Geosphere-biosphere interactions and ecosystem modelling

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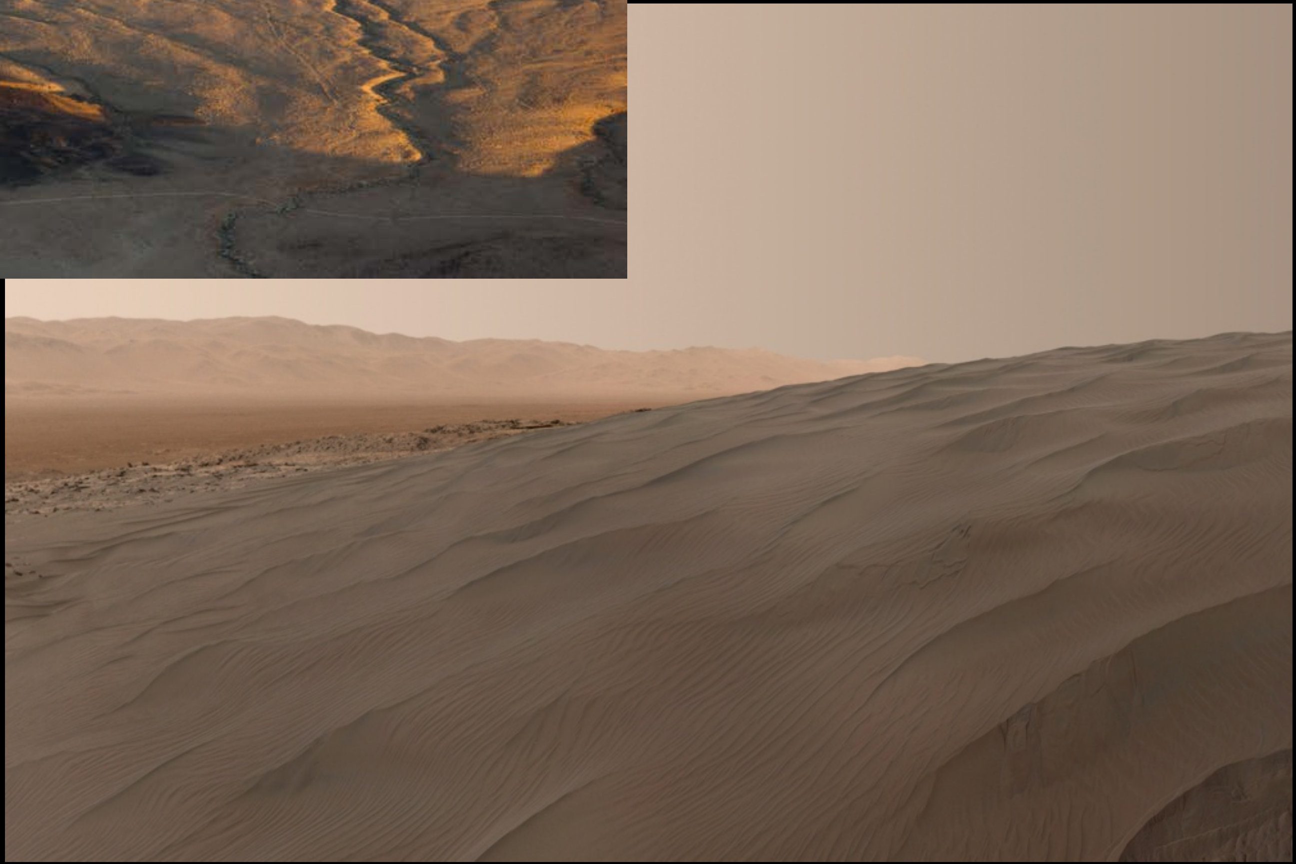
