and now for
something completely different

Earth's climate as a complex system

Antonello PROVENZALE

Istituto di Geoscienze e Georisorse, Pisa

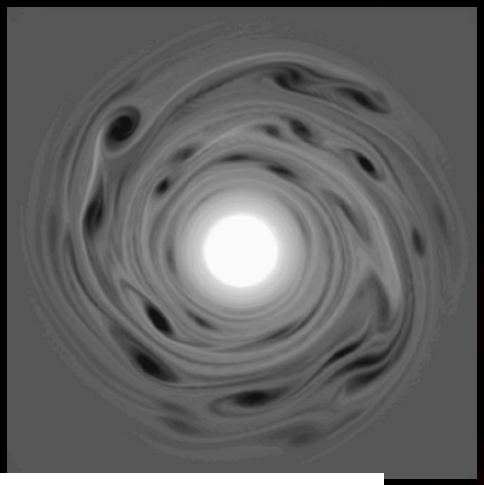
Dipartimento di Scienze del Sistema Terra

e Tecnologie per l'Ambiente

Consiglio Nazionale delle Ricerche


Once upon a time
there was a large molecular cloud
www.nasa.gov

a dusty disk around a young star was generated



Bracco et al, Phys. Fluids 1999

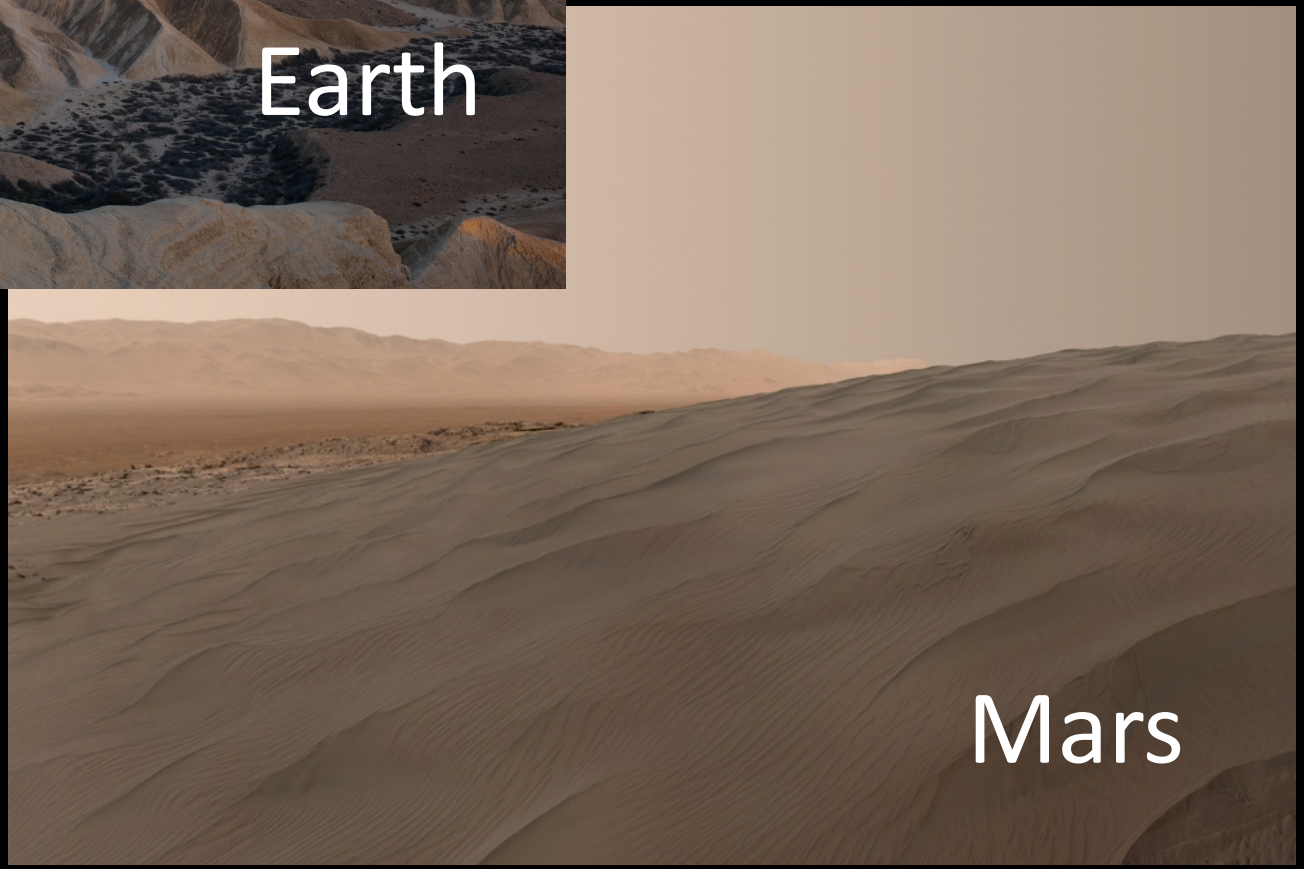
http://www.almaobservatory.org/

then Earth formed…

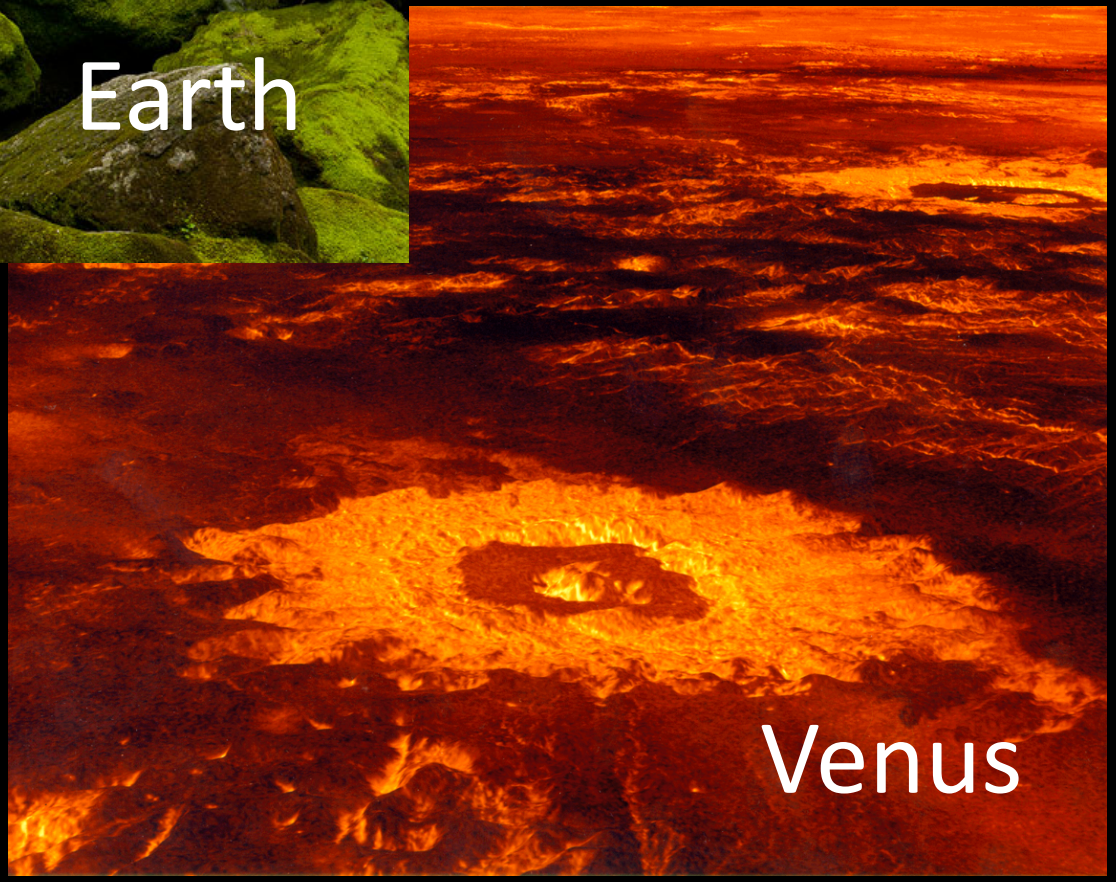
the planet cooled down with time, and life thrived on Earth

"Earthrise", Apollo 8, 24 December 1968, photo B. Anders, NASA

What makes
Sol 3 special?



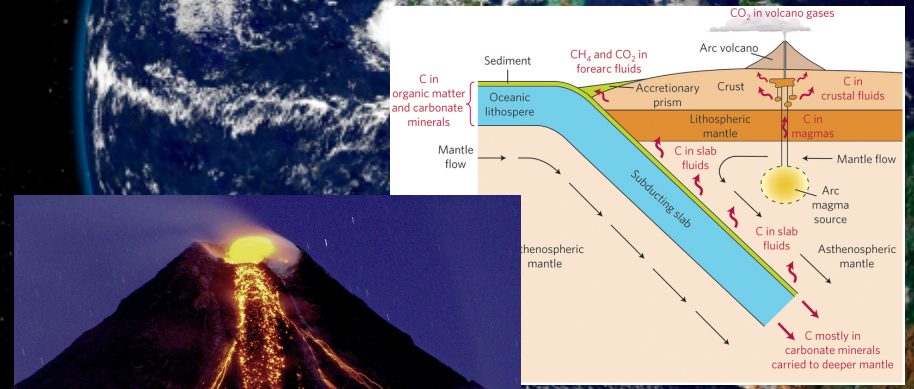
What makes Sol 3 special?



Today, planet Earth is an open nonlinear system

Solar forcing

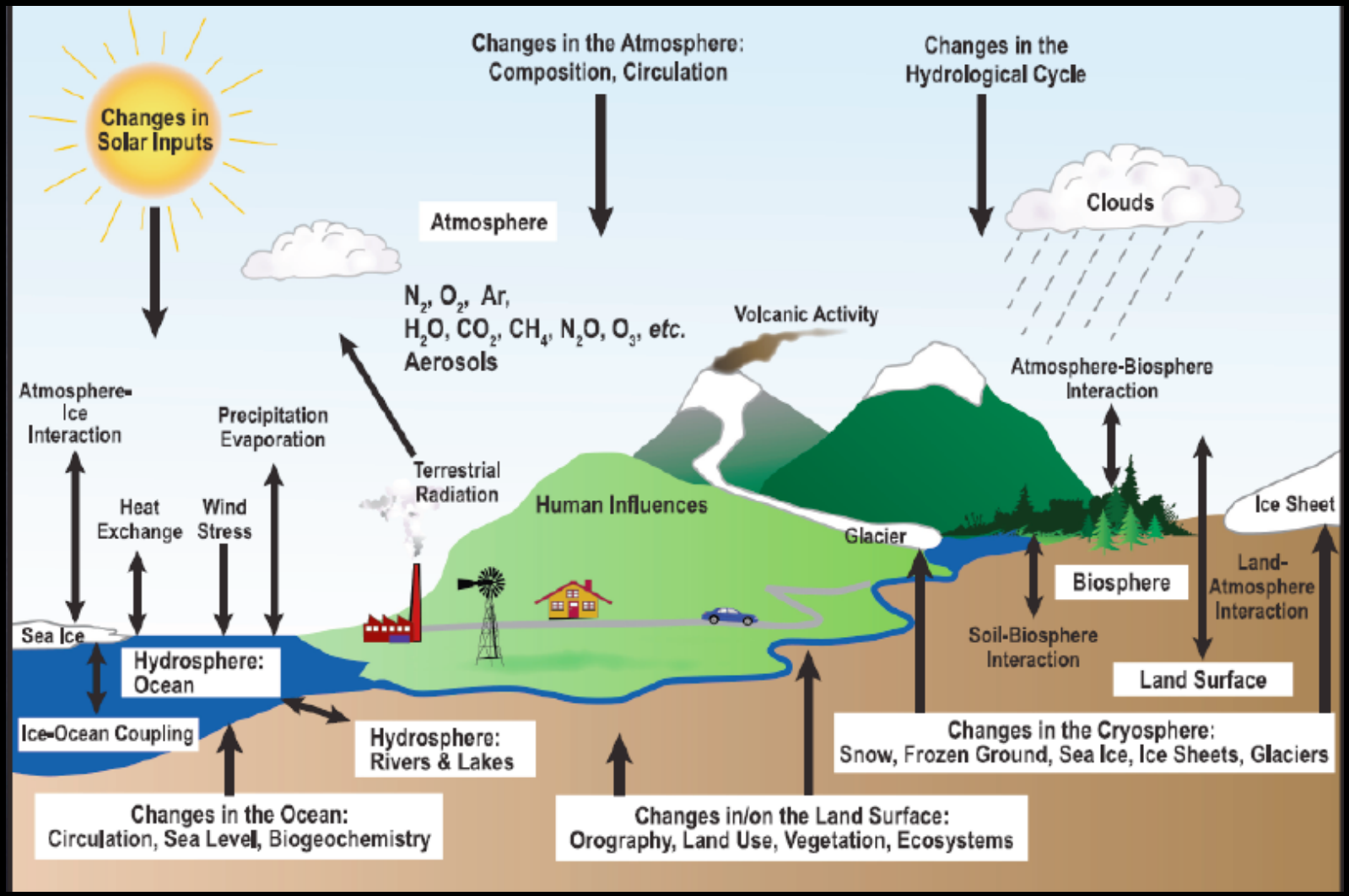
Gravitational friction



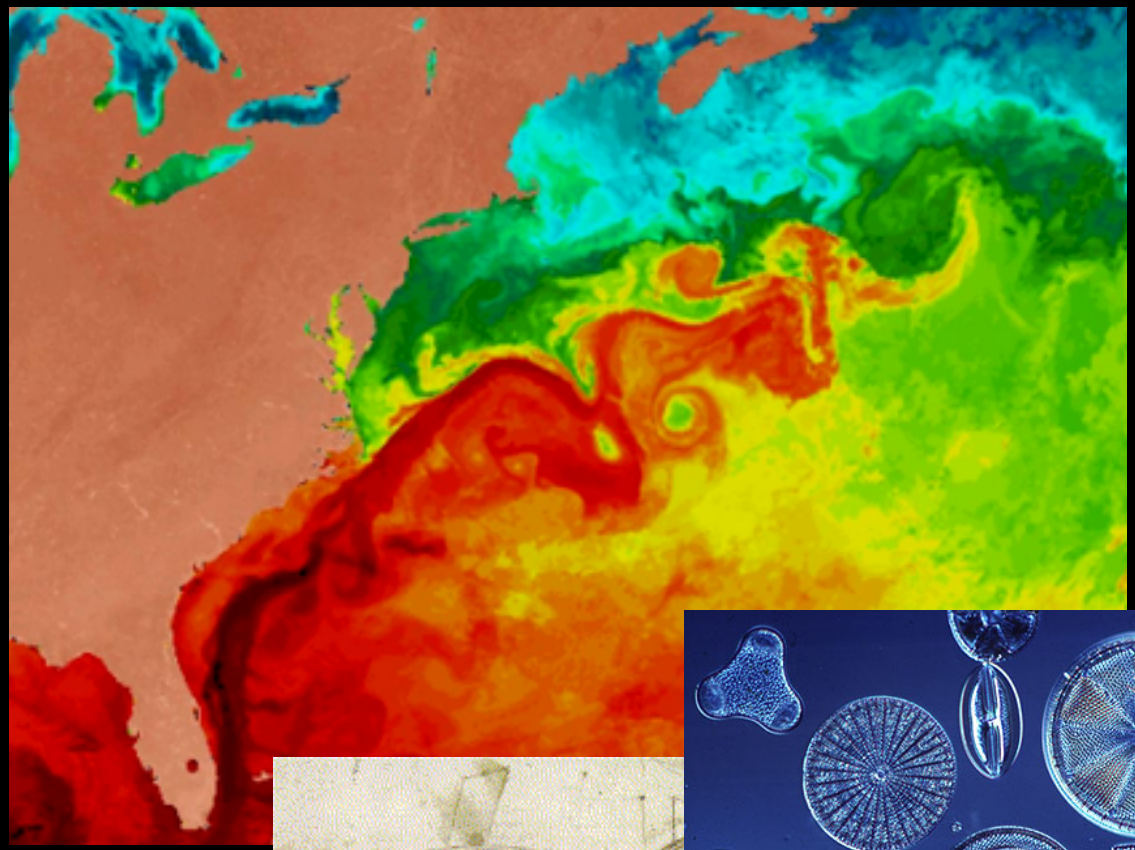
Radioactive decay + condensation in the core

