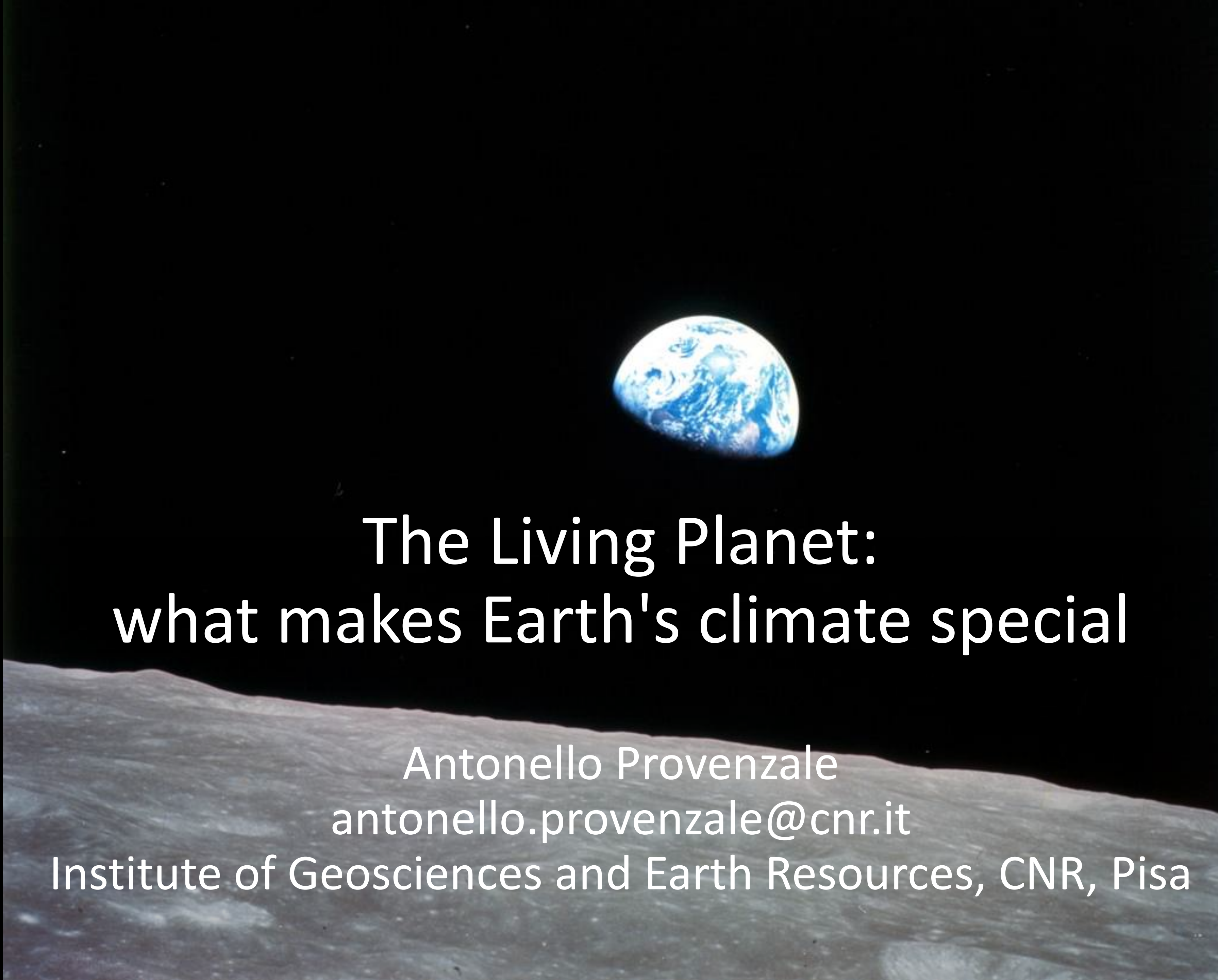
“Earthrise”, Apollo 8, 24 December 1968, photo B. Anders, NASA



The Living Planet: what makes Earth's climate special

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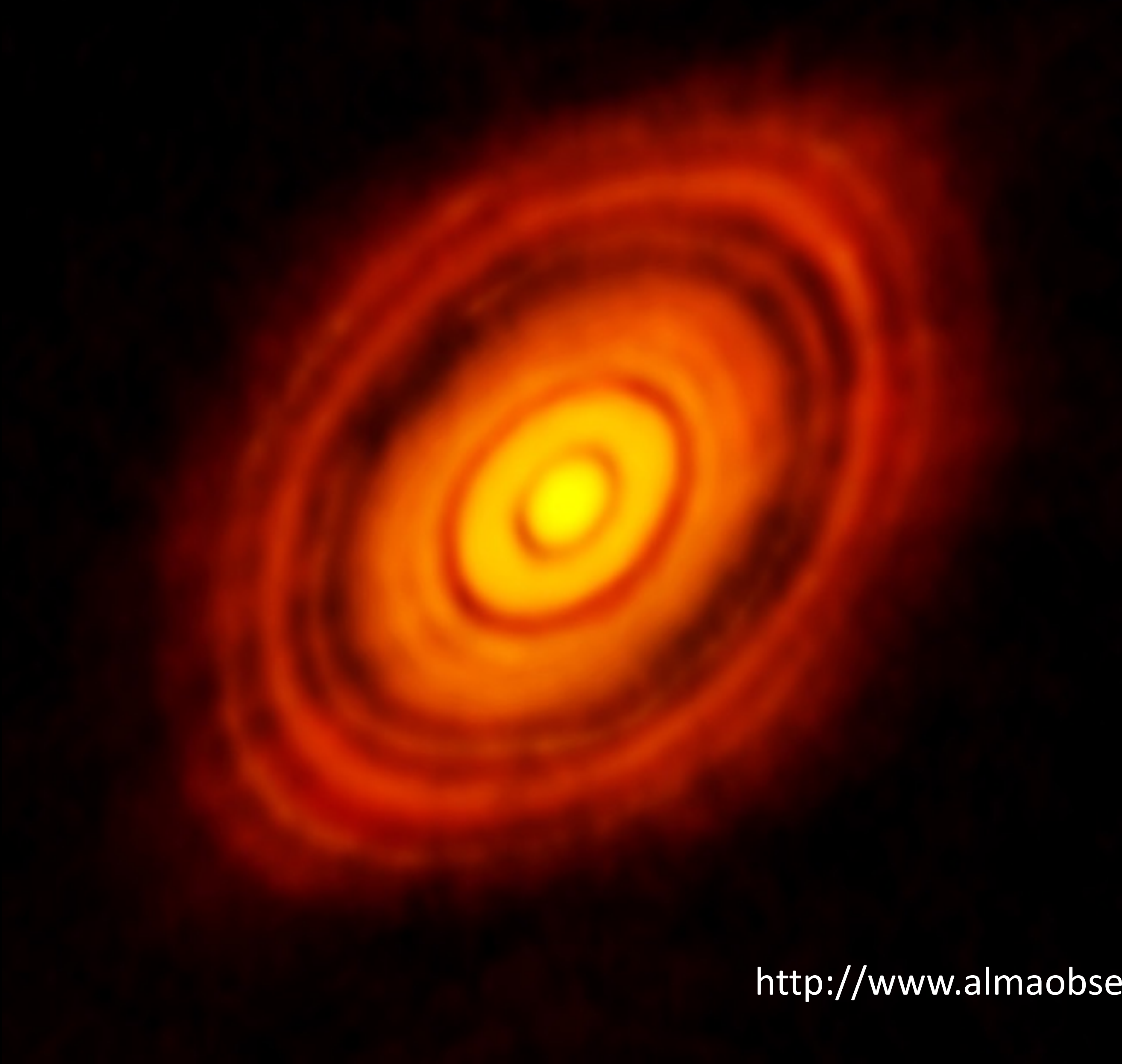
Once upon a time
there was a large molecular cloud
www.nasa.gov

a dusty disk around a young star was generated



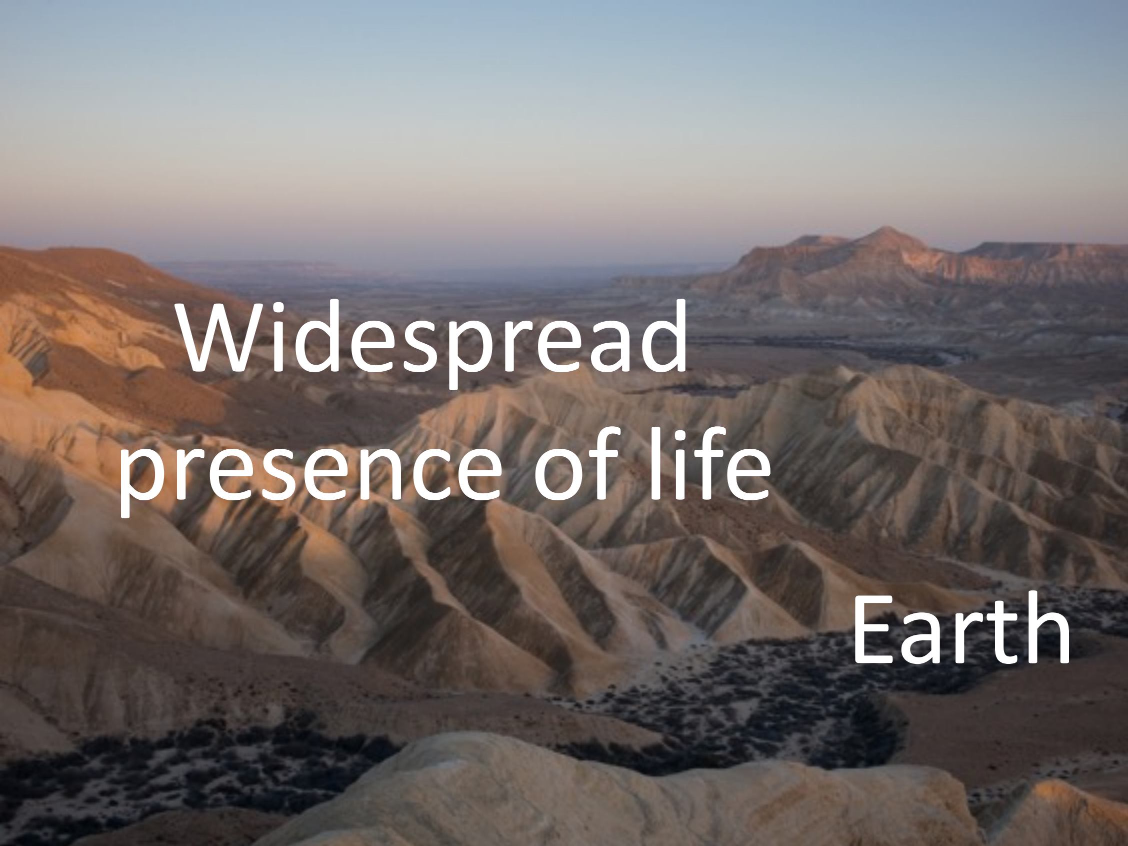
http://www.almaobservatory.org/

then the Earth formed…

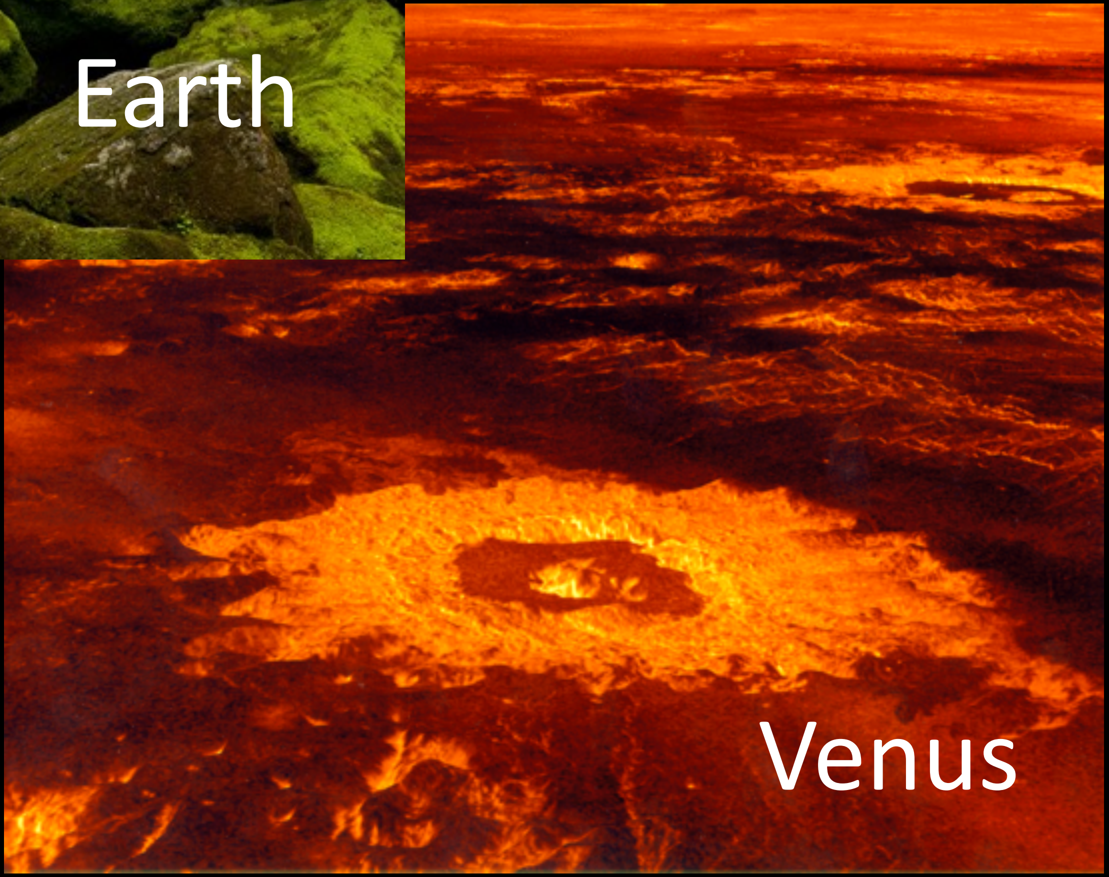
the planet cooled down with time, and life thrived on Earth

“Blue Marble” Apollo 17, December 1972, NASA

What makes Sol 3 special?



What makes Sol 3 special?



Why is the Earth "special" ?

Presence of a fluid envelope (water!)

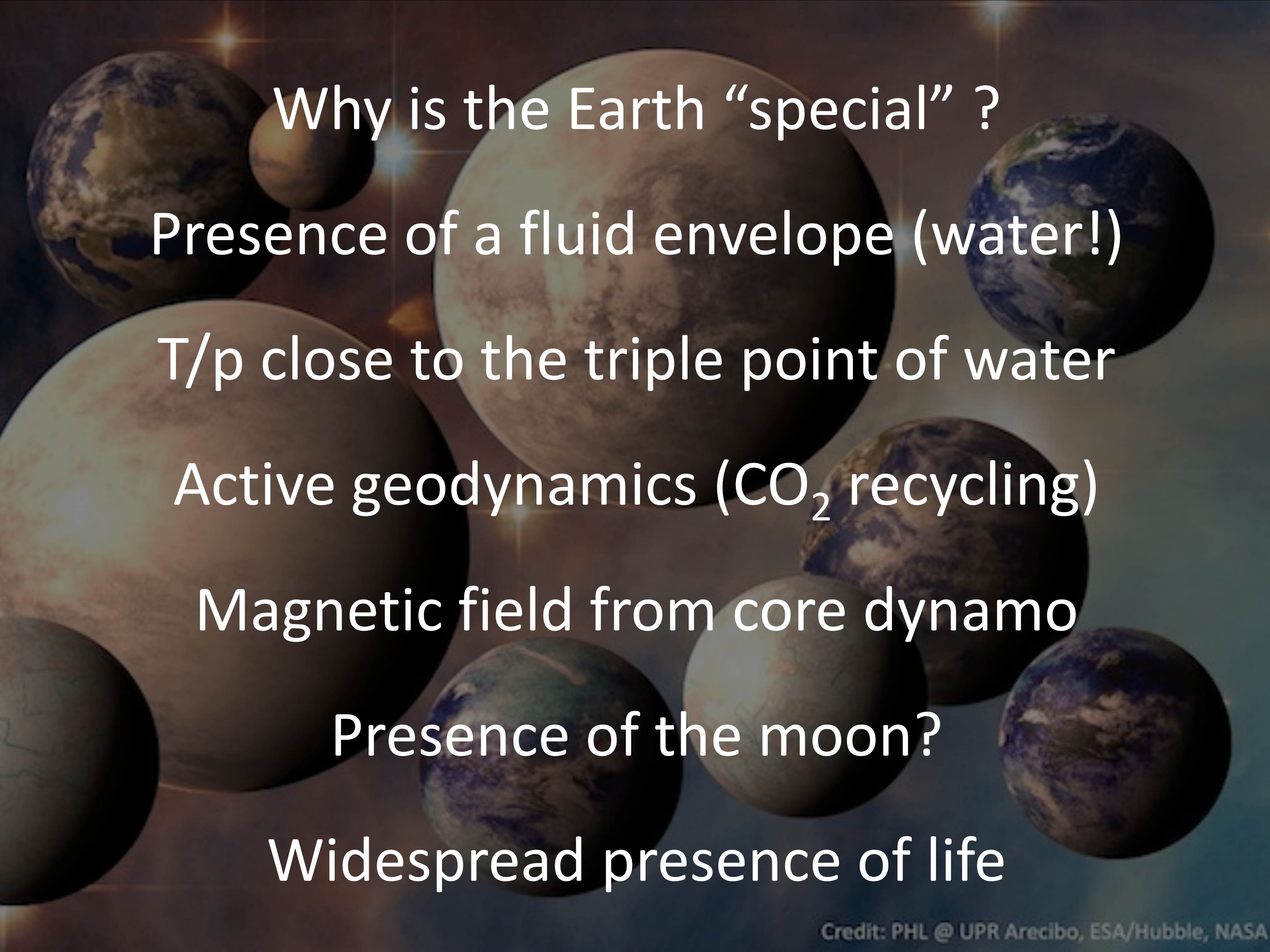
T/p close to the triple point of water

Active geodynamics (CO_2 recycling)

Magnetic field from core dynamo

Presence of the moon?

