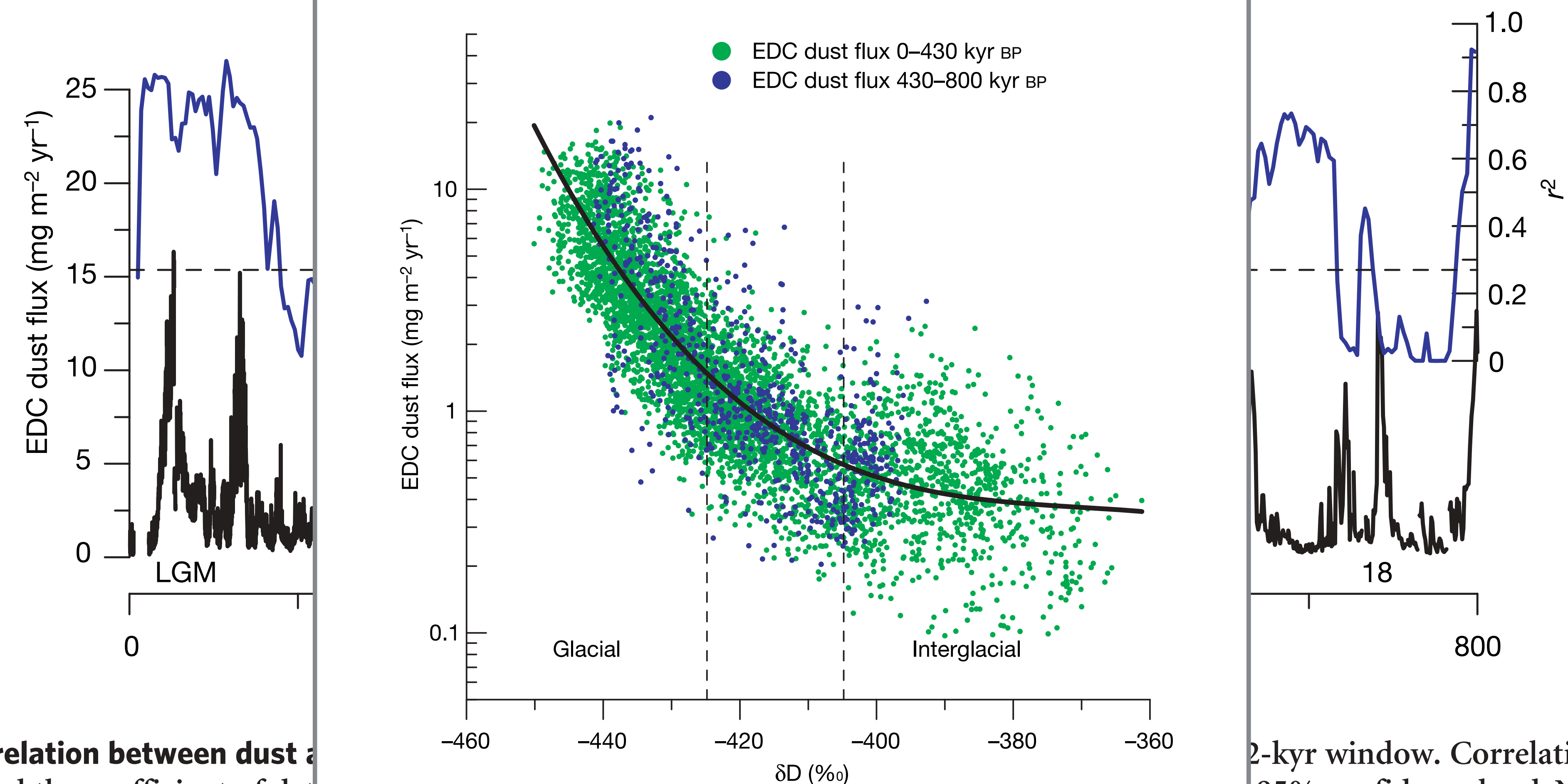


Figure 2 | EDC correlation between dust a … 2-kyr window. Correlations above $r^2 = 0.27$
dust flux (black) and the coefficient of det … 95% confidence level. Numbers indicate the
high-pass filtered values (18-kyr cut-off) o …
values of dust flux. The correlation was det …

Figure 3 | EDC dust–temperature relationship. Values of δD (ref. 8) are plotted against dust flux (both at 55-cm resolution). Green and blue dots represent data from 0–430 kyr BP and 430–800 kyr BP, respectively. Superposed is a cubic polynomial fit, $\log_{10}(f) = -3.737 \times 10^{-6}(\delta D)^3 - 4.239 \times 10^{-3}(\delta D)^2 - 1.607(\delta D) - 204$, where f is the dust flux (mg m^{-2} yr^{-1}), and δD is in ‰ ($r^2 = 0.73$, $N = 5{,}164$).

- **strong correlation between dust and temperature changes**

Dust depositions on glacial-interglacial time scales

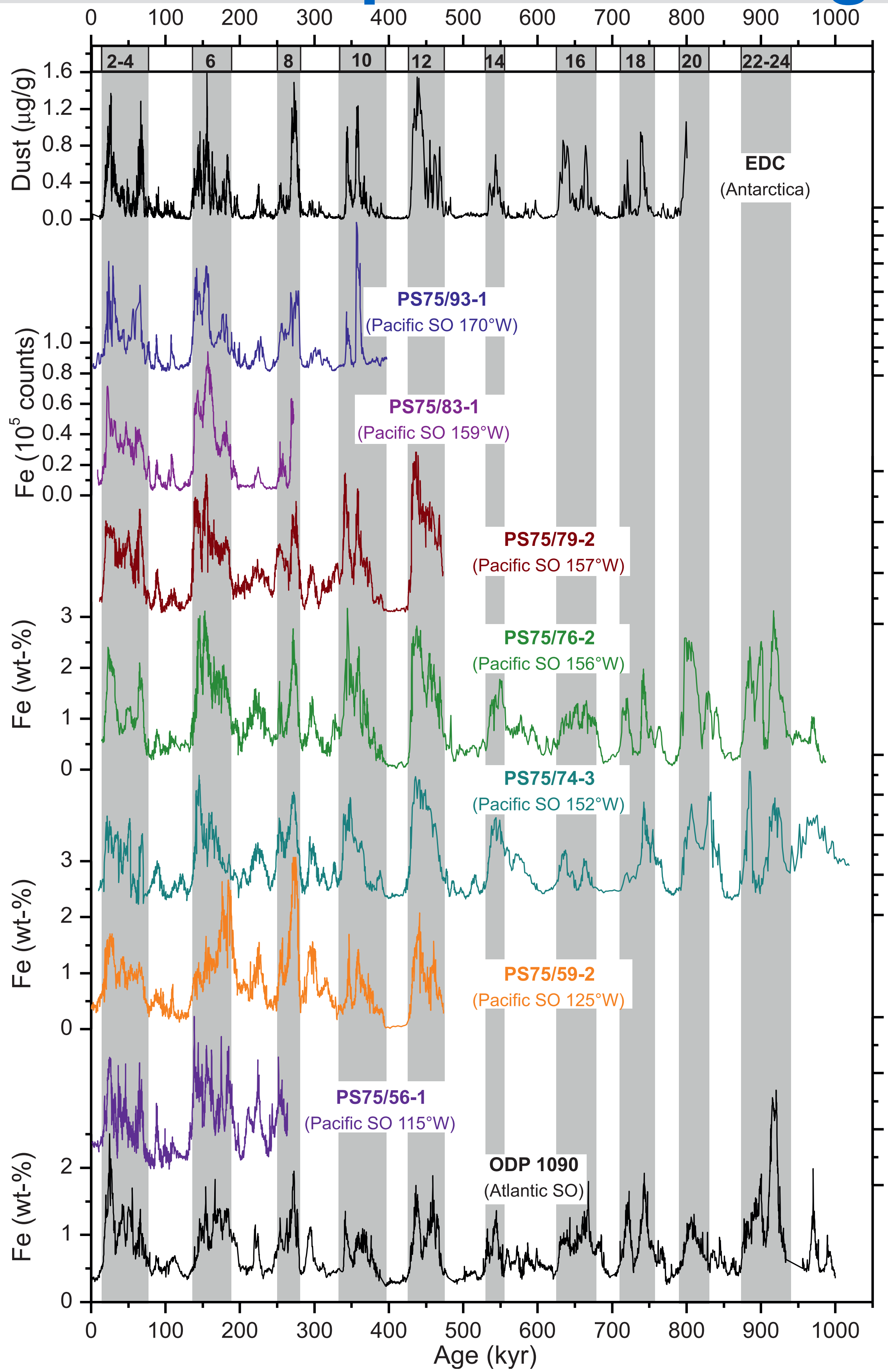


Fig. 2. Iron content fluctuations across the Pacific and Atlantic SO (*7*) compared to dust content changes in the EDC ice core (*1*).

SCIENCE VOL 343 24 JANUARY 2014

Increased Dust Deposition in the Pacific Southern Ocean During Glacial Periods

F. Lamy,[1,2]* R. Gersonde,[1,2] G. Winckler,[3,4] O. Esper,[1] A. Jaeschke,[1,2] G. Kuhn,[1] J. Ullermann,[1] A. Martinez-Garcia,[5] F. Lambert,[6] R. Kilian[7]

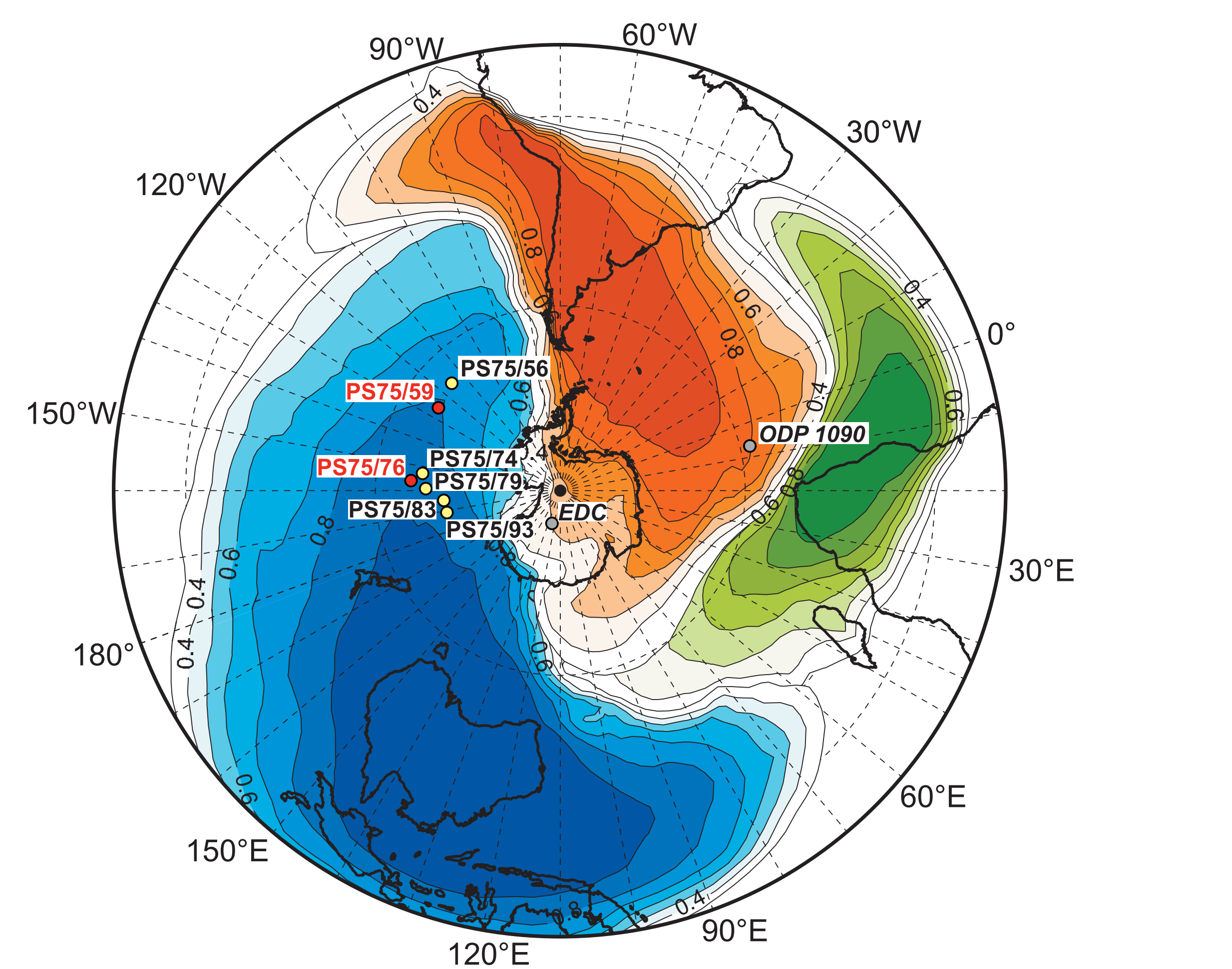
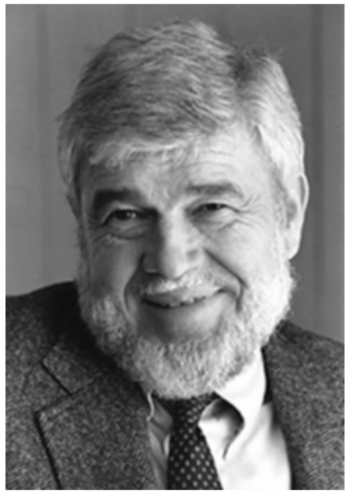


Fig. 1. Map showing the modern relative contributions of the three major dust sources in the Southern Hemisphere (blue, Australia; red, South America; green, South Africa), based on model data (*20*). Red dots mark primary core locations; yellow dots indicate additional cores; gray dots denote location of published reference records (*1*, *4*, *7*).