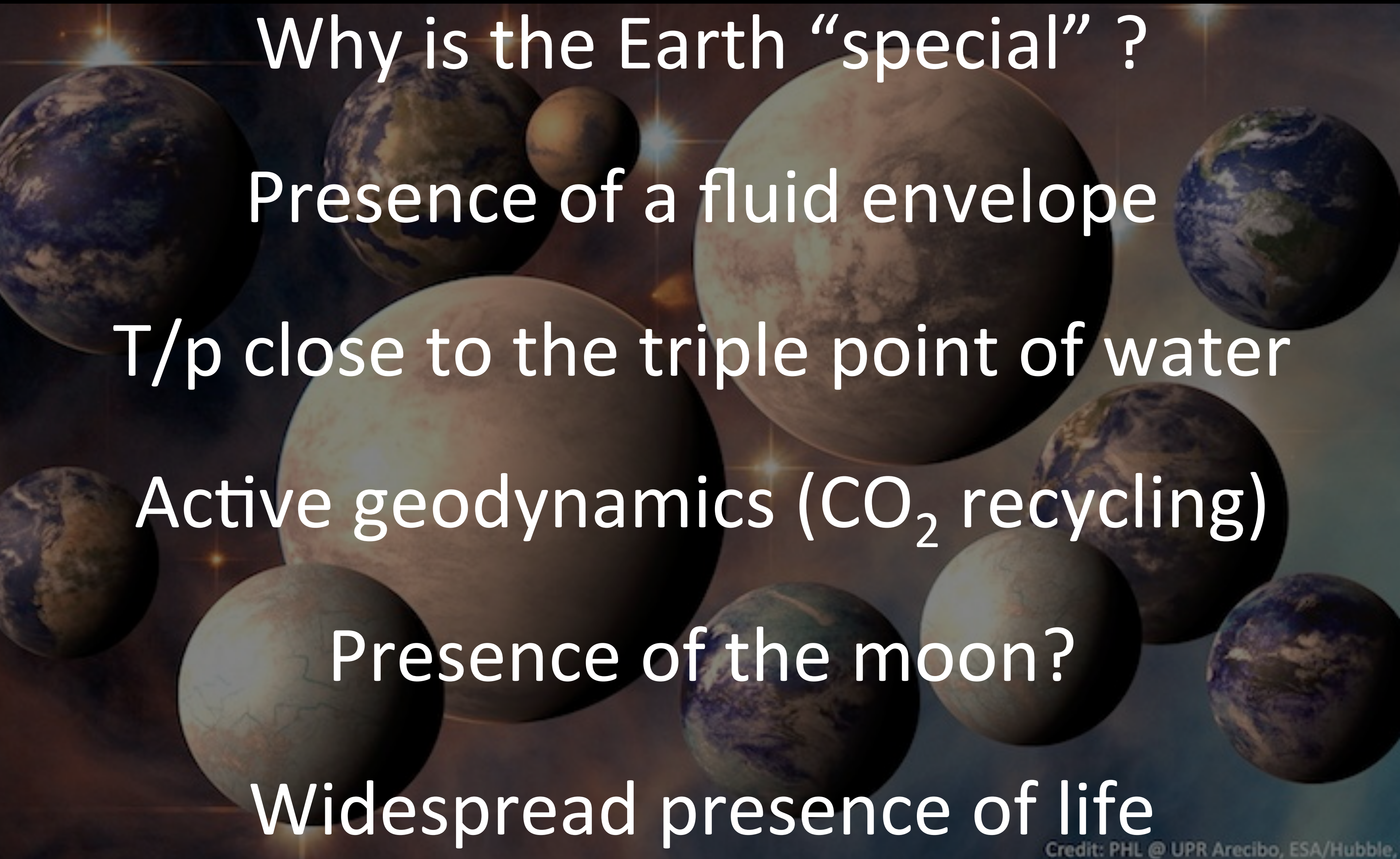
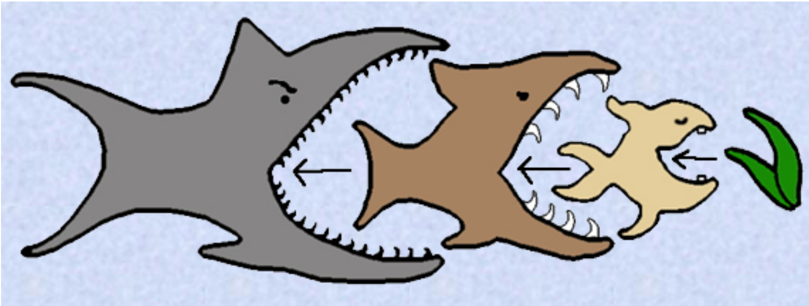
What makes Planet Earth so special?