Widespread presence of life



Credit: PHL @ UPR Arecibo, ESA/Hubble, NASA

Elementary Thermodynamics of the Earth system

Solar “constant”:

S = 1.368 kW per square meter

+- 3.5% owing to orbit ellipticity

Power that hits the top of Earth’s atmosphere:

$$\pi S R^2$$

Surface over which it is distributed: $4\pi R^2$

Average power per unit surface: $\frac{1}{4} S$

Albedo:
Part of the incident energy is reflected

The fraction of reflected energy is denoted by α

Fraction of absorbed power:

$$1 - \alpha$$

On average, Earth's albedo is

$$\bar{\alpha} = 0.3$$

Average absorbed power (per unit surface):

$$P_{in} = \frac{1}{4} S \left(1 - \bar{\alpha}\right) \approx 240\, W\, m^{-2}$$

Emitted power (black body radiation)

$$P_{out} = \sigma T^4$$

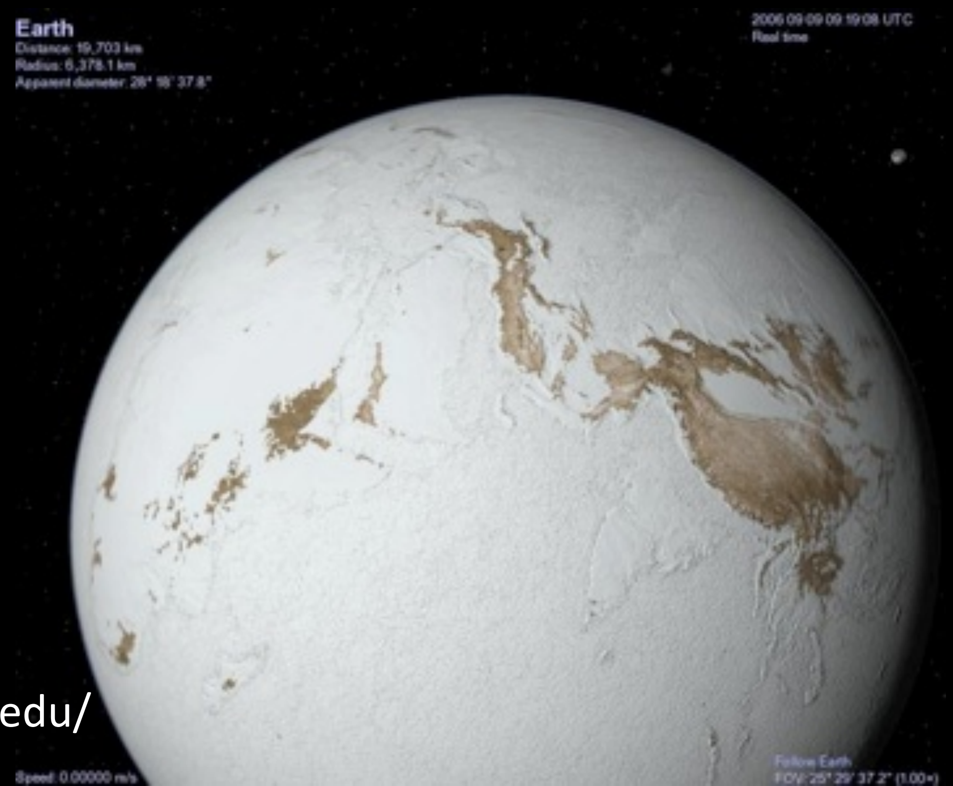
$$\sigma = 5.7 \times 10^{-8}\ W\, m^{-2}\, K^{-4}$$

Stefan-Boltzmann constant

If we look for a stationary state

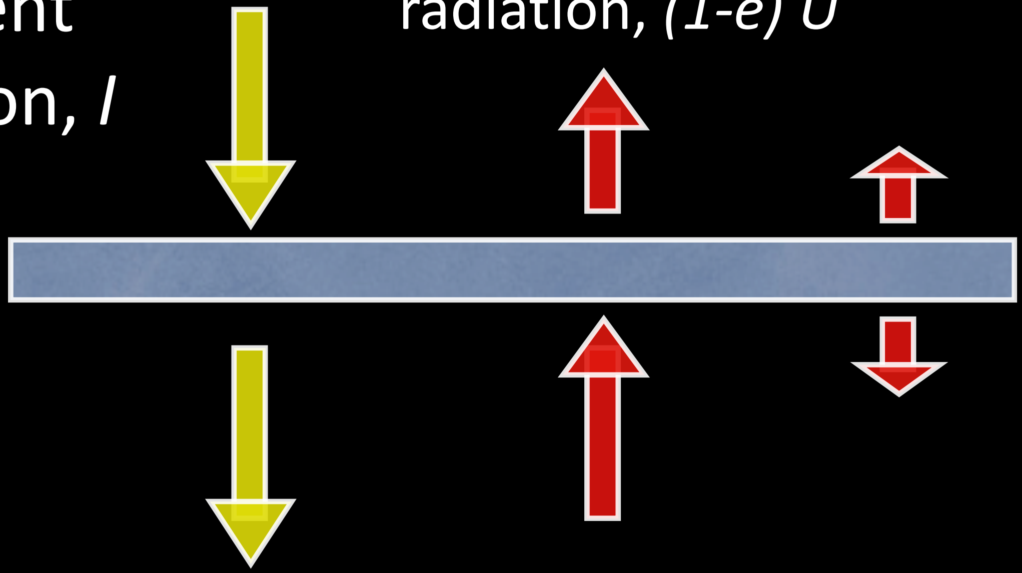
$$\frac{1}{4} S \left(1 - \bar{\alpha}\right) - \sigma T^4 = 0$$

$$T = \left[\frac{1}{4\sigma} S \left(1 - \bar{\alpha}\right) \right]^{1/4} \approx 255\, K$$



http://www.geo.mtu.edu/

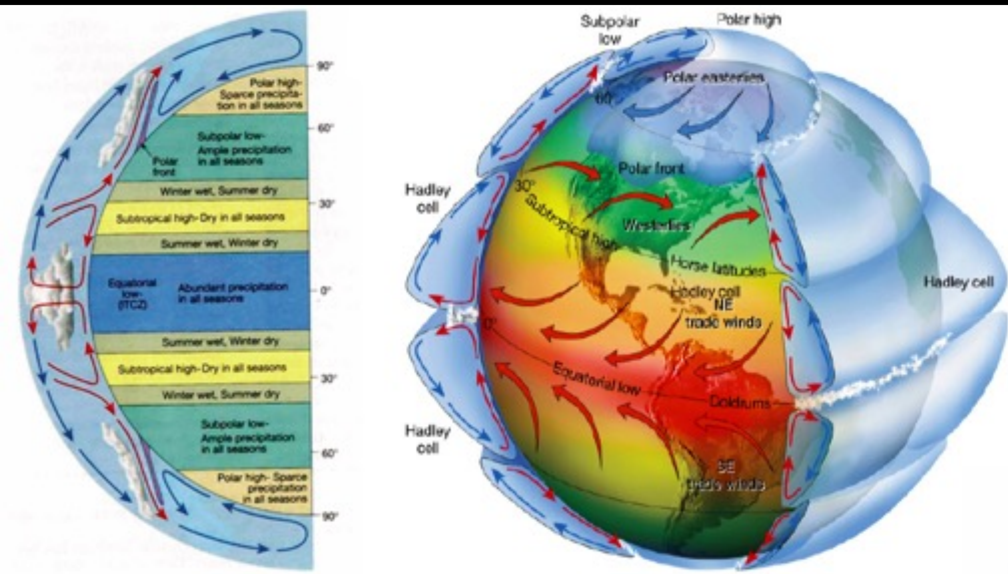
Role of the fluid envelope: greenhouse effect