LGM dust cycle: fertilisation of the marine biosphere



John Martin

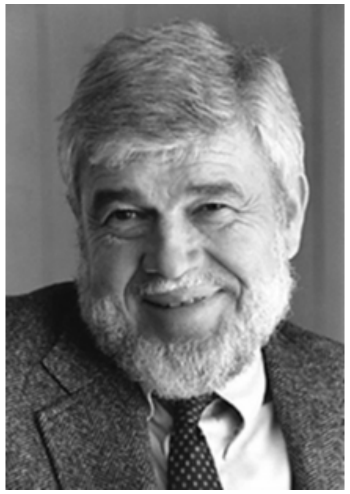
The Iron Hypothesis

Figure 1. In the equatorial Pacific Ocean and Gulf of Alaska, phytoplankton populations are relatively low (purple shaded areas on map), despite adequate sunlight and nutrients. John Martin set out to prove that a lack of dissolved iron in the water in these areas keeps populations of marine algae lower than normal.

- **Dust contains iron which is a key micro-nutrient in the Southern Ocean**

(http://www.palomar.edu/oceanography/iron.htm)

LGM dust cycle: fertilisation of the marine biosphere



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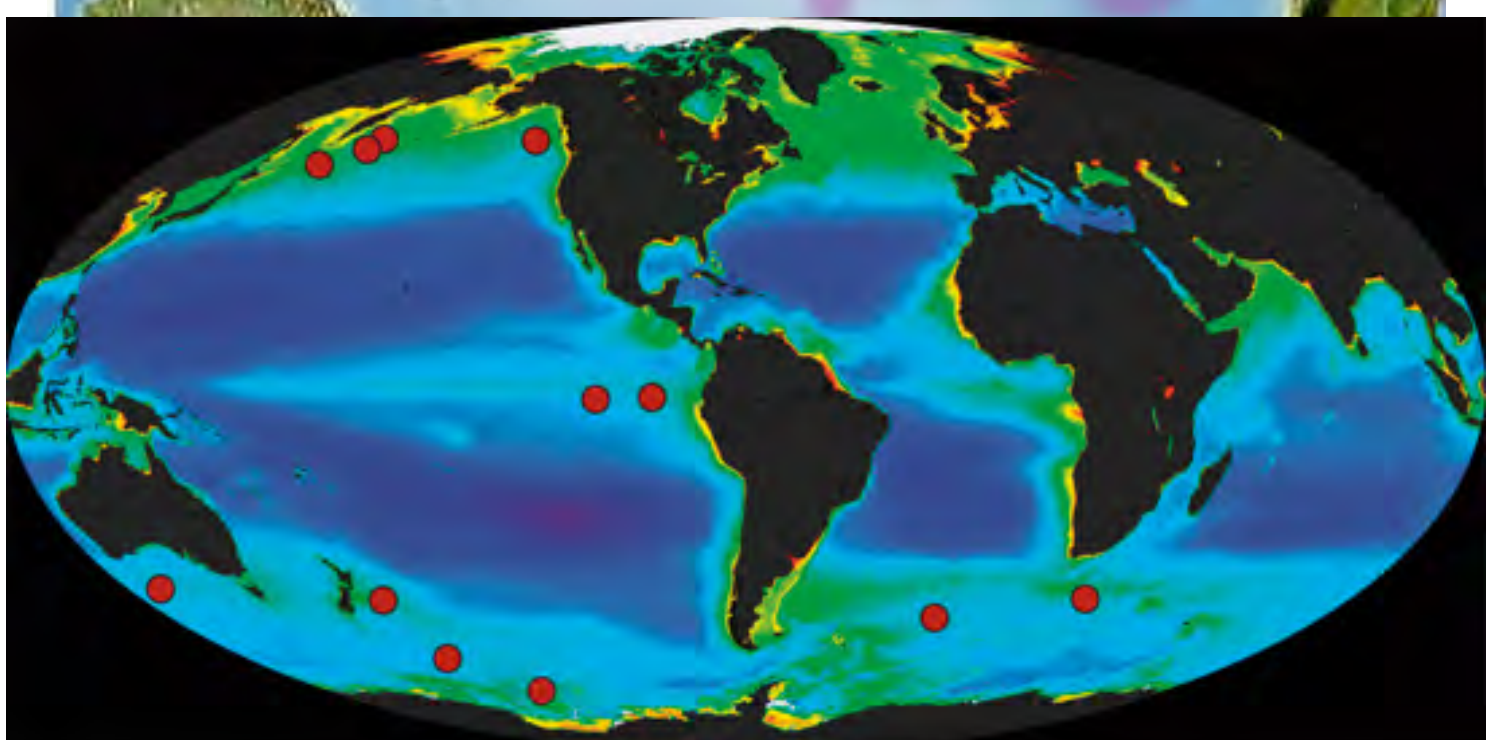
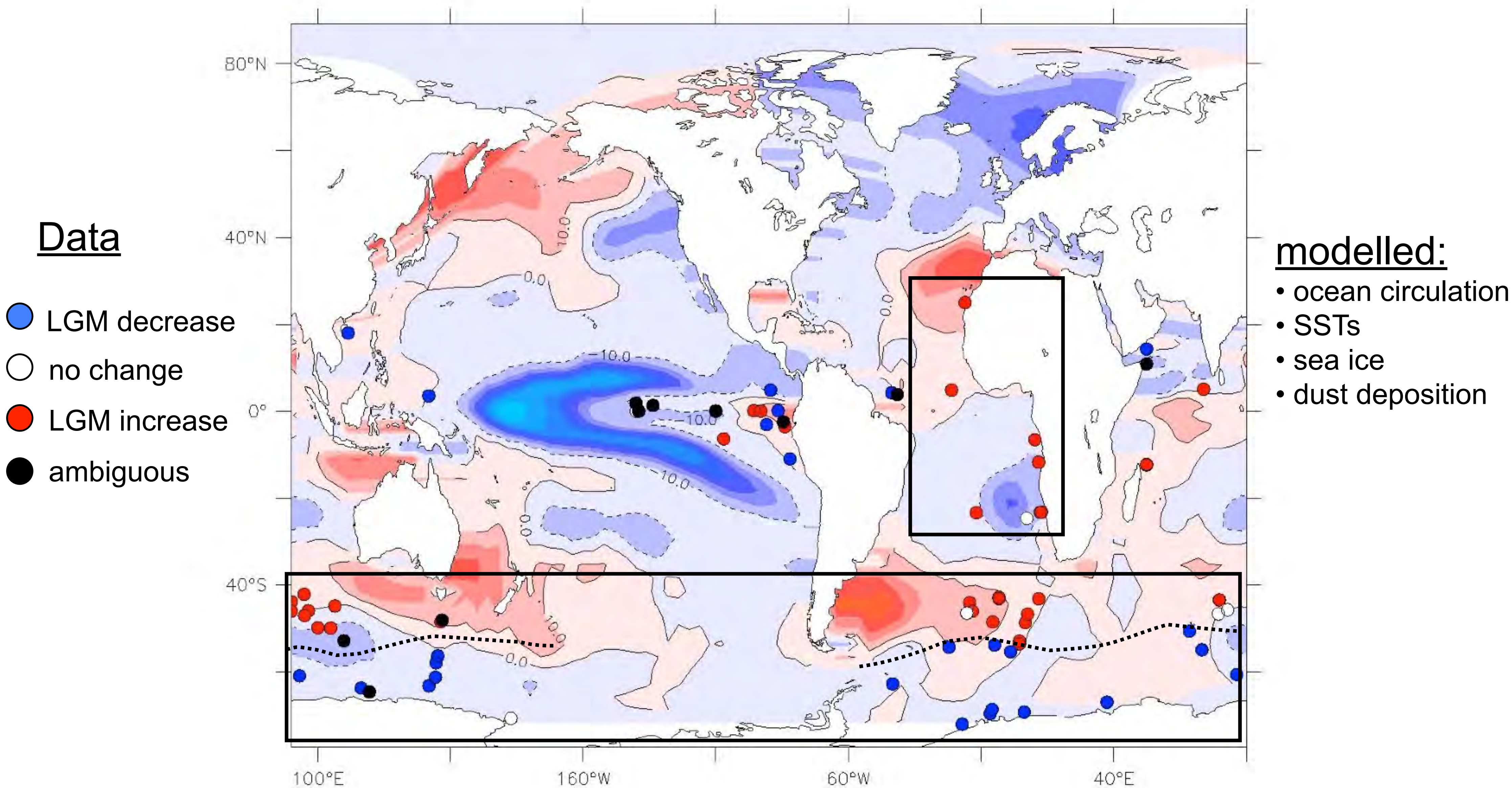


Since 1993, these 12 small-scale open ocean experiments (*red dots*) have shown that iron additions do indeed result in phytoplankton blooms, thereby drawing carbon dioxide out of the atmosphere and into the ocean

(http://www.palomar.edu/oceanography/iron.htm)

LGM dust cycle: fertilisation of the marine biosphere

Ocean Carbon Cycle: LGM-Modern Changes in Export Production



Data Compilation / LGM simulation with PISCES-OPA model

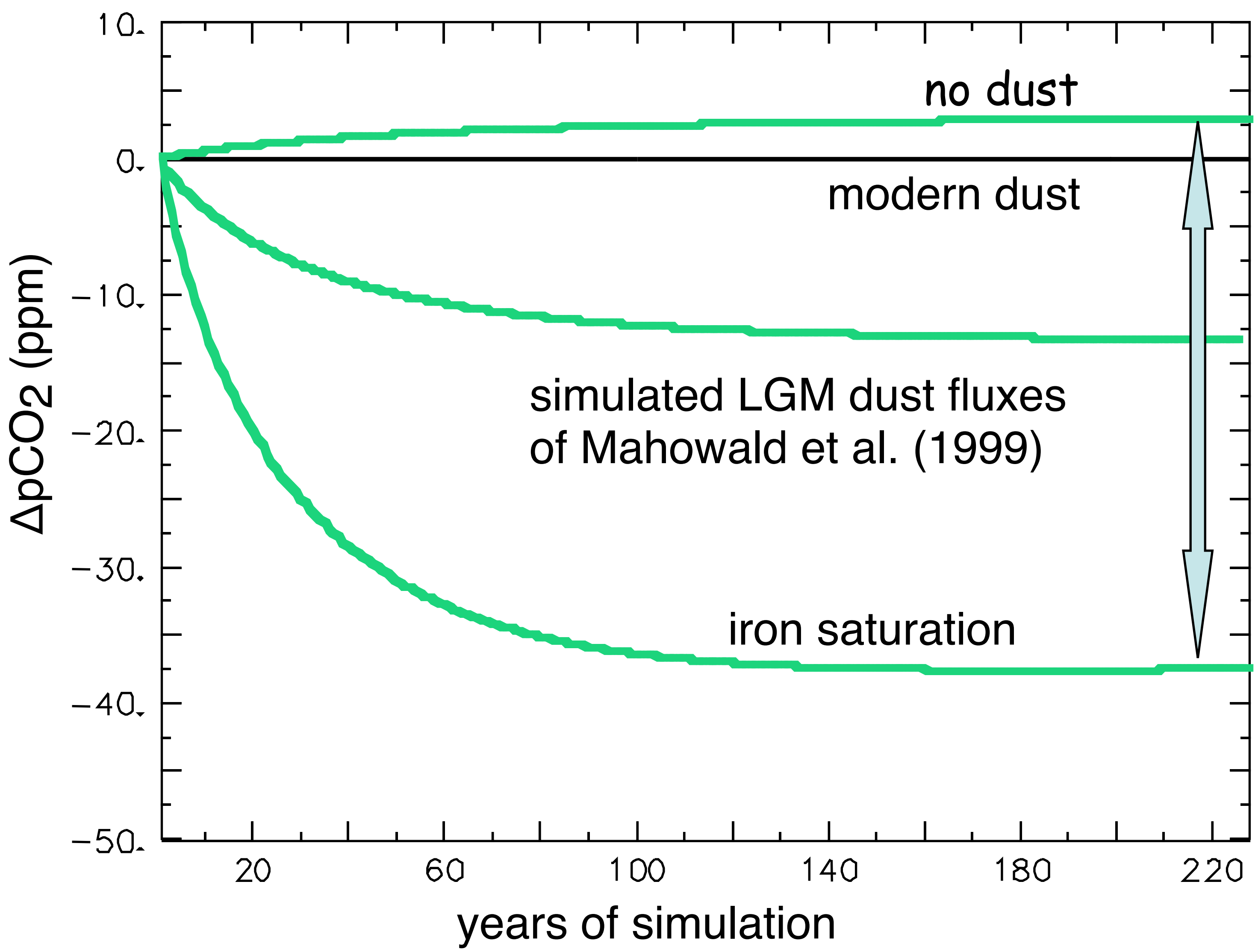
(proxies : C-org, CaCO3, Ba, assemblages…) (Export, LGM-present, gC m^{-2} yr^{-1})

(Quelle: Bopp et al.., 2003)