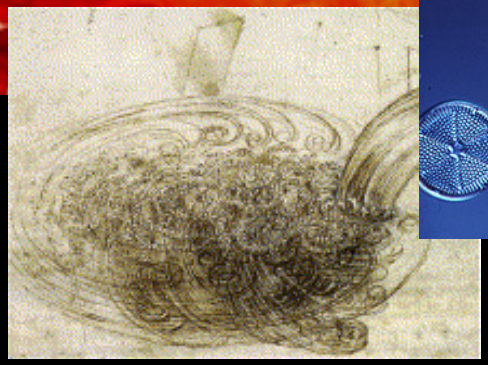
Infrared emission

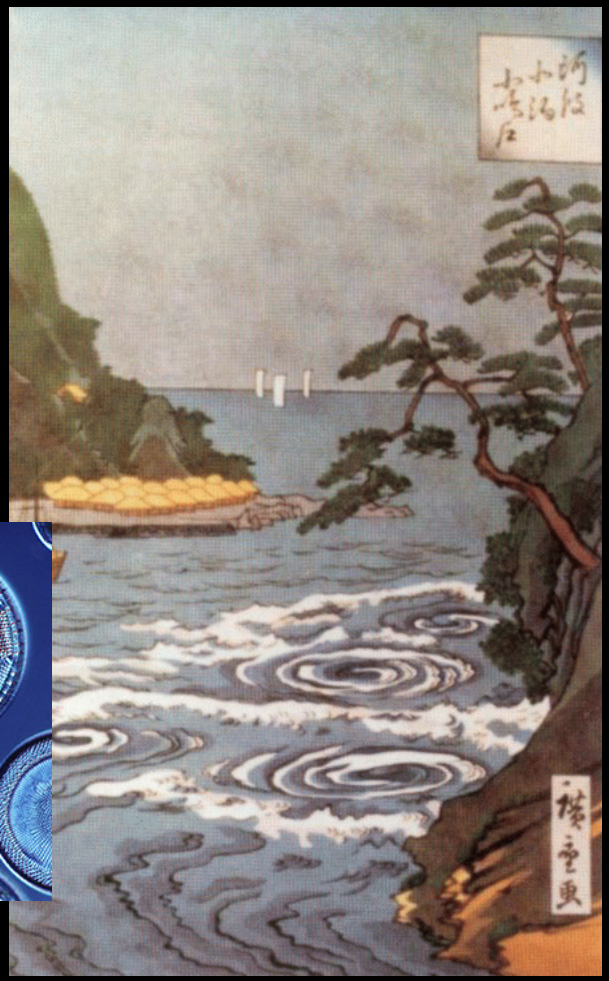
Climate:
the thermodynamical state of the Earth System



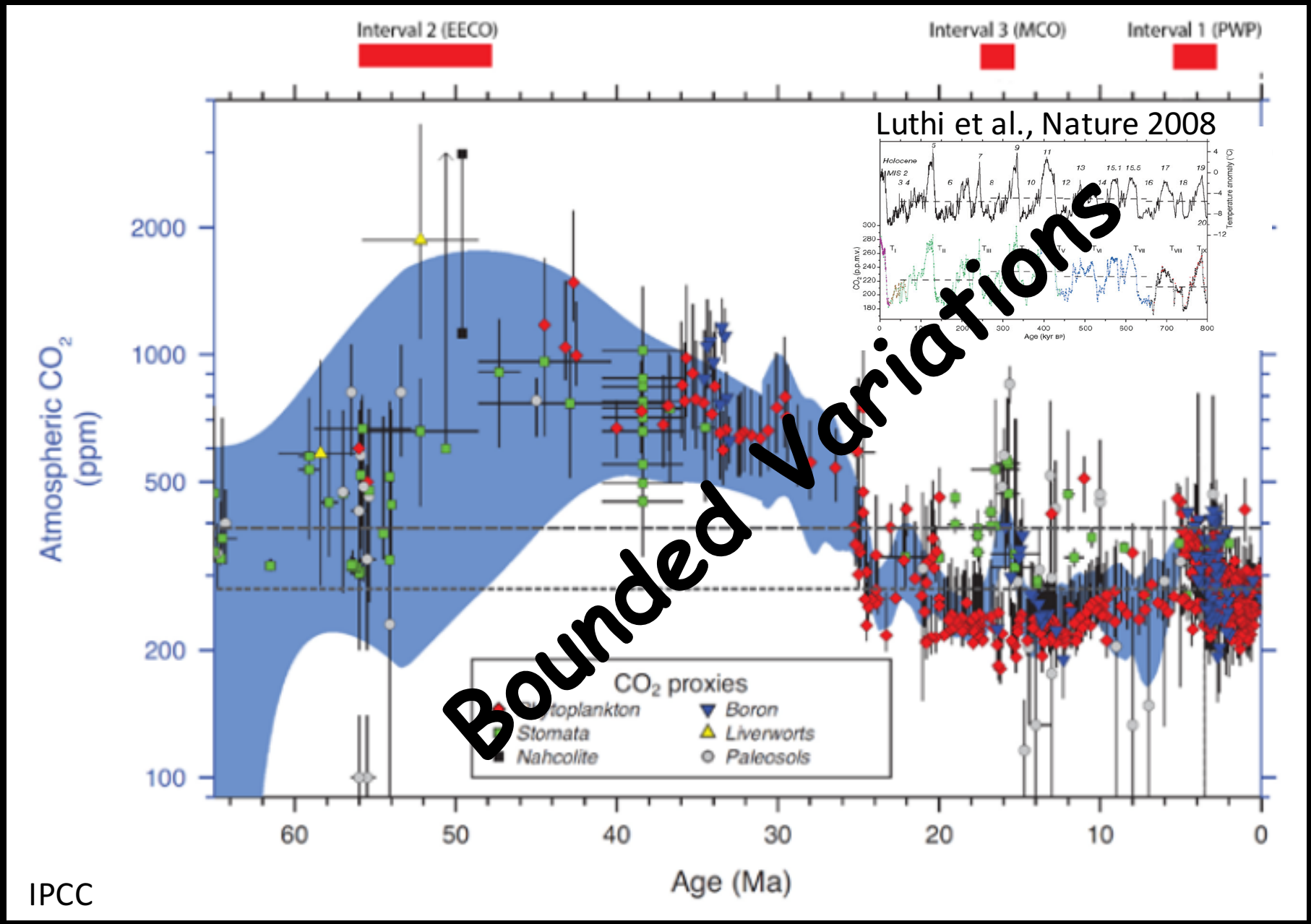
Climate:
interactions across space and time scale



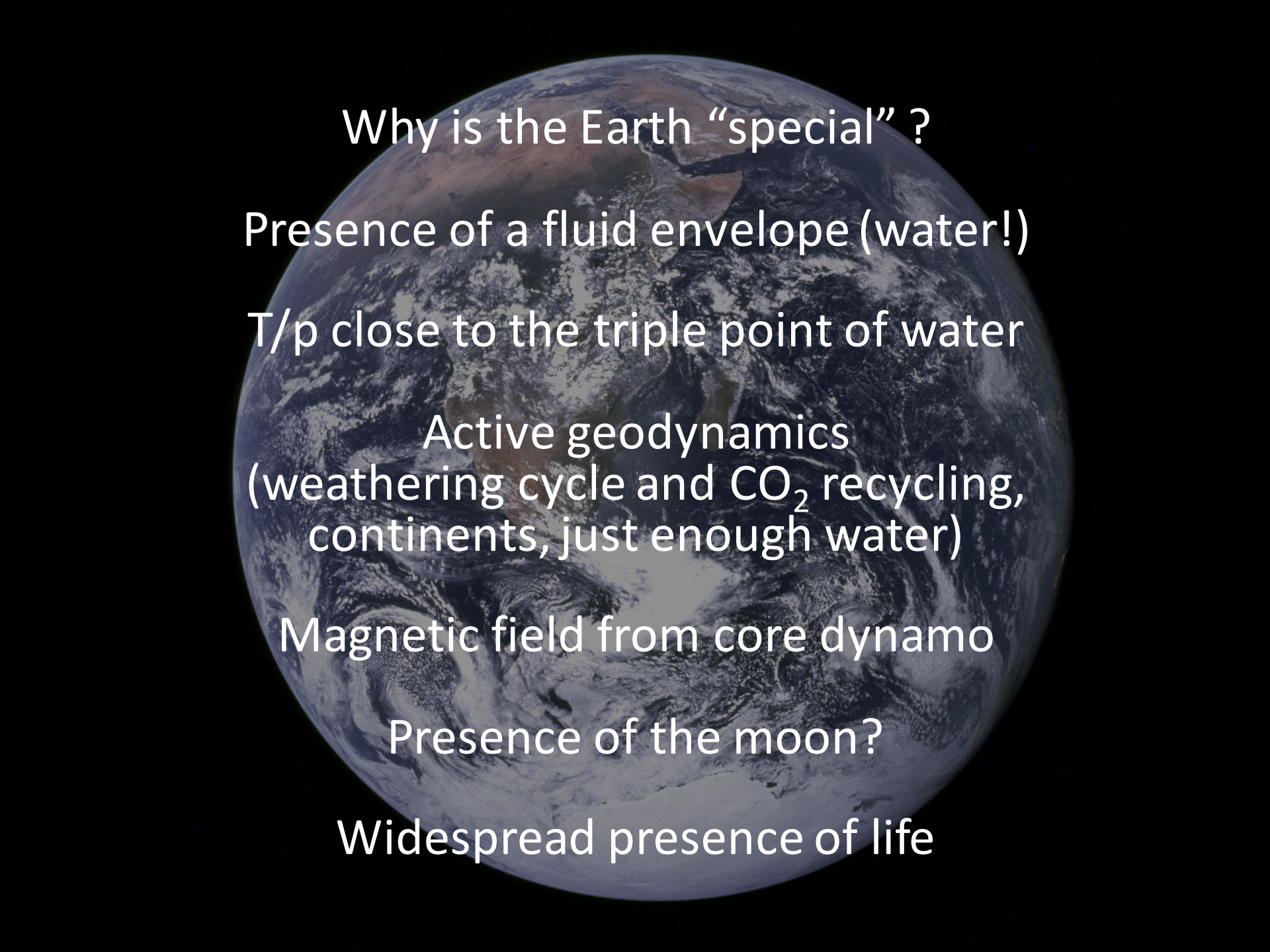




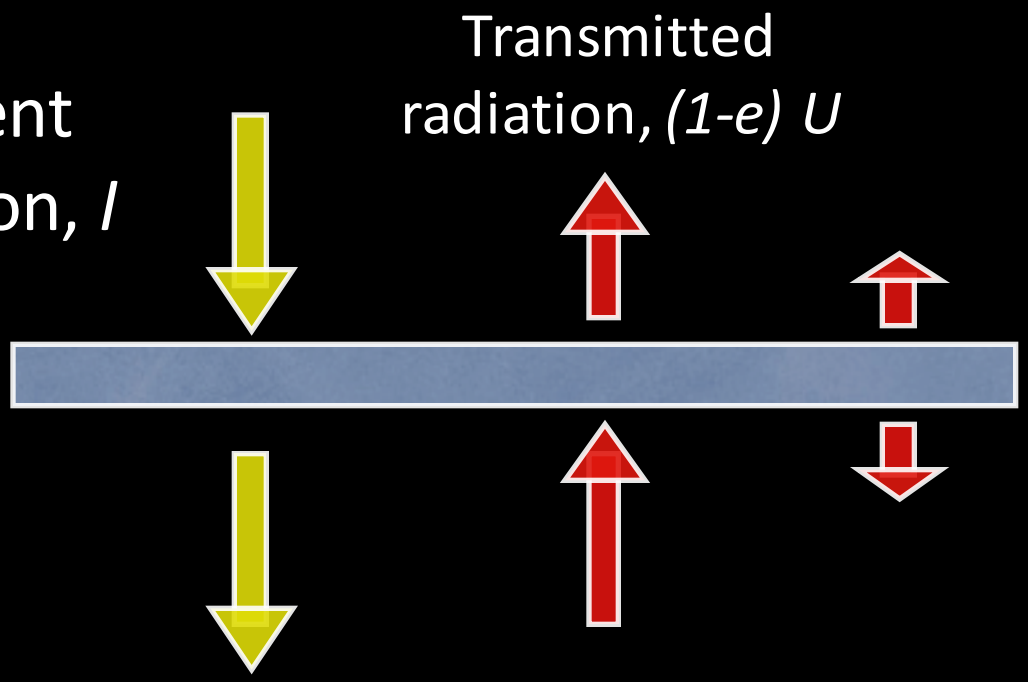
Earth's climate varies on all time scales



IPCC


Why is the Earth “special” ?
Presence of a fluid envelope (water!)
T/p close to the triple point of water
Active geodynamics
(weathering cycle and CO_2 recycling,
continents, just enough water)
Magnetic field from core dynamo
Presence of the moon?
Widespread presence of life

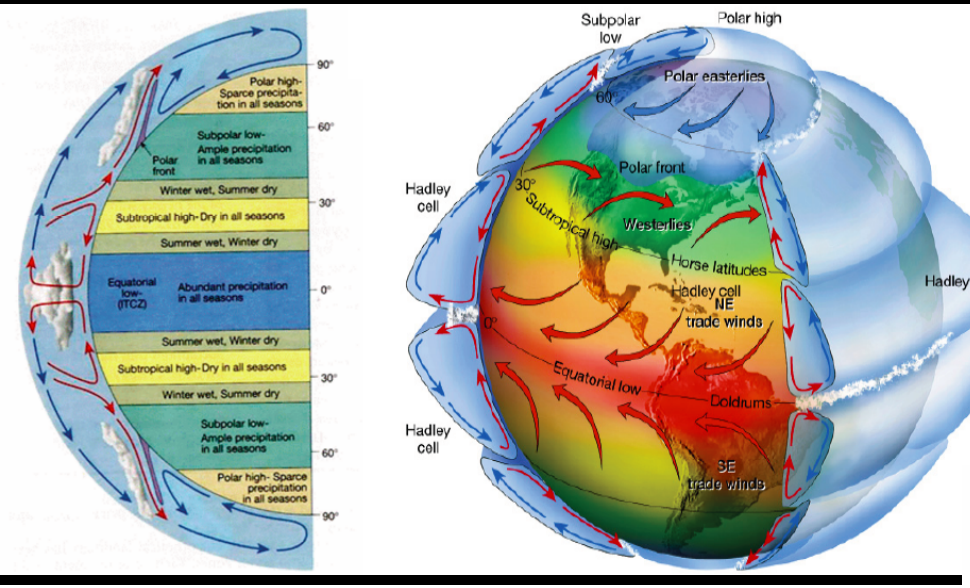
Role of the fluid envelope: greenhouse effect