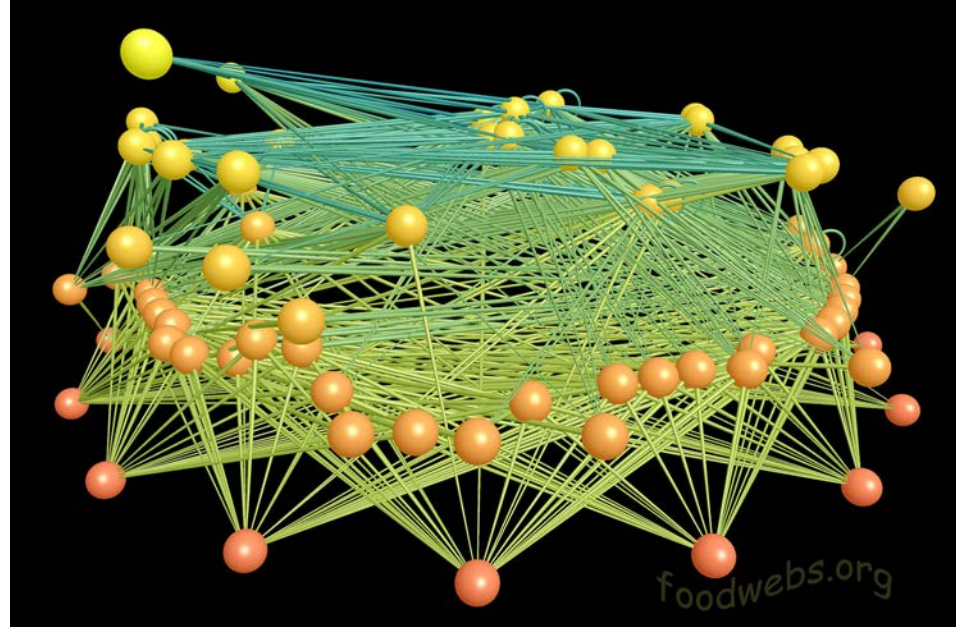



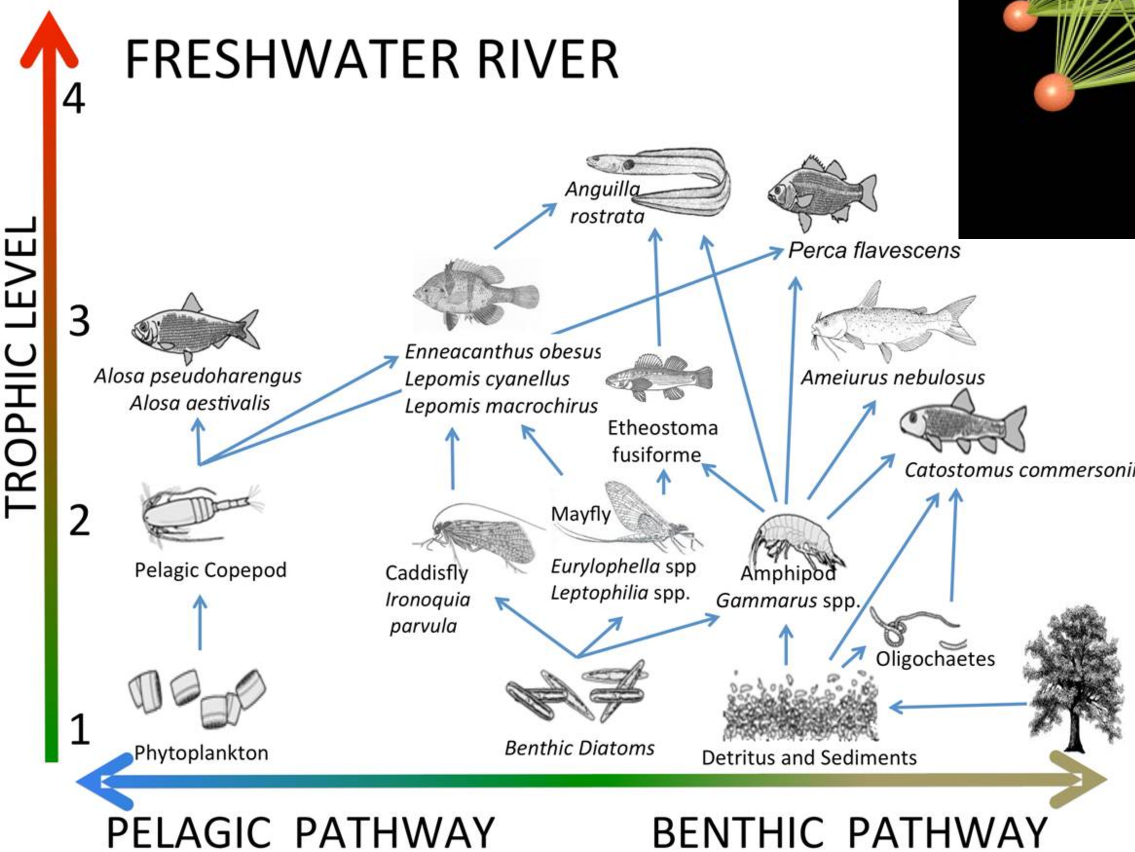

Why is the Earth “special” ?
Presence of a fluid envelope
T/p close to the triple point of water
Active geodynamics (CO_2 recycling)
Presence of the moon?
Widespread presence of life
Credit: PHL @ UPR Arecibo, ESA/Hubble,

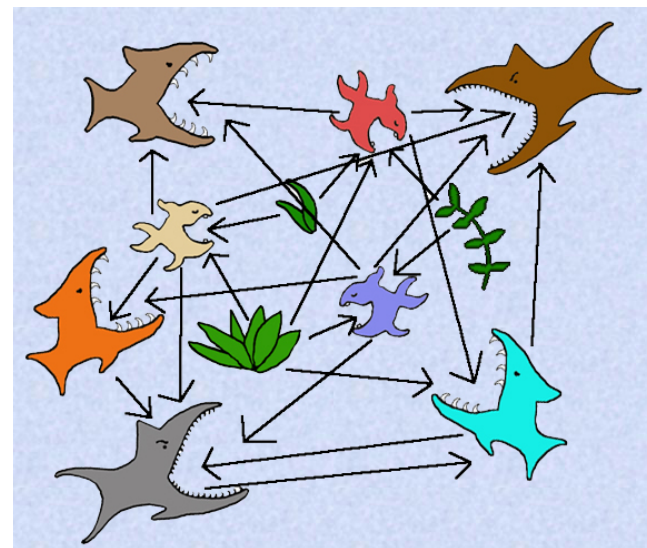

The living planet:
role of life in shaping Earth’s climate


What is an ecosystem?