LGM dust cycle: fertilisation of the marine biosphere

Ocean Carbon Cycle: Sensitivity Studies for different LGM conditions

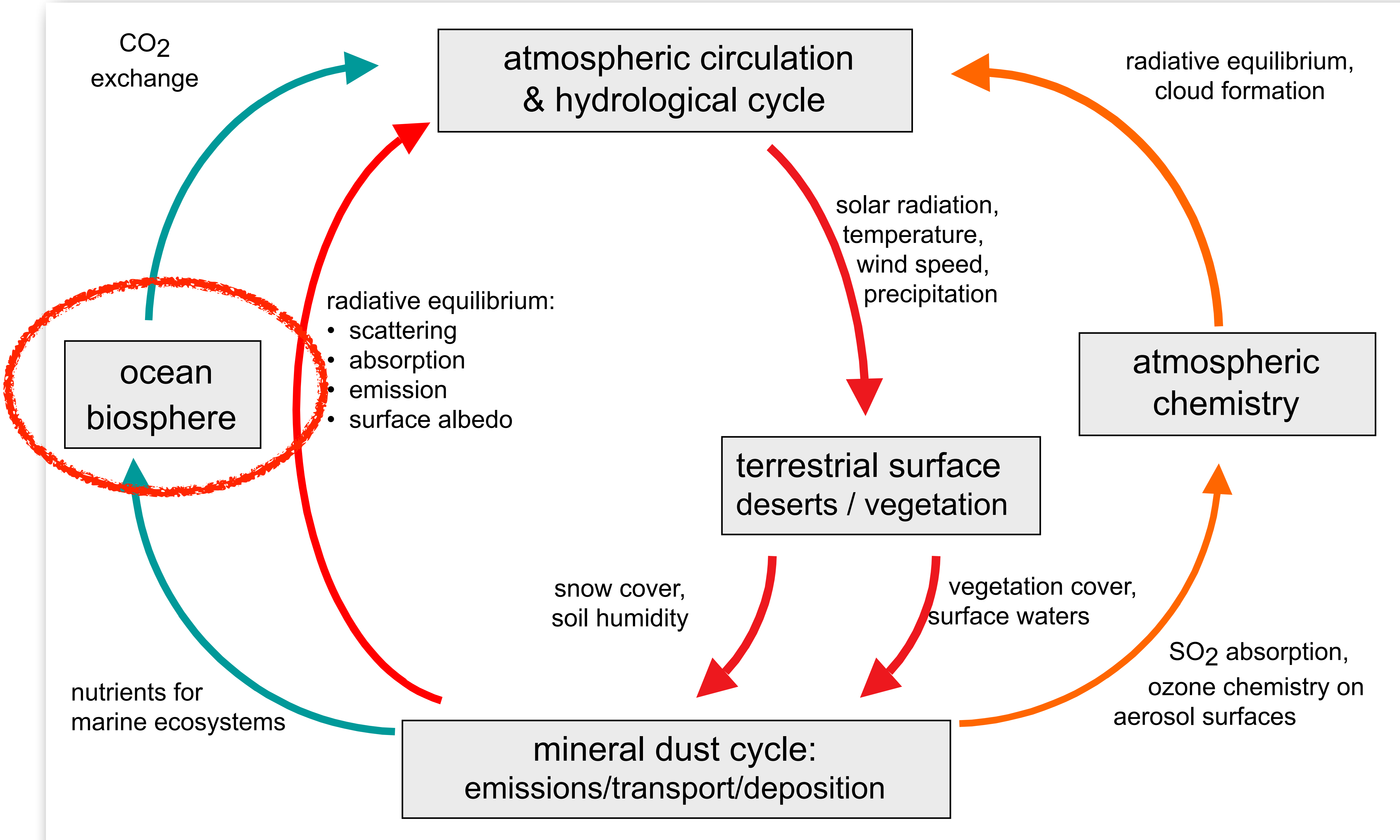
- Hypothesis of Martin (1988) : Iron Fertilisation of the Glacial Ocean



- increased LGM iron deposition: -15 ppm
- mechanisms
  - export of organic material
  - export of $CaCO_3$ (change of alkalinity)
- sensitivity
  no dust deposition: +3 ppm
  iron saturation: -39 ppm

(Quelle: Bopp et al.., 2003)

Dust in the climate system



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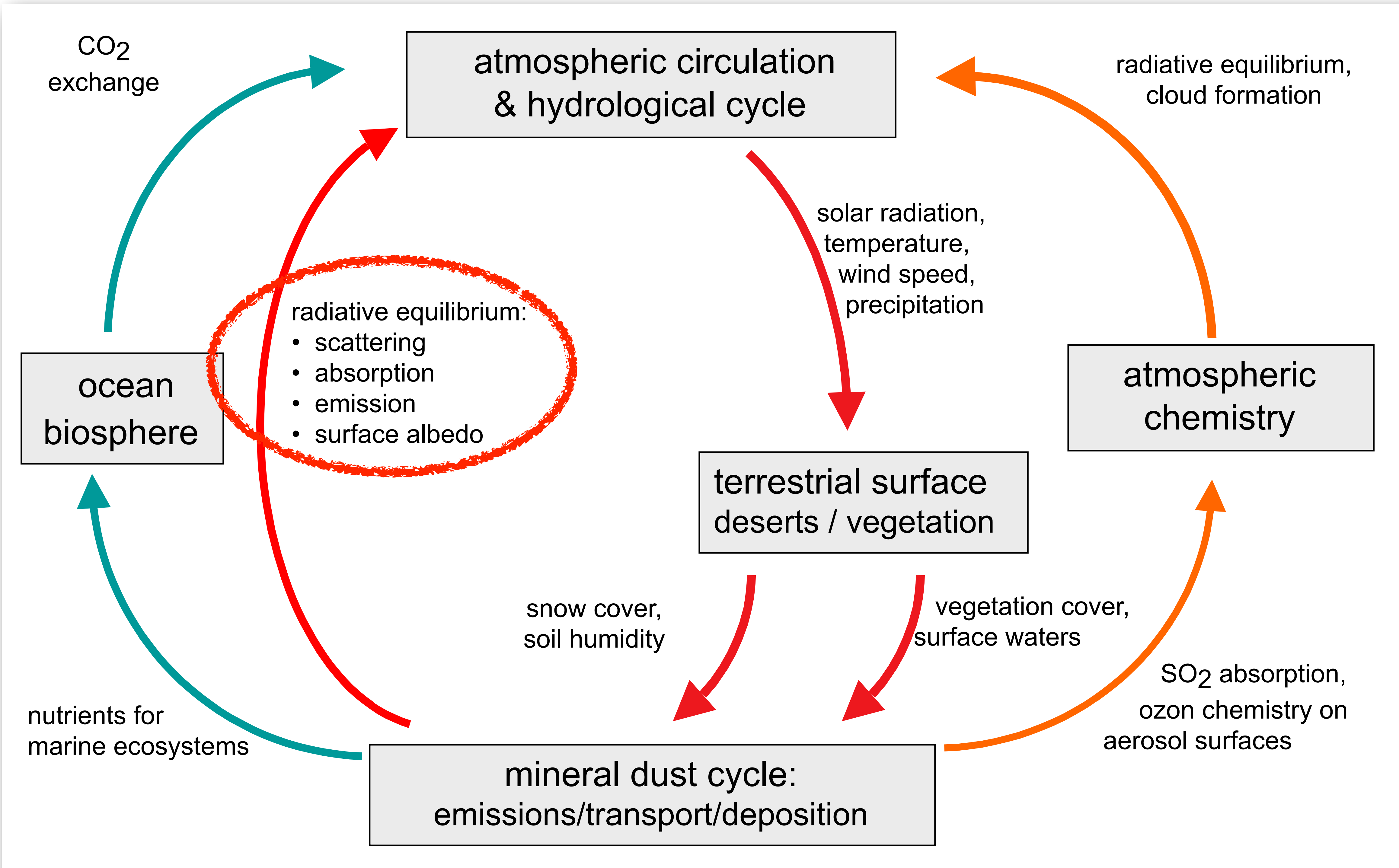
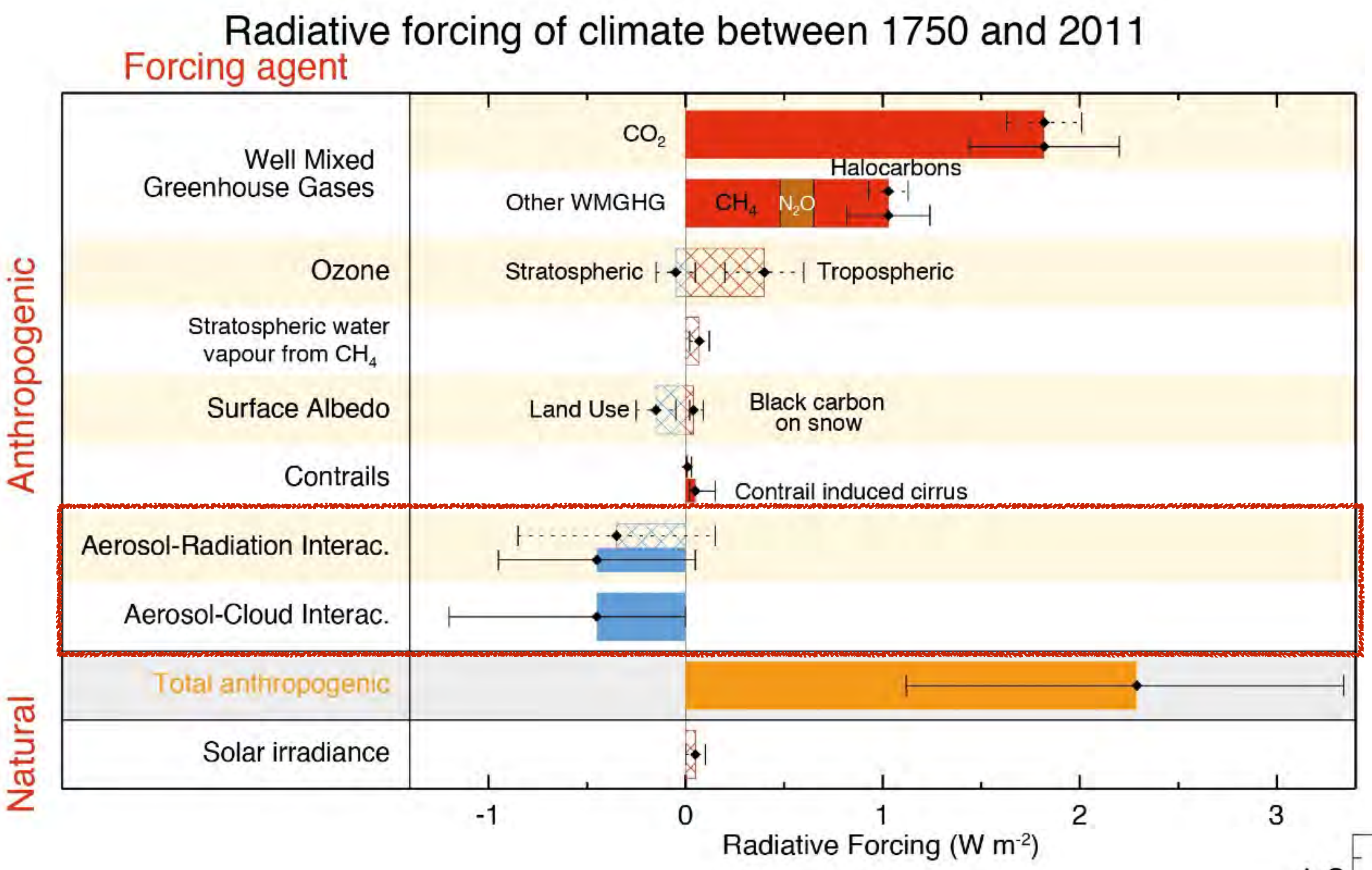
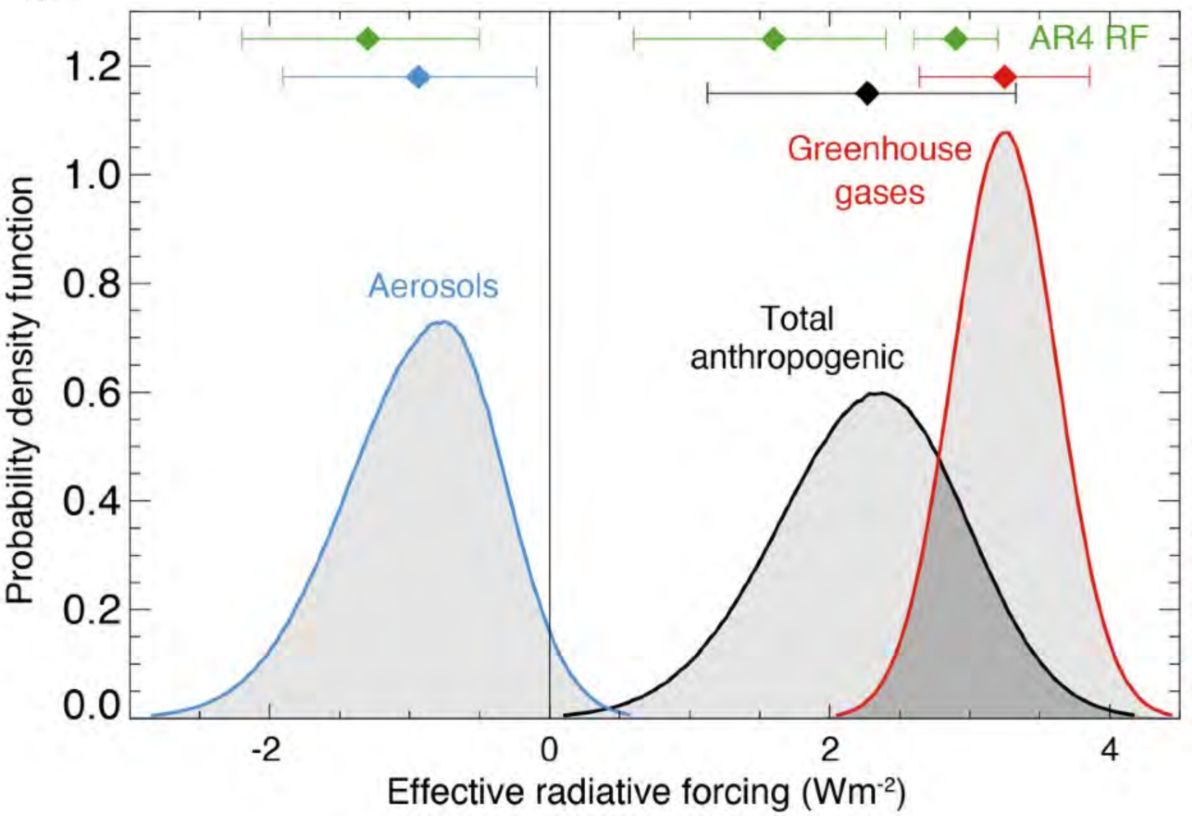
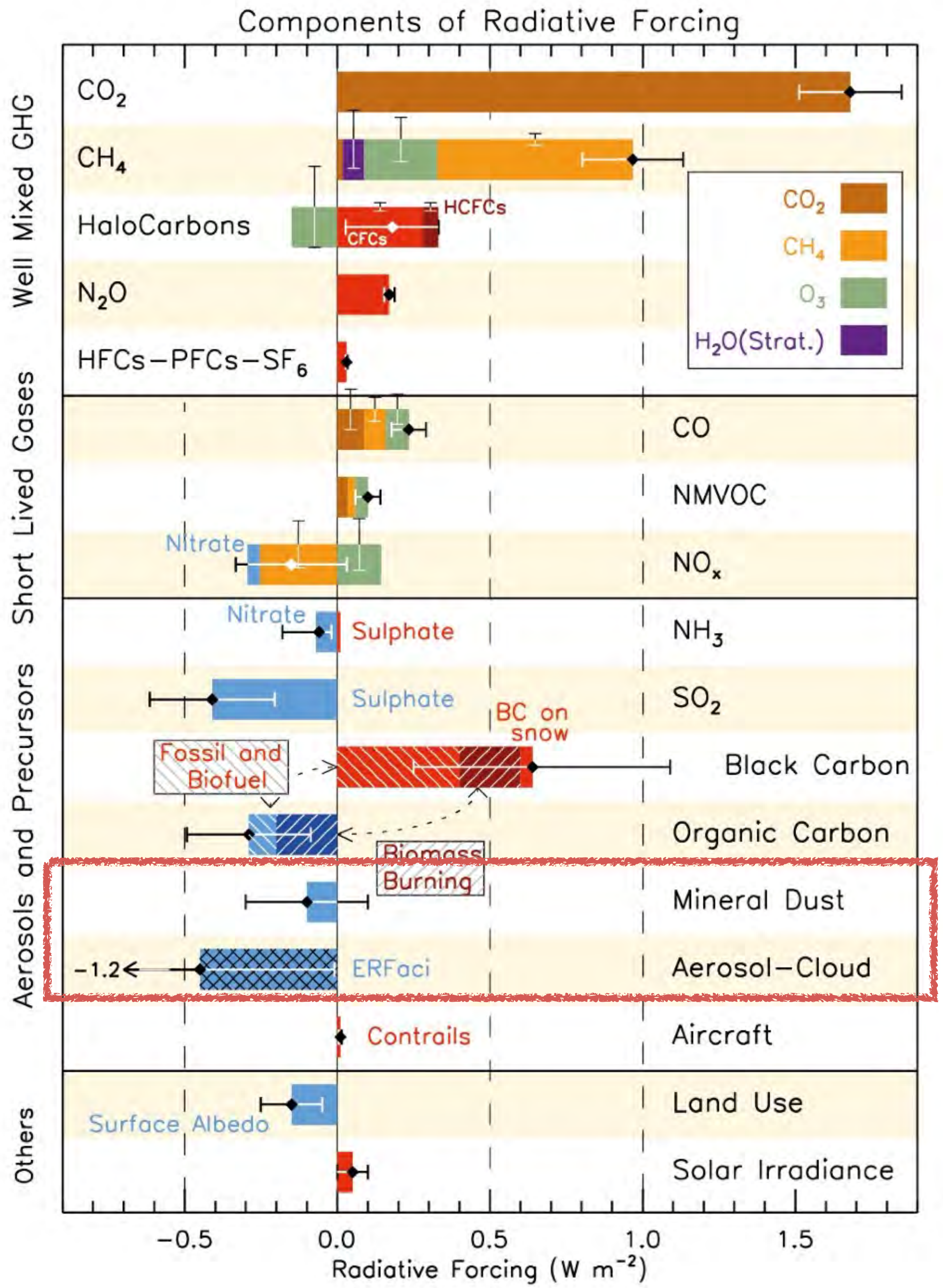