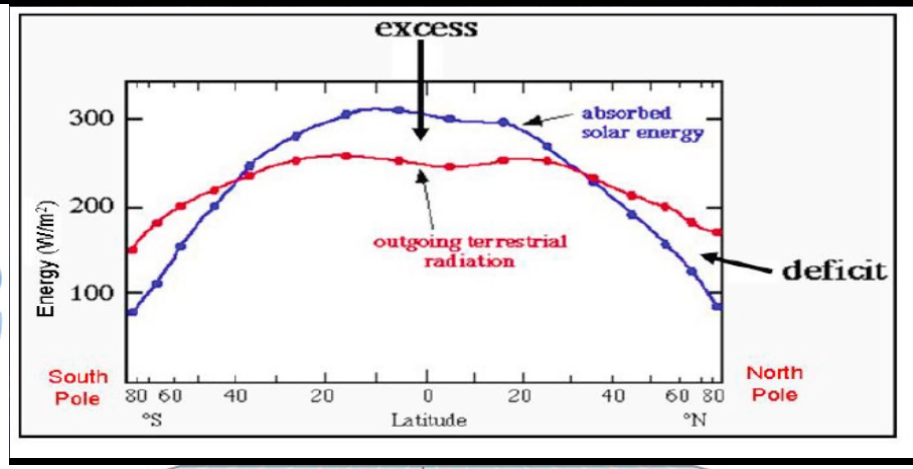


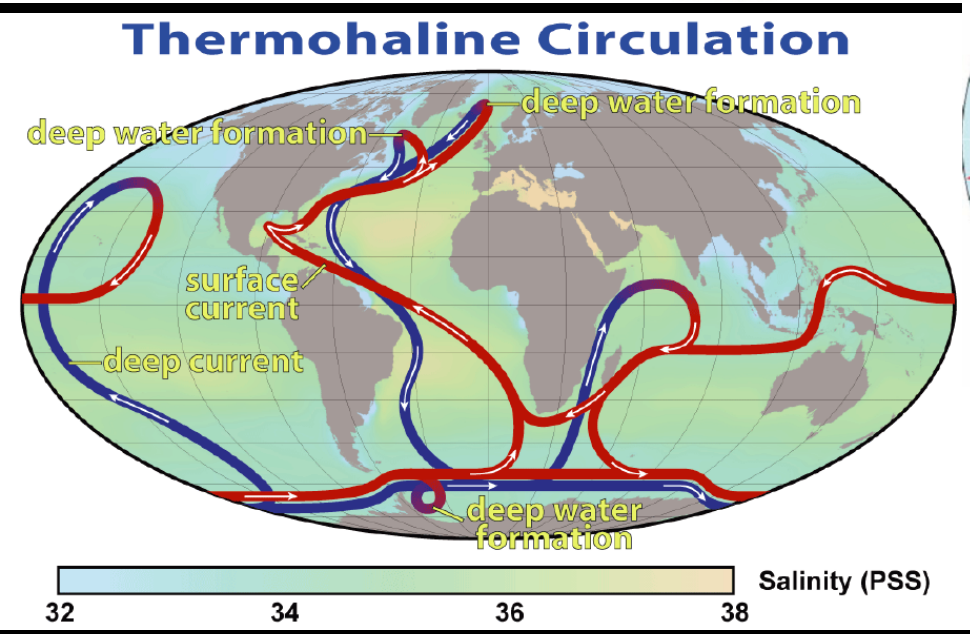
Earth surface

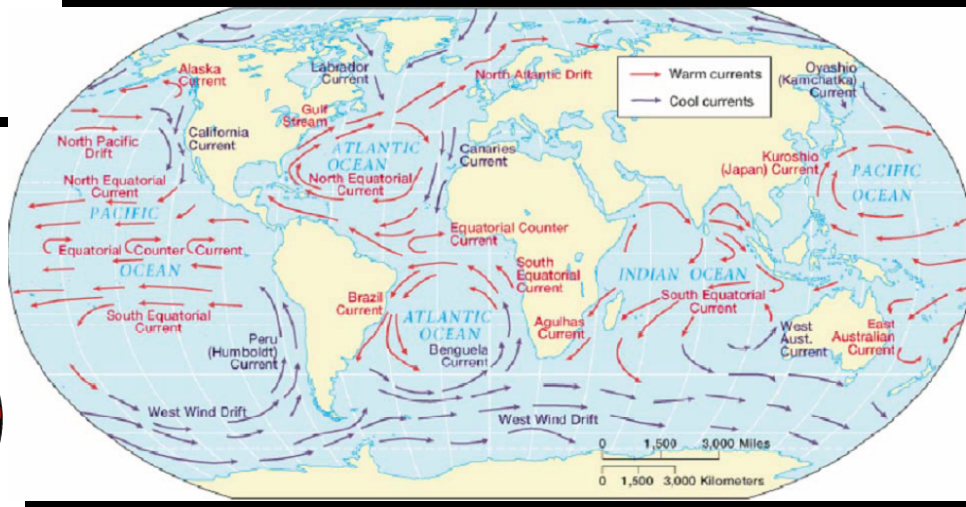
$$\sigma T^4 = U = \frac{I}{1 - e/2}$$

Meridional advective transport



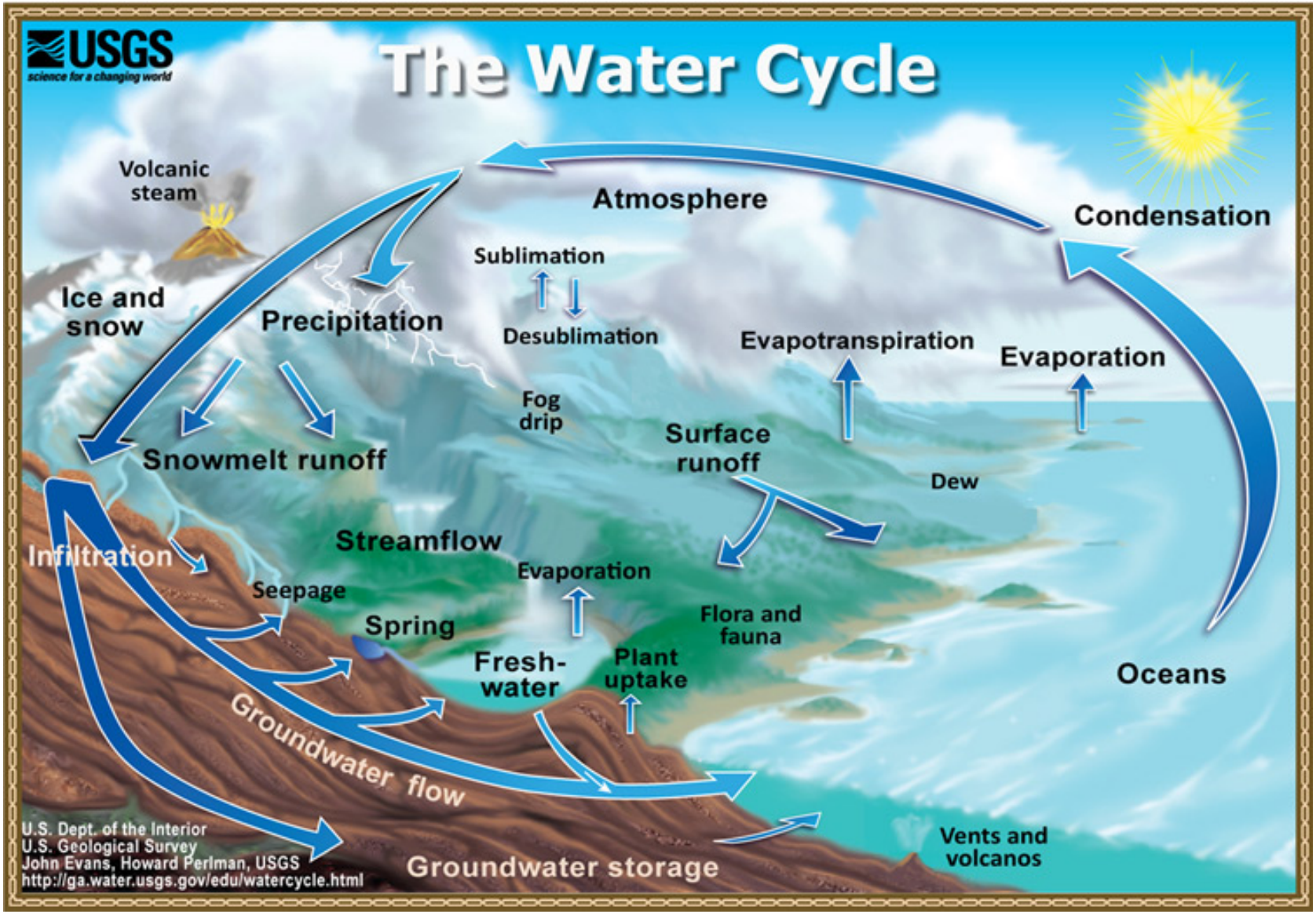






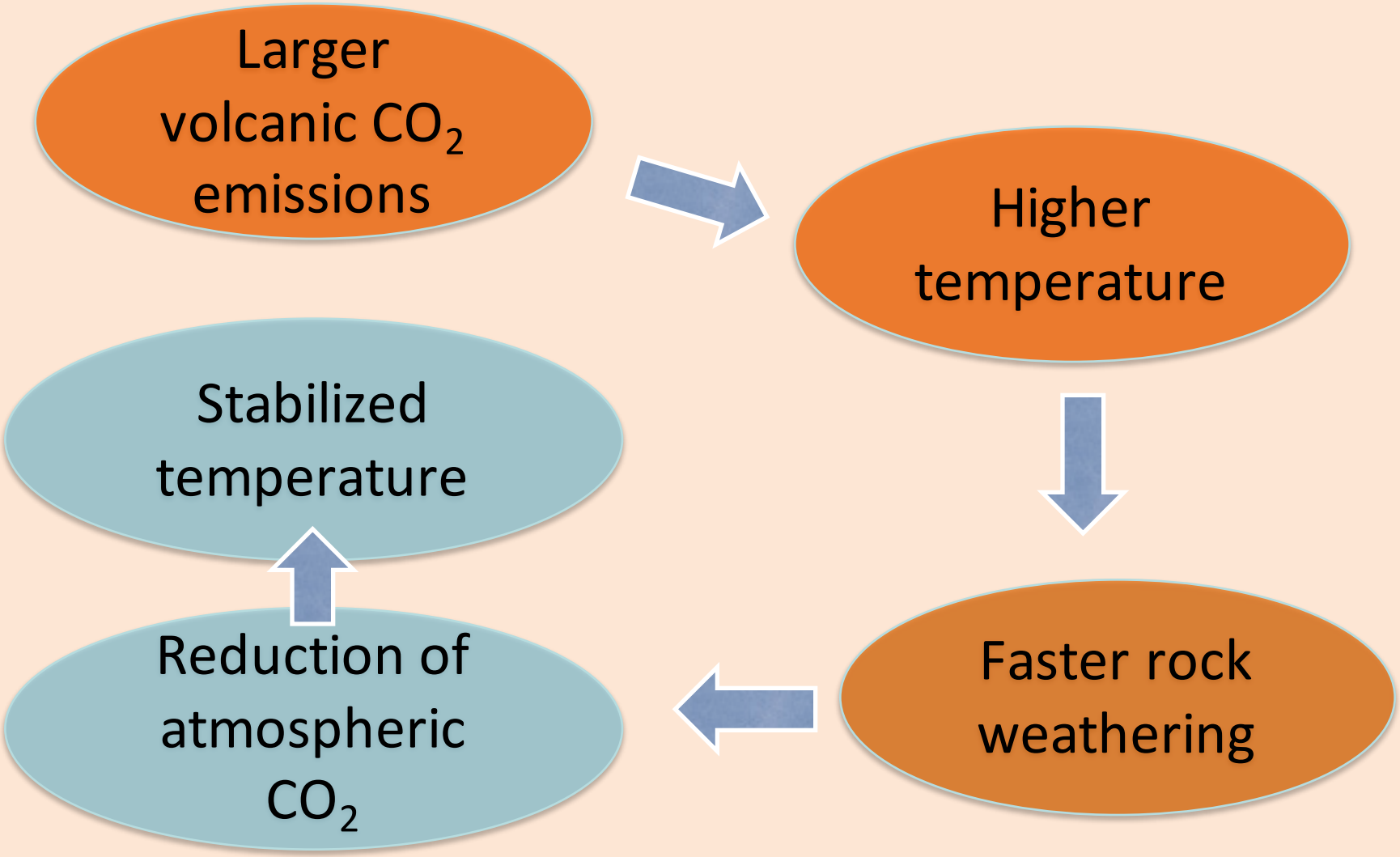
Wind-driven circulation

T/p close to the triple point of water

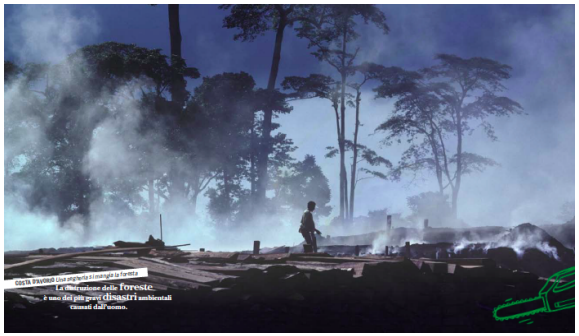


The hydrological cycle

A stabilizing mechanism: volcanic emissions and rock weathering



The global carbon cycle



0.5 PgC/yr

≈200 PgC/yr

CO_2 in volcano gase

Arc volcano

Sedim

CH_4 and CO_2 in forearc fluids

C in organic matter and carbonate minerals

Oceanic lithospere

Accretio ary prism