Biotic components: the trophic web

Biodiversity is at the core of the biotic components of ecosystems

How to write an ecological model

How to write an ecological model

Choice of the relevant dynamical variables:
Biomass, individuals, species, size class, functional groups, …
And: whole population, age or stage structure

Type of temporal dynamics:
discrete versus continuous time

Homogeneous vs spatially extended

Estimate of model parameters

Single "species"

Malthusian growth

(infinite resources)

$$\frac{1}{N}\frac{dN}{dt} = b - m = r$$

$$N(t) = N(0)\exp\left(r\,t\right)$$

Single "species": logistic equation

Finite resources

$$\frac{1}{N}\frac{dN}{dt} = b(N) - m(N) = r(N)$$

$$\text{example}: \quad r(N) = r_0\left(1 - \frac{N}{K}\right)$$

logistic equations

$$\frac{dN}{dt} = r_0\left(1 - \frac{N}{K}\right)N$$

Single "species": logistic equation

Non dimensional version

$$n = N/K \quad , \quad \tau = r_0\, t$$

$$\frac{dn}{d\tau} = (1-n)\,n$$

fixed points and linear stability analysis

$$n_0 = 0 \quad , \quad n_1 = 1$$

exact solution:

$$n(t) = \frac{n(0)\exp t}{1 + n(0)(\exp t - 1)}$$

Two species: resource-consumer (predator-prey)

$$\frac{dN}{dt} = r(N)N - h(N)P$$

$$\frac{dP}{dt} = -dP + g\,h(N)P$$

Lotka – Volterra

$$\frac{dN}{dt} = r_0 N - \alpha N P$$

$$\frac{dP}{dt} = -dP + g\alpha N P$$

Lotka (1932)

Vito Volterra, in full academic regalia. From The Biology of Numbers: The Correspondence of Vito Volterra on Mathematical Biology.

Volterra (1926)

Two species: resource-consumer (predator-prey)