Present-day radiative forcing



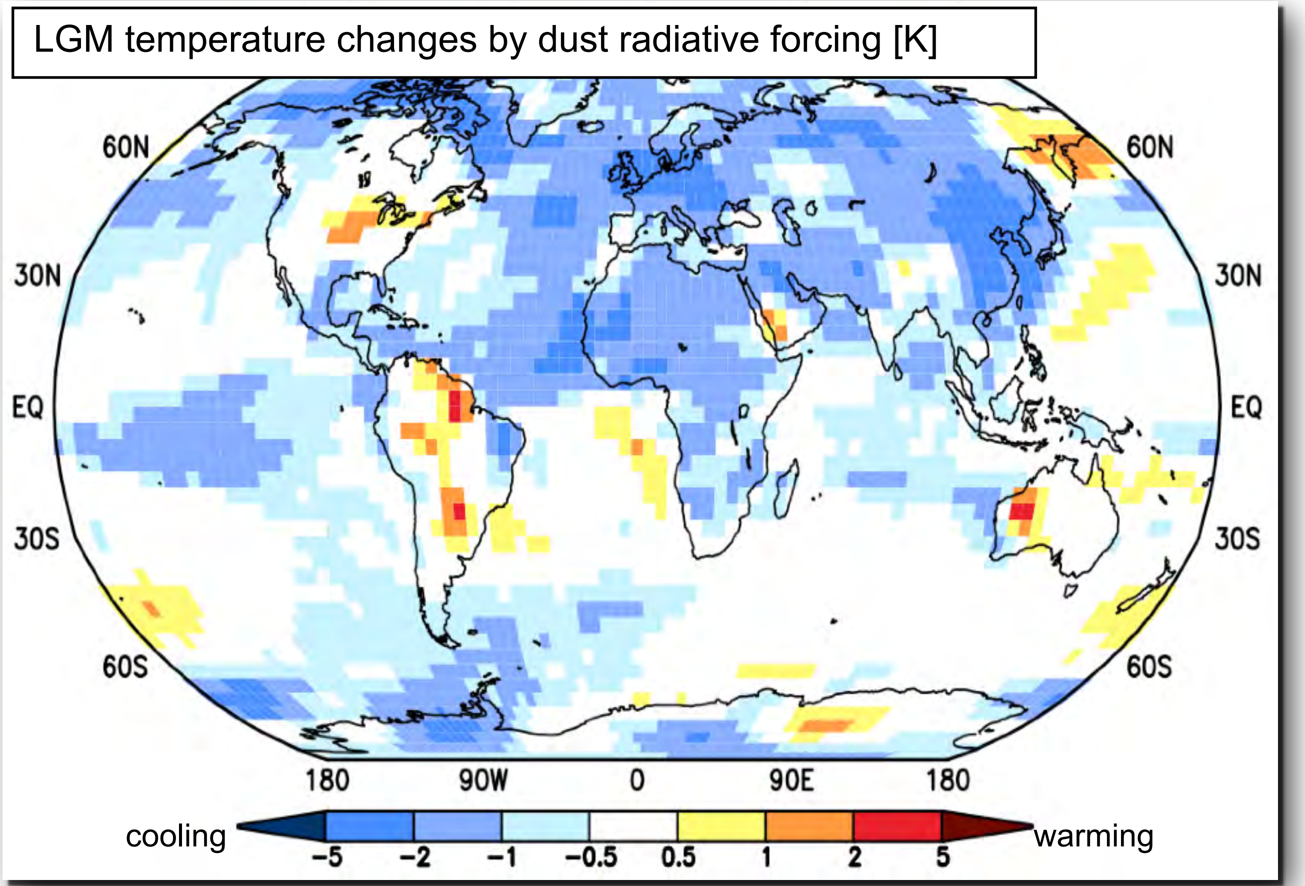


The radiative effect of mineral dust



(IPCC, AR5, 2013)

Changes of the LGM radiative budget by dust



optical properties of mineral aerosols:

- only aerosol particles between 0.3 - 4 μm have been considered
- uniform mineralogy: 98% clay, 2% hematite, intern mixing
- refractive indices based on Sokolik und Toon (1999)

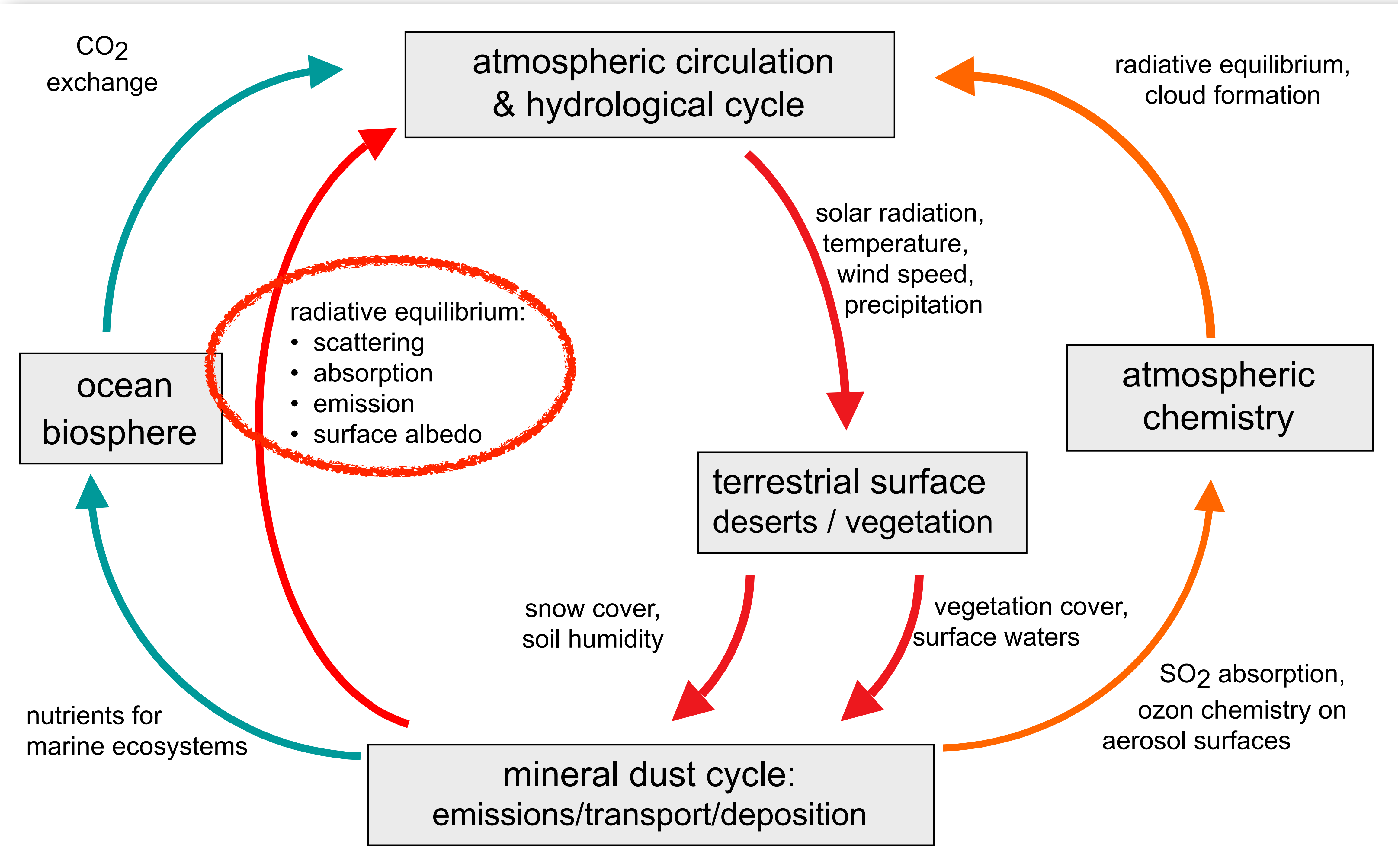
- largest radiative cooling effect near the source regions (between 45°S und 45°N)
- no *linear* relation between radiative effect and temperature changes
- feedback processes of radiative changes to the dust cycle (emission/transport/deposition) are relatively small

Zonal changes of radiative forcing and temperature:

	Claquin et al. [2003]	ECHAM5-HAM		
	TOA forcing [W/m2]	TOA forcing [W/m2]	Δ T_{surf} [K] (by dust)	Δ T_{surf} [K] (CO_2, albedo*, ice)
Global	***-1***	***-1.4***	***-0.6***	***-4.3***
90°N-45°N	-0.3	-0.6	-1.1	-14.6
45°N-45°S	-1.6	-1.8	-0.5	-1.7
45°S-90°S	+0.2	-0.8	-0.4	-6.3

(*change of albedo by dust deposition has been neglected)