Crust

C in crustal fluids

Lithospheric mantle

C in magmas

Mantle flow

in slab fluids

Mant flow

Subducting slab

Arc magma sourc

C in slab fluids

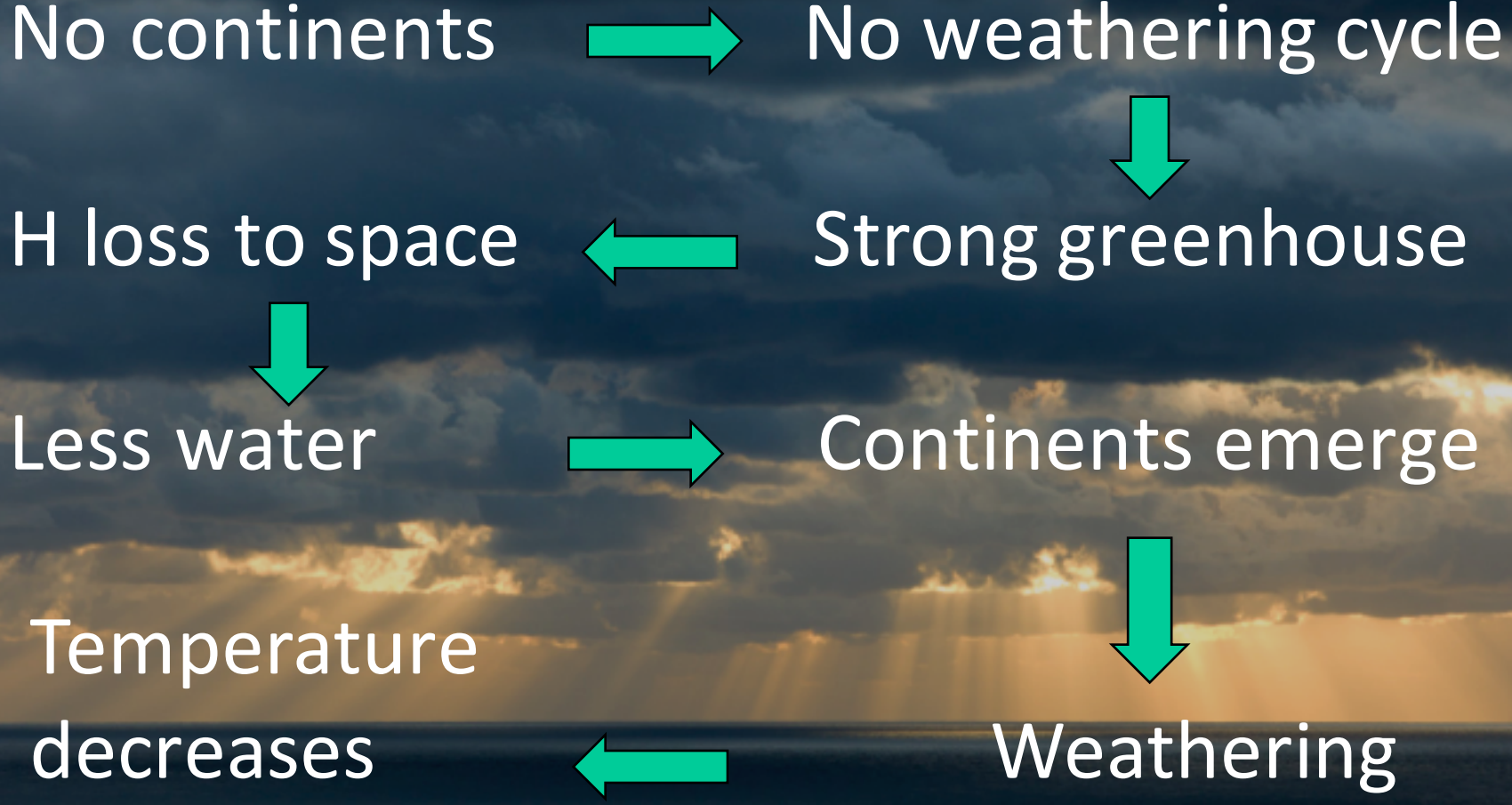
Asthenospheric mantle

Asthenospheric mantle

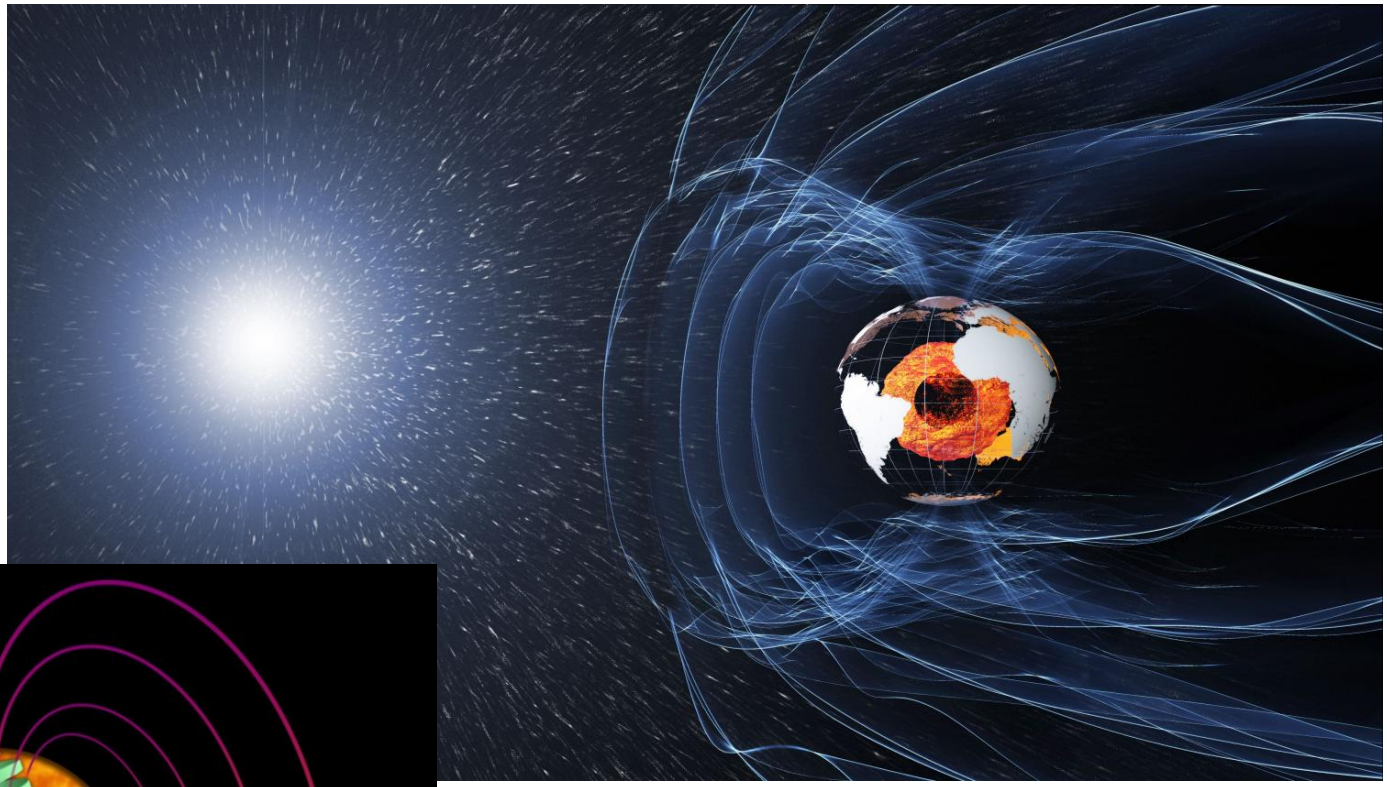
2014 human emissions ≈ 9.8 PgC/yr

C mostly in carbonate minerals carried to deeper mantle

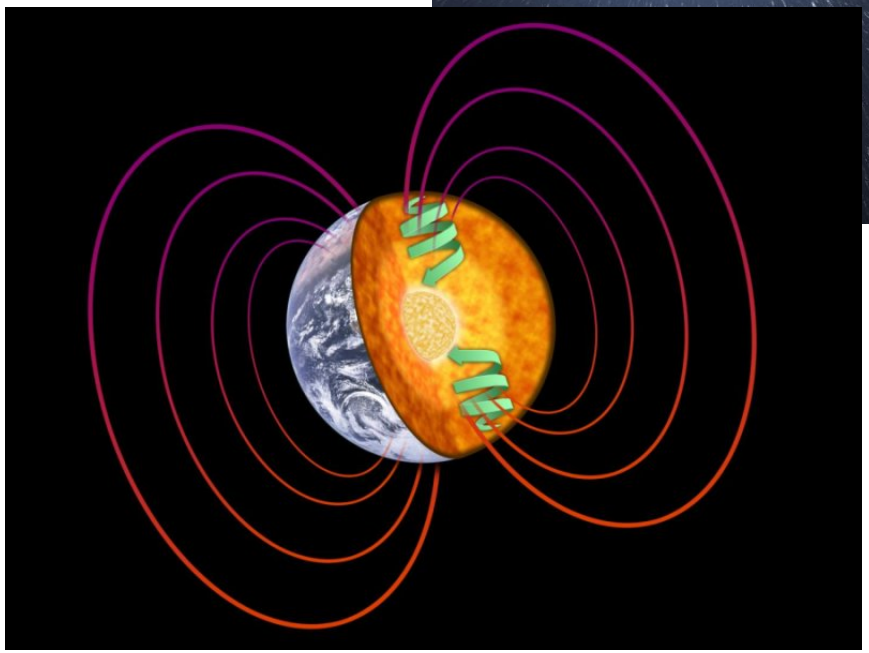
How much water there is on Earth?



The Earth's magnetic field



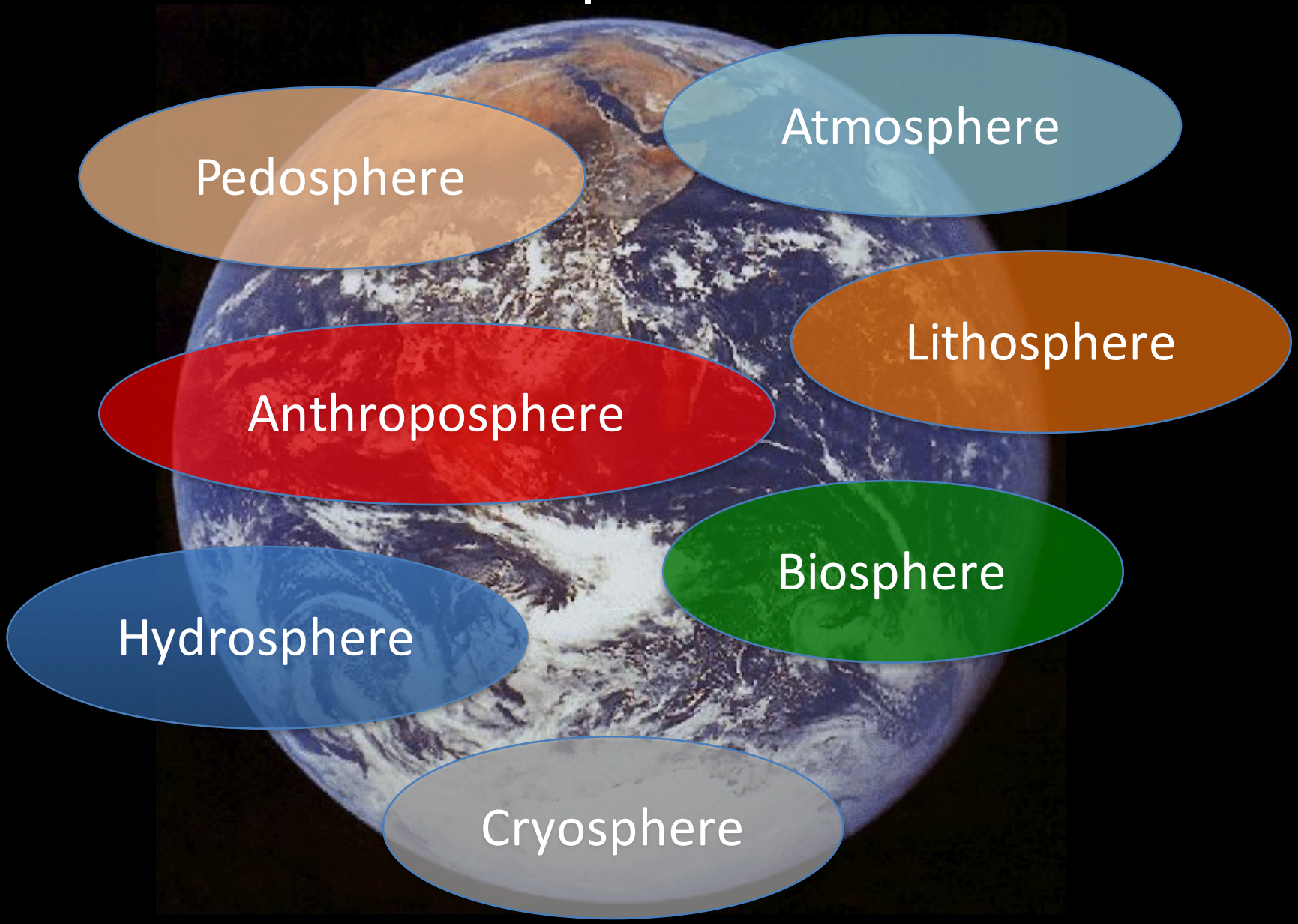
https://phys.org/news/2016-05-strength-earth-magnetic-field.html



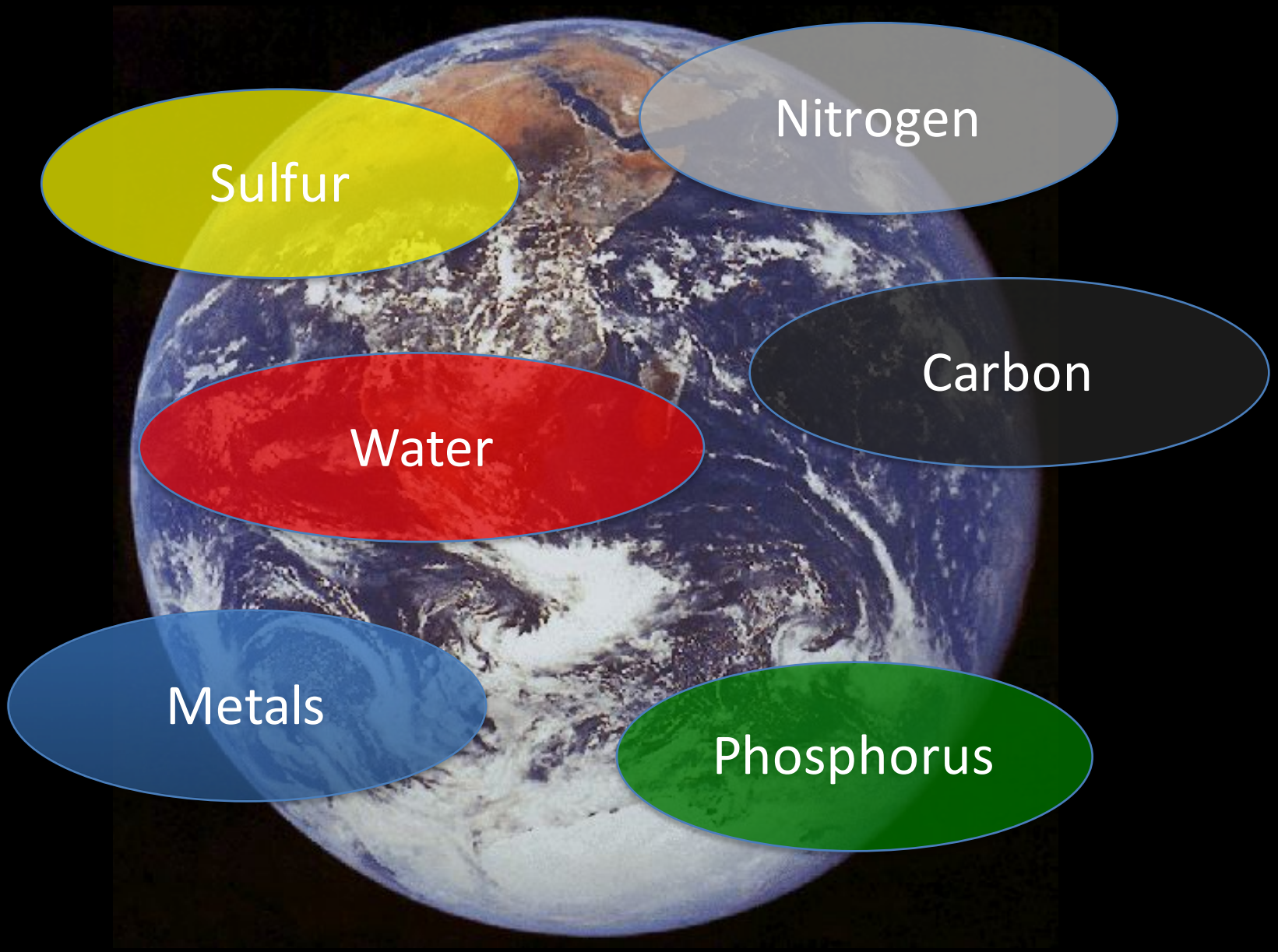
https://www.sciencedaily.com/releases/2017/07/170713154912.htm