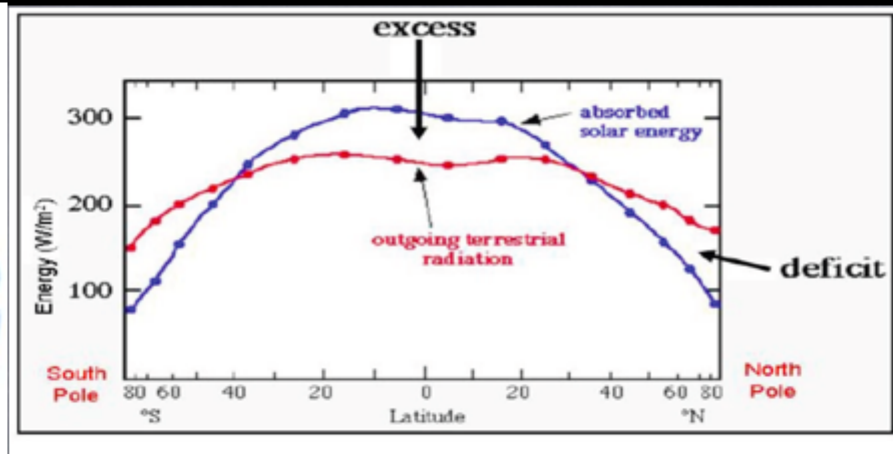


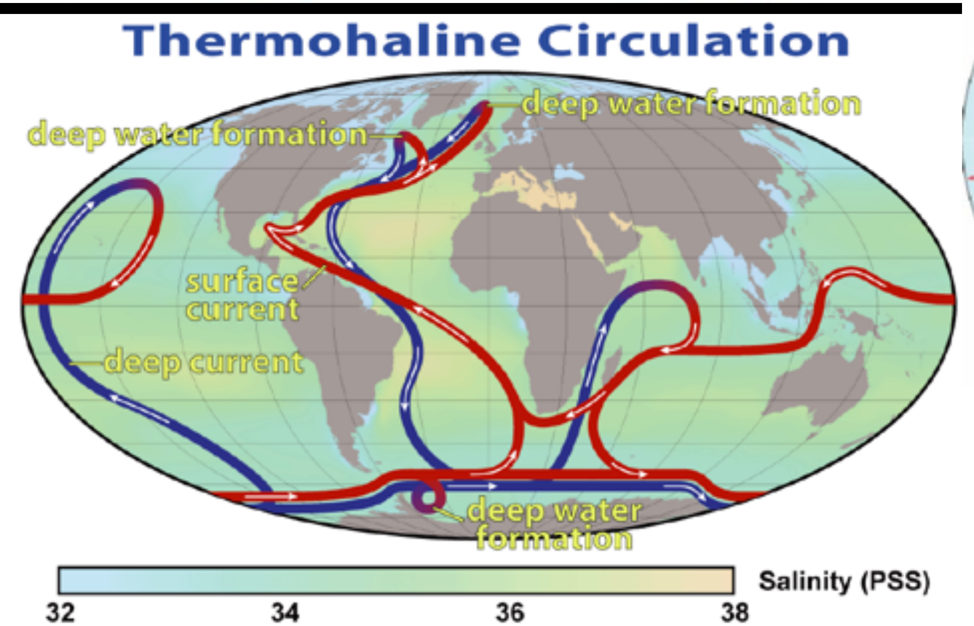
Earth surface

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

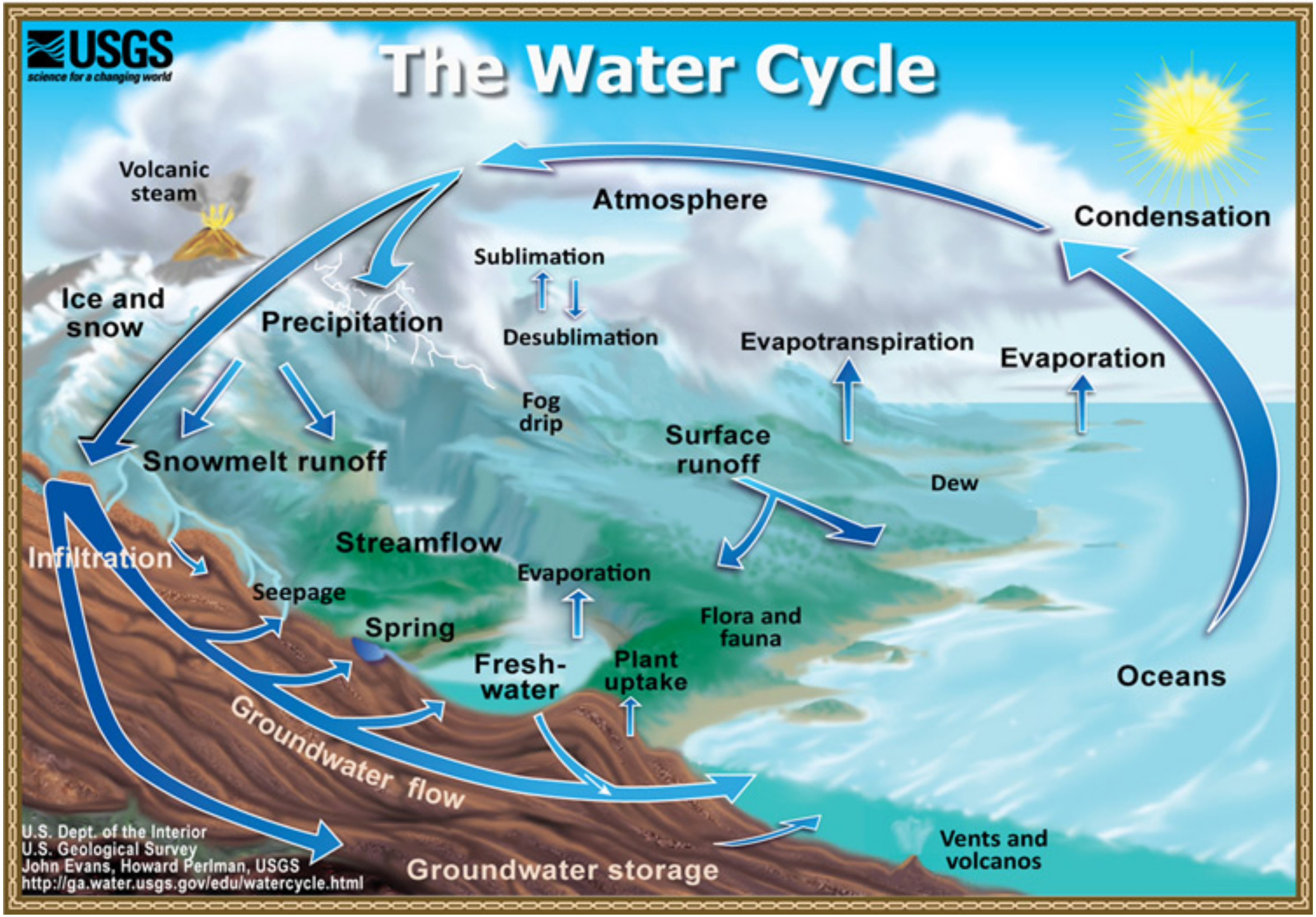
Latitudinal advective transport





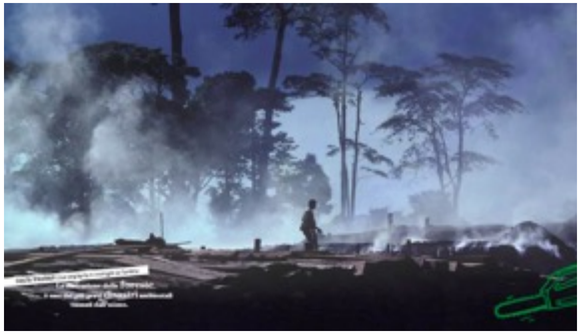


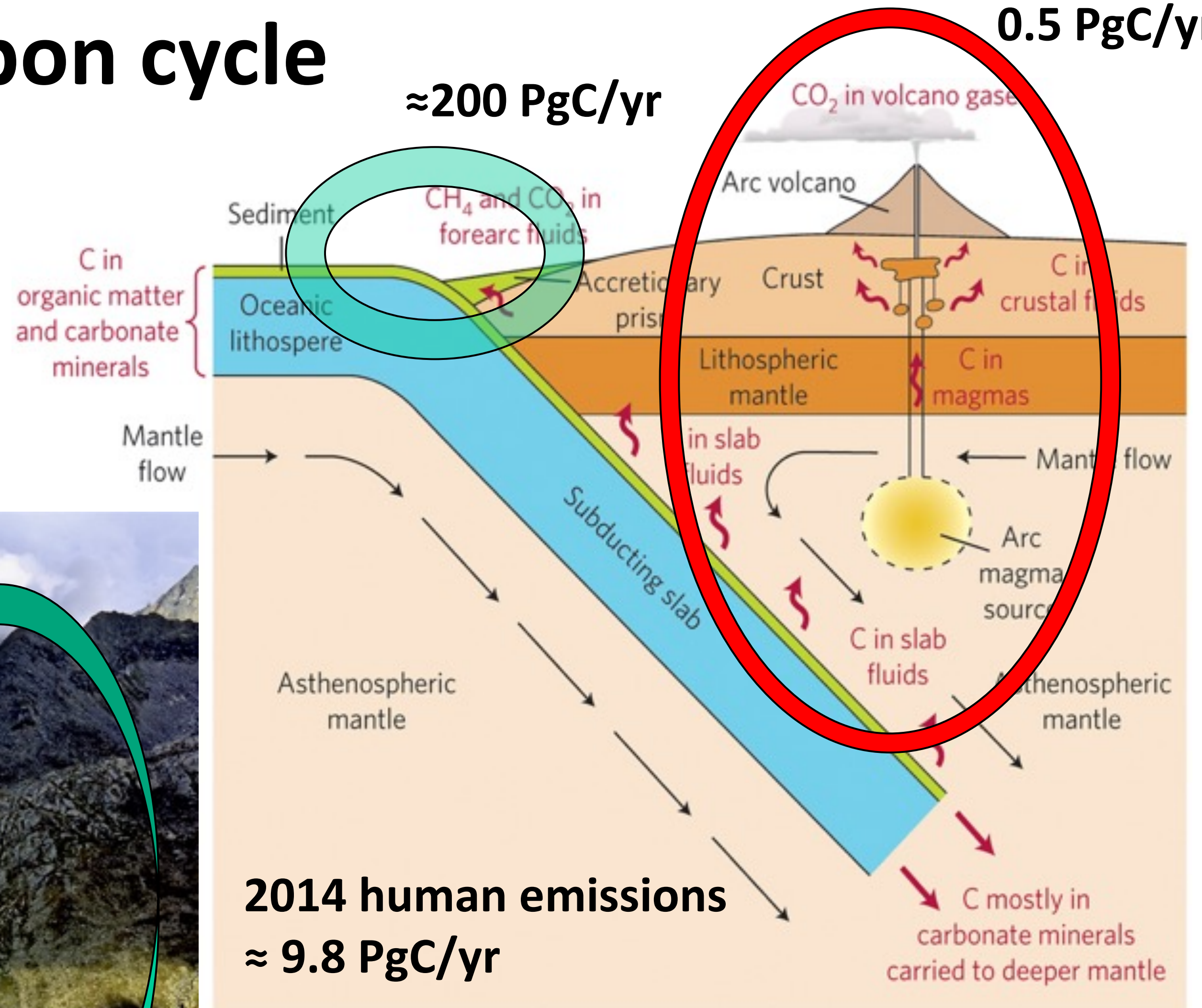
Wind-driven circulation



The hydrological cycle

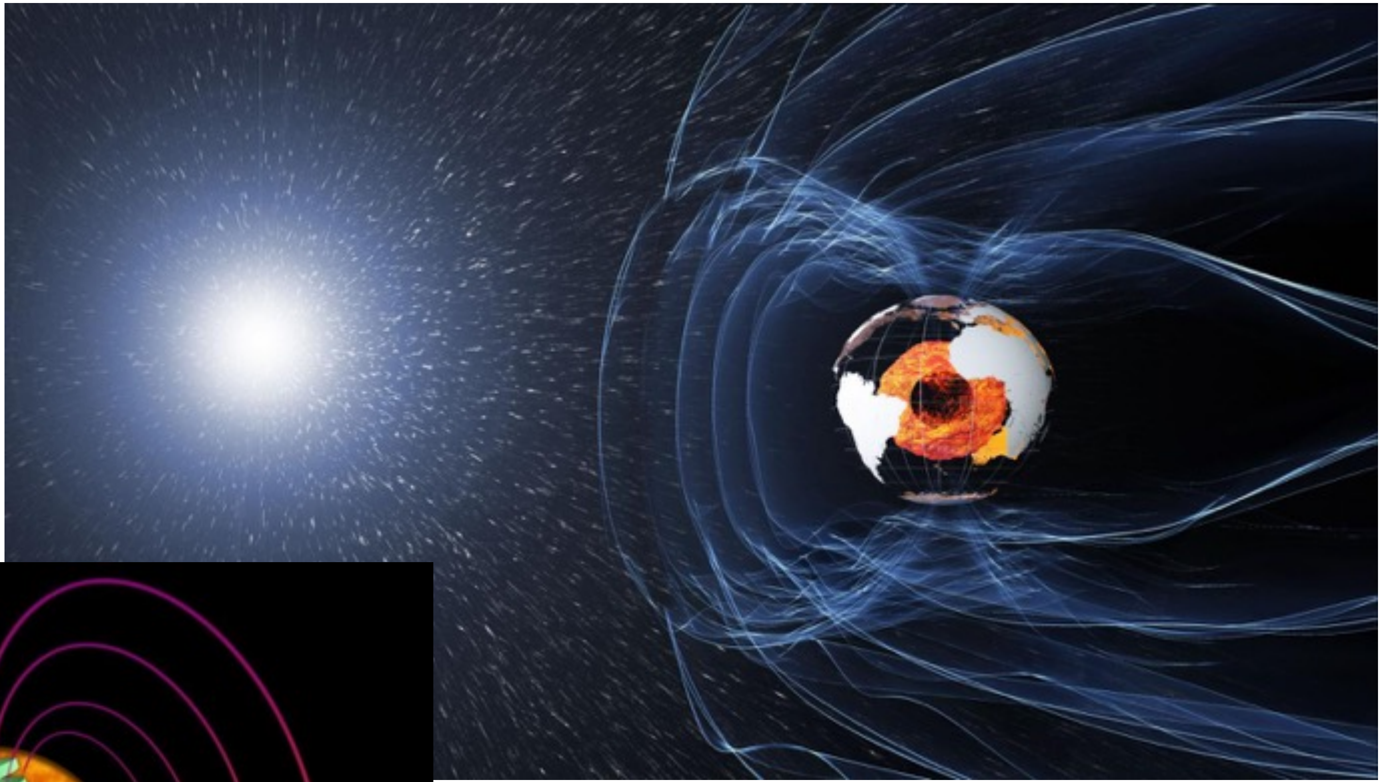
The global carbon cycle



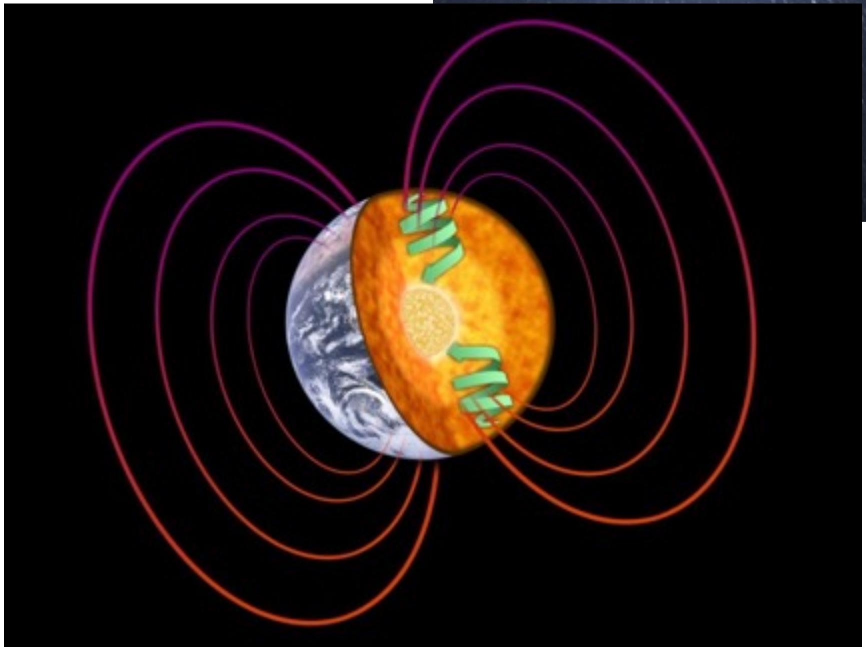


2014 human emissions
≈ 9.8 PgC/yr

The Earth's magnetic field

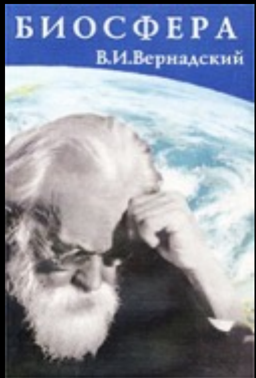


https://phys.org/news/2016-05-strength-earth-magnetic-field.html



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

and the Moon…

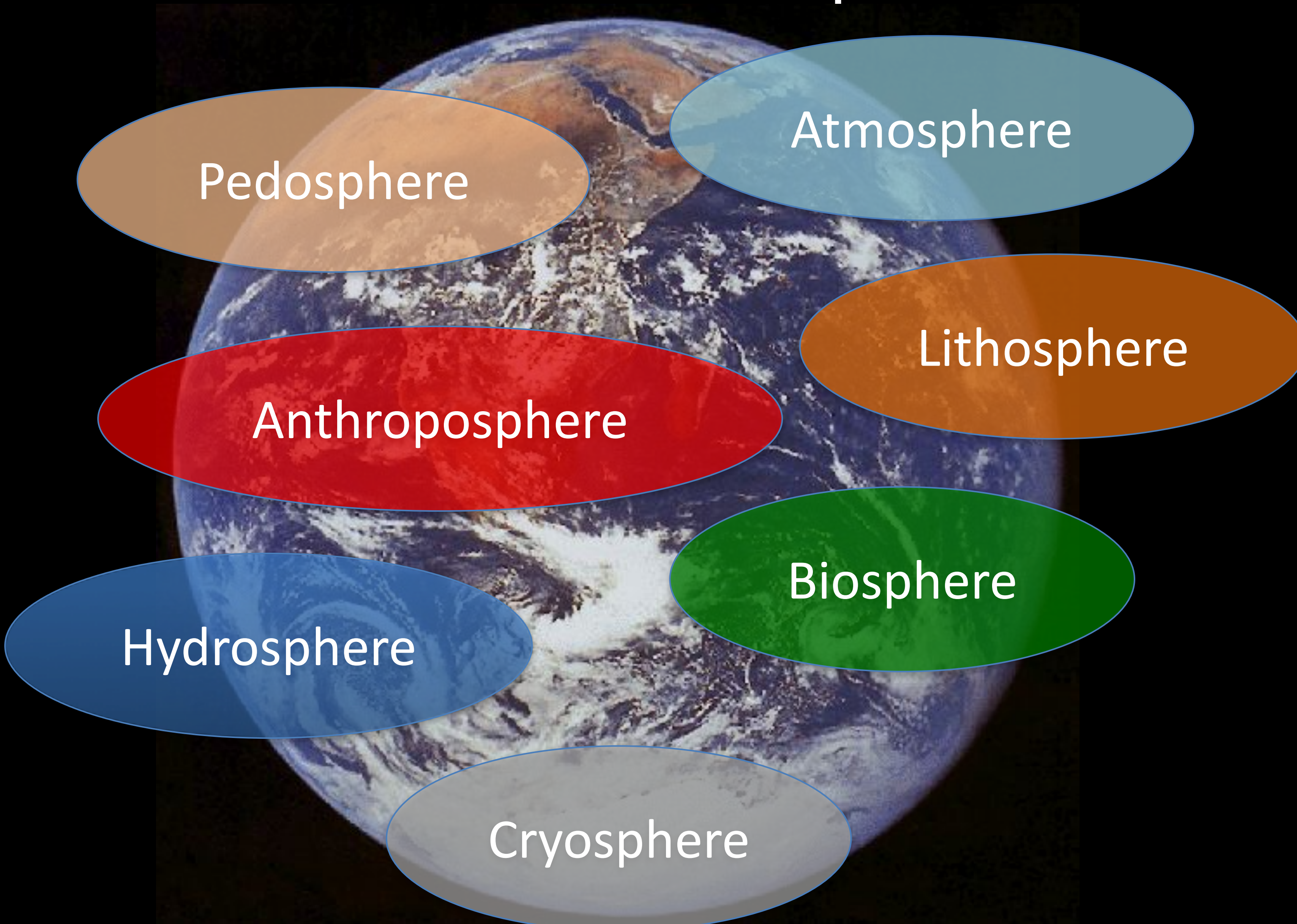


Geosphere

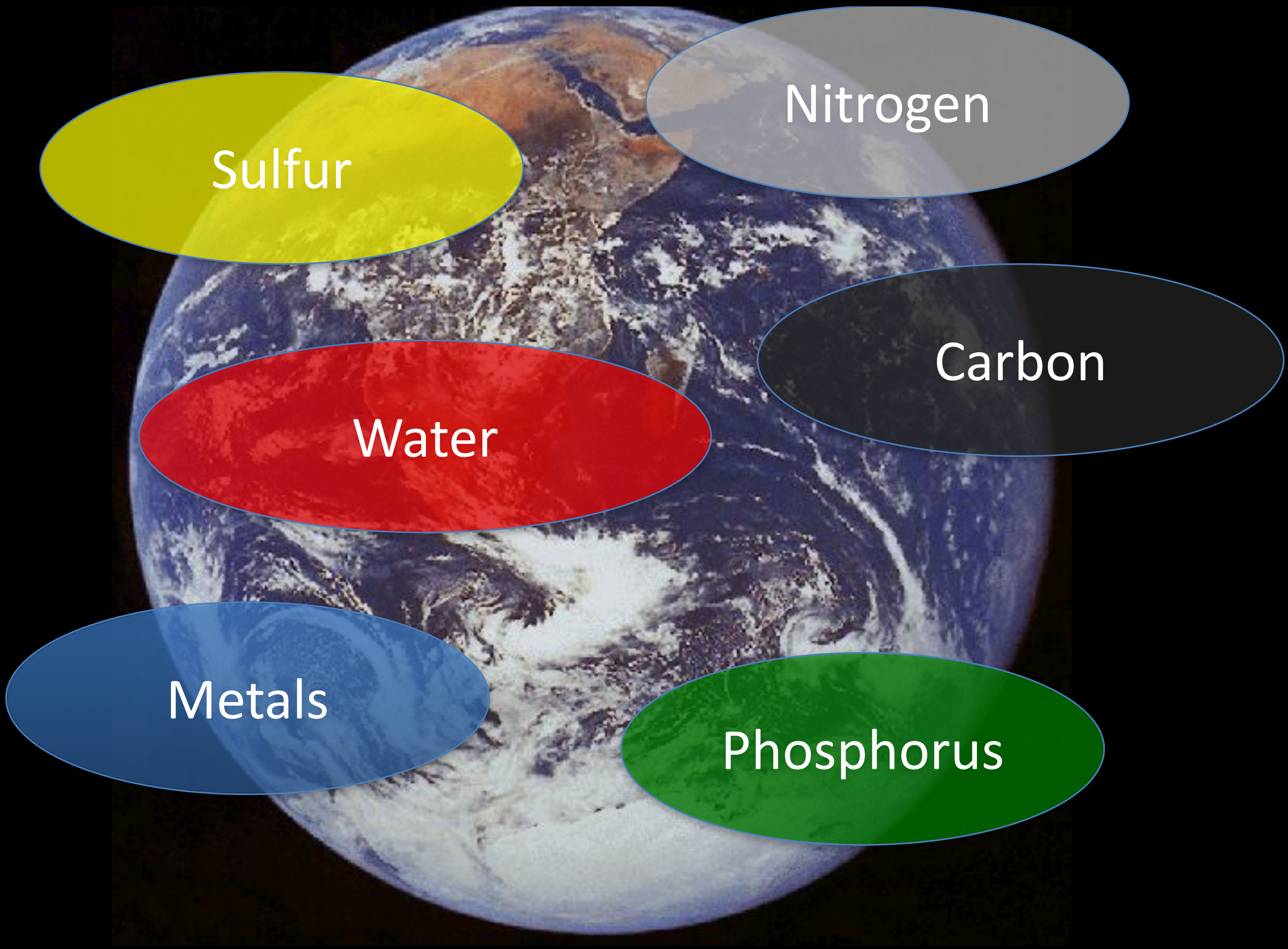
“One Grand Organic Whole”
(A.R. Wallace)

Biosphere

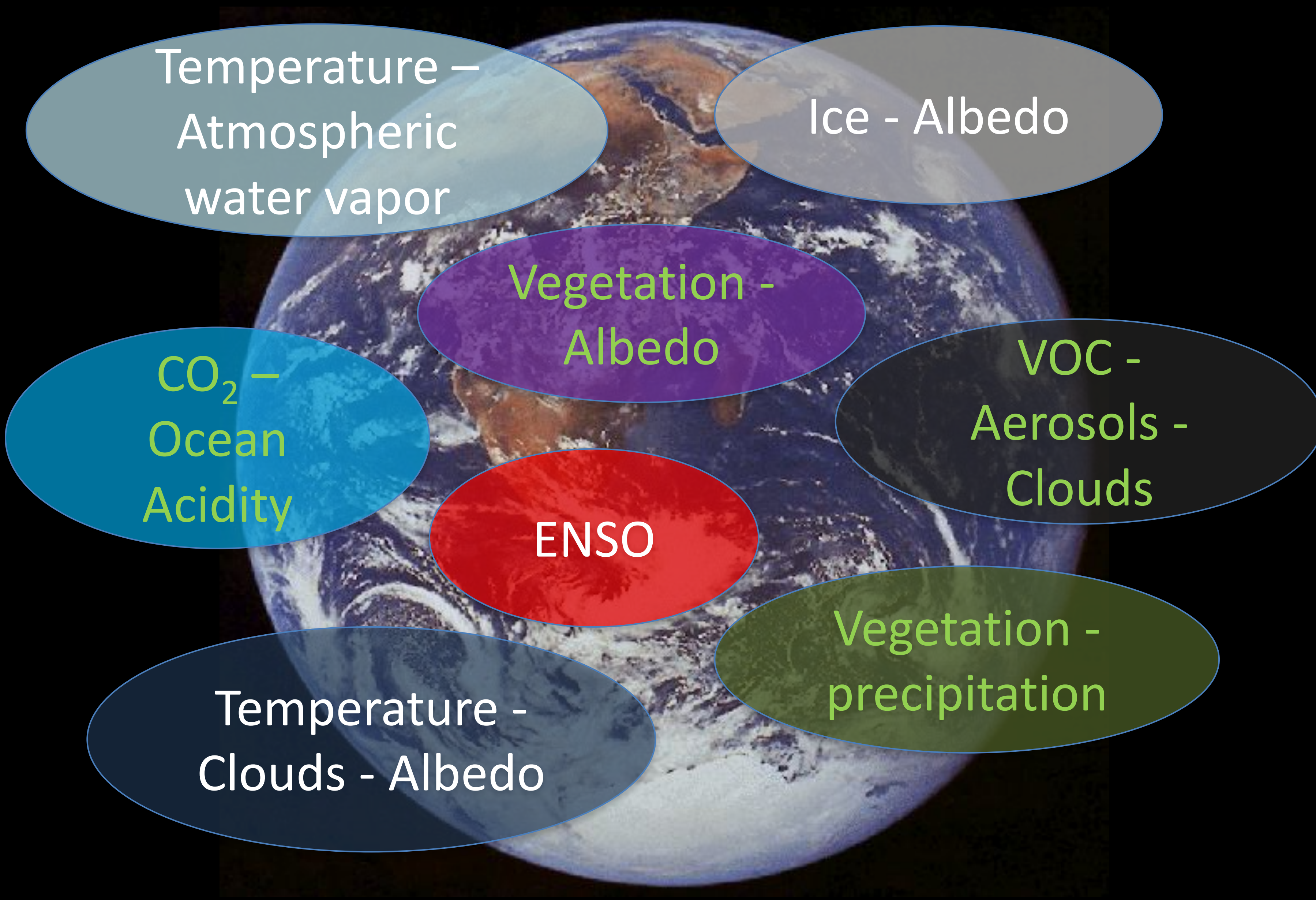
How to approach the Earth System: Reductionism I: the "spheres"



Fluxes and reservoirs: biogeochemical cycles



The inner workings: feedbacks in the Earth System



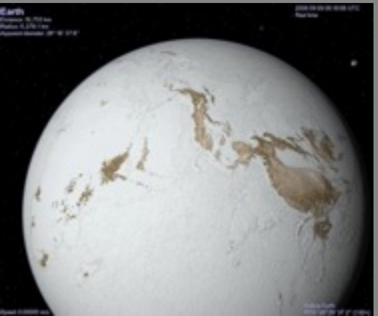
A well-known amplifying feedback: ice-albedo

Higher surface temperature

Less ice/snow

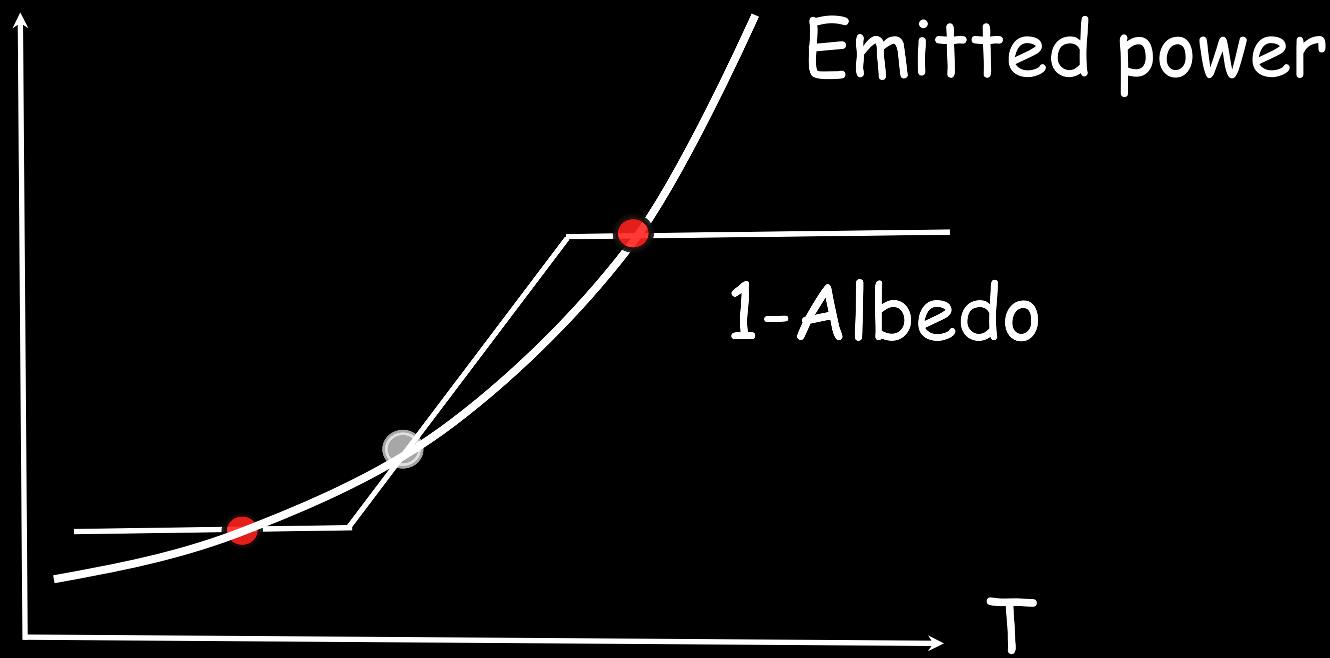
Lower albedo

More absorbed heat



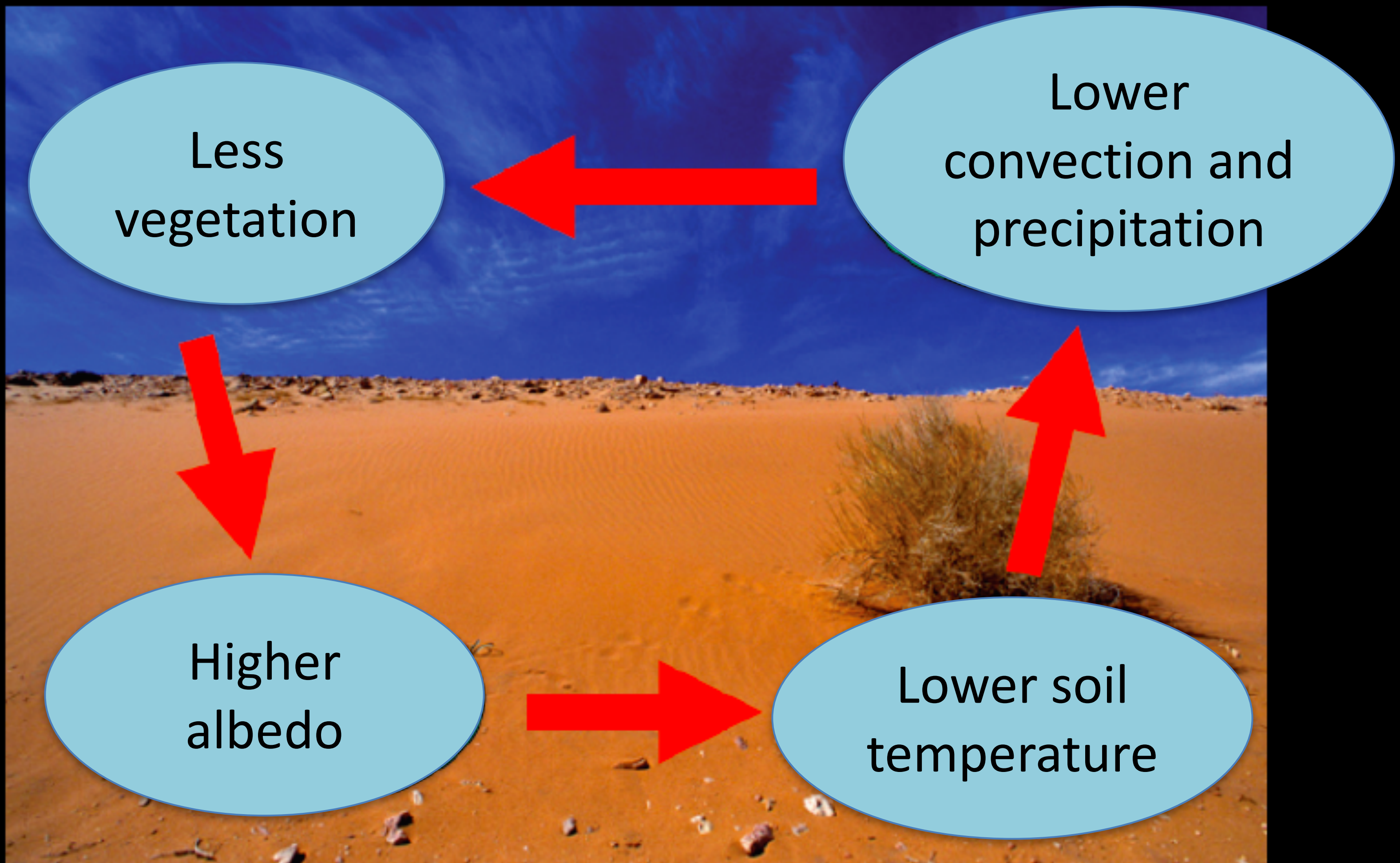
first principle of Thermodynamics

$$c_V \frac{dT}{dt} = \frac{1}{4} S\,(1-\bar{\alpha}) - \sigma\, T^4$$



equivalent to overdamped motion in a double potential well

Albedo and the Charney mechanism (1975)