Dust in the climate system



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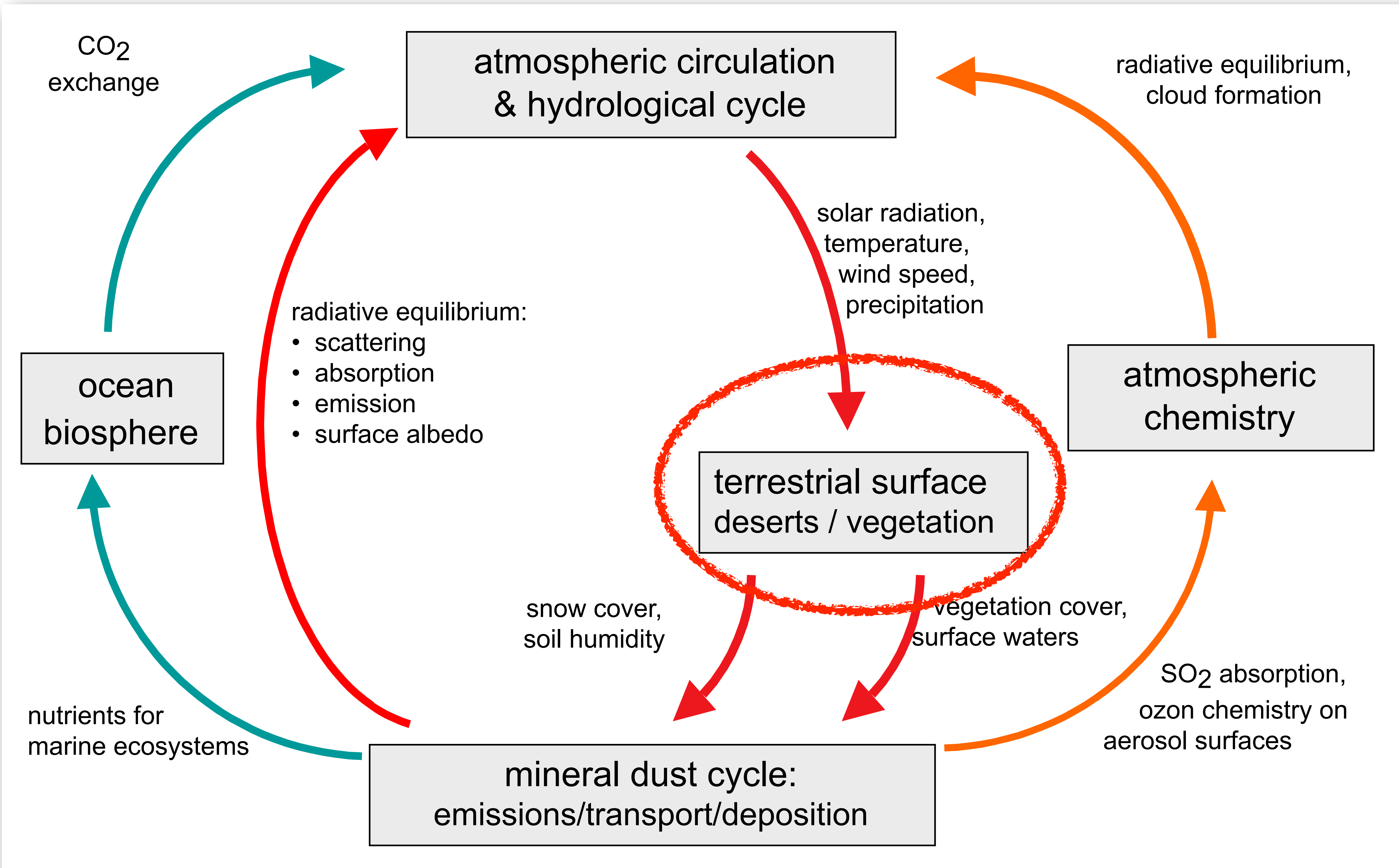
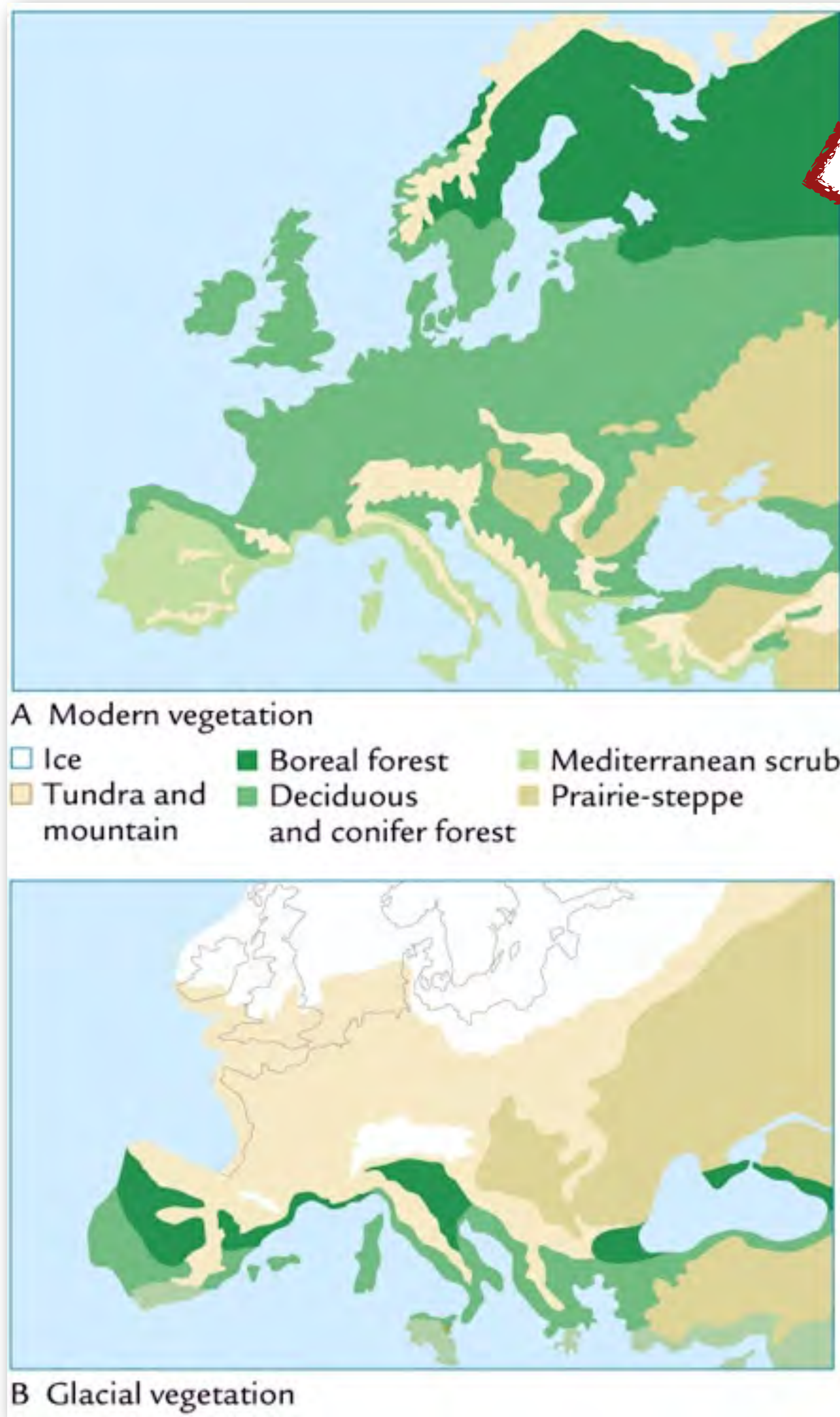


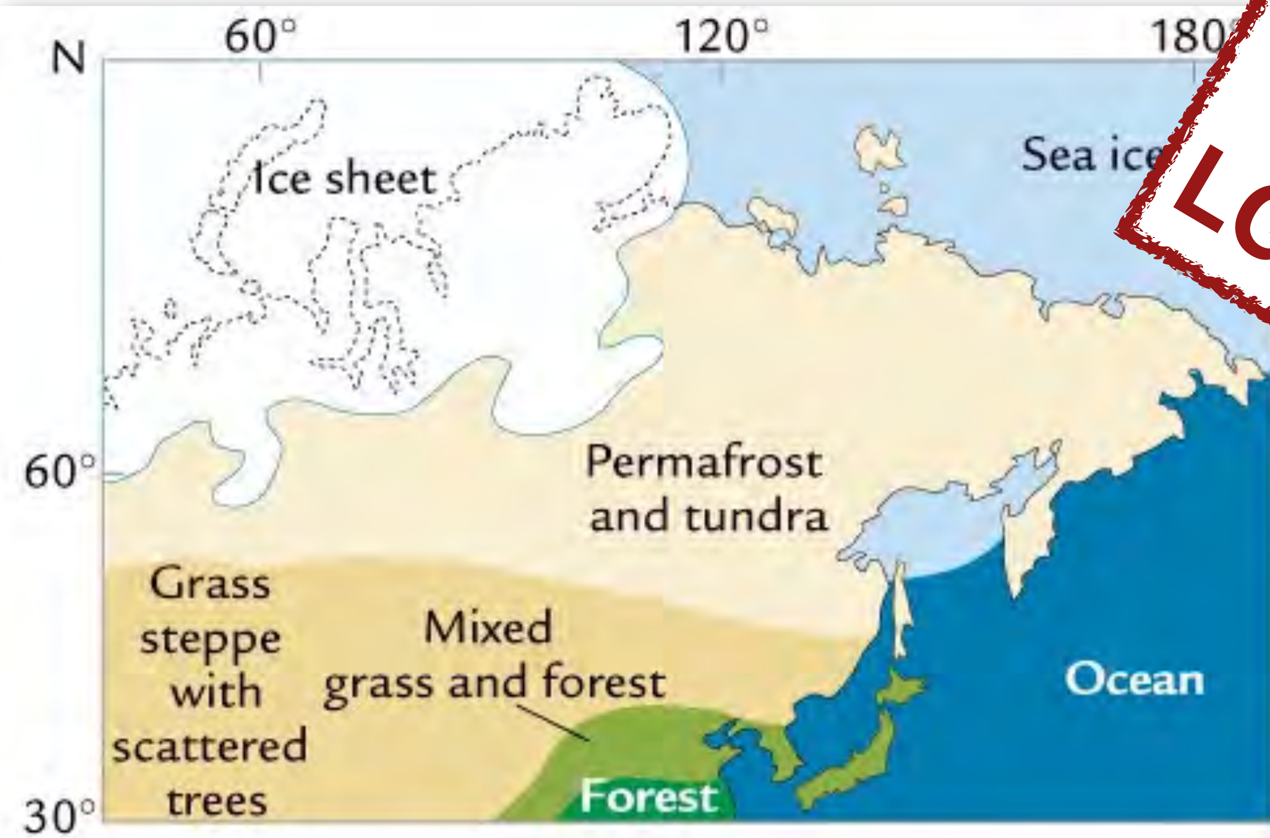
LGM climate of North America and Europe



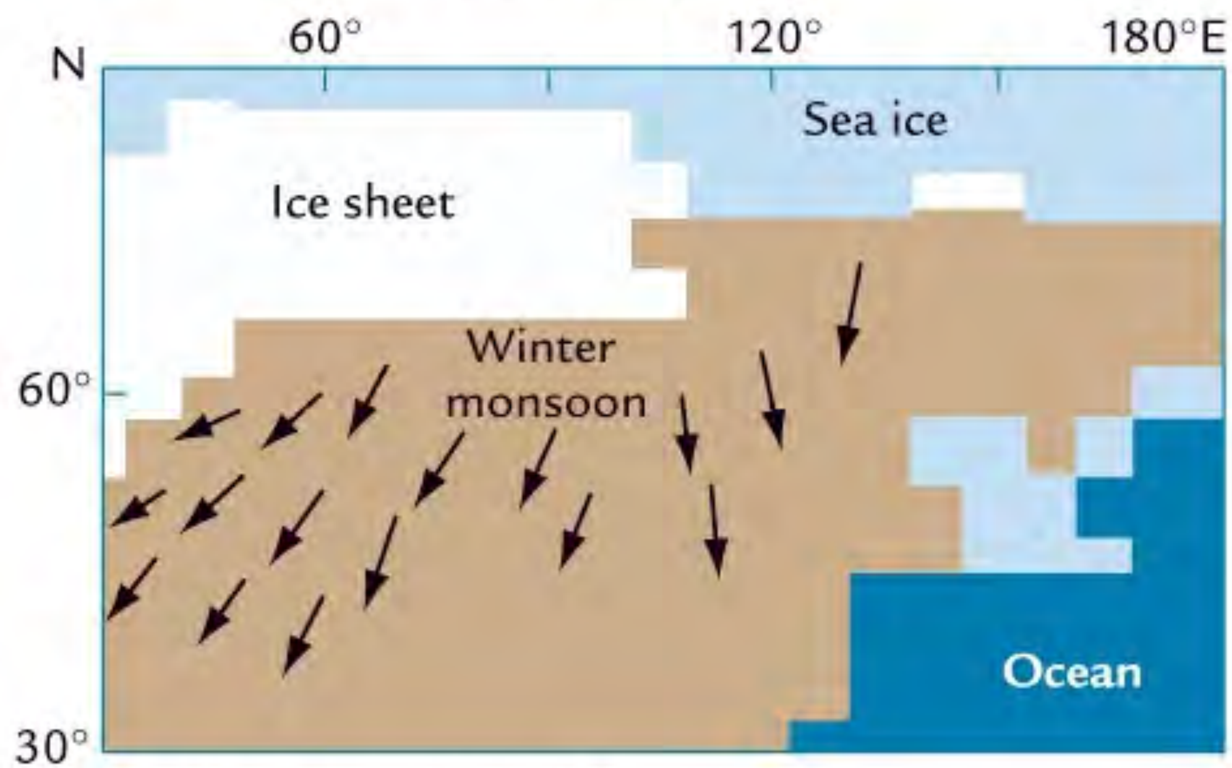
remember LGM lecture!