and the Moon…

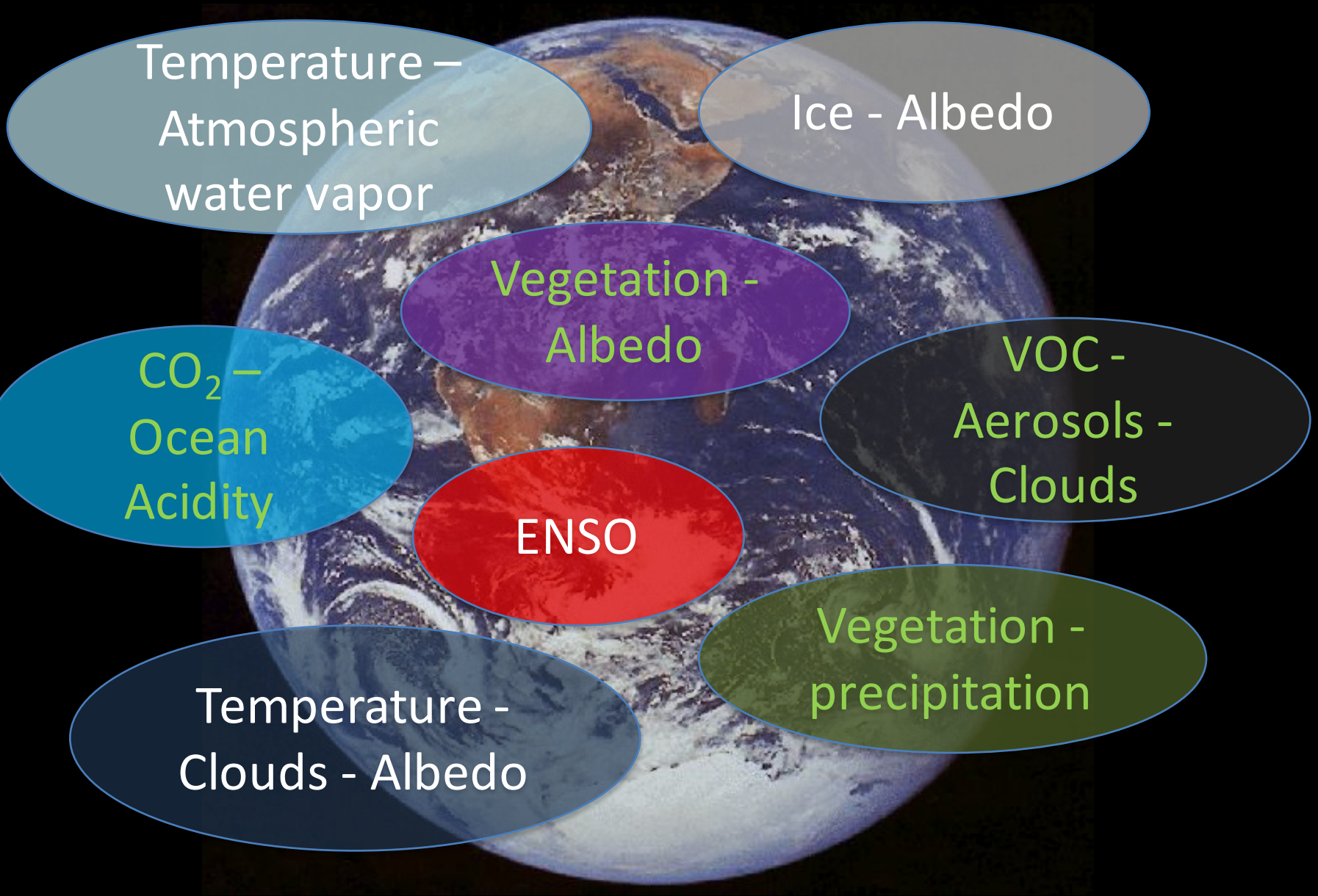
How to approach the Earth System: the “spheres”



Fluxes and reservoirs: biogeochemical cycles



The inner workings: feedbacks in the Earth System



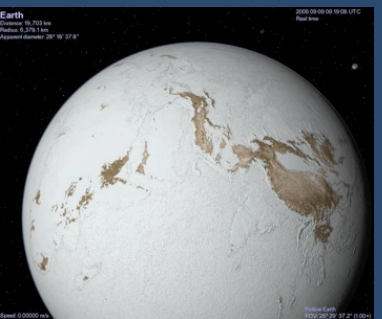
A well-known amplifying feedback: ice-albedo

Higher surface temperature

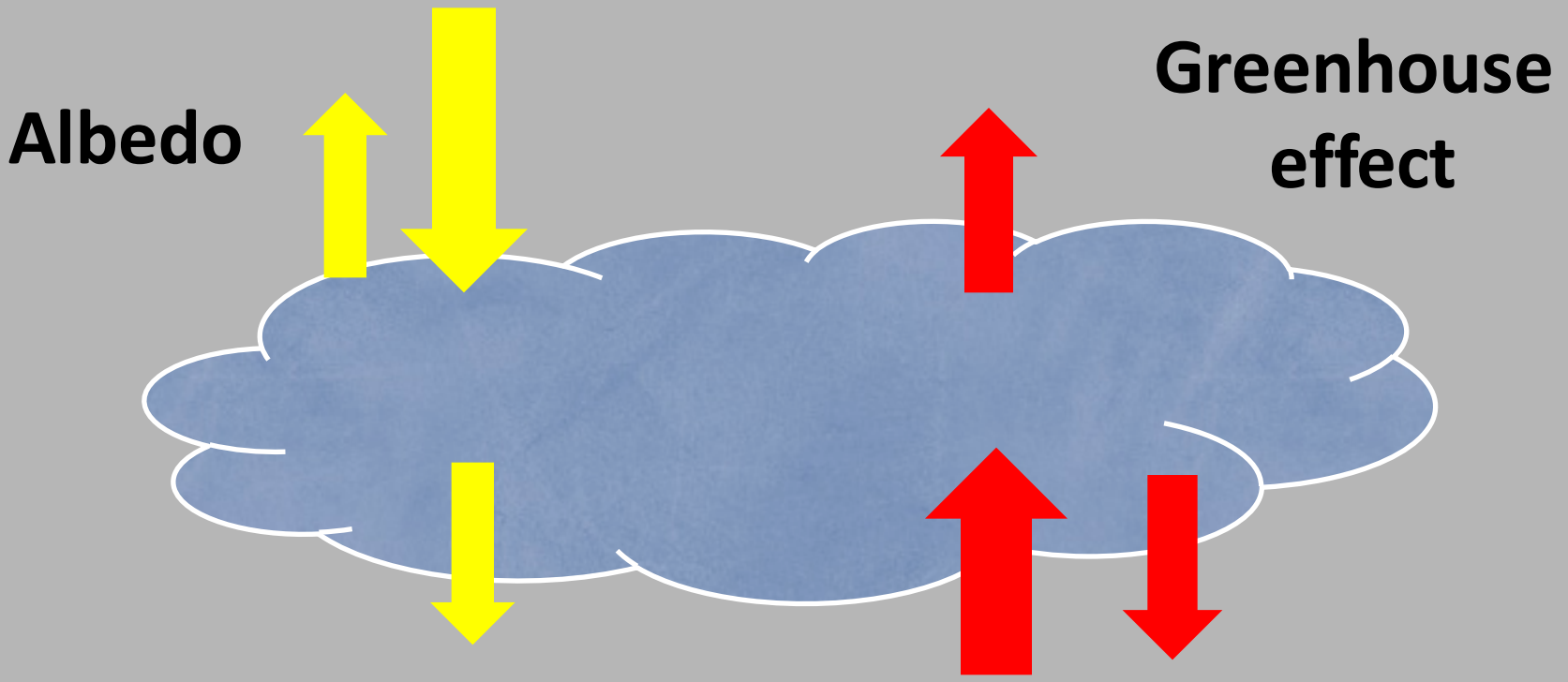
Less ice/snow

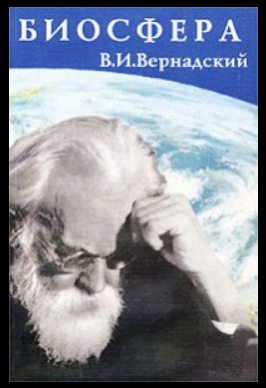
Lower albedo

More absorbed heat

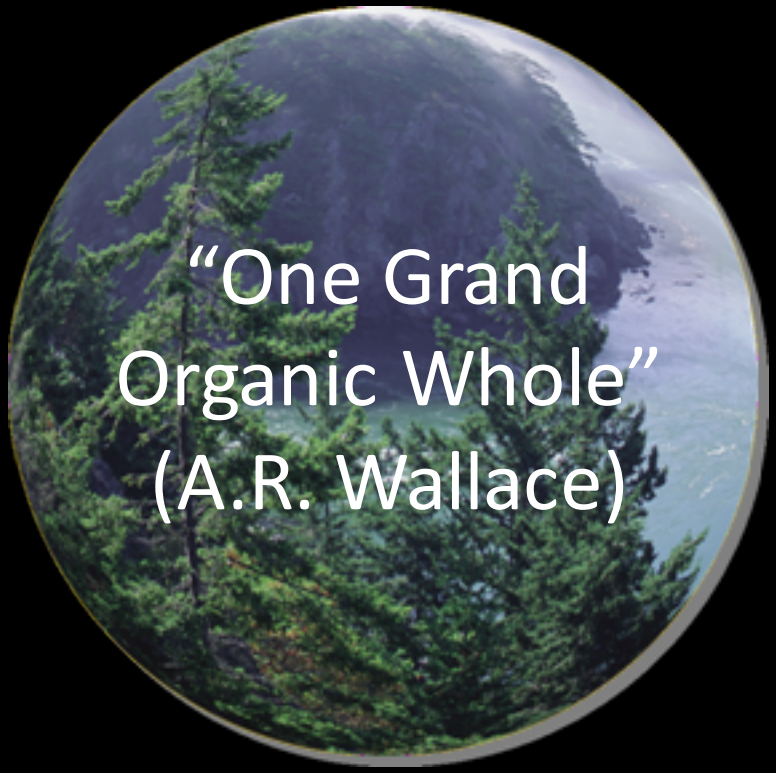


A complicated case:
Cloud – temperature feedback





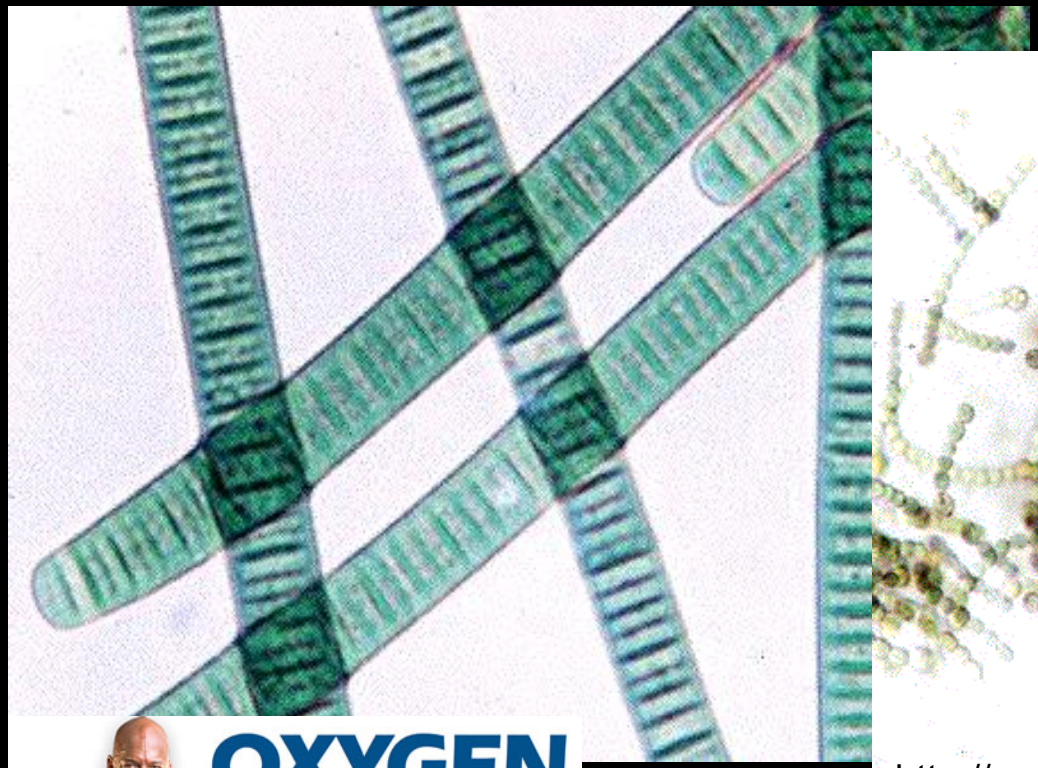
Geosphere



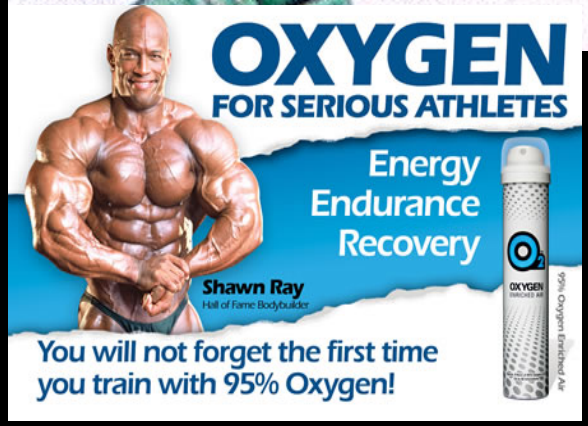
"One Grand Organic Whole" (A.R. Wallace)

Biosphere

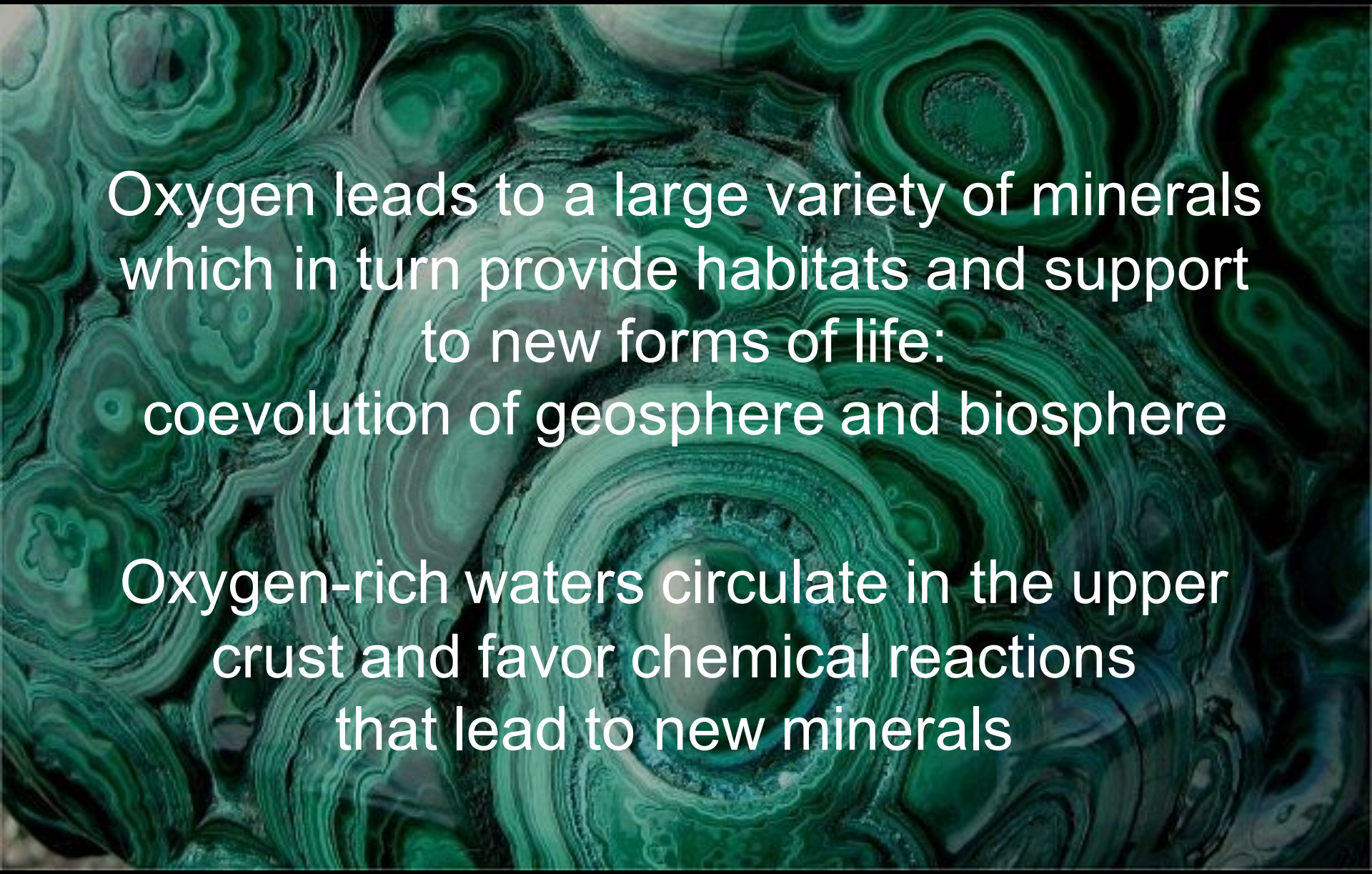
The Great Oxydation Event
Oxygen production from Cyanobacteria



http://www.ucmp.berkeley.edu/bacteria/nostoc.gif



"Great Oxygenation Event" about 2,4 Ga
Huronian Glaciation,
an example of Snowball Earth?