the Charney mechanism (1975):

$$\frac{dV}{dt} = gV(1-V) - mV$$

$$g = g(P) \quad , \quad P \propto T$$

Vegetation dynamics:

a logistic equation
for the fraction of soil
covered by vegetation, V

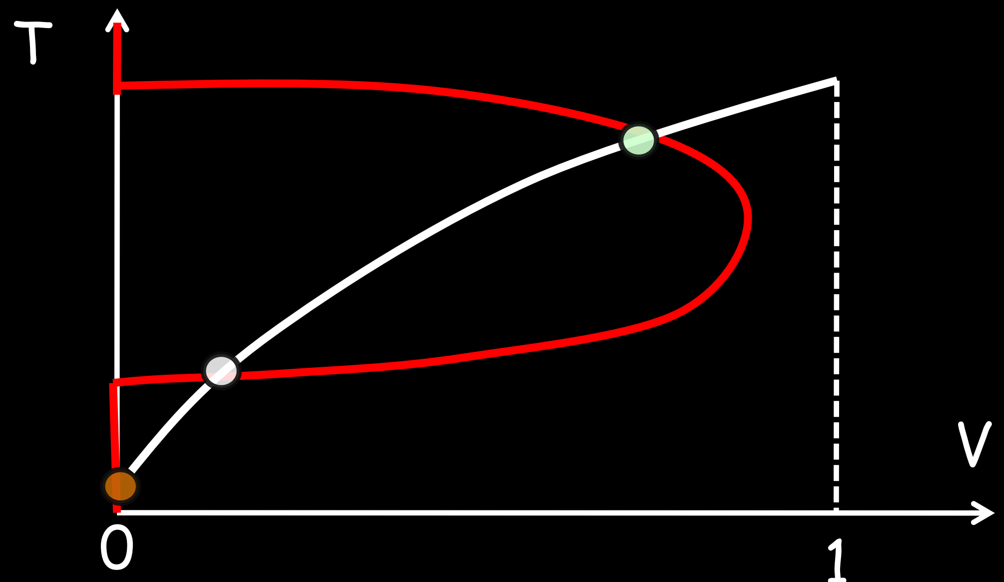
$$c_V \frac{dT}{dt} = \frac{S}{4}\left[1 - \alpha_V V - \alpha_B (1-V)\right] - \sigma T^4$$

First principle
of Thermodynamics

A classic example: the Charney mechanism (1975):

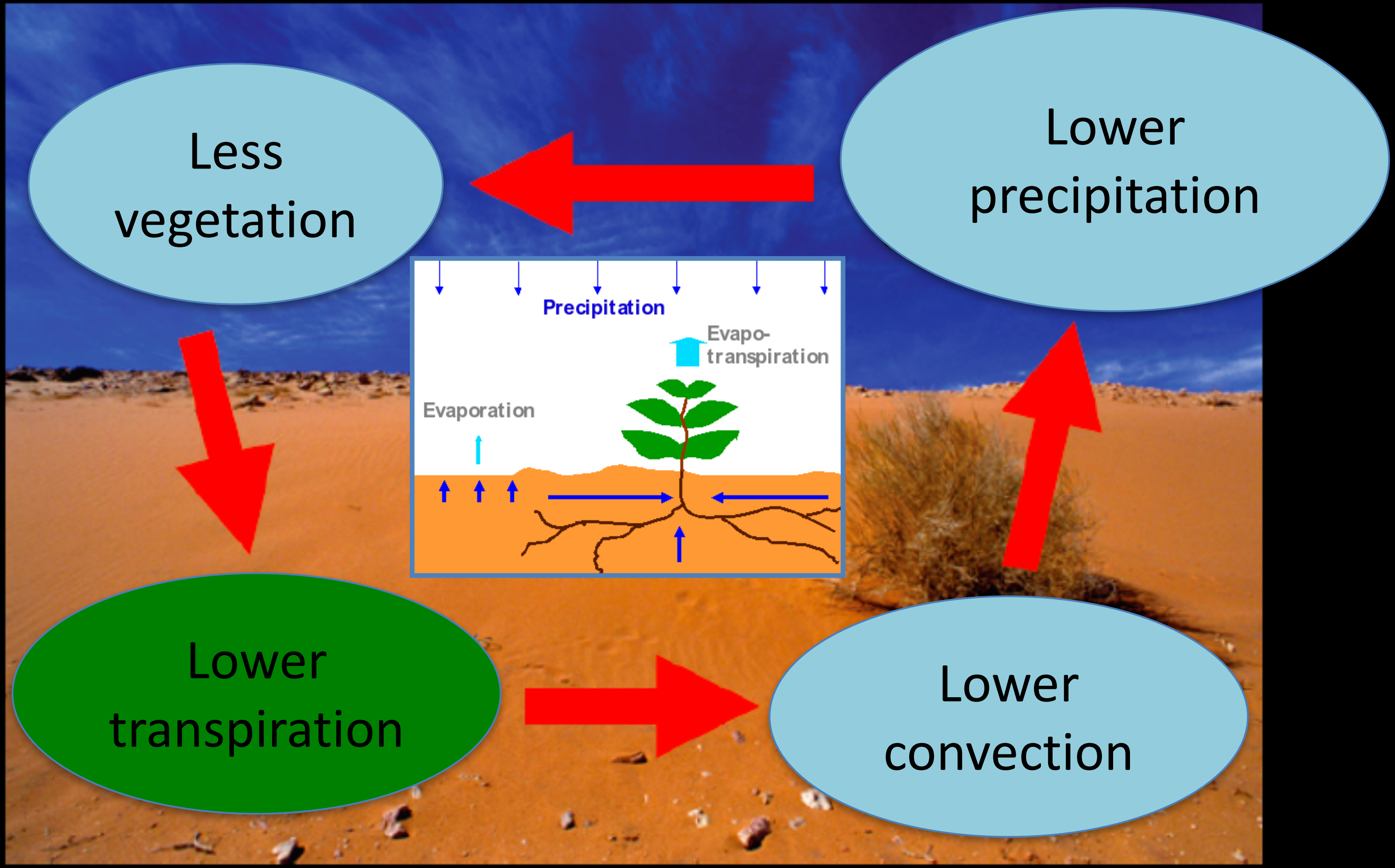
$$0 = g(T)V\left(1-V\right) - mV \quad \Rightarrow \quad V = 1 - \frac{m}{g(T)}$$

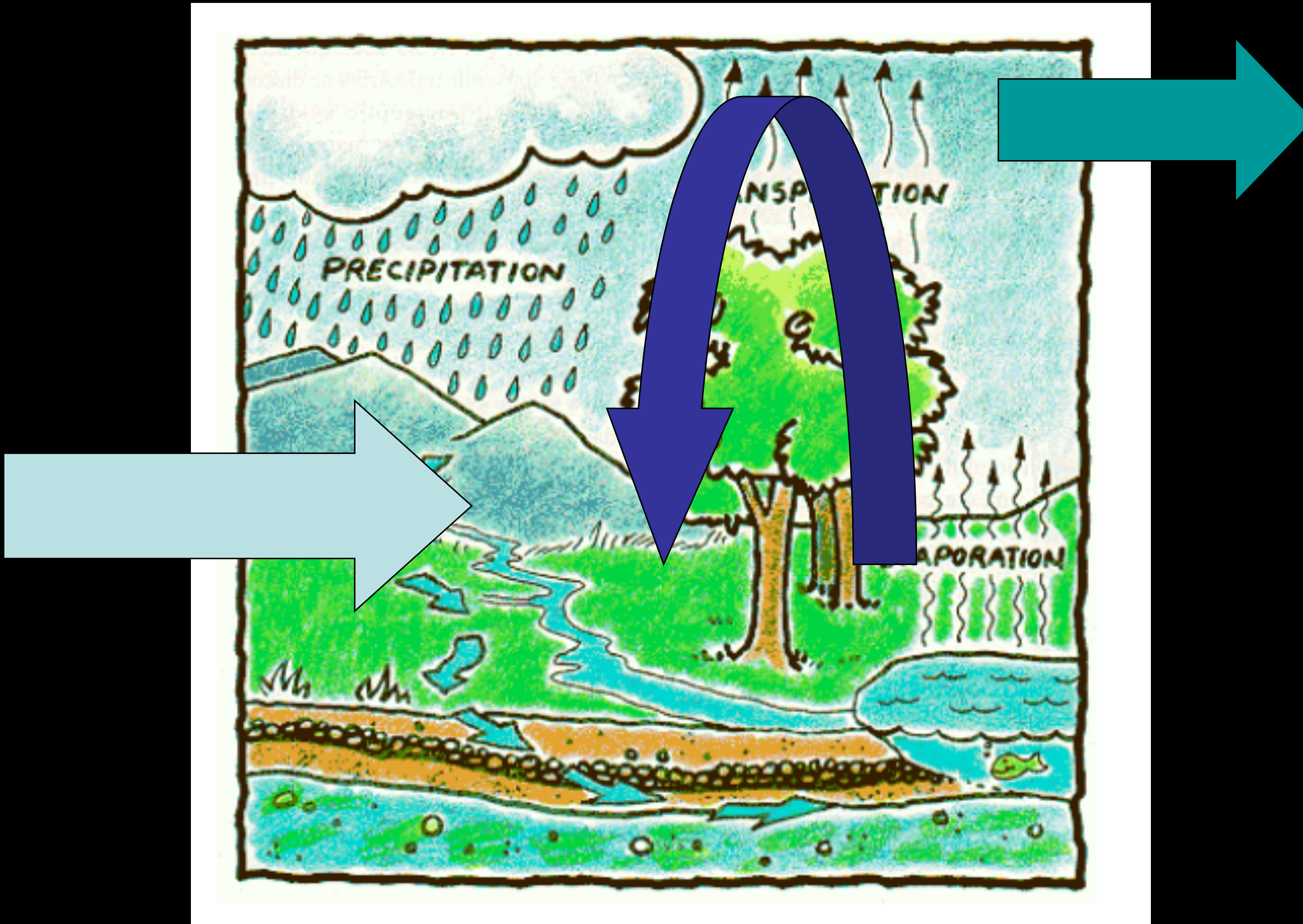
$$0 = \frac{S}{4}\left[1-\alpha_V V - \alpha_B\left(1-V\right)\right] - \sigma T^4 \quad \Rightarrow \quad T = \sqrt[4]{\frac{S}{4\sigma}\left[1-\alpha_V V - \alpha_B\left(1-V\right)\right]}$$



Brovkin et al JGR 1998

Plant transpiration and the hydrological cycle





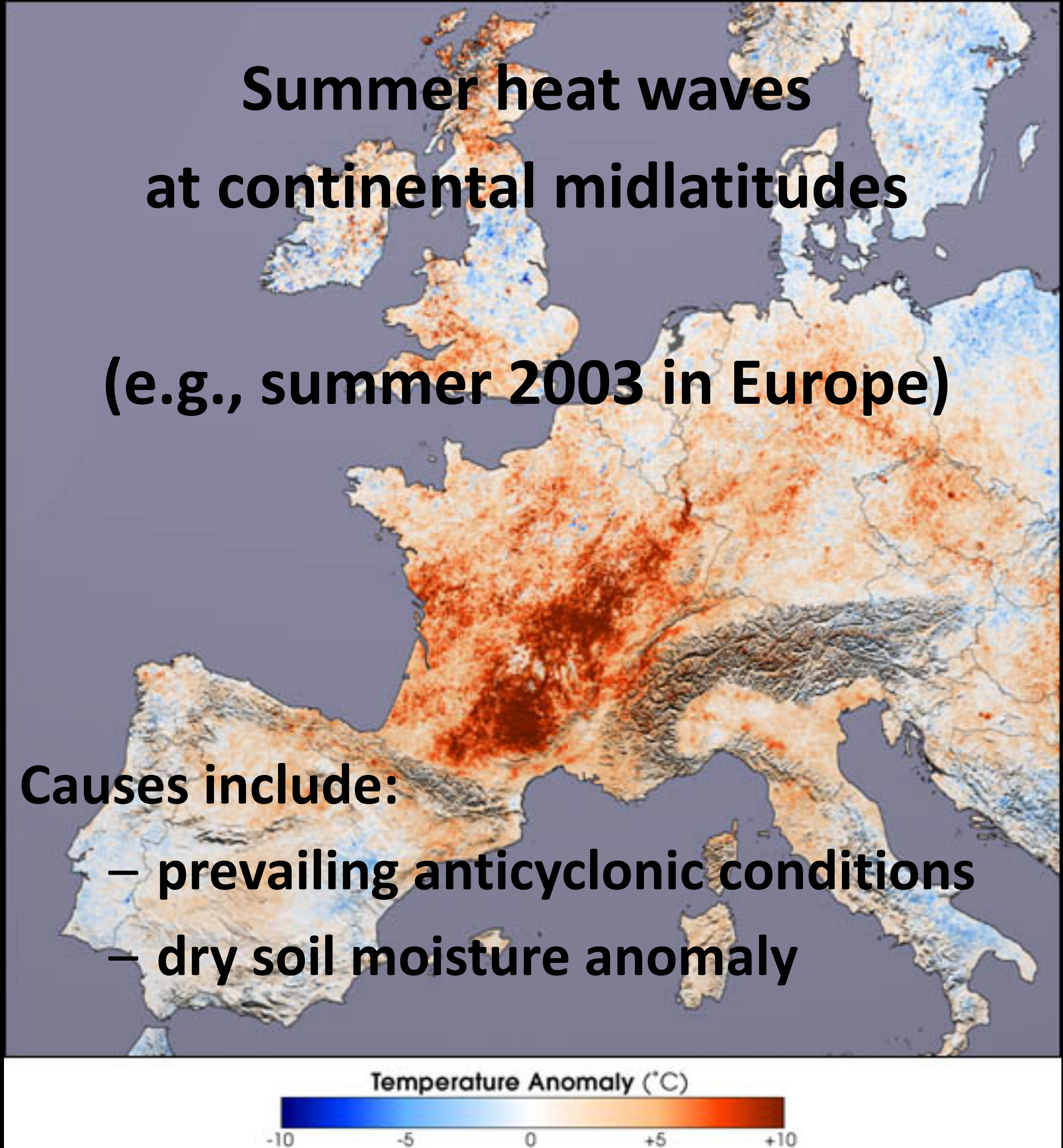
Continental water cycle: Long-range transport vs “local” recycling

Summer heat waves at continental midlatitudes

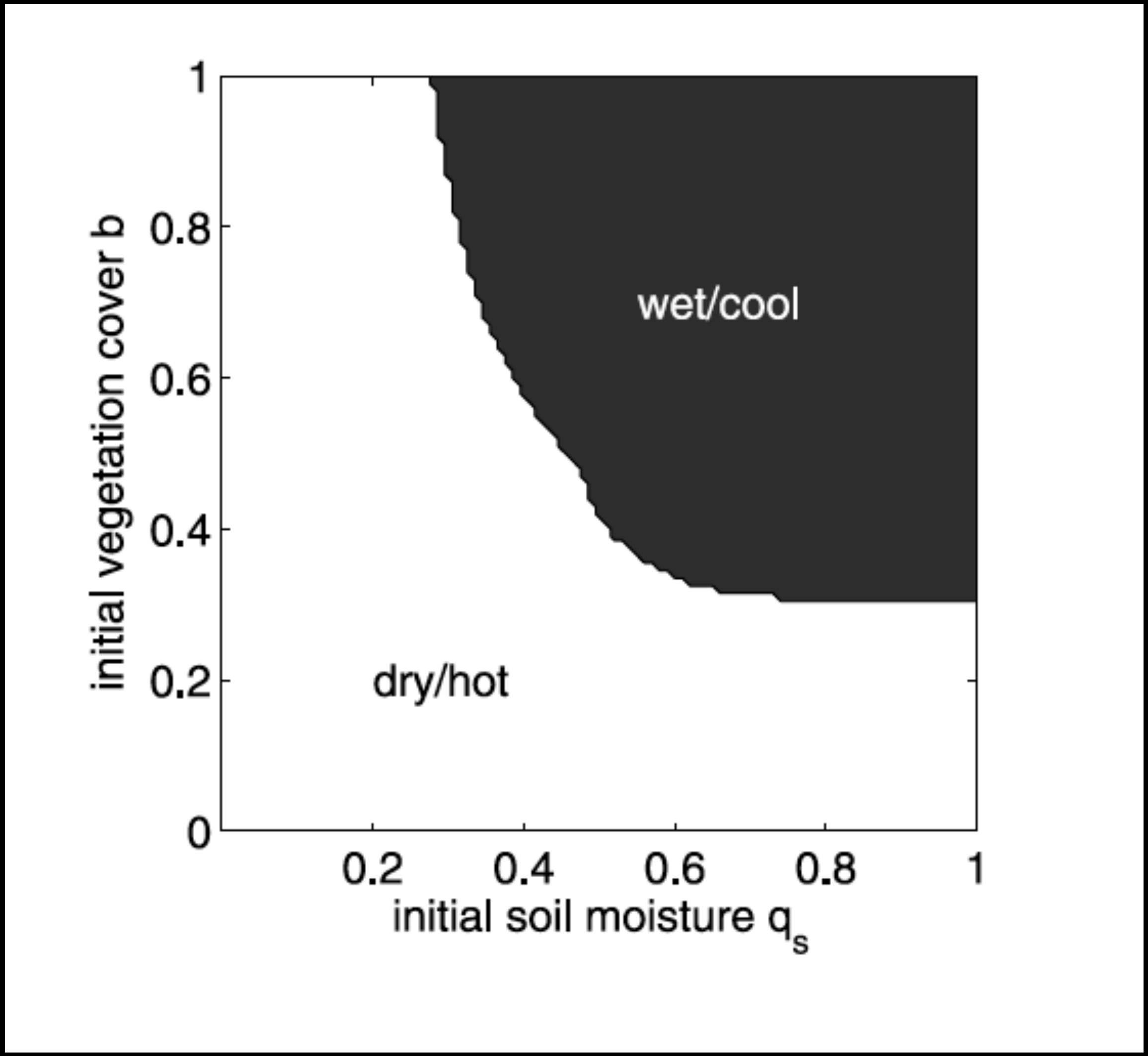
(e.g., summer 2003 in Europe)

Causes include:

- prevailing anticyclonic conditions
- dry soil moisture anomaly



Multiple equilibria of the soil-atmosphere system



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

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

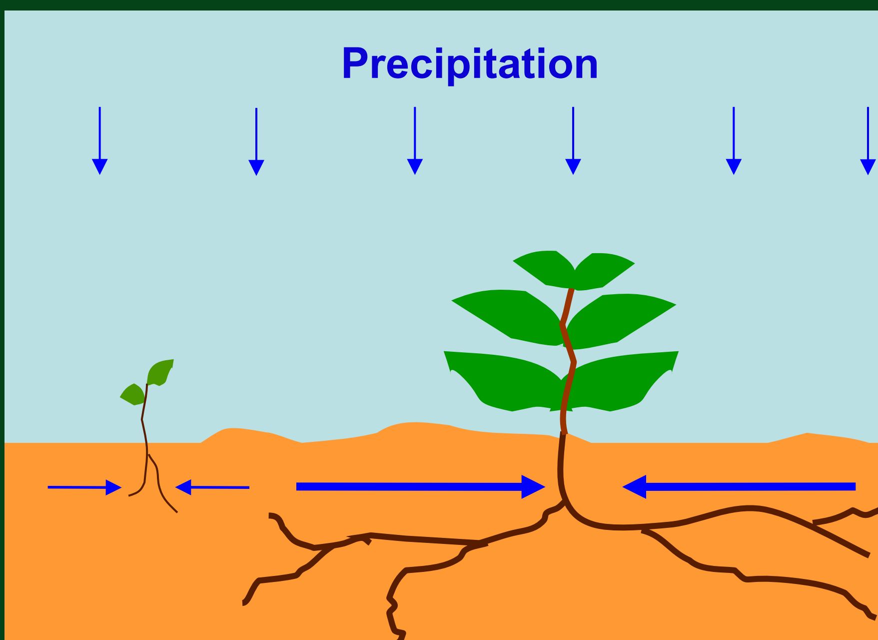
Rietkerk et al., *The American Naturalist* **160** (4), 2002

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

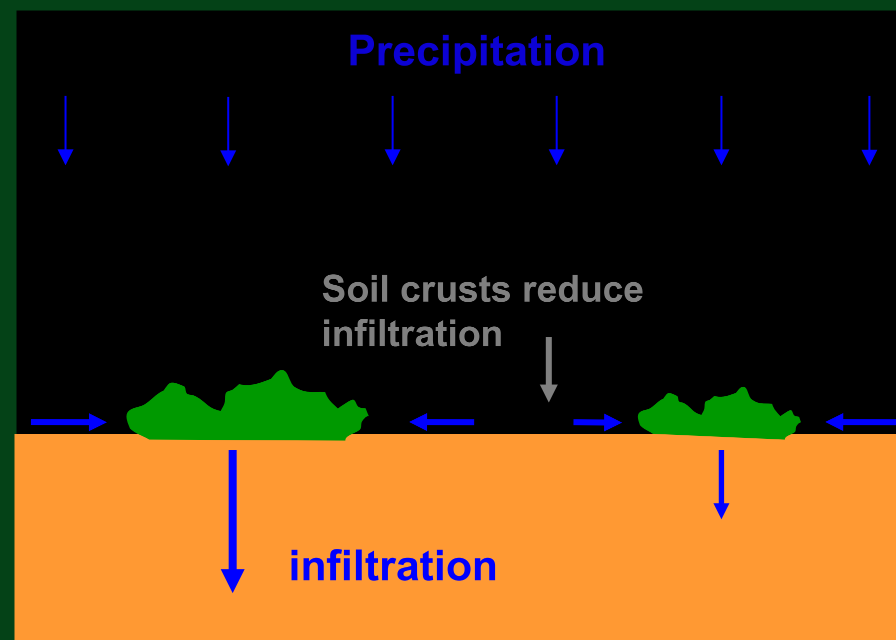
Feedbacks leading to vegetation patterns

Positive feedback between biomass and water + competition

Water uptake by roots

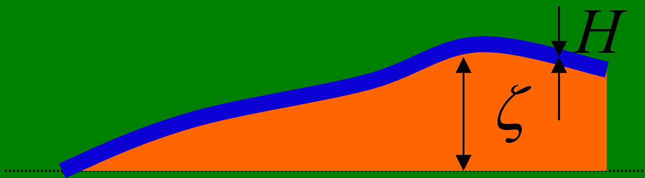


Increased infiltration



Vegetation - soil moisture - surface flow model

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

$$\frac{\partial B}{\partial t} = G_B[s]B\left(1 - \frac{B}{K}\right) - MB + D_B\nabla^2 B$$

$$\frac{\partial s}{\partial t} = \frac{IH}{W_{MAX}} - \frac{N\,s}{1 + RB/K} - G_s[B]\mathcal{F}(s) + D_W\nabla^2 s$$

$$\frac{\partial H}{\partial t} = P - IH + D_H\nabla^2\left(H^2\right)$$

$$G_B[s] = \Lambda_{MAX}\int G(\mathbf{x},\mathbf{x}',t)\mathcal{F}\left(s(\mathbf{x}',t)\right)d\mathbf{x}' \ .$$

$$G_s[B] = \Gamma\int G(\mathbf{x}',\mathbf{x},t)B(\mathbf{x}',t)d\mathbf{x}'$$

$$G_B[s] = \Lambda_{MAX} \int G(\mathbf{x}, \mathbf{x}', t) \mathcal{F}\left(s(\mathbf{x}', t)\right) d\mathbf{x}' \ .$$

$$G(\mathbf{x}, \mathbf{x}', t) = \frac{1}{2\pi S_0} \exp\left[-\frac{|\mathbf{x} - \mathbf{x}'|^2}{2\left[S_0(1 + EB\left(\mathbf{x}, t\right))\right]^2} \right] \ .$$

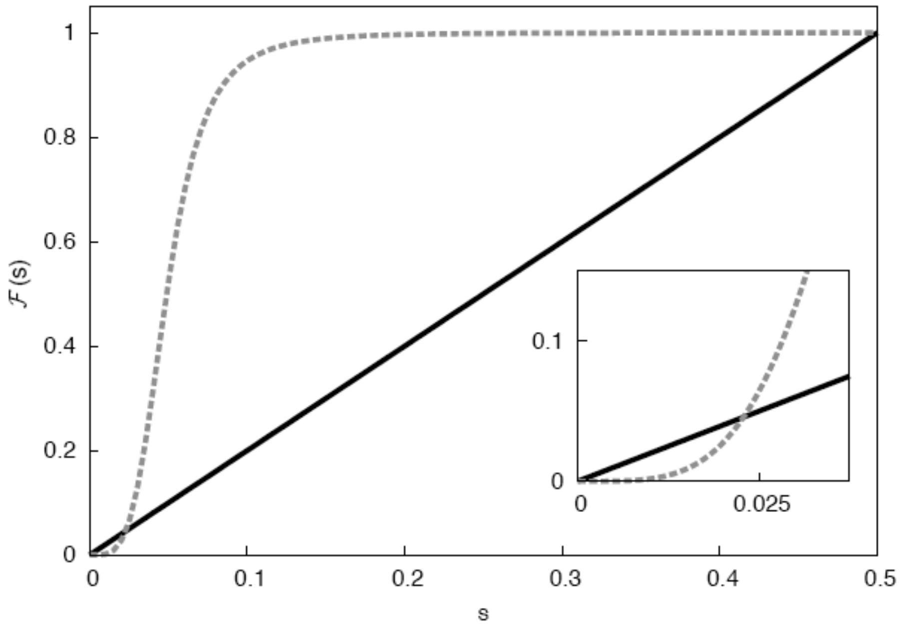
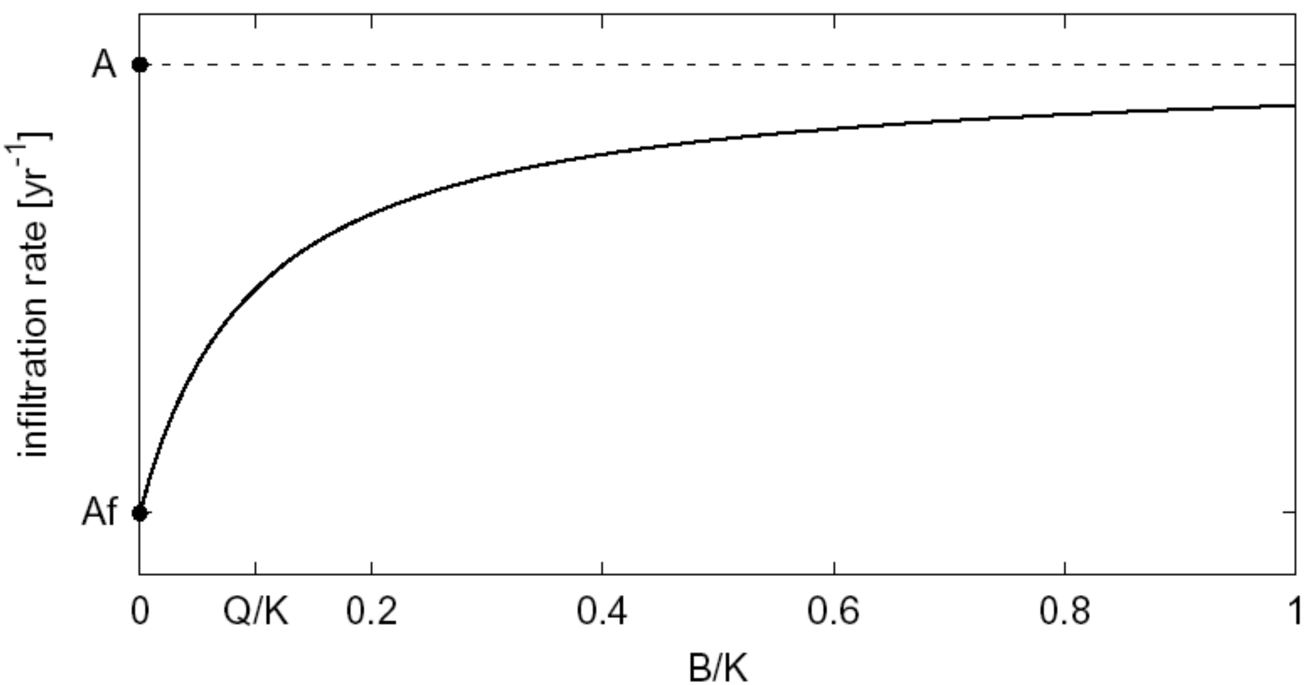
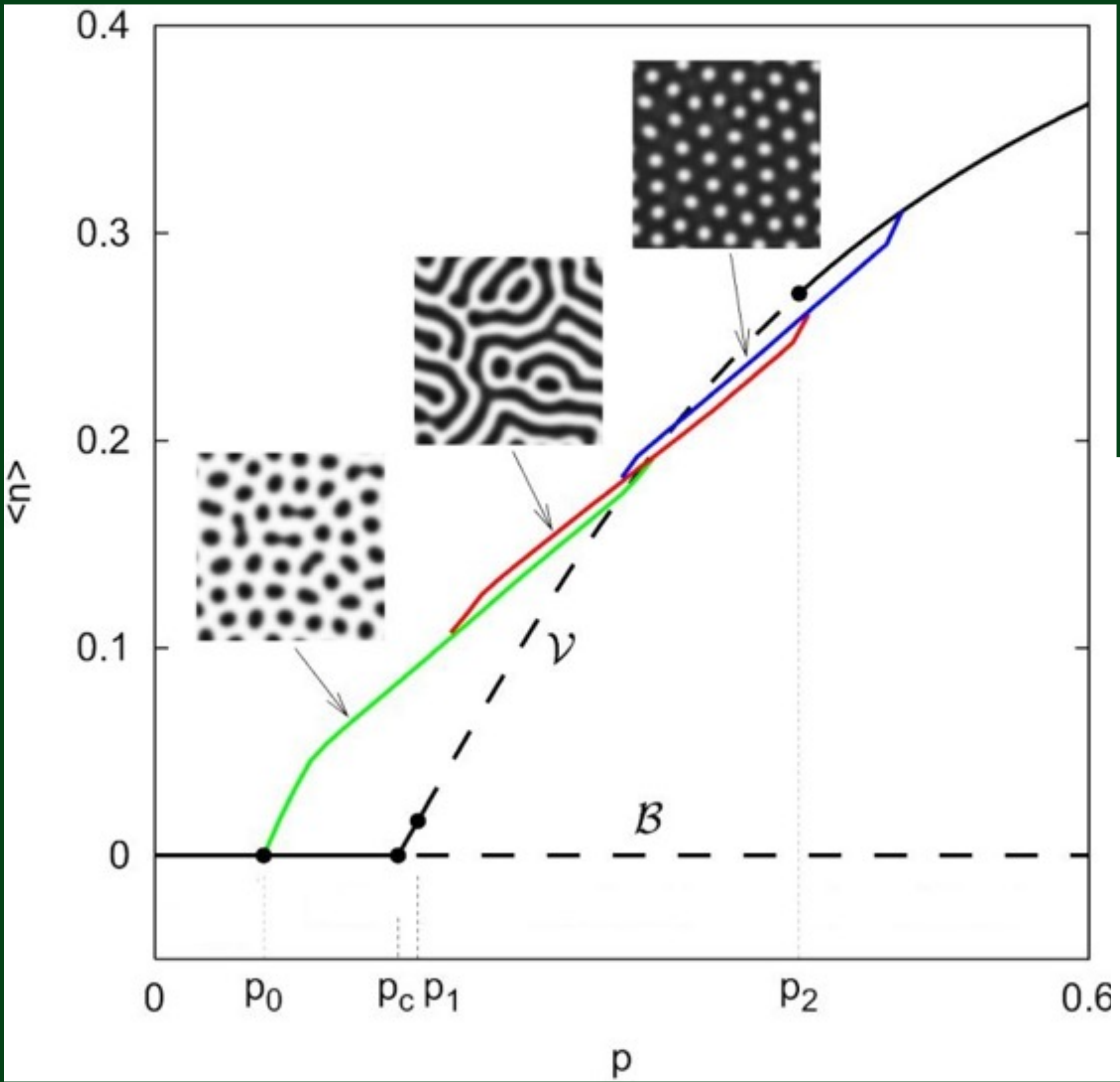
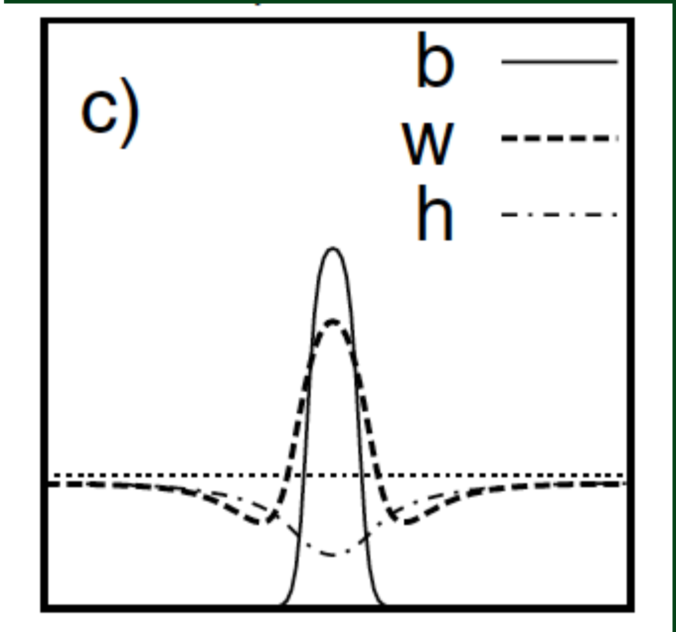


Fig. 1.— Functional forms of the water uptake term, $\mathcal{F}(s)$ where $s = W/W_{MAX}$, adopted in this work. The inset shows an enlargment of the region for small s.

$$I = A \frac{B(\mathbf{x}, t) + Qf}{B(\mathbf{x}, t) + Q} \quad ,$$





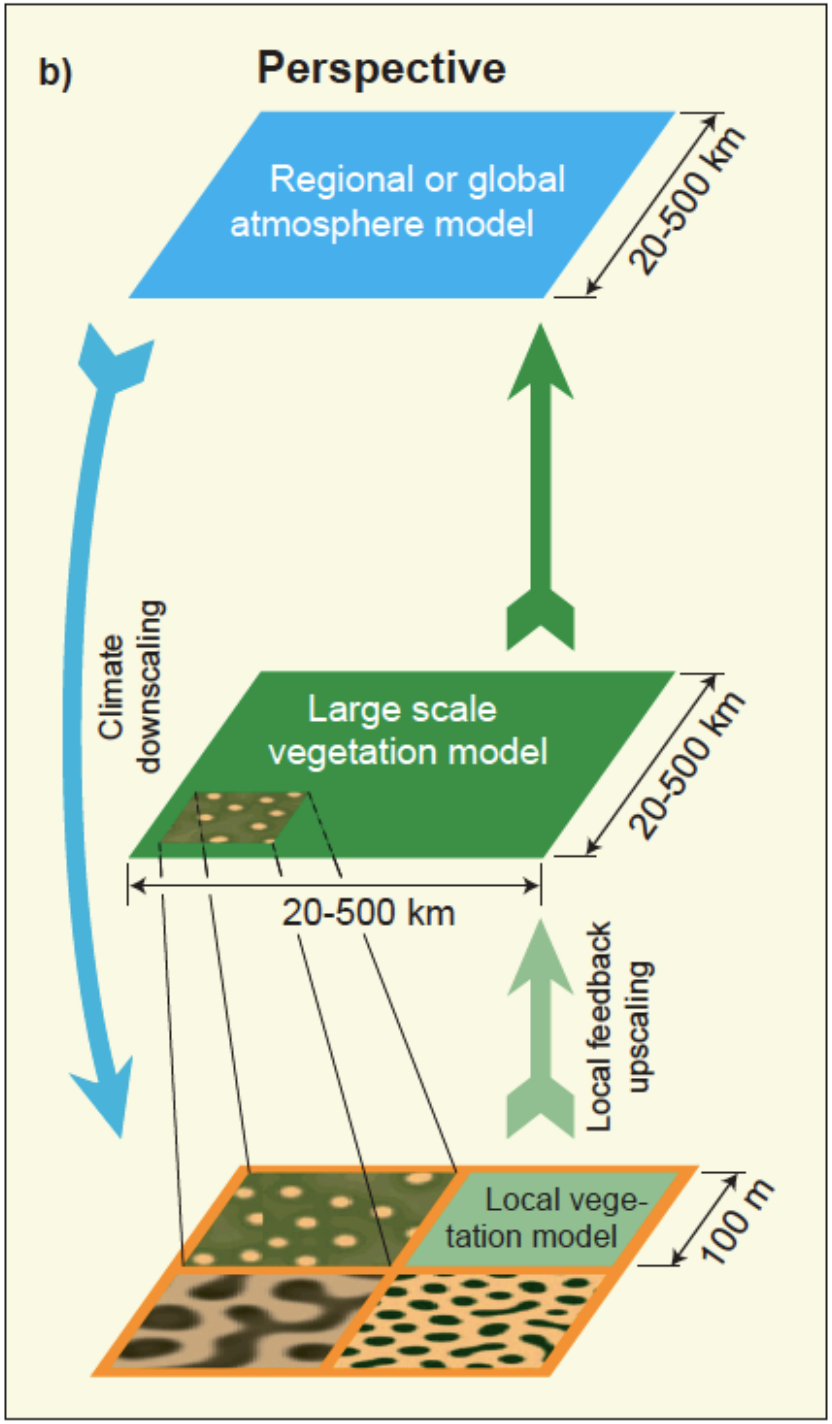


Vegetation patterns in arid and semi-arid regions

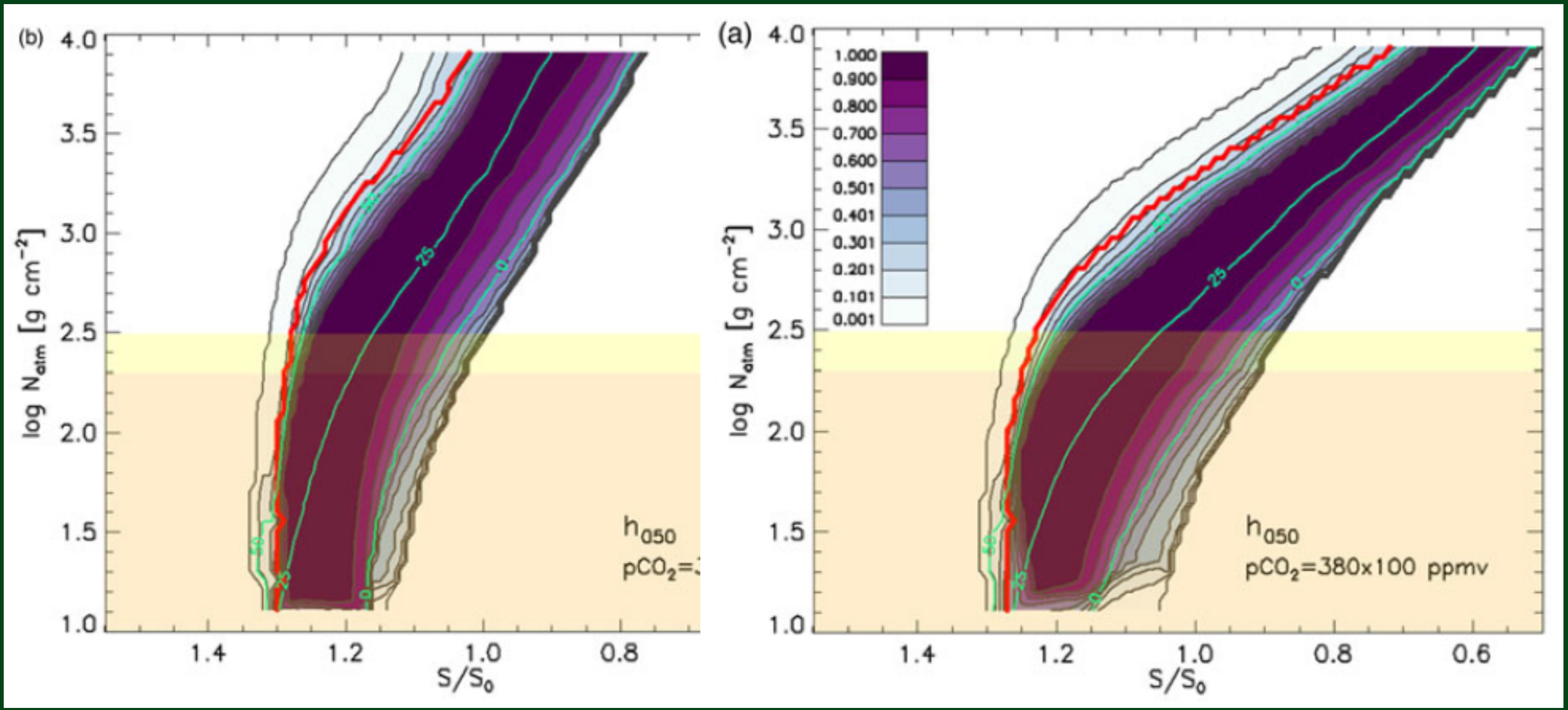
Gilad et al PRL 2004, JTB 2007, Kletter et al JTB 2009, Baudena et al AWR 2013