[from: Ruddiman, 2008]

LGM climate of Asia



A Glacial maximum (observed)

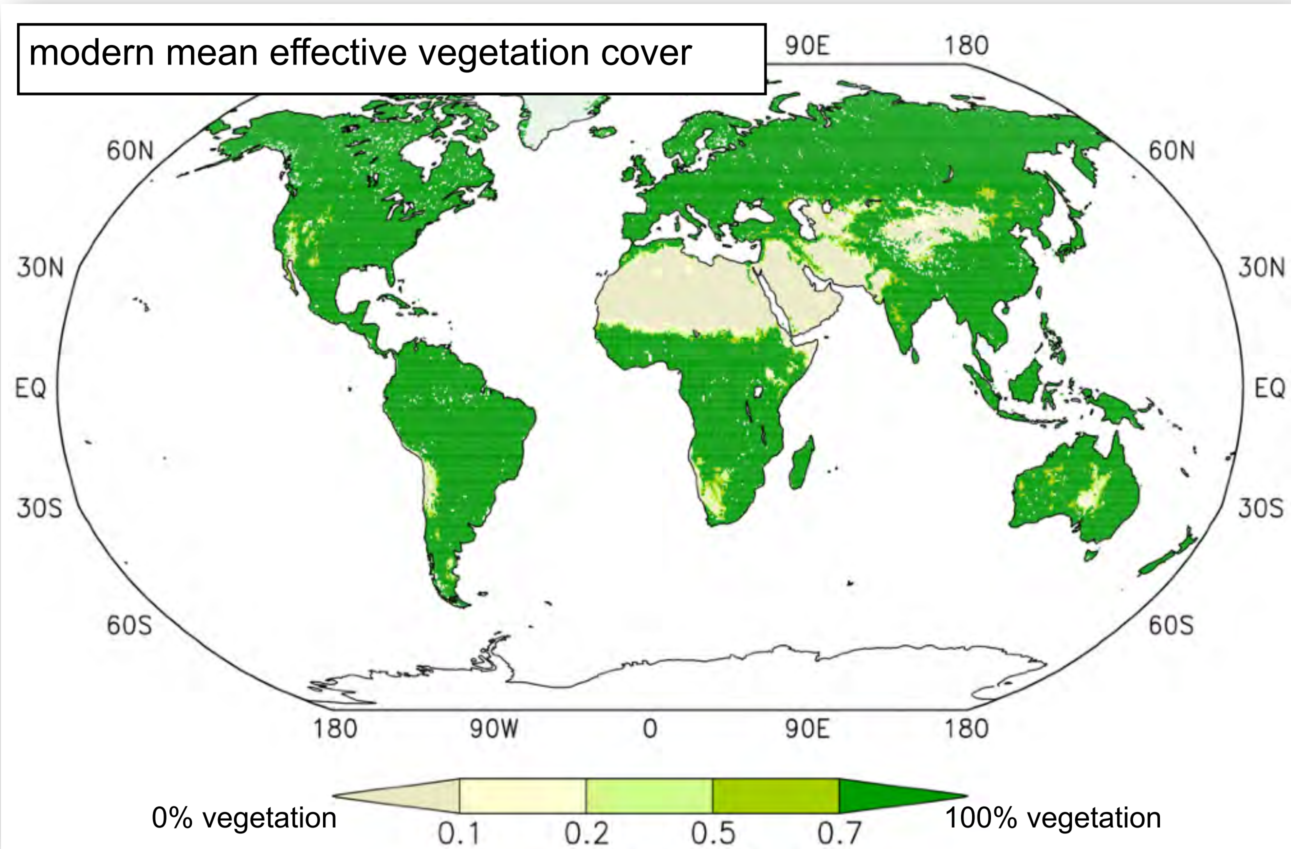


B Glacial maximum (model)

remember LGM lecture!

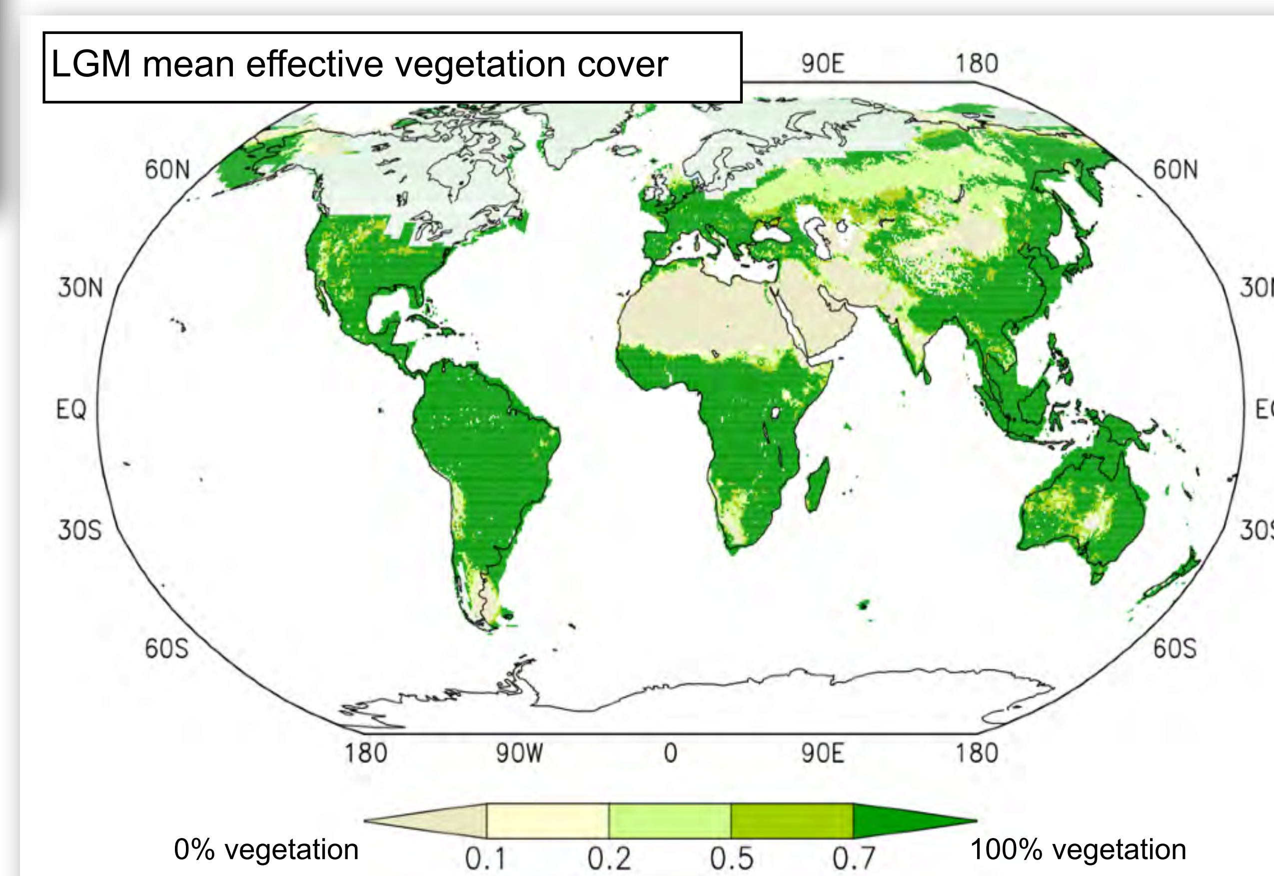
[from: Ruddiman, 2008]

Simulation of glacial vegetation changes

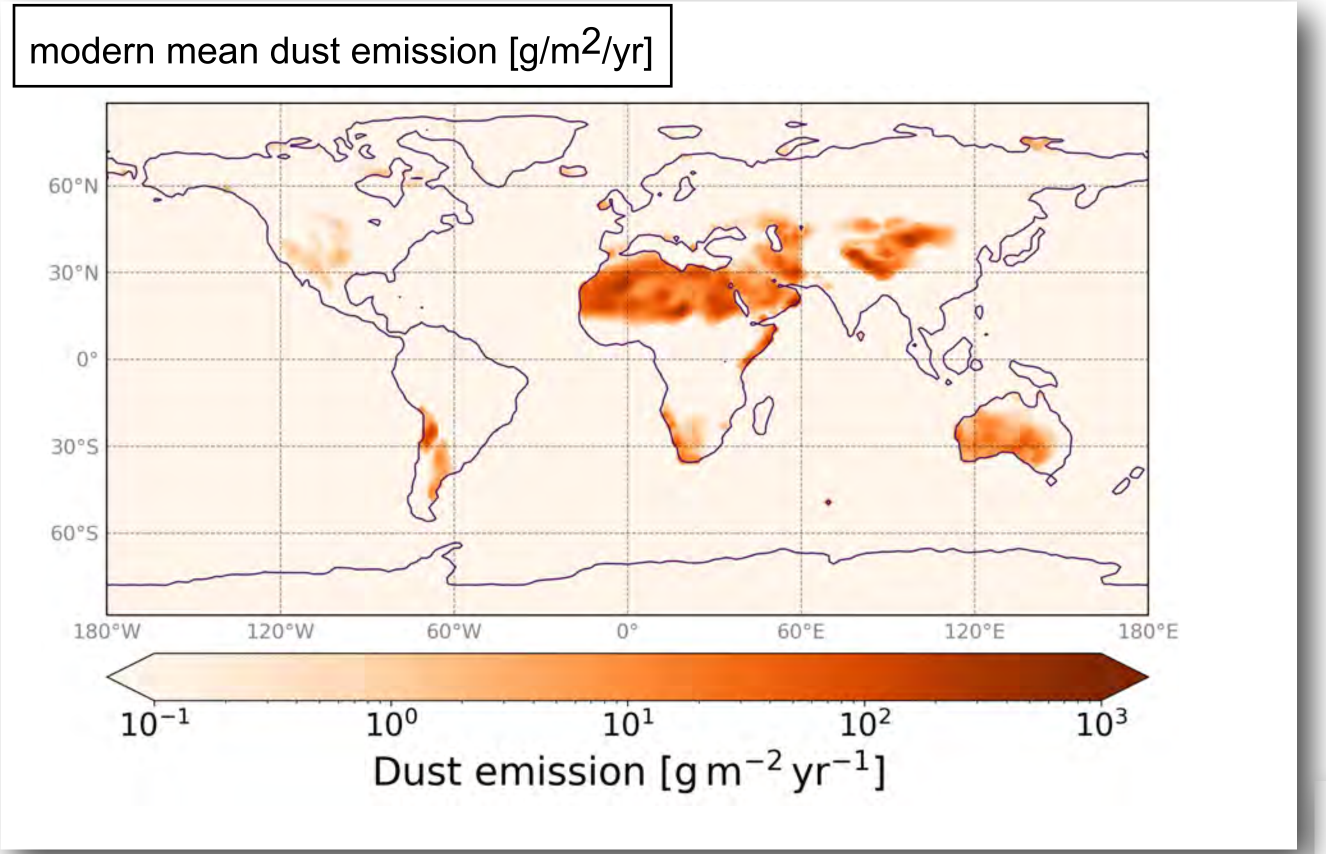


changes in glacial vegetation cover:

- **major decrease in vegetation cover in central and northern Asia, South America and lesser changes in Australia**
- **(almost) no change of vegetation cover in present-day desert regions, e.g. Sahara**

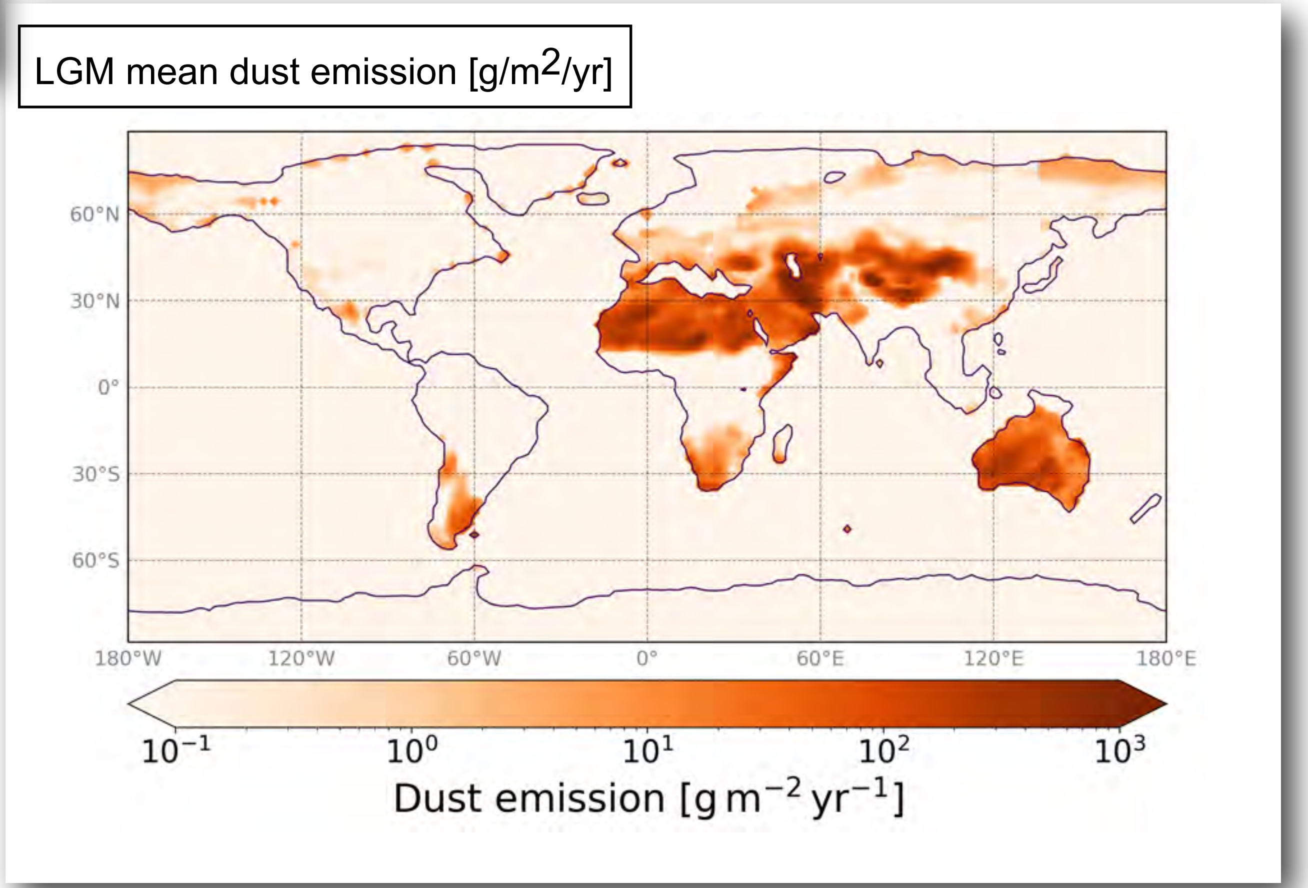


Simulation of glacial dust emissions



changes of glacial dust emissions:

- global emission increase of factor ~2-3
- glacial increase is not uniform, but varies for the different source regions



- Sahara: increased dust emissions by increased number and intensity of dust storms
- Asia: increased dust emissions by increase of (potential) source areas
- seasonal changes of LGM dust emissions are mainly related to changes in vegetation cover

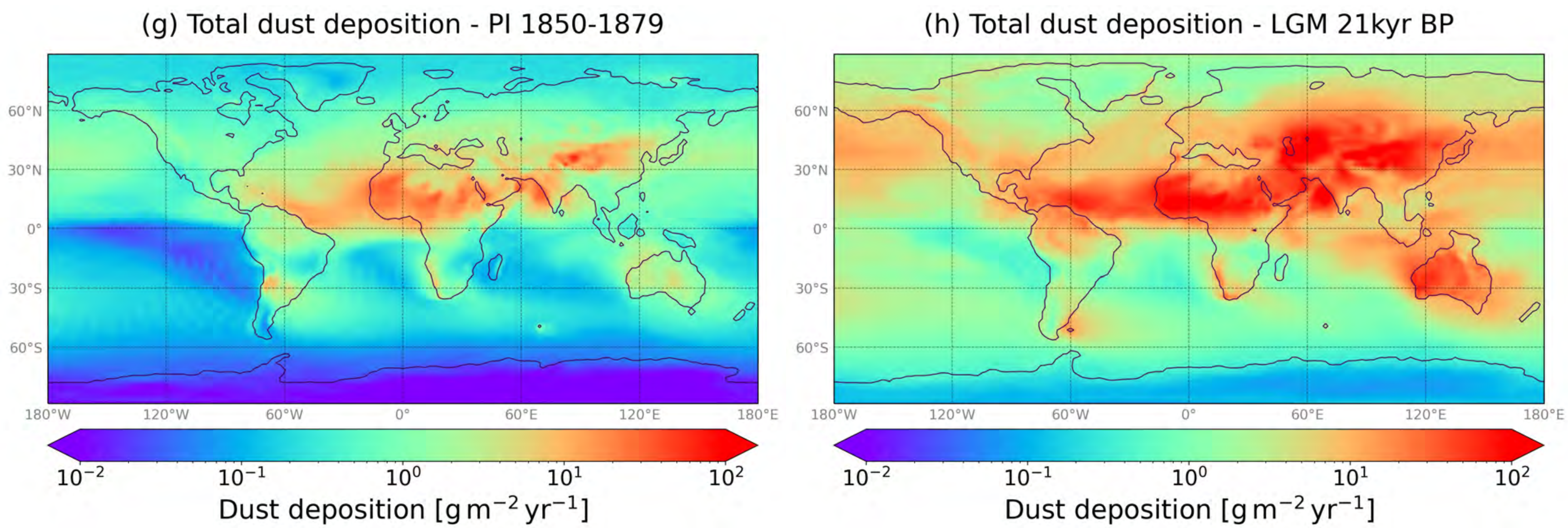
[plots from: Krätschmer et al., Climate of the Past, 2021, accepted]

Modern and LGM dust deposition fluxes

simulation: ECHAM-6.3-HAM2.3 (modern and LGM, respectively)

reconstructions: DIRTMAP Datenbank

(DIRTMAP: Dust Indicator and Records of Terrestrial and Marine Paleoenvironments)



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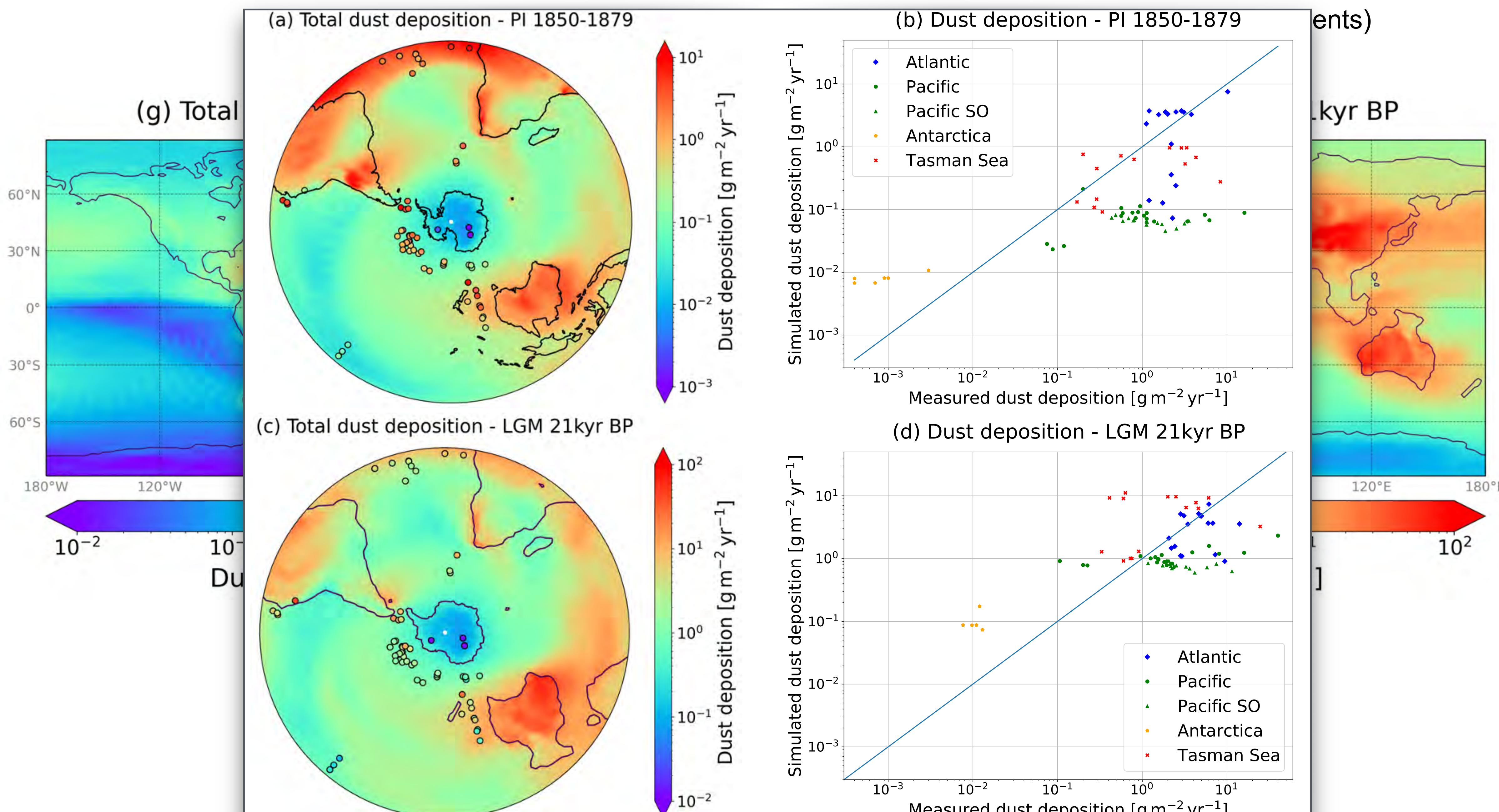

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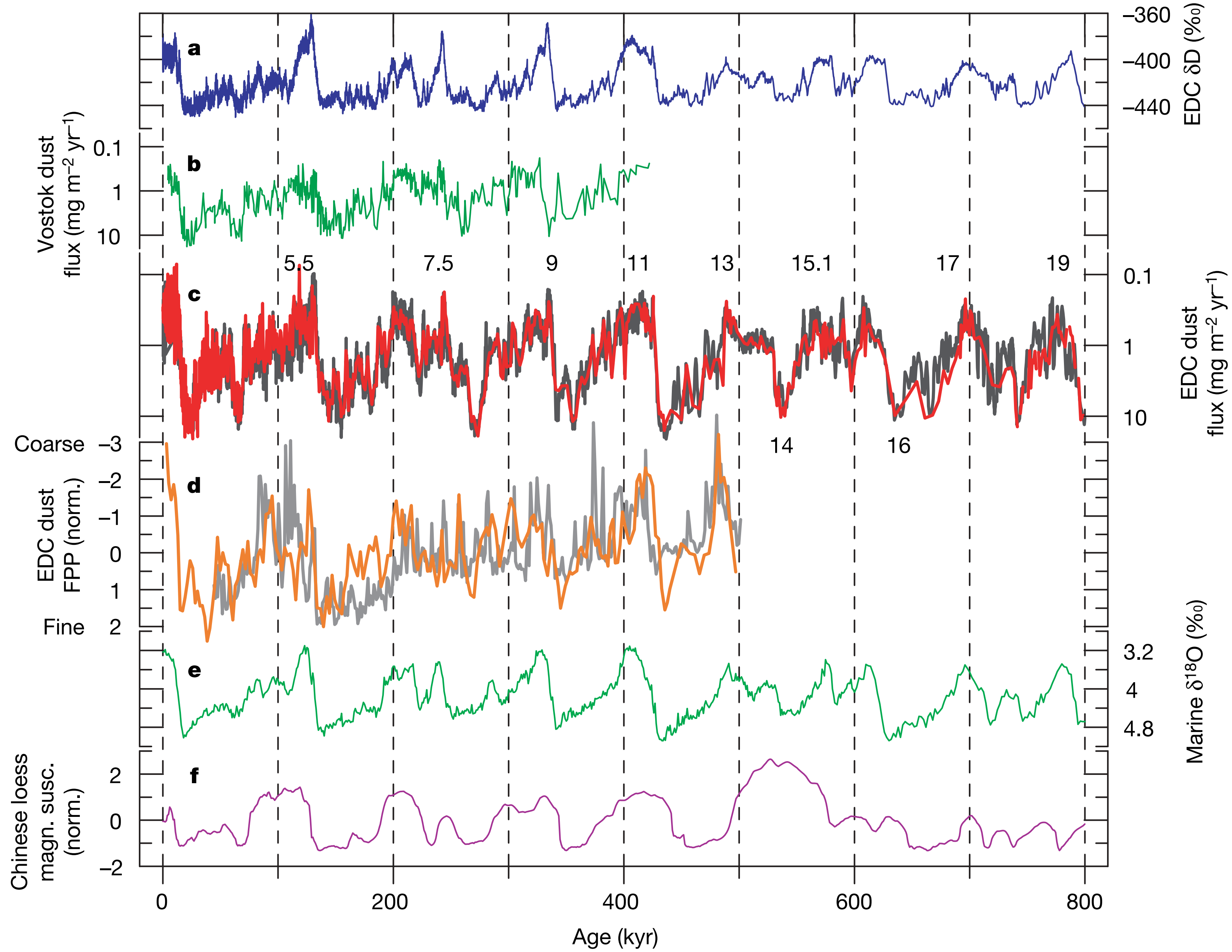


temperature

dust

ice volume

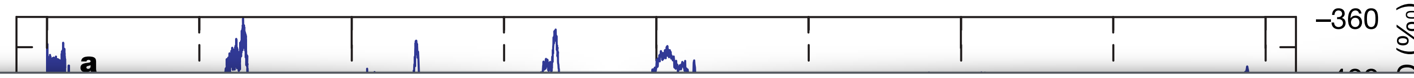
Figure 1 | EDC dust data in comparison with other climatic indicators. **a**, Stable isotope (δD) record from the EPICA Dome C (EDC) ice core[8] back to Marine Isotopic Stage 20 (EDC3 timescale) showing Quaternary temperature variations in Antarctica. **b**, Vostok dust flux record (Coulter counter) plotted on its original timescale[11]. **c**, EDC dust flux records. Red and grey lines represent, respectively, Coulter counter (55-cm to 6-m resolution) and laser-scattering data (55-cm mean). Numbers indicate Marine Isotopic Stages. Note that the vertical extent of the scales of **b** and **c** is larger than for the other records. **d**, EDC dust size data expressed as FPP (see Methods). The orange and grey curves represent measurements by Coulter counter (2-kyr mean) and laser (1-kyr mean), respectively. **e**, Marine sediment $\delta^{18}O$ stack[18], giving the pattern of global ice volume. **f**, Magnetic susceptibility stack record for Chinese loess[17] (normalized).