Oxygen leads to a large variety of minerals
which in turn provide habitats and support
to new forms of life:
coevolution of geosphere and biosphere
Oxygen-rich waters circulate in the upper
crust and favor chemical reactions
that lead to new minerals

Two-way feedbacks between organisms and the environment

Ecosystem engineers
Niche construction
Complex adaptive landscapes
Global biogeochemical cycles

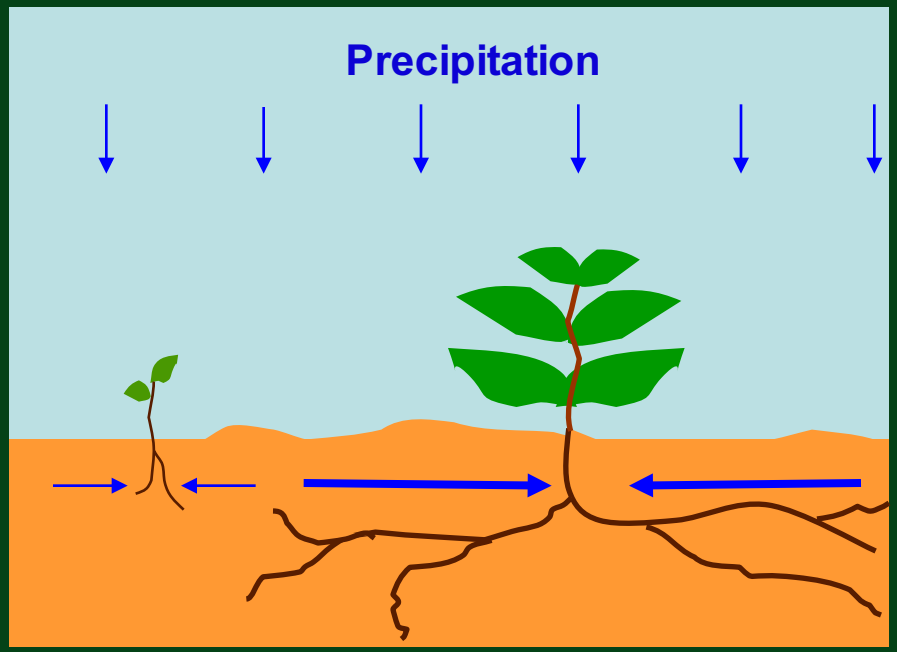
The shrub-cyanobacteria system in arid regions

In arid and semi-arid regions vegetation often forms patterned states

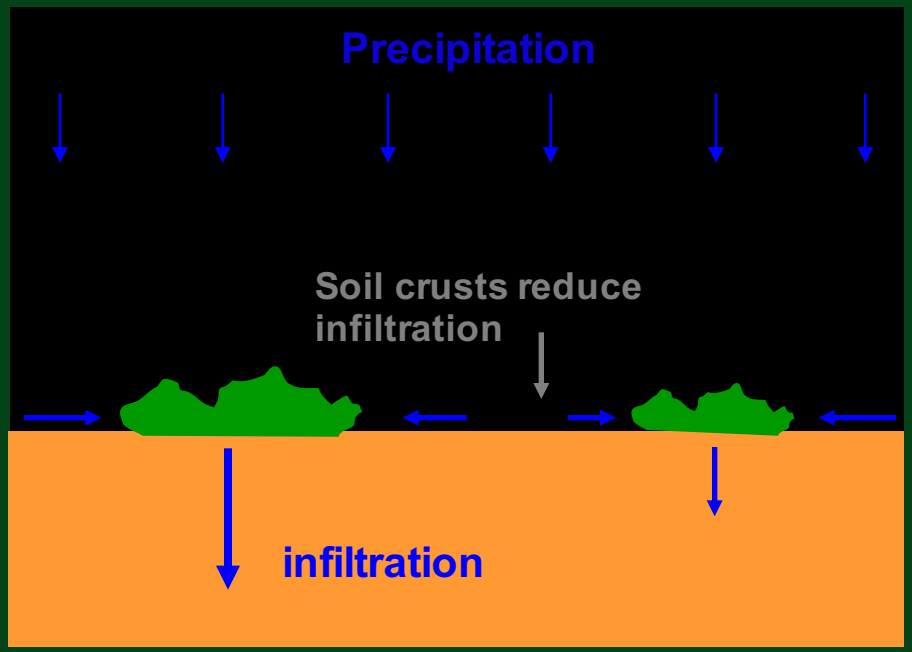
Feedbacks leading to vegetation patterns

Positive feedback between biomass and water + competition

Water uptake by roots

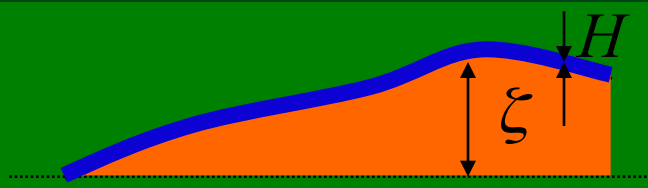


Increased infiltration



Vegetation - soil moisture - surface flow model

Plant biomass density $B(x,t)$ [Kg/m^2]
Relative soil moisture $s(x,t)$
Surface water height $H(x,t)$ [mm] or [Kg/m^2]



$$\frac{\partial B}{\partial t} = \text{Growth} - \text{Mortality} + \text{Dispersion}$$

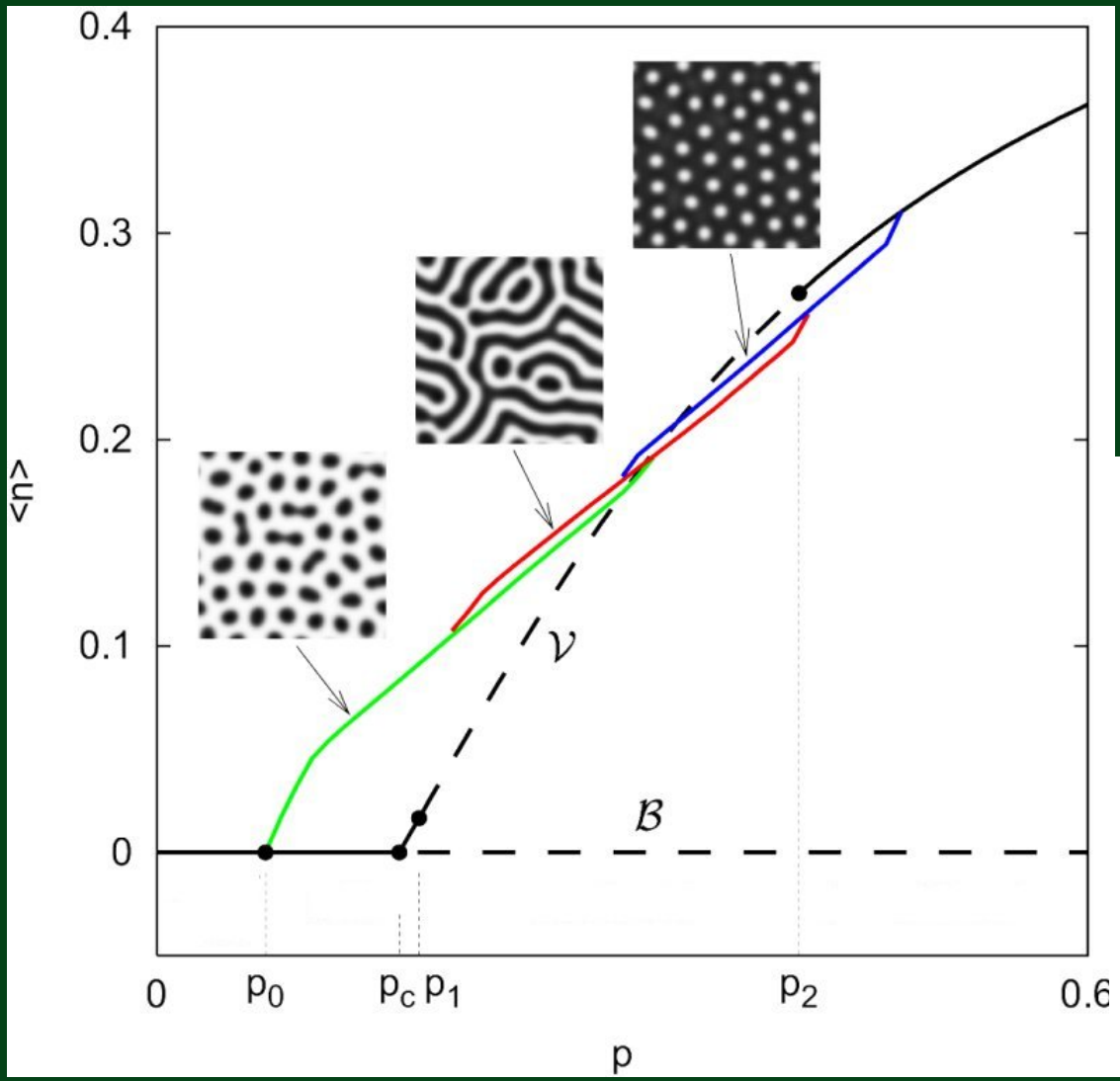
$$\frac{\partial s}{\partial t} = \text{Precipitation} - \text{Infiltration} + \text{Runoff}$$

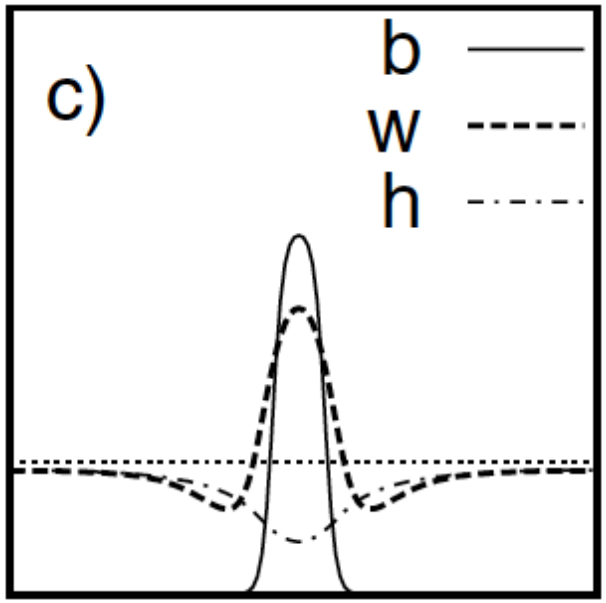
$$\frac{\partial H}{\partial t} = \text{Infiltration} - \text{Evaporation} - \text{Root uptake} + \text{Diffusion}$$