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

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



Planetary habitability and complex life

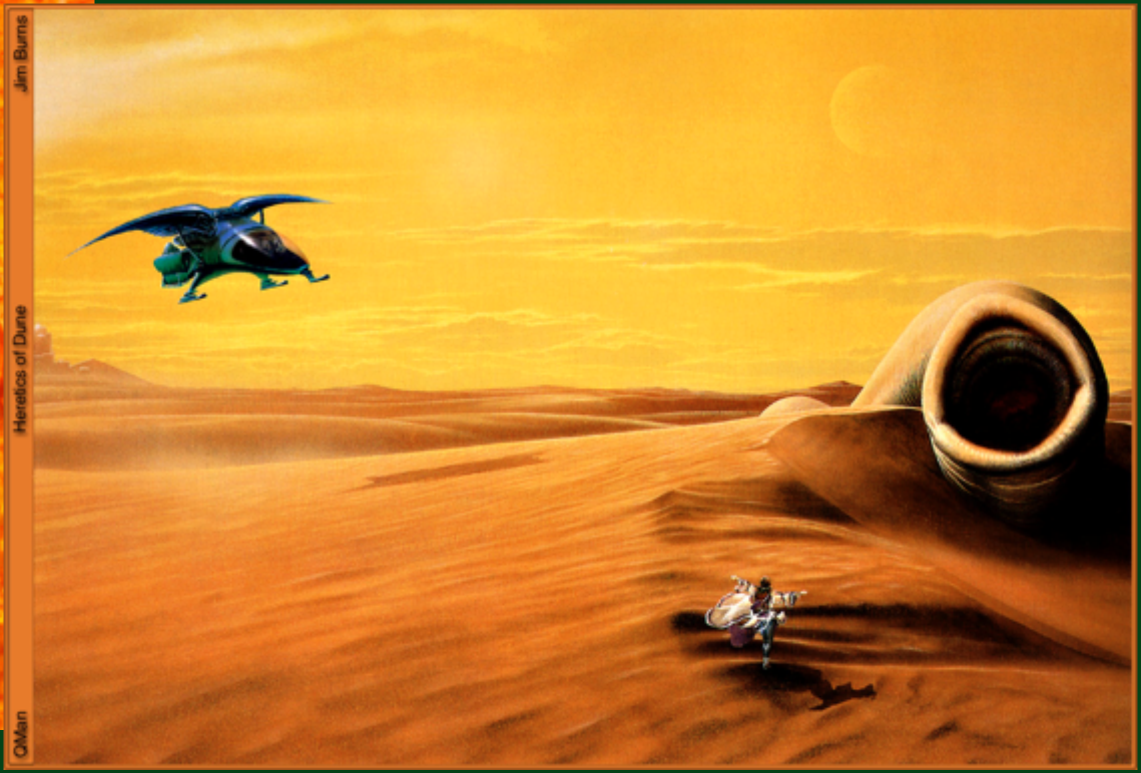


Vladilo et al., ApJ 2015, 2016; Silva et al., Int. J. Astrobiology 2016, MNRAS 2017

Imagine a sandy planet with no ocean; water is in the sand

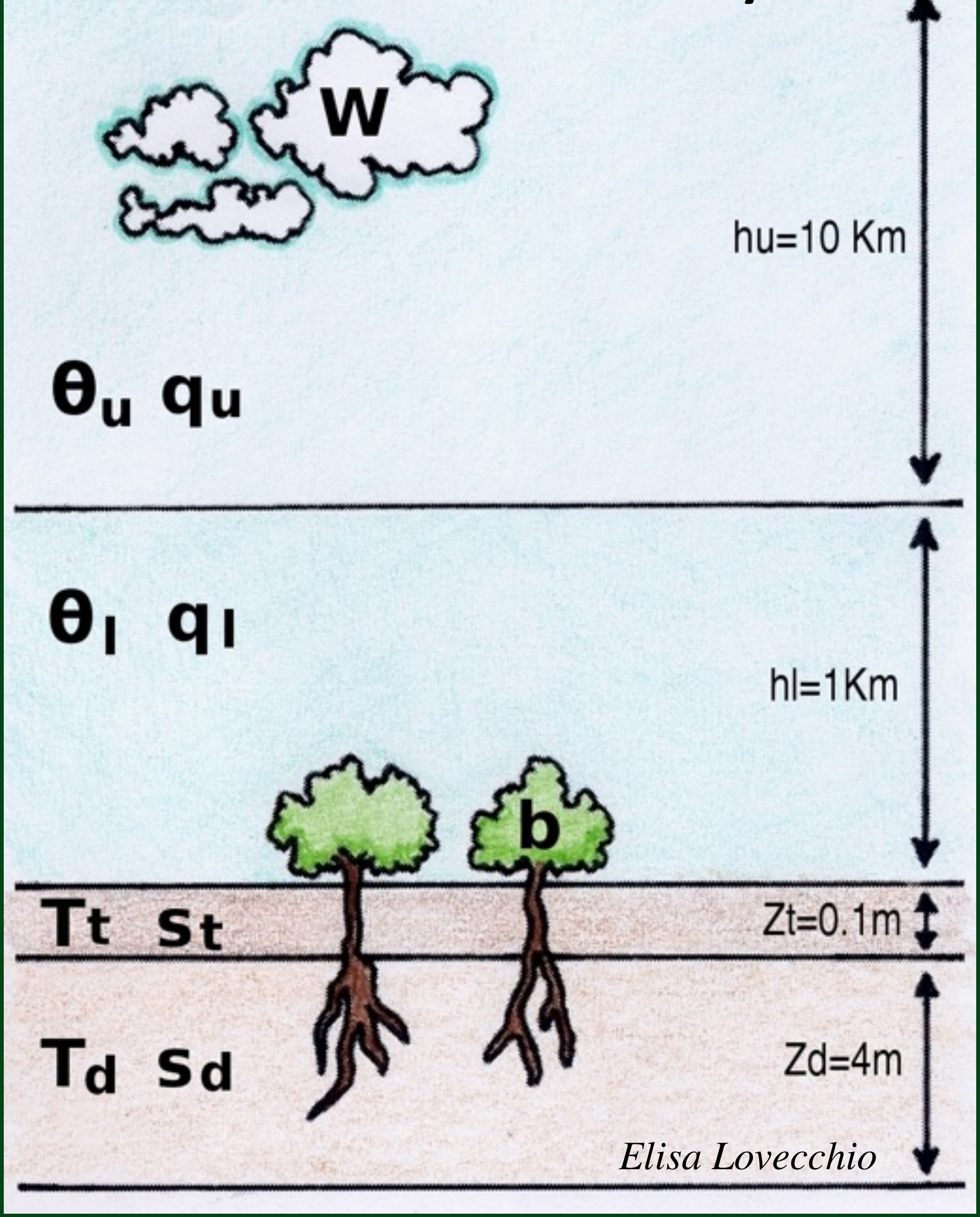
No vegetation → only evaporation

Could transpiration from vegetation generate a full hydrological cycle ?

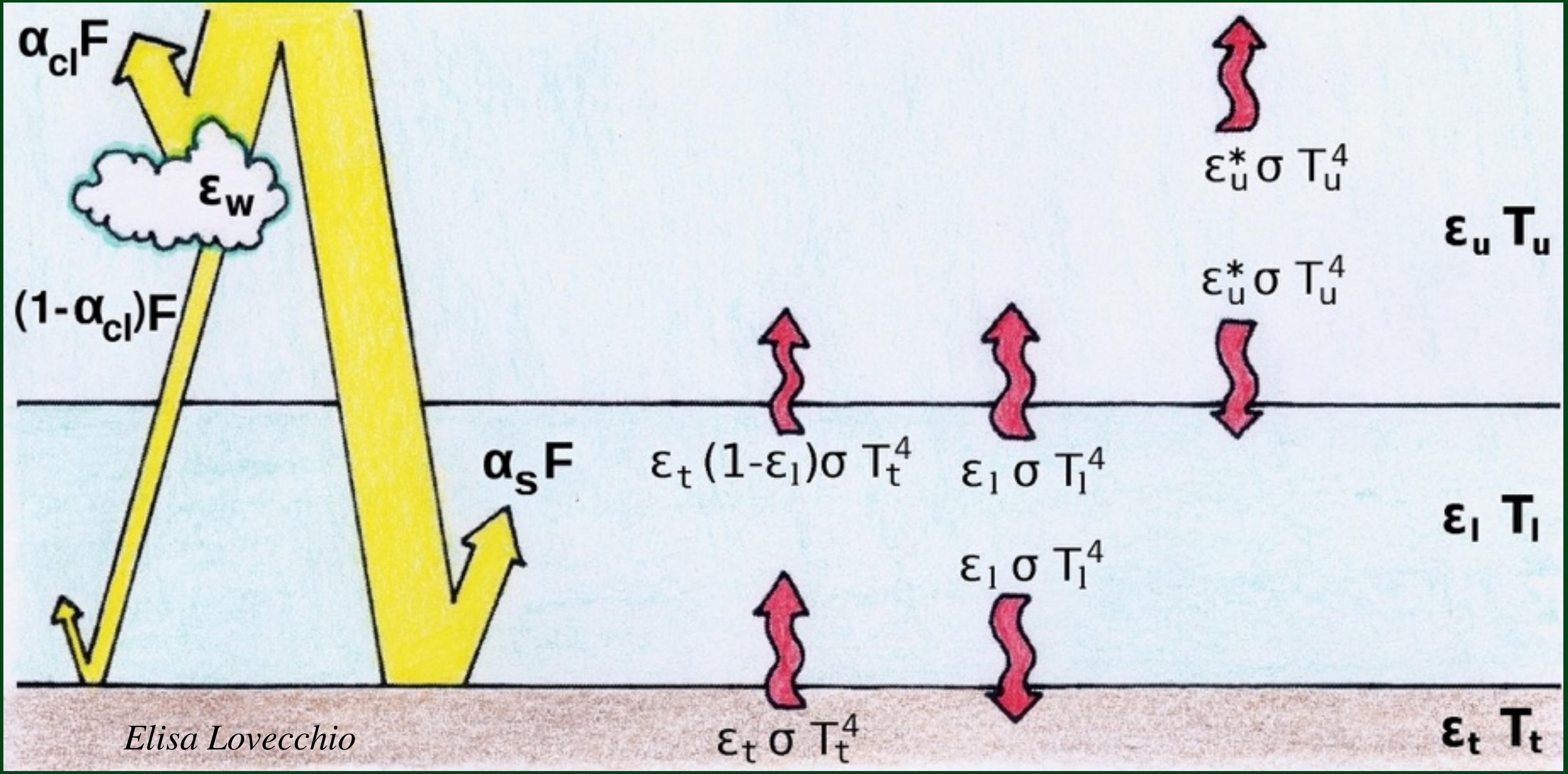


F. Cresto Aleina, M. Baudena, F. D'Andrea, AP, *Tellus B* 2013
Elisa Lovecchio, *Laurea Thesis*, 2013, Sara Lenzi, *Laurea Thesis*, 2016