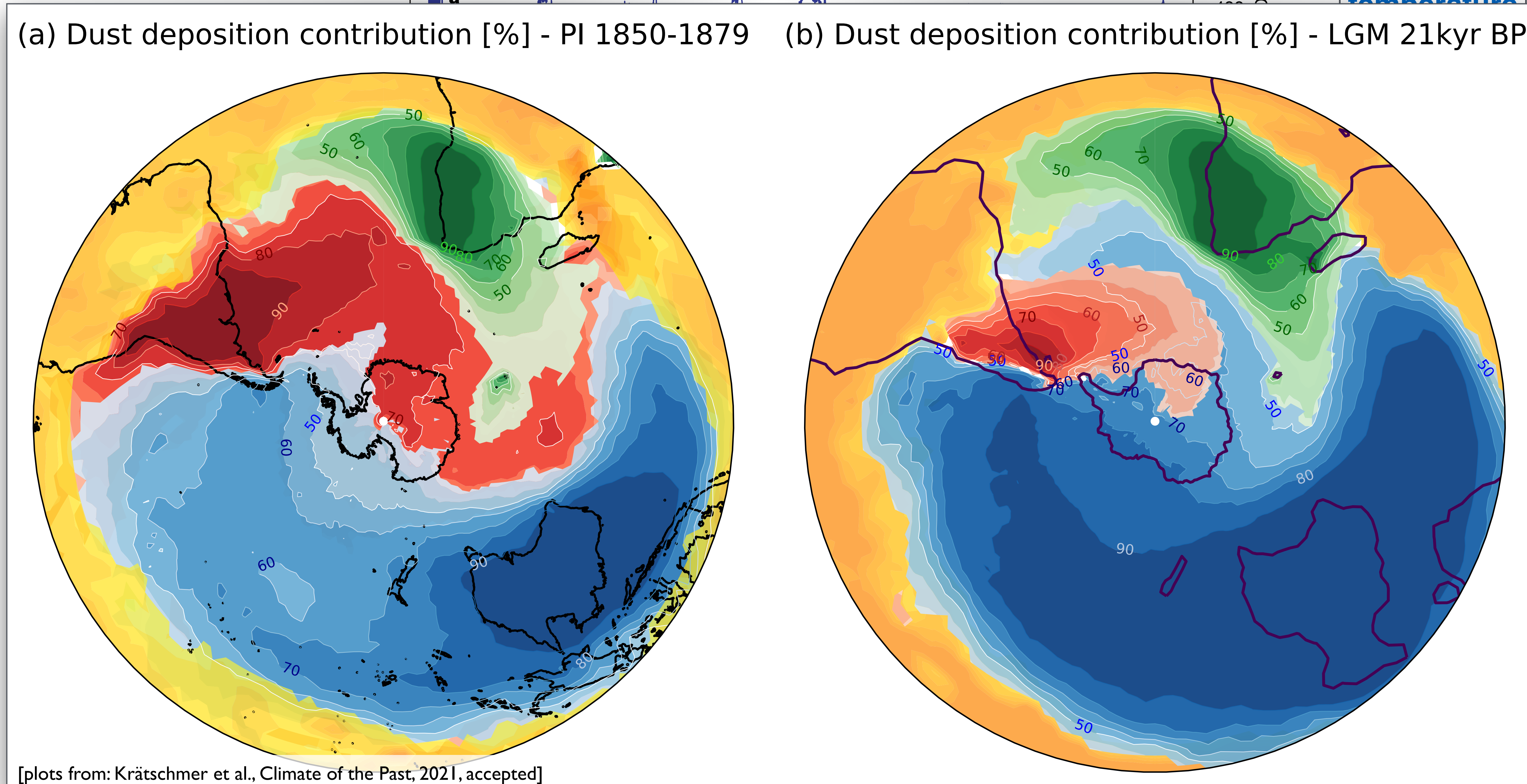
Dust depositions on glacial-interglacial time scales

Dust–climate couplings over the past 800,000 years from the EPICA Dome C ice core

Vol 452|3 April 2008|**doi:10.1038/nature06763**

F. Lambert[1,2], B. Delmonte[3], J. R. Petit[4], M. Bigler[1,5], P. R. Kaufmann[1,2], M. A. Hutterli[6], T. F. Stocker[1,2], U. Ruth[7], J. P. Steffensen[5] & V. Maggi[3]





[plots from: Krätschmer et al., Climate of the Past, 2021, accepted]

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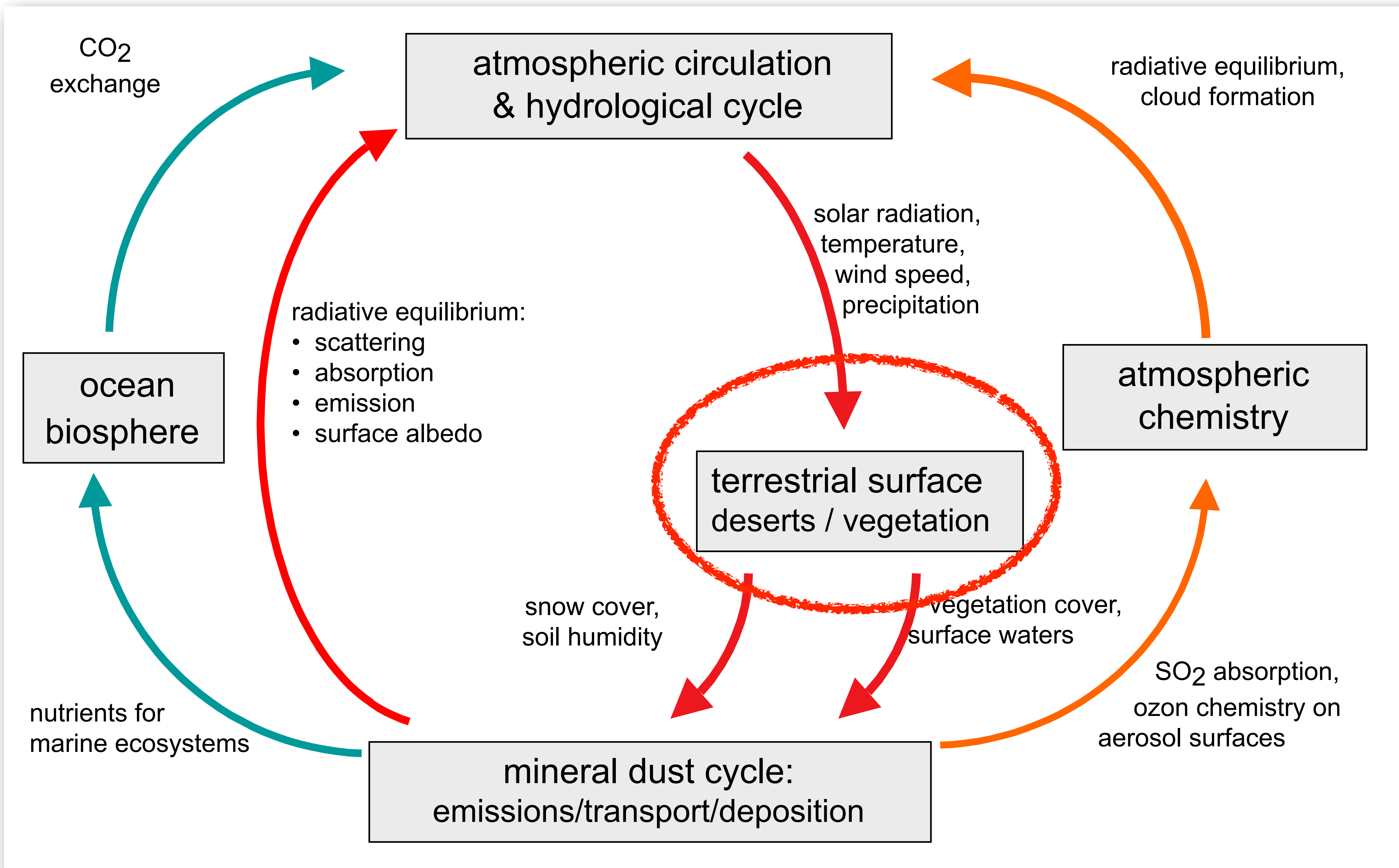
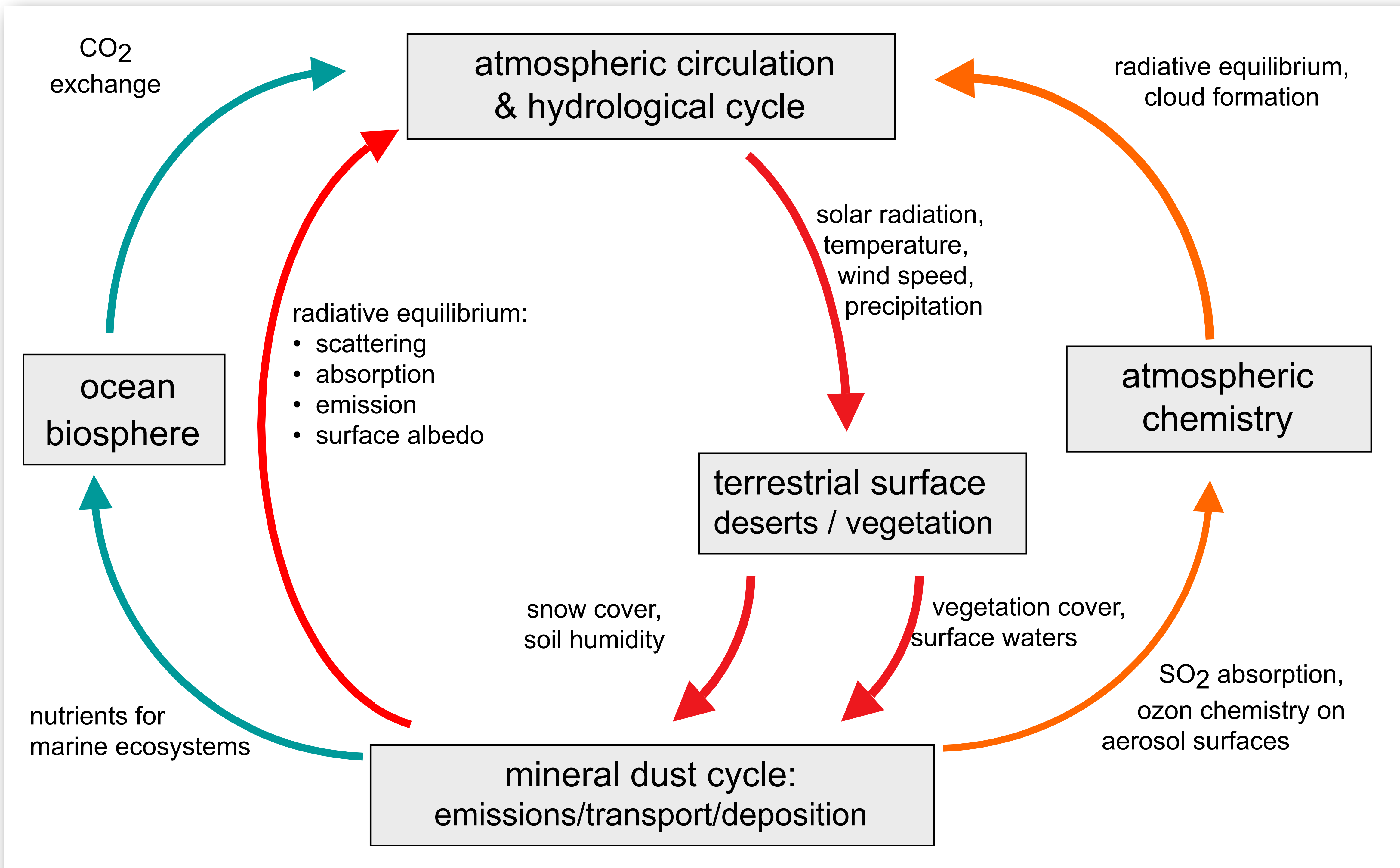
Methods). The orange and grey curves represent measurements by Coulter counter (2-kyr mean) and laser (1-kyr mean), respectively. **e**, Marine sediment $\delta^{18}O$ stack[18], giving the pattern of global ice volume. **f**, Magnetic susceptibility stack record for Chinese loess[17] (normalized).

Dust in the climate system



Dust in the climate system



The glacial dust cycle: summary

- during LGM: 3- to 5-fold increase of dust cycle intensity (global value)
  - about 1/2 - 2/3 of glacial increase in dust emissions might be caused by the increased wind strength during the LGM
  - about 1/3 - 1/2 of the glacial dust emissions might stem from glacial-only source regions (change of glacial vegetation cover)
- mineral dust aerosol might be responsible for about 1/4 of the glacial temperature cooling in the (sub)tropical low latitudes
  - in higher northern latitudes these radiative effects are minor as compared to radiative changes caused by the glacial ice sheet
- model simulations with marine biogeochemistry models reveal that the glacial atmospheric CO2 concentration may have been decreased by up to 40-50ppm
  - it seems unlikely that glacial dust input into the oceans is the only reason for the observed total glacial-interglacial CO_2-reduction of ~80-100 ppm

Climate System II

(Winter 2021/2022)

8th lecture:

Dust and Vegetation

(glacial dust increase, iron fertilisation, radiative forcing, vegetation and aridity)

End of lecture.

Slides available at:

https://paleodyn.uni-bremen.de/study/climate2021_22.html