Soil water *w*

Biomass *b*

Feedbacks

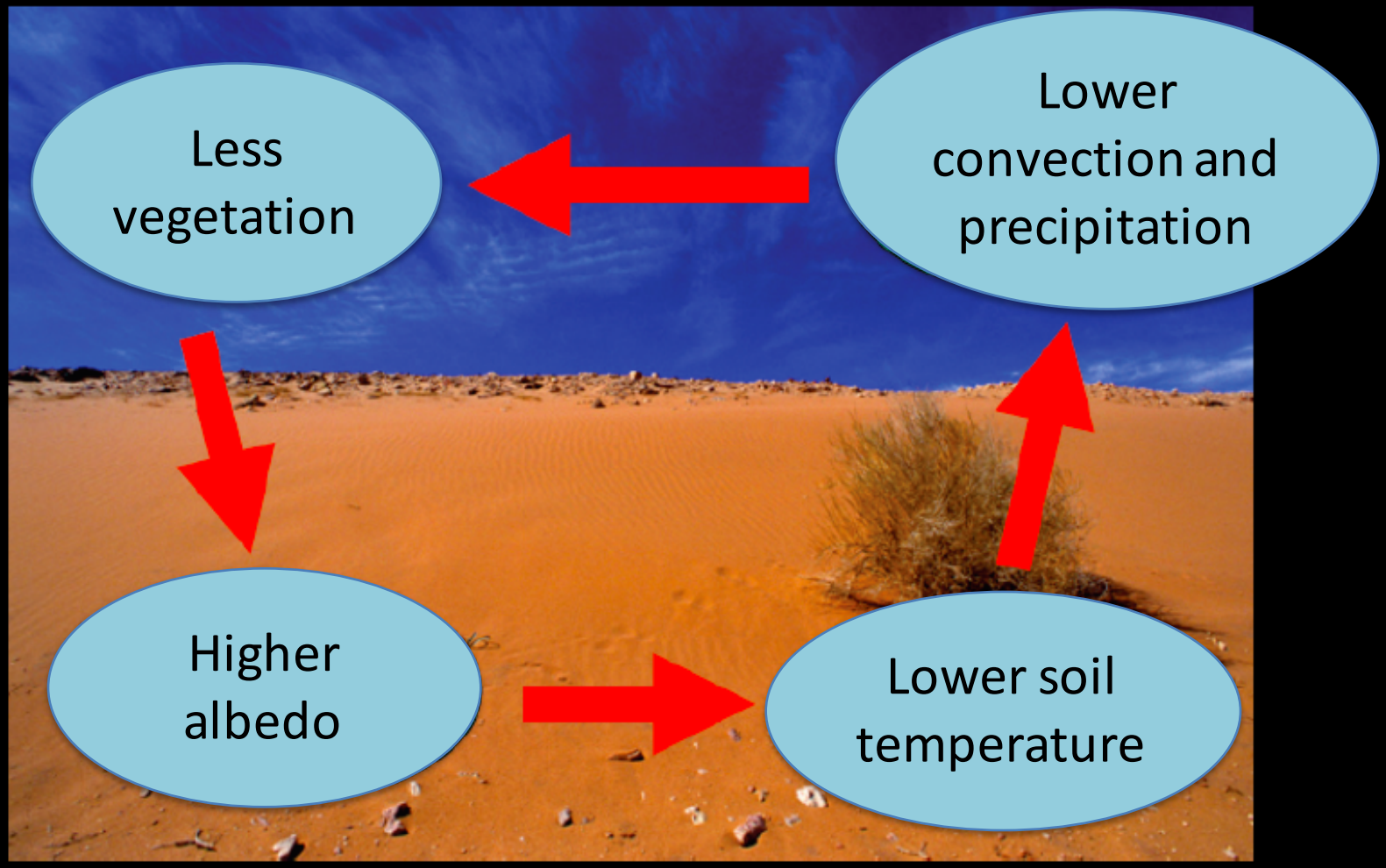




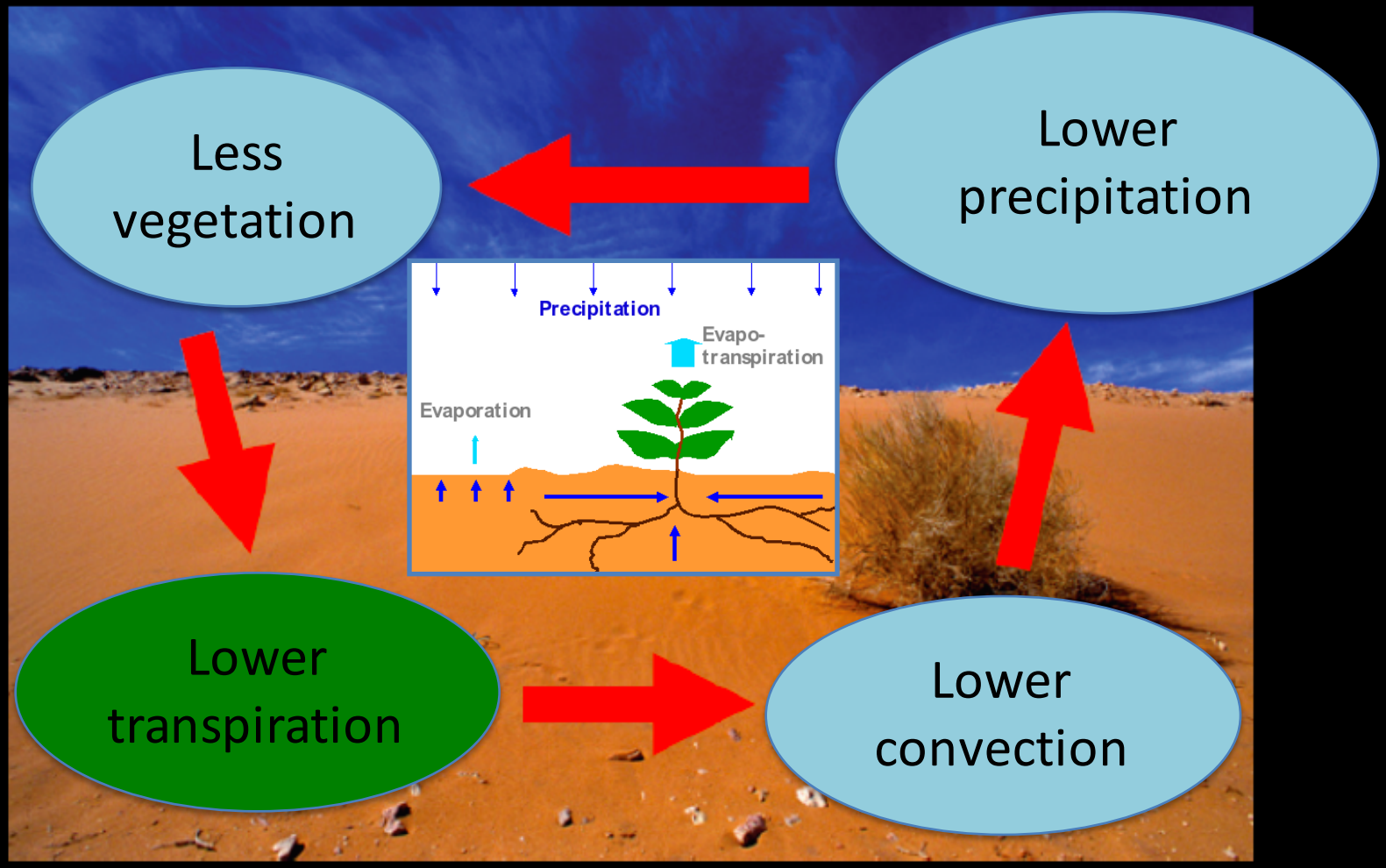
Vegetation patterns in arid and semi-arid regions

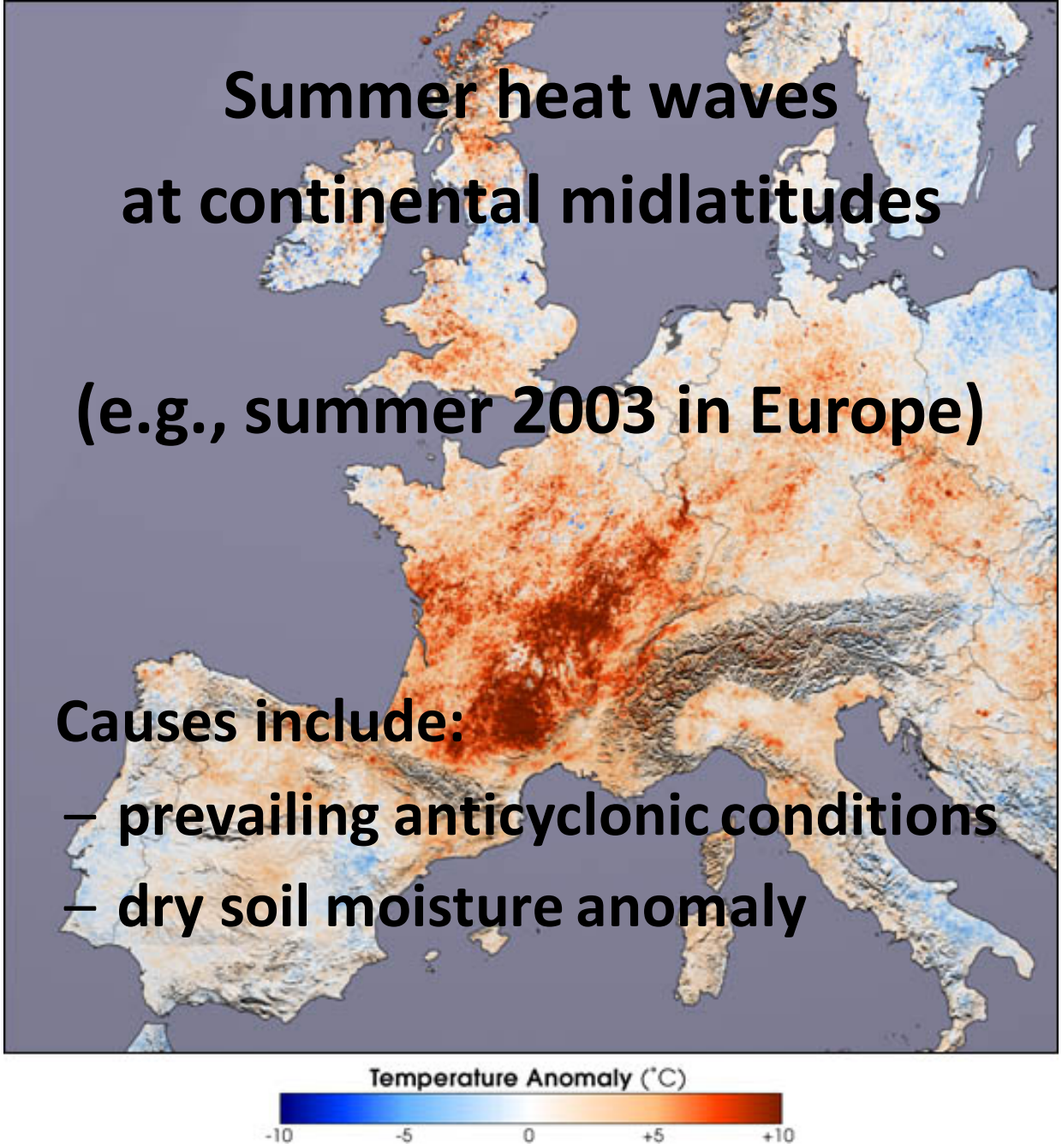
Gilad et al PRL 2004, JTB 2007, Kletter et al JTB 2009, Baudena et al AWR 2013

Albedo and the Charney mechanism (1975)



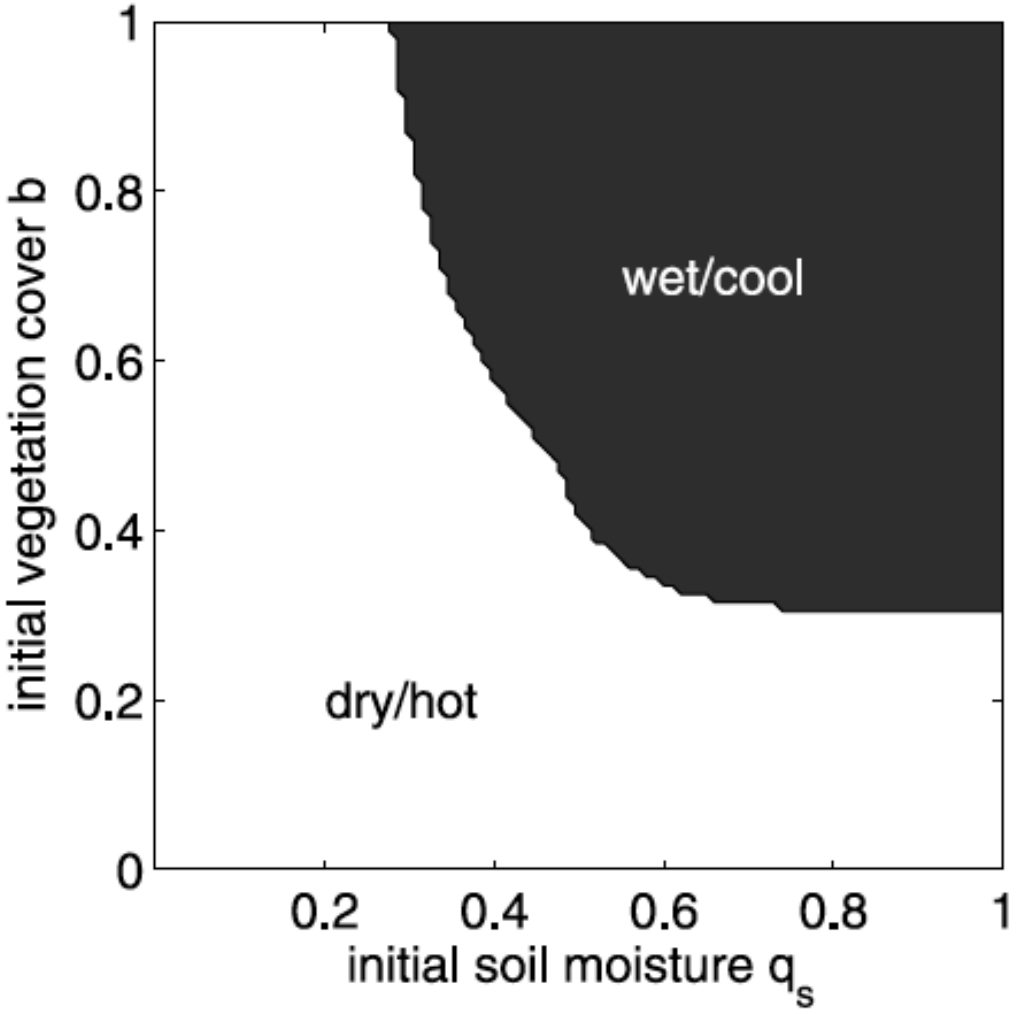
Plant transpiration and the hydrological cycle





D'Andrea et al *GRL* 2006, Baudena et al *WRR* 2009

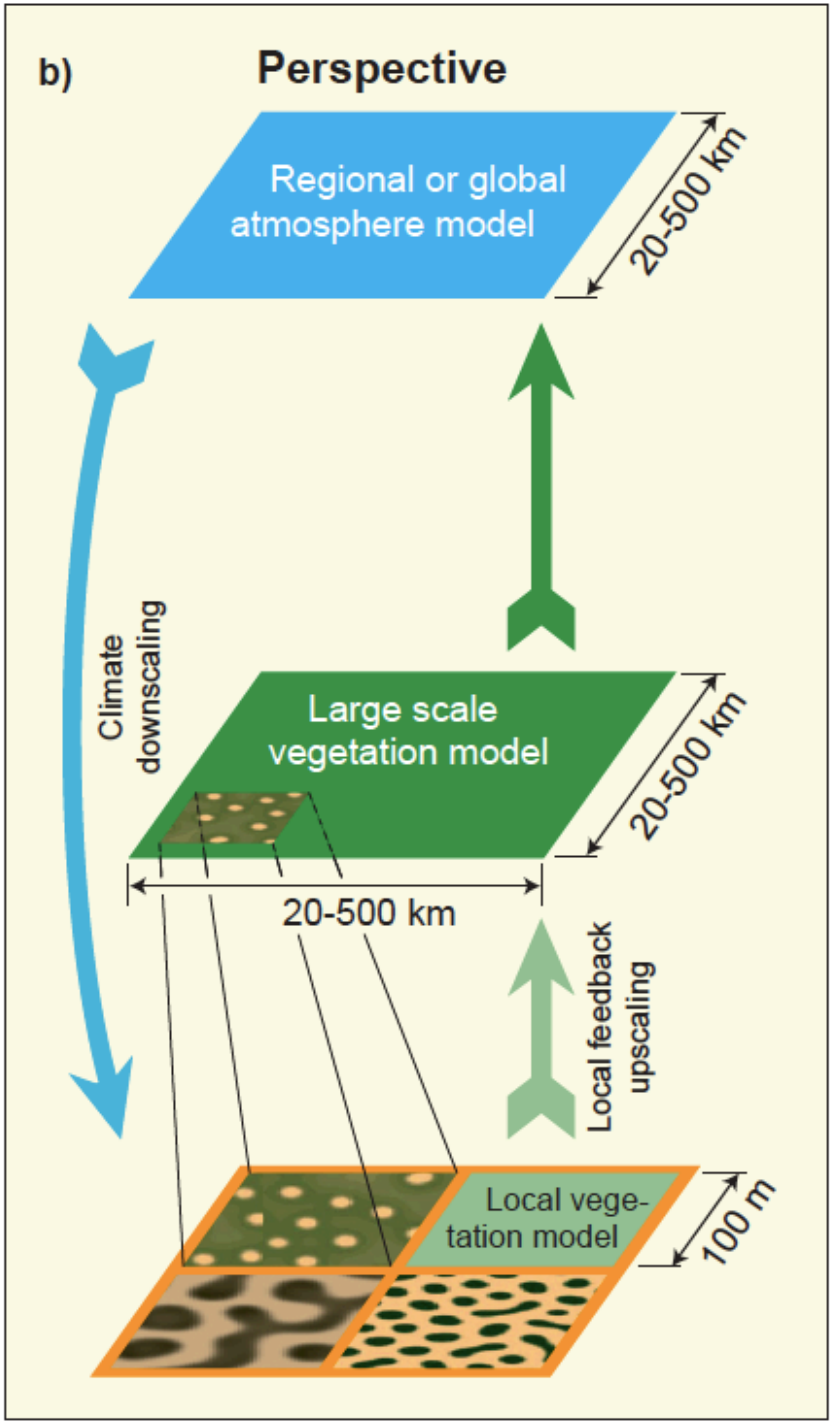
Multiple equilibria of the soil-atmosphere system