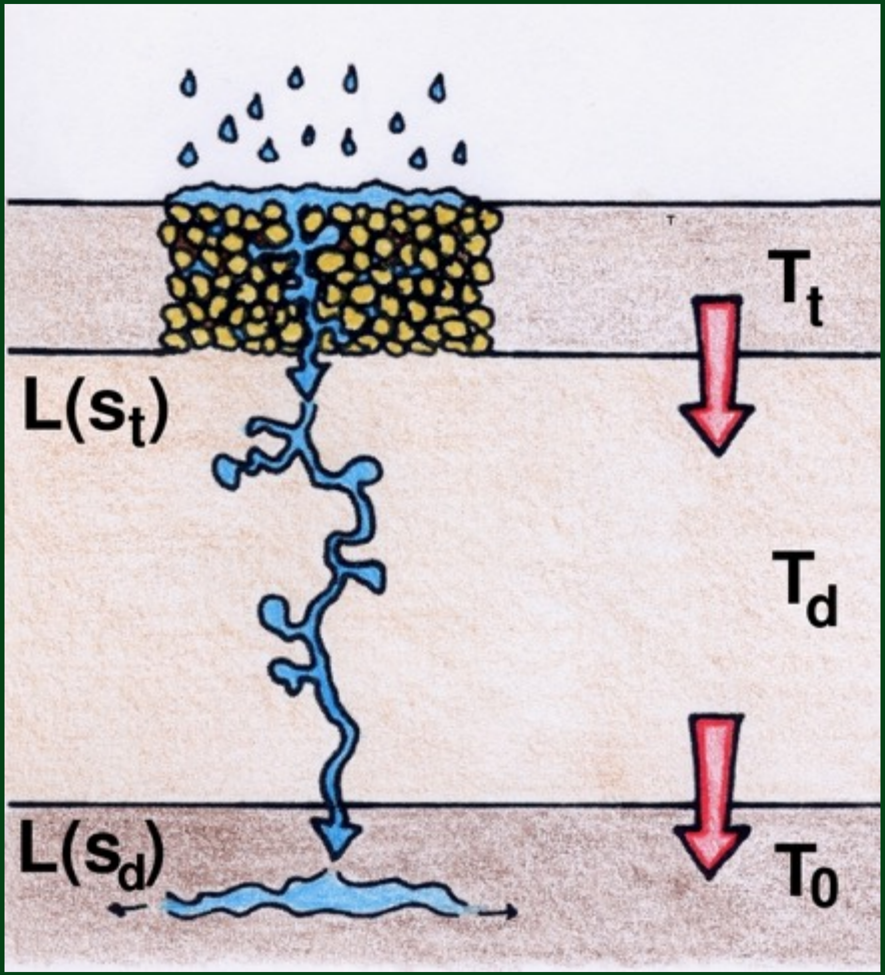
A box model with four layers

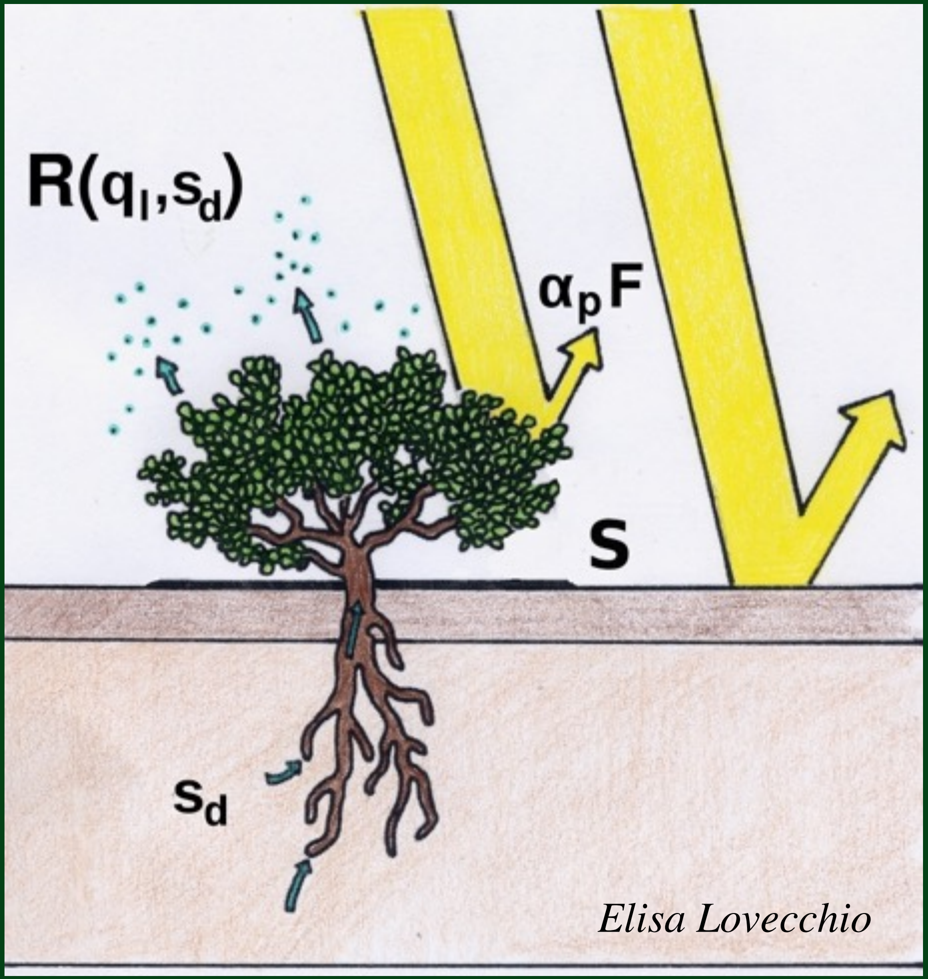


Radiation processes

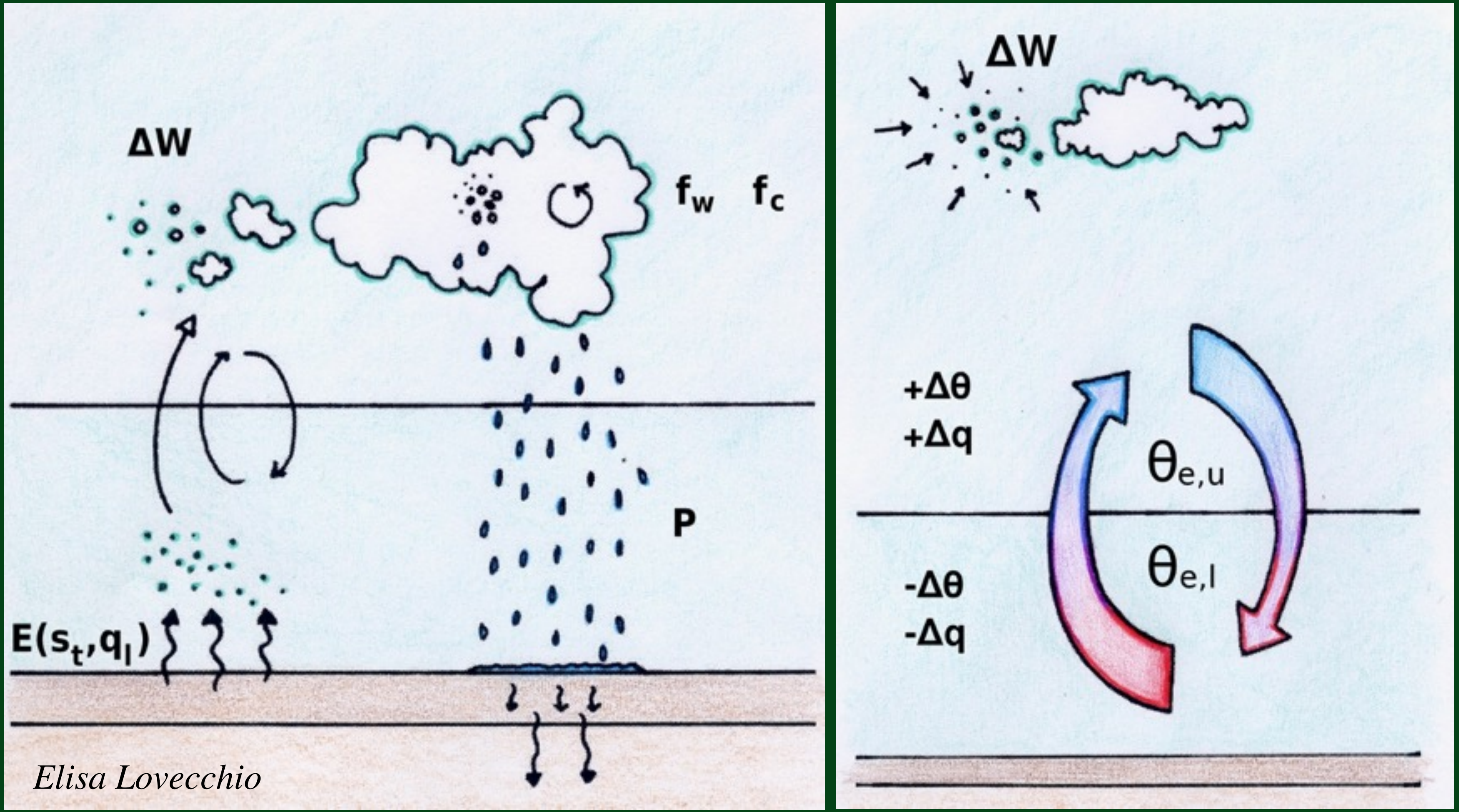


Soil processes and vegetation



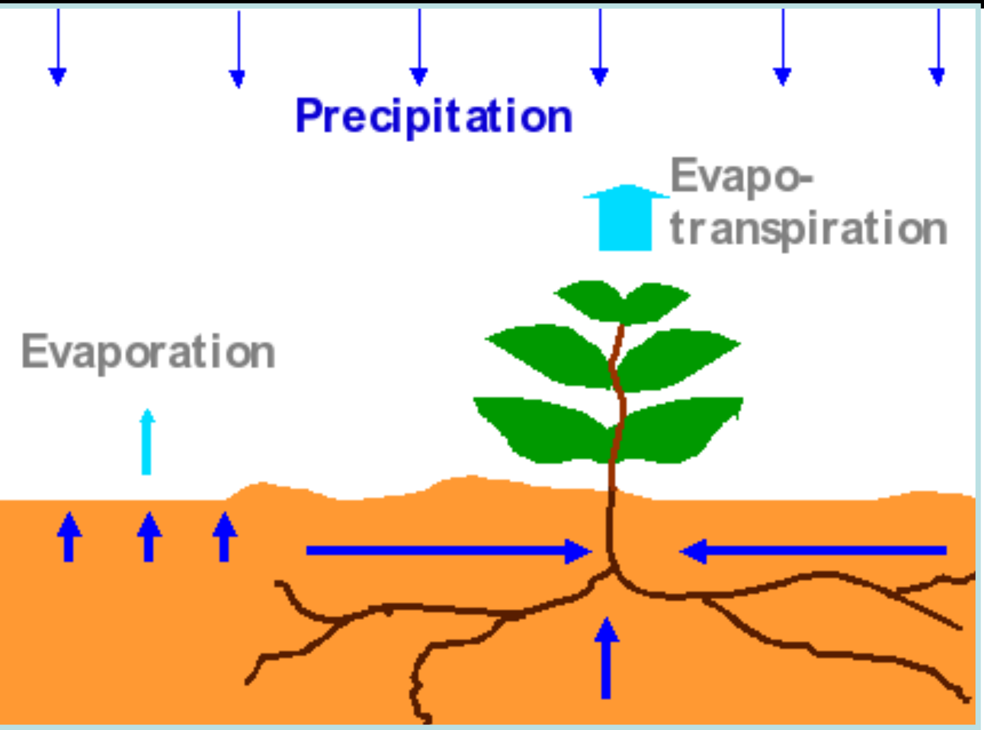


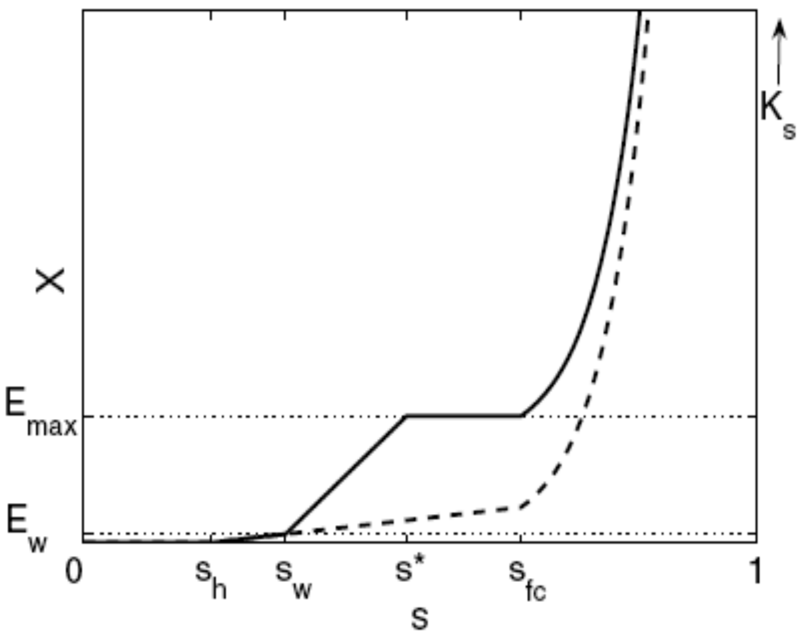
Moist atmospheric processes and convection



Evapotranspiration

$$X(s,b) = E + L = b\chi_b(q_s) + (1-b)\chi_0(q_s)$$





Vegetation response to rainfall intermittency in drylands: Results from a simple ecohydrological box model

M. Baudena [a,*], G. Boni [a], L. Ferraris [a], J. von Hardenberg [b], A. Provenzale [b]

Laio, F., A. Porporato, L. Ridolfi, and I. Rodriguez-Iturbe (2001), Plants in water controlled ecosystem: Active role in hydrologic processes and respose to water stress II. Probabilistic soil moisture dynamic, *Adv. Water Resour.*, *24*, 707–723.

Rodriguez-Iturbe, I., and A. Porporato (2004), *Echohydrology of Water Controlled Ecosystems*, Cambridge Univ. Press, New York.

Albedo

$$\alpha = b\alpha_b + (1-b)\alpha_0$$

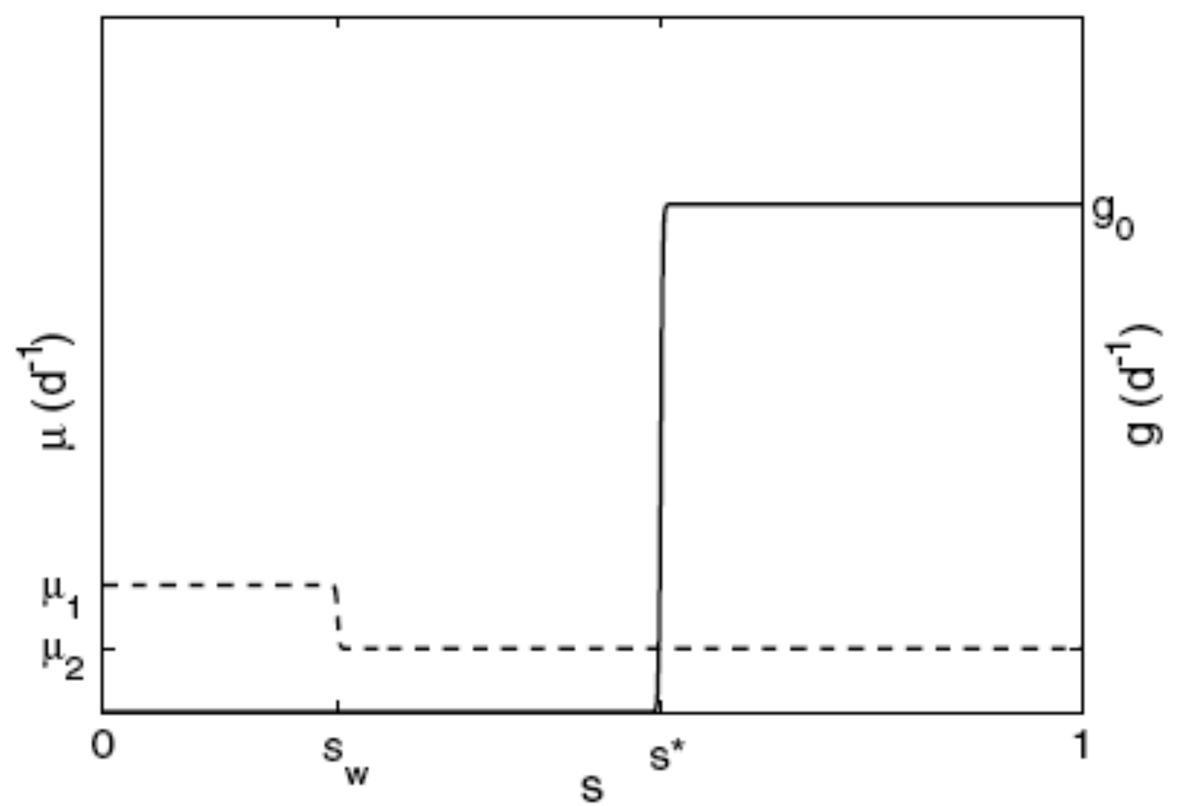
$$\alpha_0 = 0.35$$
$$\alpha_b = 0.14$$

As in Charney [1975]

Vegetation dynamics

Levins, *Bull. Entomol. Soc. Am*. 1969; Tilman, *Ecology* 1994

$$\frac{db}{dt} = gb(1-b) - \mu b.$$



Baudena, AP, HESS 2008

Convection parameterization:

If $\theta_e = \theta_a \exp \frac{L_e q_a}{c_p \theta_a} > \theta_e^*$ convection occurs

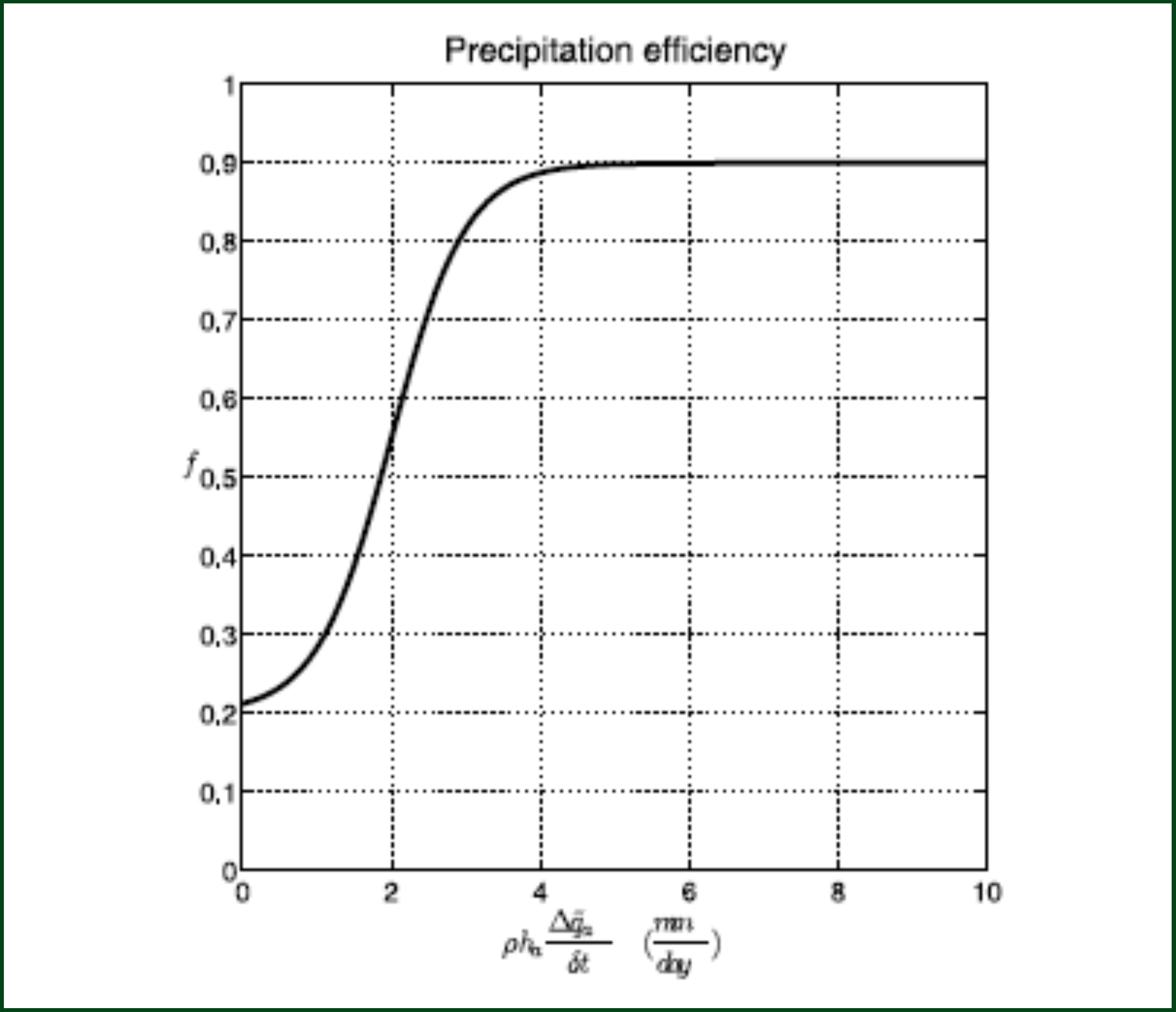
We assume that convection is instantaneous

$$(\theta_L - \widetilde{\Delta\theta}) e^{\frac{L_e (q_L - \widetilde{\Delta q})}{c_p (\theta_L - \widetilde{\Delta\theta})}} = (\theta_U + \widetilde{\Delta\theta}) e^{\frac{L_e \left(q_U + \widetilde{\Delta q} \frac{\rho_L h_L}{\rho_U h_U} \right)}{c_p (\theta_U + \widetilde{\Delta\theta})}}.$$

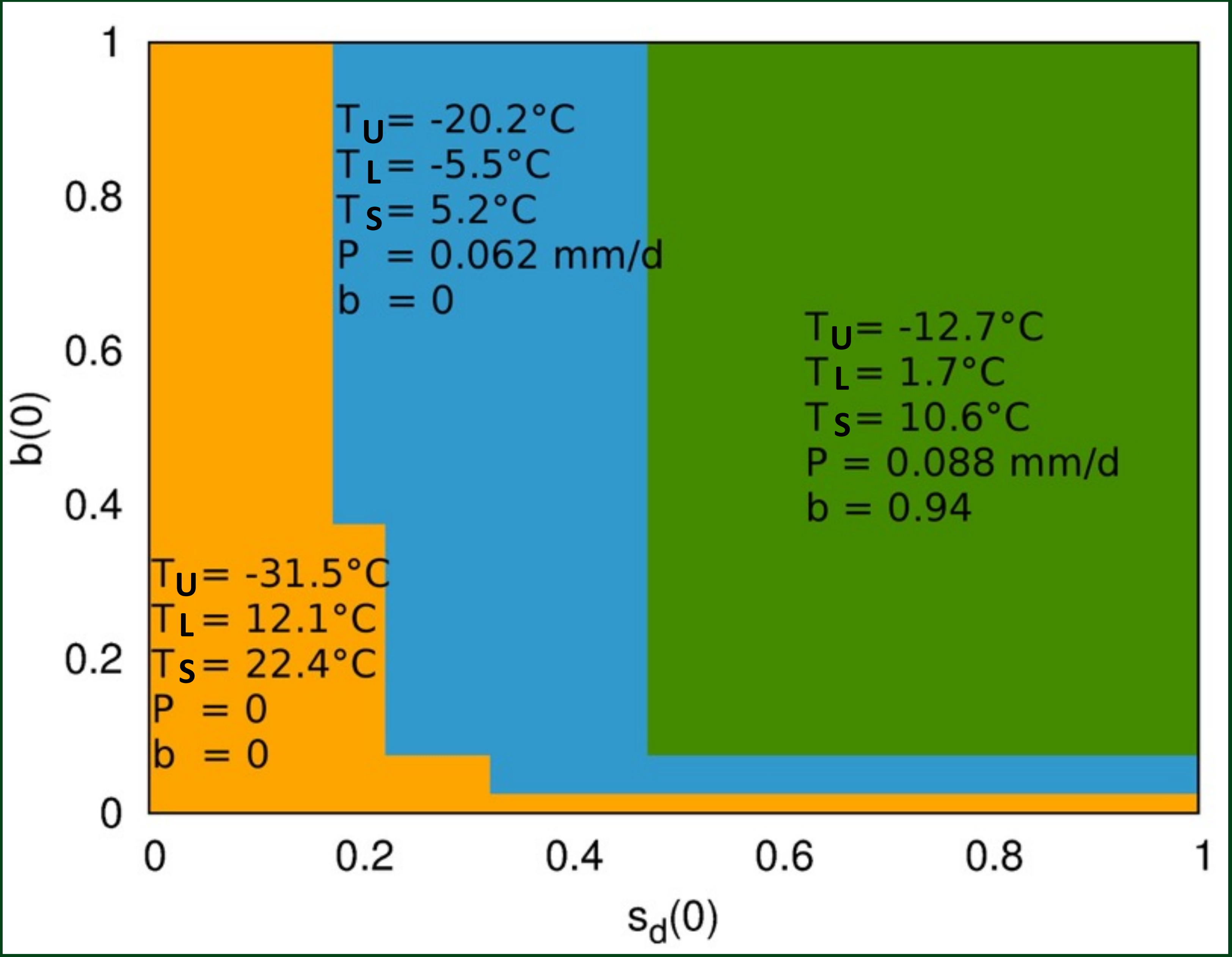
$$\beta = \frac{c_p \widetilde{\Delta\theta}}{L_e \widetilde{\Delta q}}.$$

or: constant relative humidity in the PBL

Precipitation: the fraction of liquid water which does not stay suspended



Multiple equilibria on Planet Dune



Hints from this simple model world

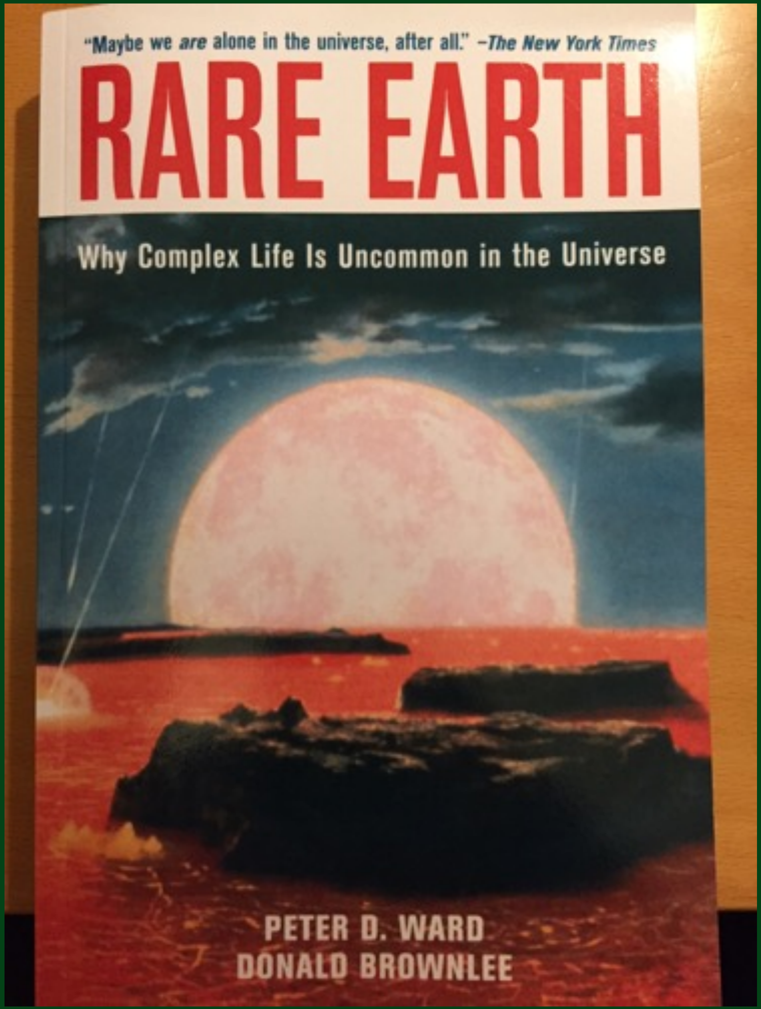
Transpiration from terrestrial vegetation
is able to sustain a hydrologic cycle
(and vegetation itself)