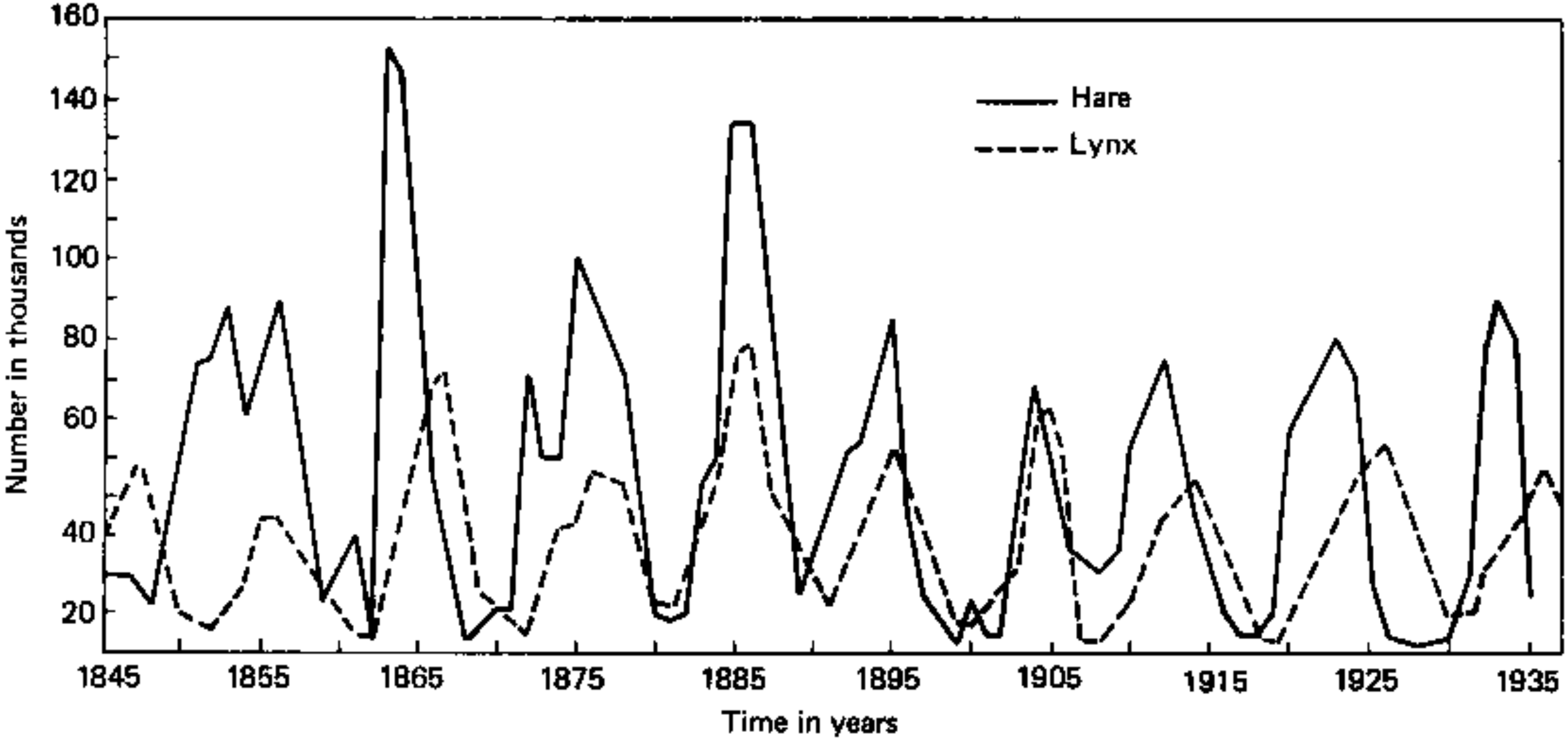


Figure 9-3. Changes in the abundance of the lynx and the snowshoe hare, as indicated by the number of pelts received by the Hudson's Bay Company. This is a classic case of cyclic oscillation in population density. (Redrawn from MacLulich 1937.)

Two species: resource-consumer (predator-prey)

$$r(N) = r_0\left(1 - \frac{N}{K}\right)$$

$$\frac{dN}{dt} = r_0\left(1 - \frac{N}{K}\right)N - \alpha N P$$

$$\frac{dP}{dt} = -dP + g\alpha N P$$

Functional form for predation/consumer
Michaelis-Menten, or Monod, or Holling type II form

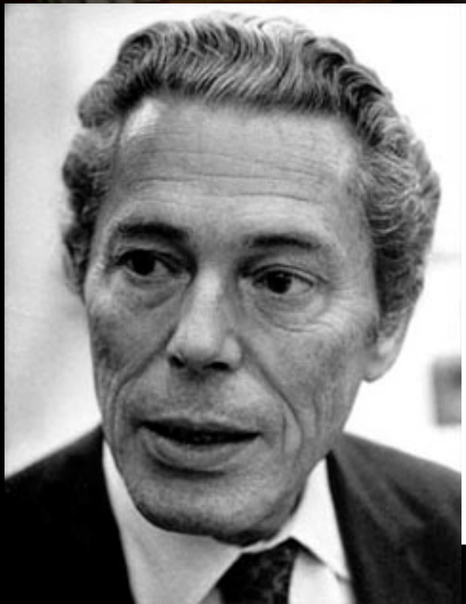
$$r(N) = r_0\left(1 - \frac{N}{K}\right)$$

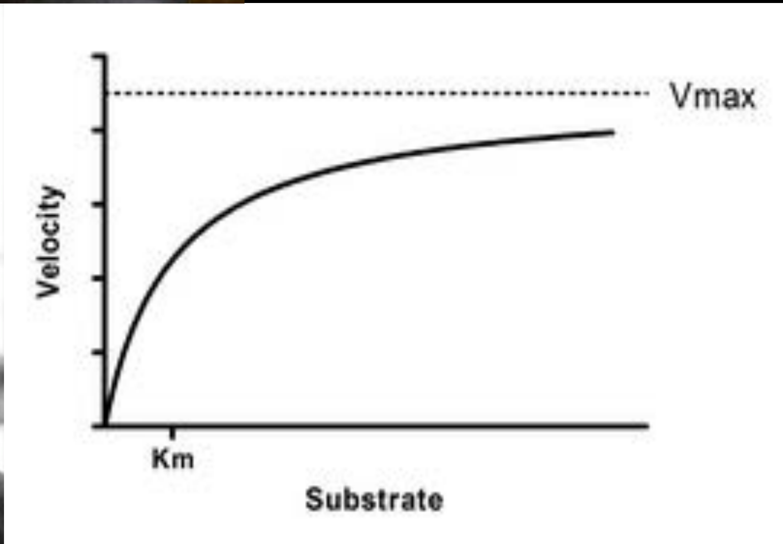
$$\frac{dN}{dt} = r_0\left(1 - \frac{N}{K}\right)N - h(N)P$$

$$\frac{dP}{dt} = -dP + g\,h(N)P$$

Functional form for predation/consumer
Michaelis-Menten, or Monod, or Holling type II form