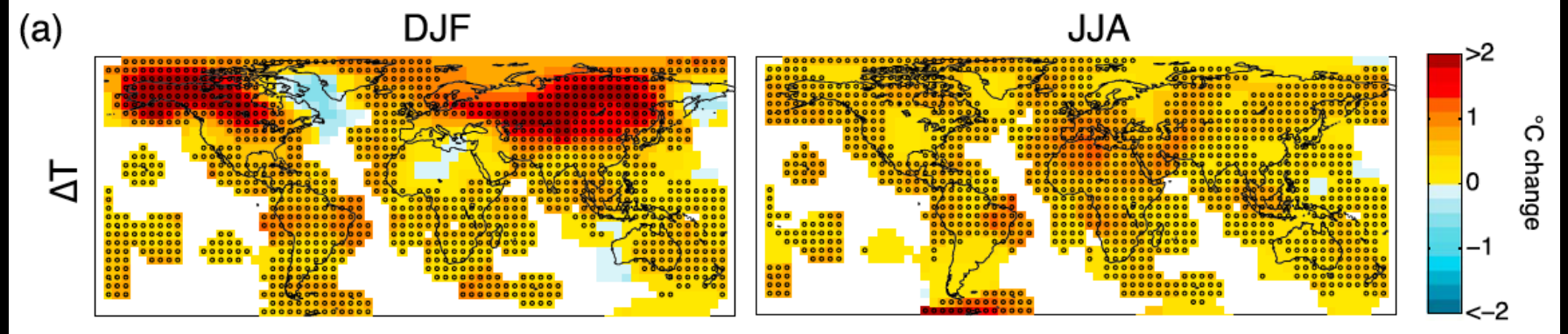
D'Andrea et al *GRL* 2006, Baudena et al *WRR* 2009

Cross-scale feedbacks
(Rietkerk et al 2011)
(Soranno et al 2014)

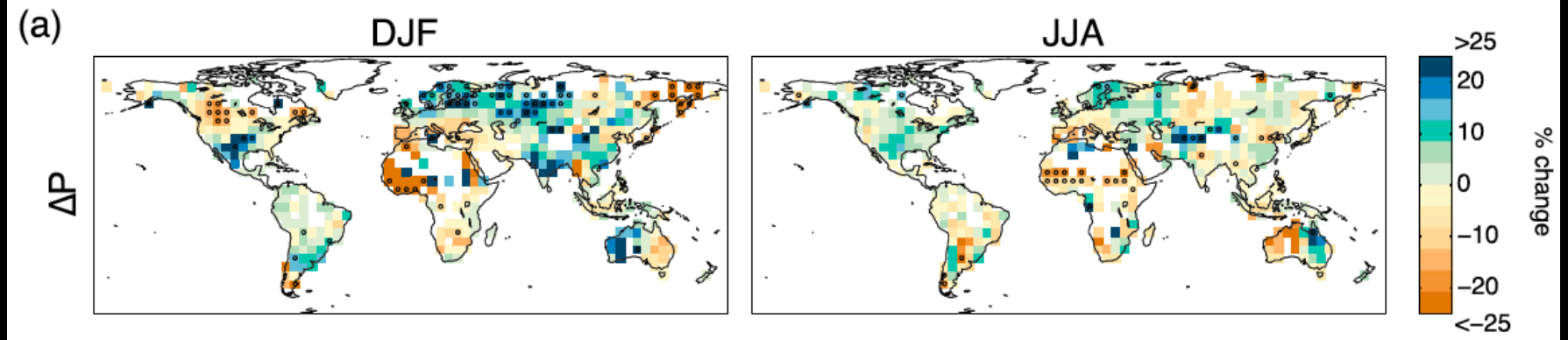
Do changes in small scales affect large-scale behavior (and how and where)?



Back to Earth:
In the last 150 years, a global uncontrolled climate experiment, with uncertain outcome



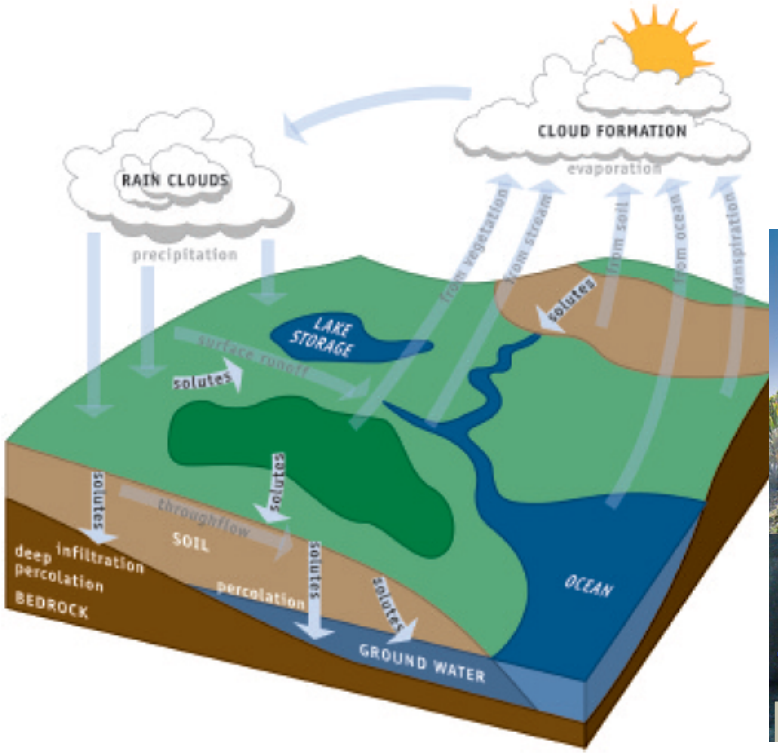
Back to Earth:
In the last 150 years, a global uncontrolled climate experiment, with uncertain outcome

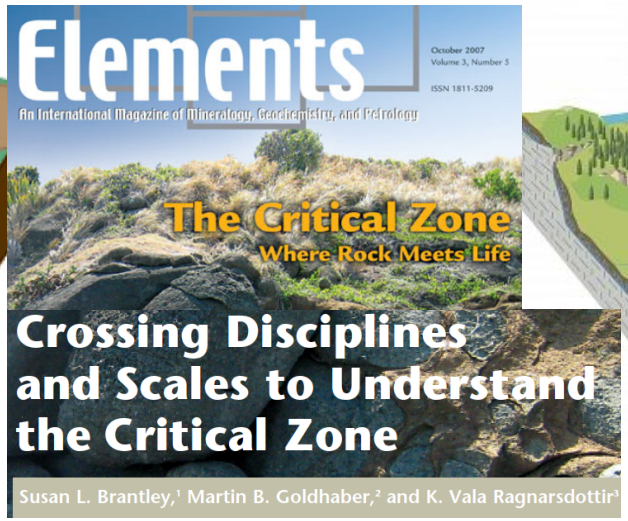


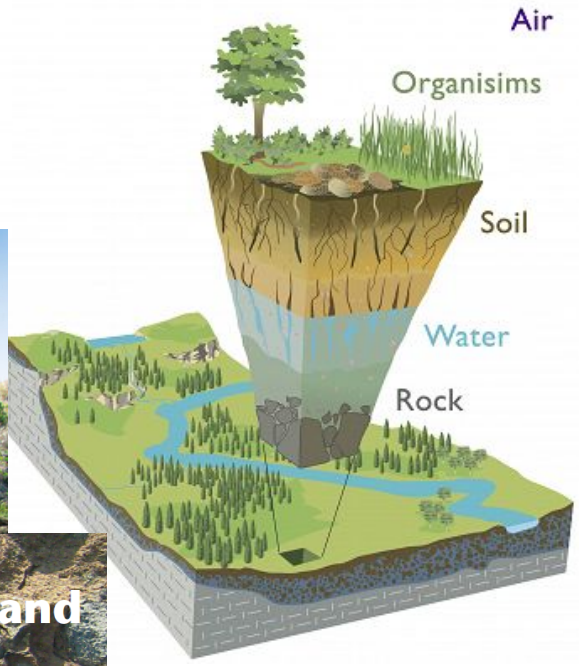
Understanding climate processes
Future scenarios

Emission reduction and mitigation
Adaptation

A focus on geosphere-biosphere interactions: The Critical Zone



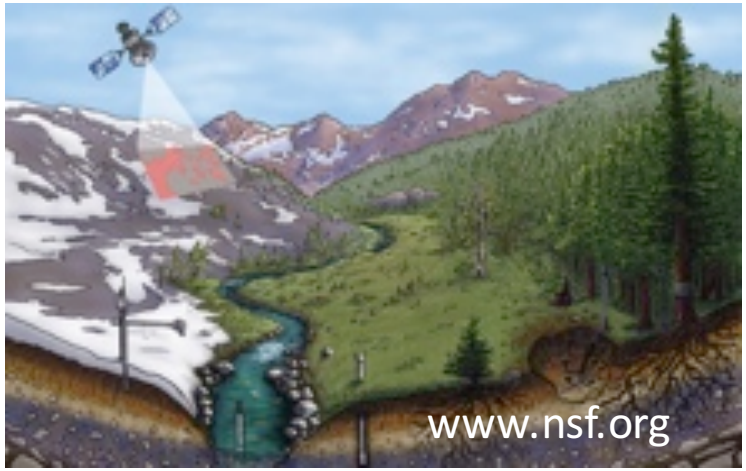




www.czen.org , http://criticalzone.org/national/

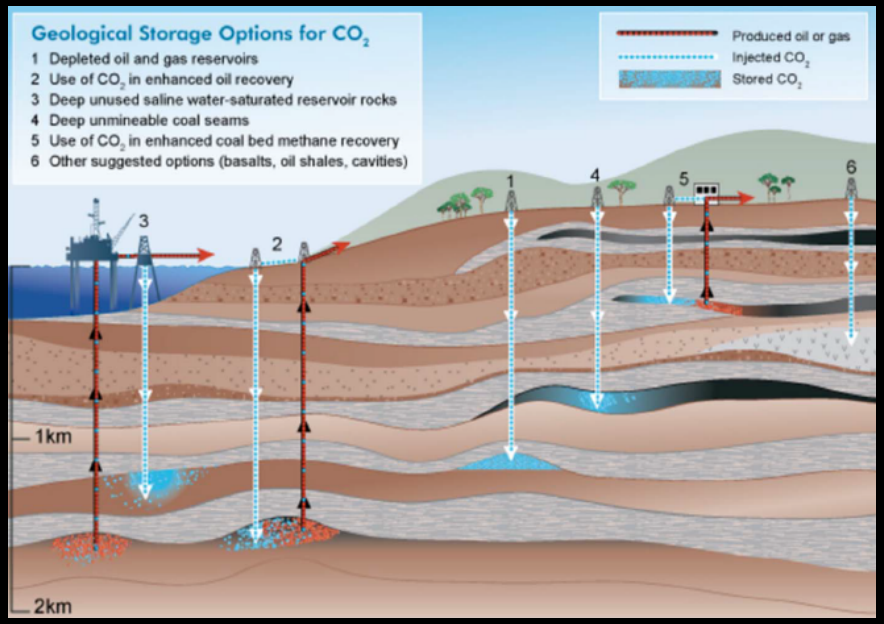
The layer between the top of vegetation canopy and the "rocky matrix", where physics, chemistry, hydrology, eco-hydrology, geology and biology closely interact

The Critical Zone and Ecosystem Observatory at Nivolet



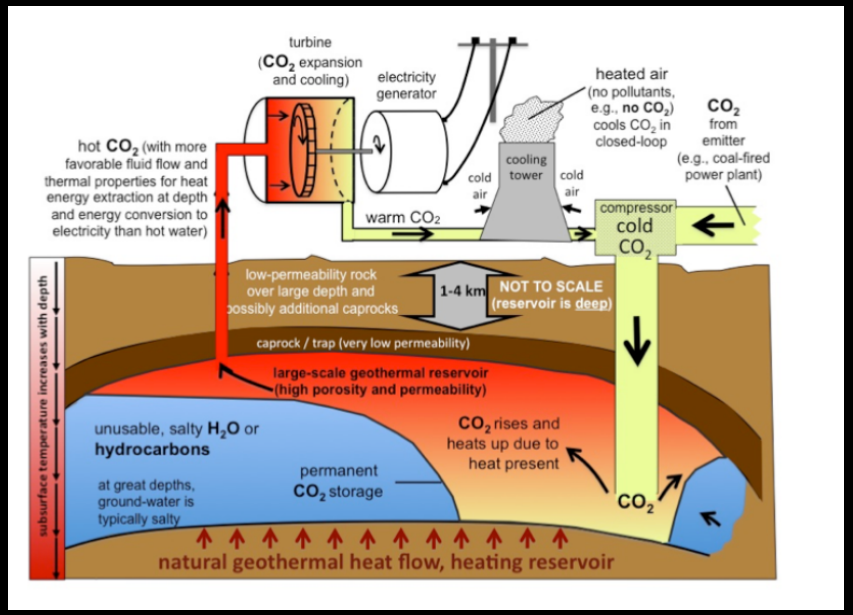
Need for combining in-situ measurements, remote sensing and modeling

Carbon sequestration

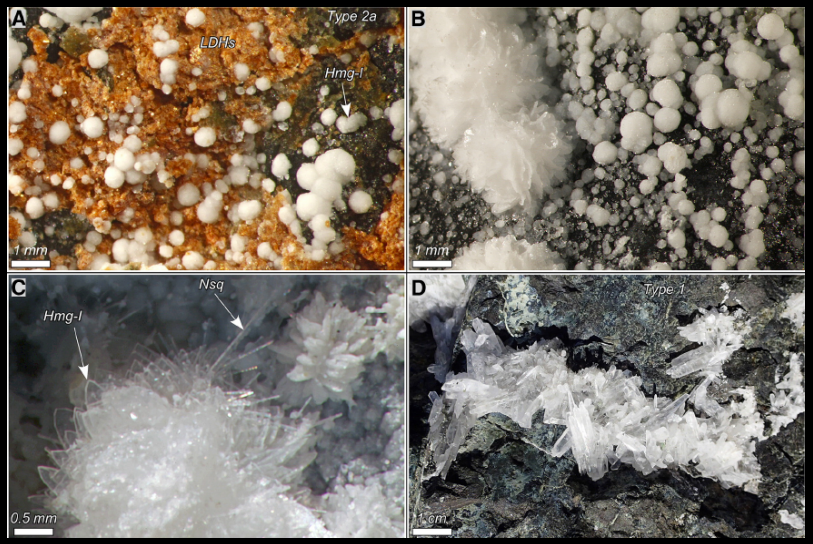


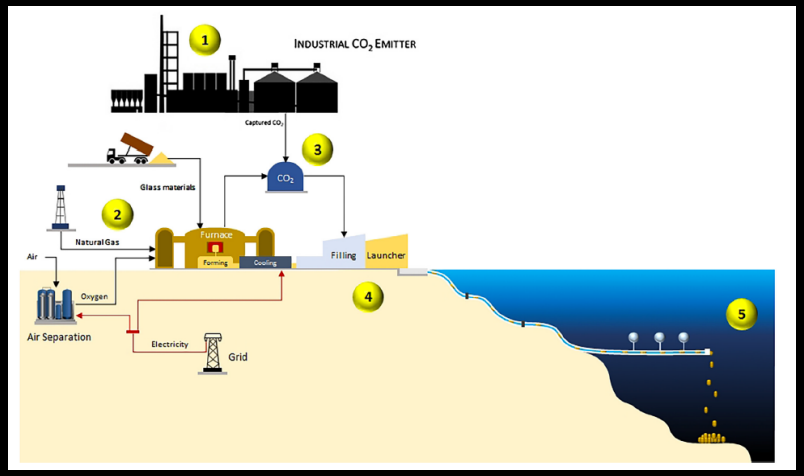
Aminu et al 2017

Saar et al 2012



Boschi et al 2017





Caserini et al 2017

Conclusions

A physicist's place in geosciences:
quantitatively understand the dynamics of the fascinatingly complex system called Planet Earth

Unravel geosphere-biosphere interactions and how the biosphere makes our planet special (and perhaps others as well)

Contribute to formulate a «Theory of planetary climates» for our planet and other rocky bodies


Thank you for your attention!