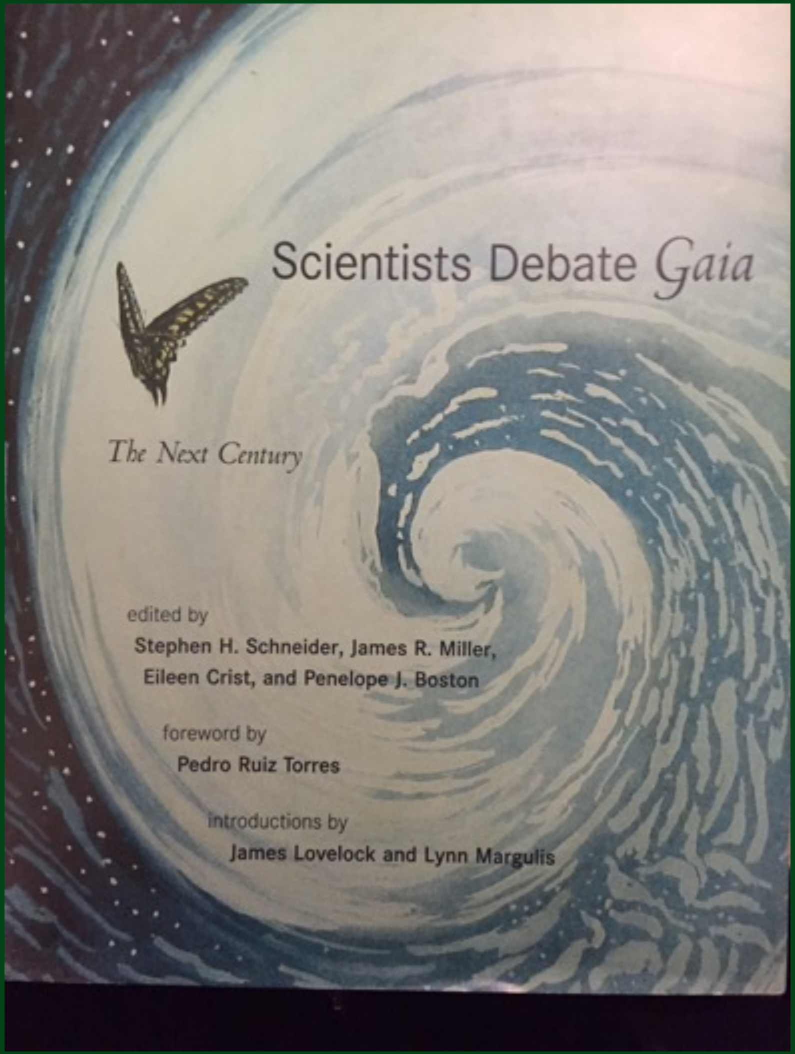
For the same external forcing,
the system exhibits multiple steady states

Transpiration feedback is more important
than albedo feedback

Importance of the convection parameterization

"Rare Earth" versus widespread life (and what life?)

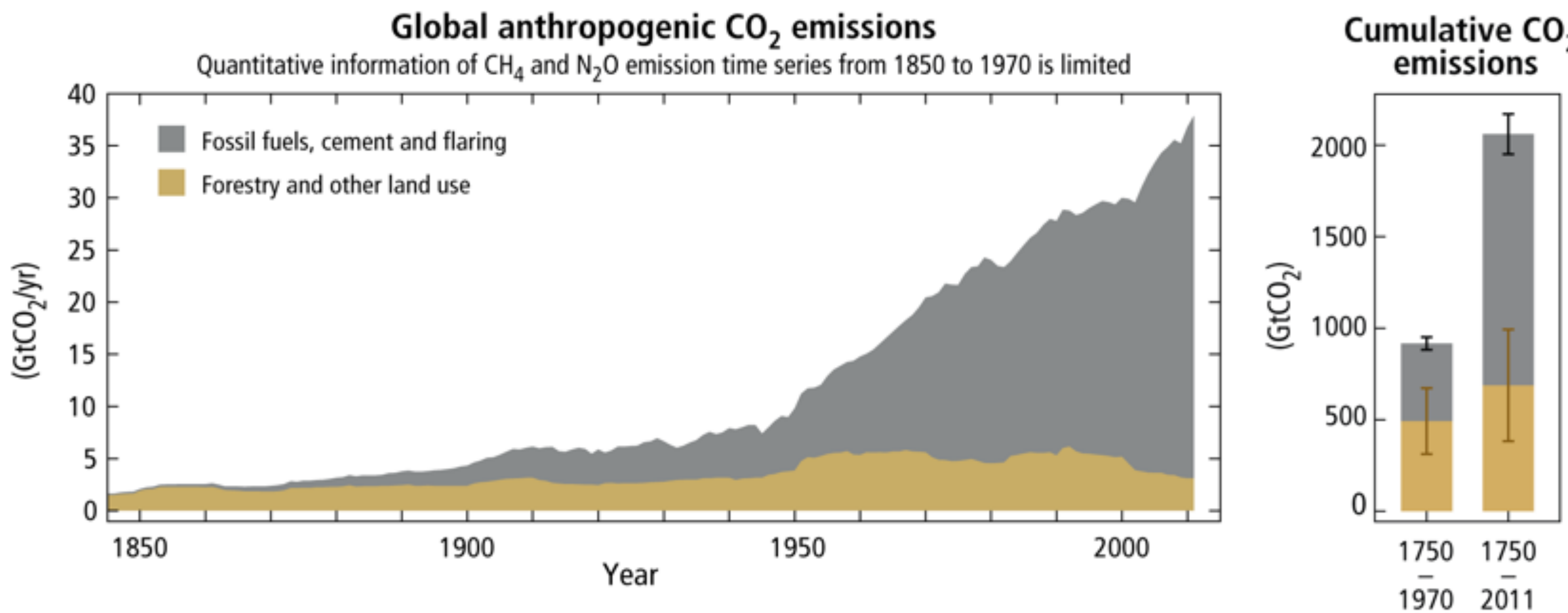





Back to our planet

The role of the Naked Ape

http://ar5-syr.ipcc.ch/
topic_observedchanges.php



ECOPOTENTIAL

This project is funded by the European Union

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Working in partnership with Protected Areas in Europe and beyond

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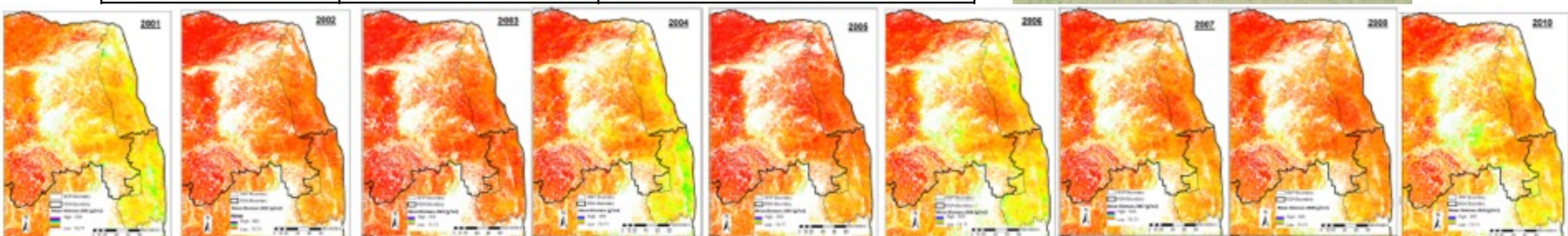
Spatial-temporal dynamics of savanna ecosystems in and around Kruger National Park (A. Ramoelo et al, CSIR)

SoE	Indicator	Method [reference] (type)*
Distribution of grazing and browsing resources in the semi-arid environments	amount of grass per unit area (biomass)	empirical techniques [Ramoelo et al. 2015] (M)
	percentage of nutrients in dry matter (leaf N (%))	empirical techniques [Ramoelo et al. 2012; 2015] (M)
	percentage of tree cover per unit area (%)	field, LiDAR and SAR empirical techniques [Mathieu et al. 2013, Naidoo et al. 2014, Urbazaev et al. 2015] (M)
	above ground woody biomass per unit area (ha) & woody volume as biomass proxy	field, LiDAR and SAR empirical techniques [Mathieu et al. 2013, Naidoo et al. 2014] (M)



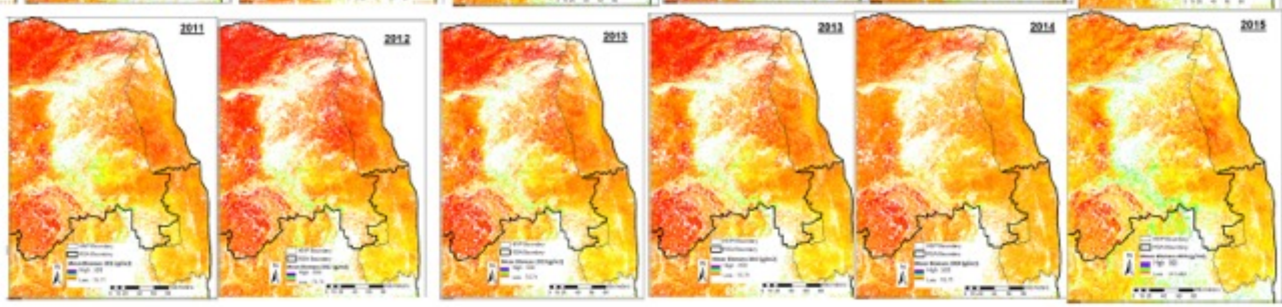


Figure 2: Time series of mean annual biomass data based on 500m spatial resolution MODIS data (2001 – 2015).

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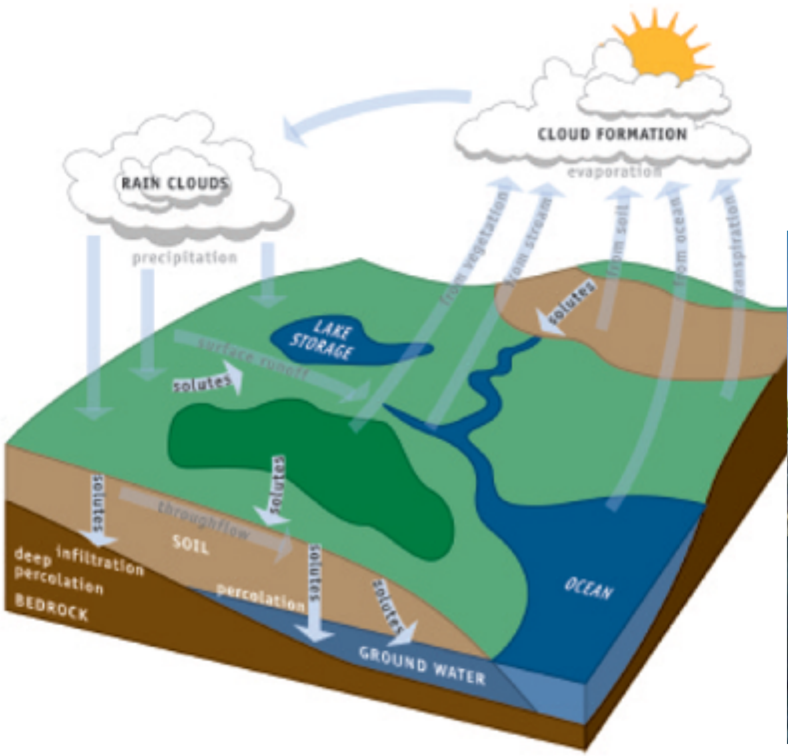
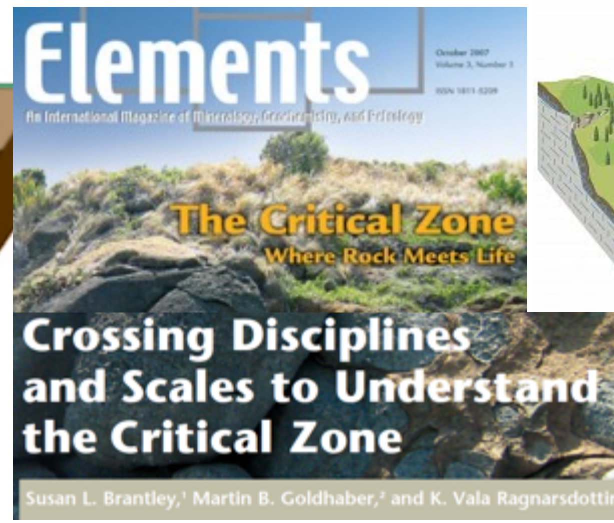
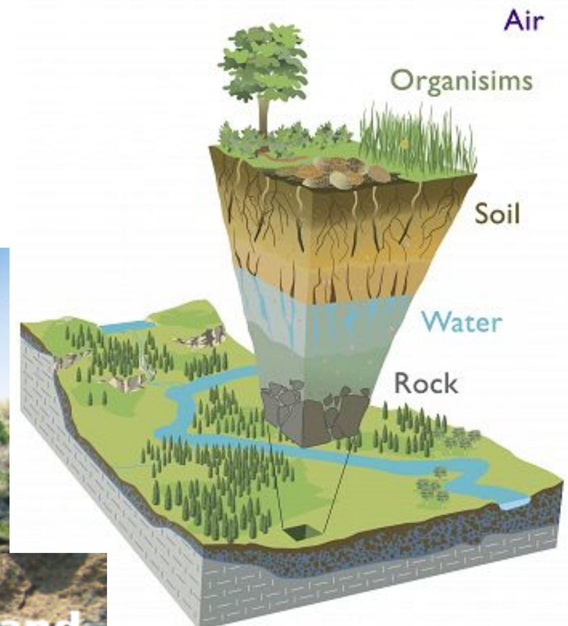
A focus on geosphere-biosphere interactions: The Earth Critical Zone



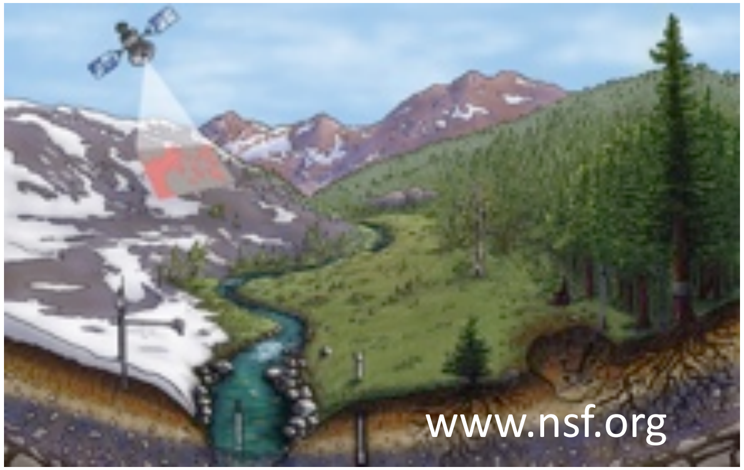




www.czen.org , http://criticalzone.org/national/

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

Conclusions

A geoscientist's goal:
understand the dynamics of the fascinatingly complex system called Planet Earth

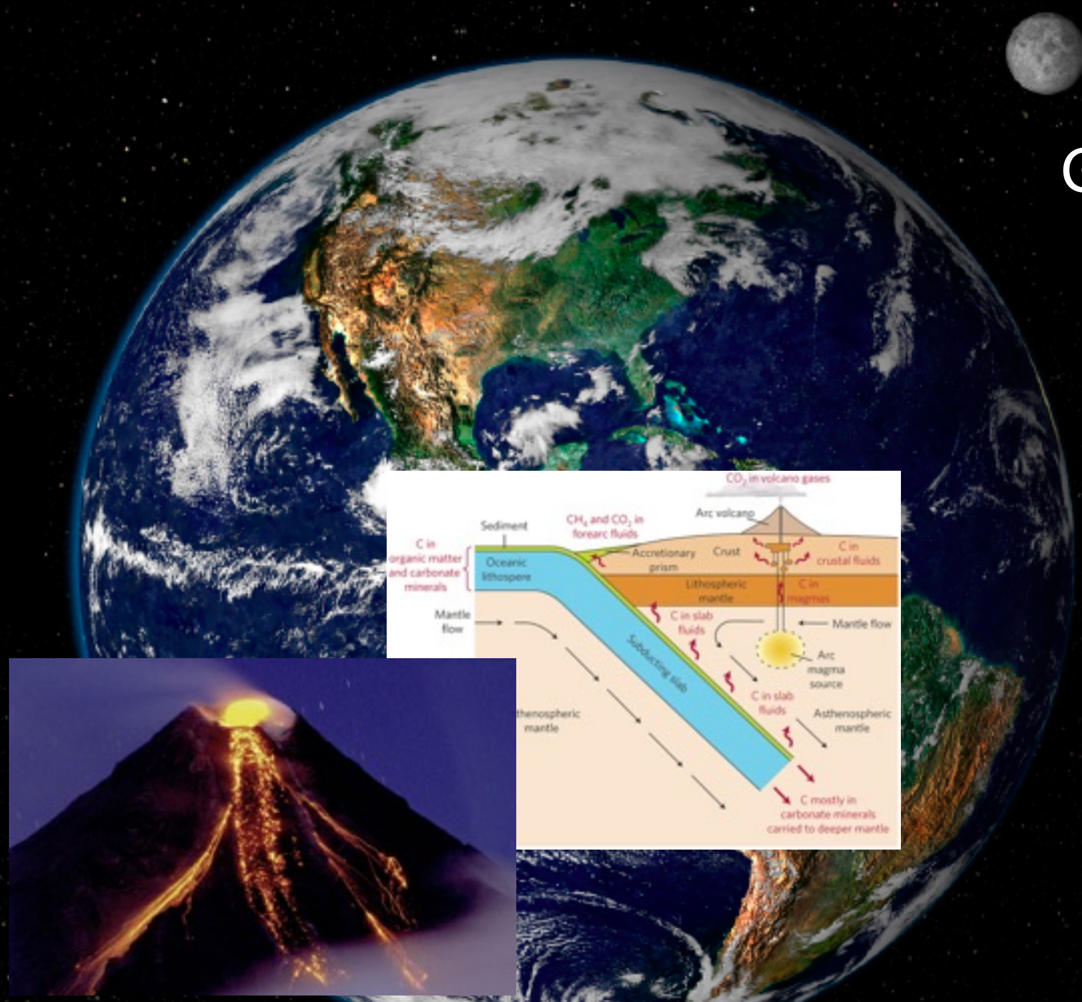
Unravel geosphere-biosphere interactions and how the biosphere makes our planet special (and perhaps others as well)


Thank you for your attention!

Today, planet Earth is an open nonlinear system

Solar forcing

Gravitational friction



Infrared emission

Radioactive decay
+ condensation in the core