$$h(N) = \frac{cN}{a+N}$$





The role of the handling time

T total time

T_h handling time for each prey item

N number of potential prey

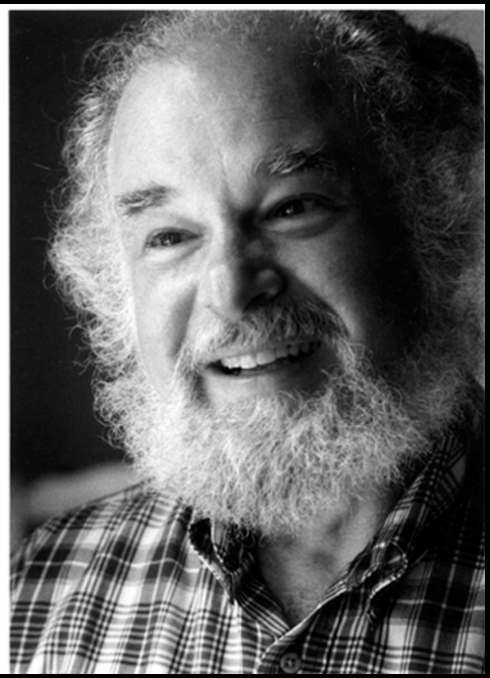
V number of prey caught (victims) per unit time

$$V = \gamma \left(1 - \frac{V}{V_0} \frac{T_h}{T} \right) N$$

$$\mathrm{V} = \frac{\gamma N}{1 + \gamma \frac{T_h}{T} \frac{N}{V_0}} = \frac{c N}{a + N}$$

$$a = \frac{V_0 T}{\gamma T_h} \quad , \quad c = \frac{V_0 T}{T_h}$$

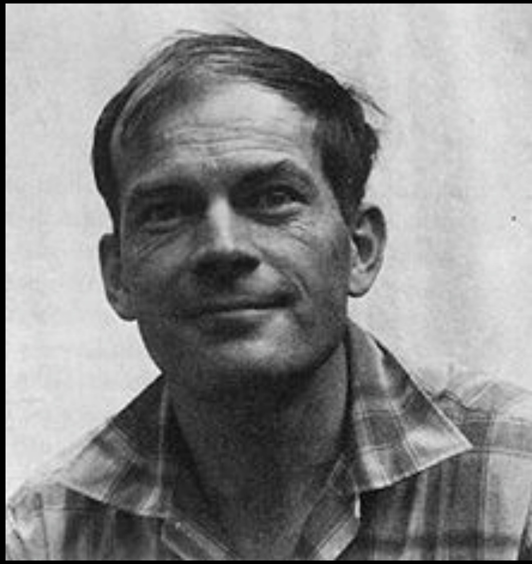
Two species: resource-consumer (predator-prey)
the Rosenzweig-McArthur model (1963)



$$r(N) = r_0\left(1 - \frac{N}{K}\right)$$

$$\frac{dN}{dt} = r_0 N\left(1 - \frac{N}{K}\right) - \frac{cNP}{a+N}$$

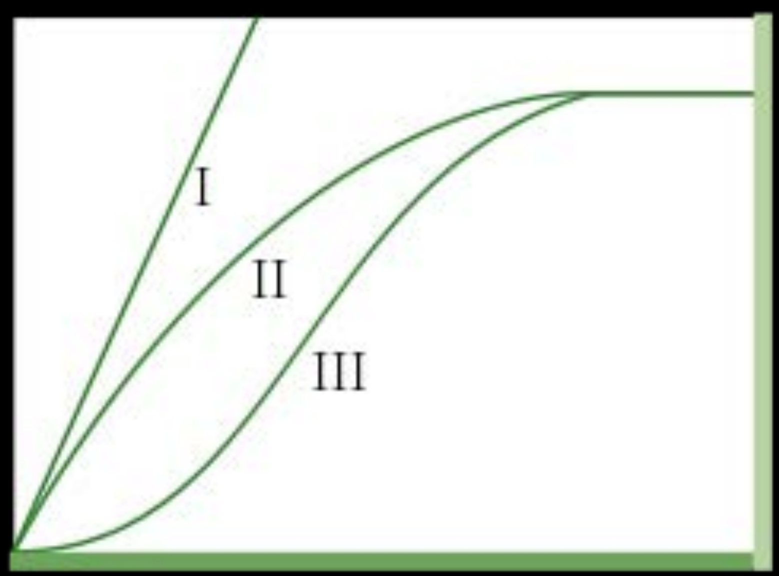
$$\frac{dP}{dt} = -dP + g\frac{cNP}{a+N}$$



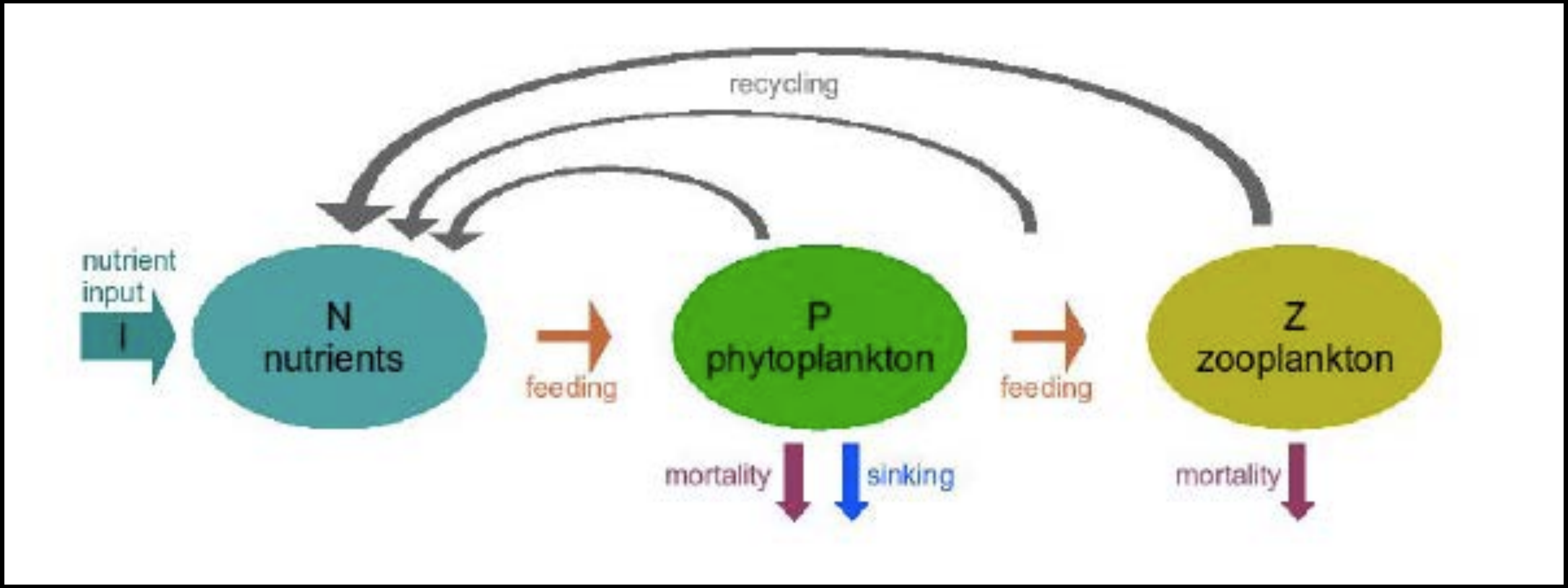
The paradox of enrichment (Rosenzweig 1971)

Functional form for predation/consumer
Holling type III form

$$f(N) = \frac{c N^2}{b^2 + N^2}$$



A trophic chain: Nutrient-Phytoplankton-Zooplankton (NPZ)



Chemostat models: source of nutrients

$$\frac{dN}{dt} = -\mu\left(N - N_0\right) - \frac{cNP}{a+N}$$

$$\frac{dP}{dt} = g\frac{cNP}{a+N} - dP$$

A trophic chain: Nutrient-Phytoplankton-Zooplankton (NPZ)

$$\frac{DN}{Dt} = -s\left(N - N_0\right) - \beta \frac{N}{k_N + N} P$$

$$+ \gamma \left\{ Q_P \left[(1 - g_P)\beta \frac{N}{k_N + N} P + \mu_P P \right] + Q_Z \left[(1 - g_Z) \frac{a\varepsilon P^2}{a + \varepsilon P^2} Z + \mu_Z Z \right] \right\}$$

$$\frac{DP}{Dt} = g_P \beta \frac{N}{k_N + N} P - \frac{a\varepsilon P^2}{a + \varepsilon P^2} Z - \mu_P P$$

$$\frac{DZ}{Dt} = g_Z \frac{a\varepsilon P^2}{a + \varepsilon P^2} Z - \mu_Z Z$$

The issue of quadratic mortality (Steele and Henderson 1992)

$$\frac{DN}{Dt} = -s\left(N - N_0\right) - \beta \frac{N}{k_N + N} P$$

$$+ \gamma \left\{ Q_P \left[(1 - g_P)\beta \frac{N}{k_N + N} P + \mu_P P \right] + Q_Z \left[(1 - g_Z) \frac{a\varepsilon P^2}{a + \varepsilon P^2} Z + \mu_Z Z^2 \right] \right\}$$

$$\frac{DP}{Dt} = g_P \beta \frac{N}{k_N + N} P - \frac{a\varepsilon P^2}{a + \varepsilon P^2} Z - \mu_P P$$

$$\frac{DZ}{Dt} = g_Z \frac{a\varepsilon P^2}{a + \varepsilon P^2} Z - \mu_Z Z^2$$

The role of detritus: NPZD

$$\frac{dN}{Dt} = -s\left(N - N_0\right) - \beta \frac{N}{k_N + N} P + \frac{D}{\tau_D}$$

$$\frac{dP}{dt} = g_P \beta \frac{N}{k_N + N} P - \frac{a\varepsilon P^2}{a + \varepsilon P^2} Z - \mu_P P$$

$$\frac{dZ}{dt} = g_Z \frac{a\varepsilon P^2}{a + \varepsilon P^2} Z - \mu_Z Z^2$$

$$\frac{dD}{dt} = Q_P \left[(1 - g_P)\beta \frac{N}{k_N + N} P + \mu_P P \right] + Q_Z \left[(1 - g_Z) \frac{a\varepsilon P^2}{a + \varepsilon P^2} Z + \mu_Z Z^2 \right] - \mu_D D - \frac{D}{\tau_D}$$

Fast and slow bacterial processes

$$\frac{dN}{Dt} = -s\left(N - N_0\right) - \beta\frac{N}{k_N + N}P + \frac{D}{\tau_D} + Q_P(1 - g_P)\beta\frac{N}{k_N + N}P + Q_Z(1 - g_Z)\frac{a\varepsilon P^2}{a + \varepsilon P^2}Z$$

$$\frac{dP}{dt} = g_P\beta\frac{N}{k_N + N}P - \frac{a\varepsilon P^2}{a + \varepsilon P^2}Z - \mu_P P$$

$$\frac{dZ}{dt} = g_Z\frac{a\varepsilon P^2}{a + \varepsilon P^2}Z - \mu_Z Z^2$$

$$\frac{dD}{dt} = Q_P\mu_P P + Q_Z\mu_Z Z^2 - \mu_D D - \frac{D}{\tau_D}$$

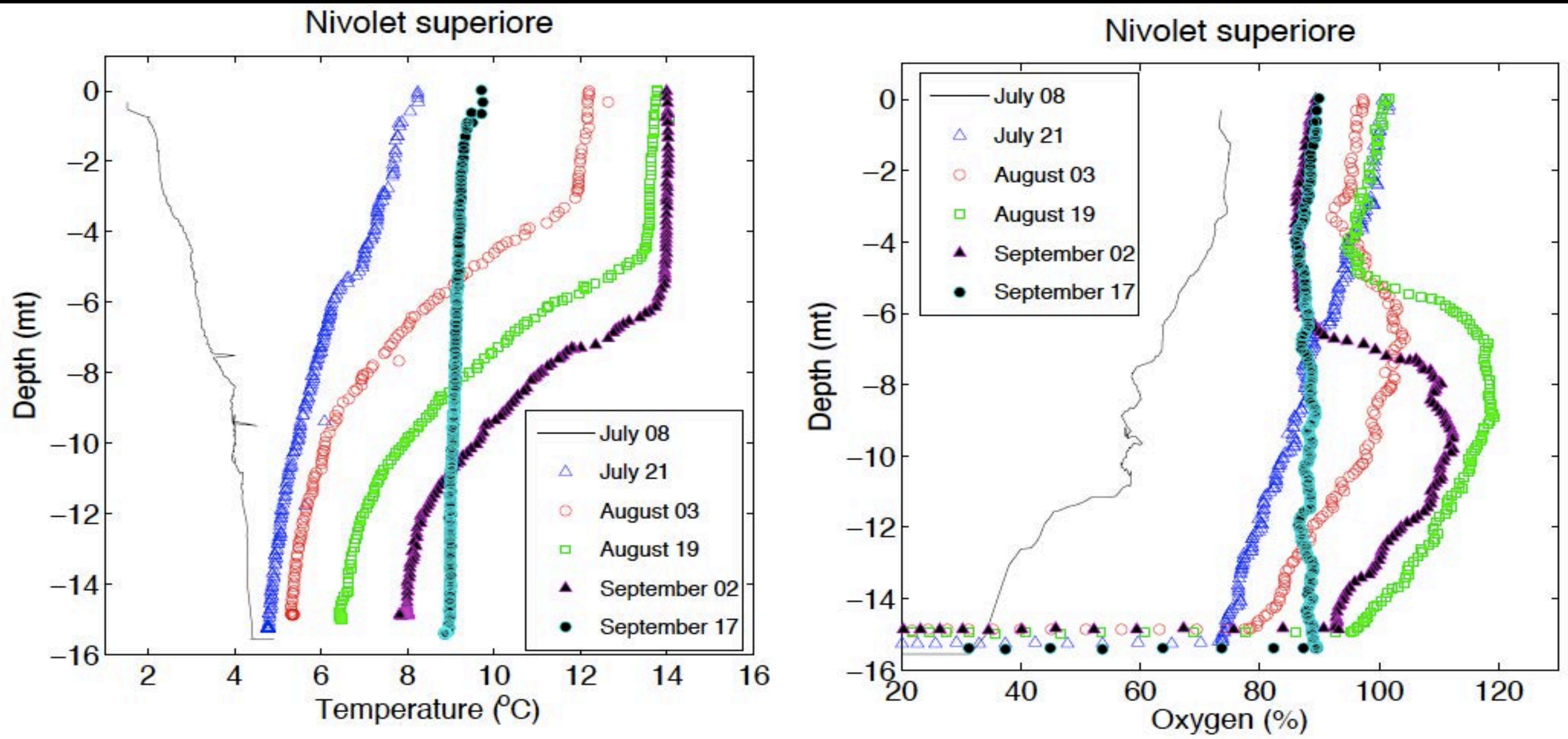
A “realistic” model ?

Lake Trebecchi, GPNP, Italy
2729 m a.s.l.

Lake Nivolet sup, GPNP, Italy
2538 m a.s.l.

A “realistic” model ?

A “realistic” model ?

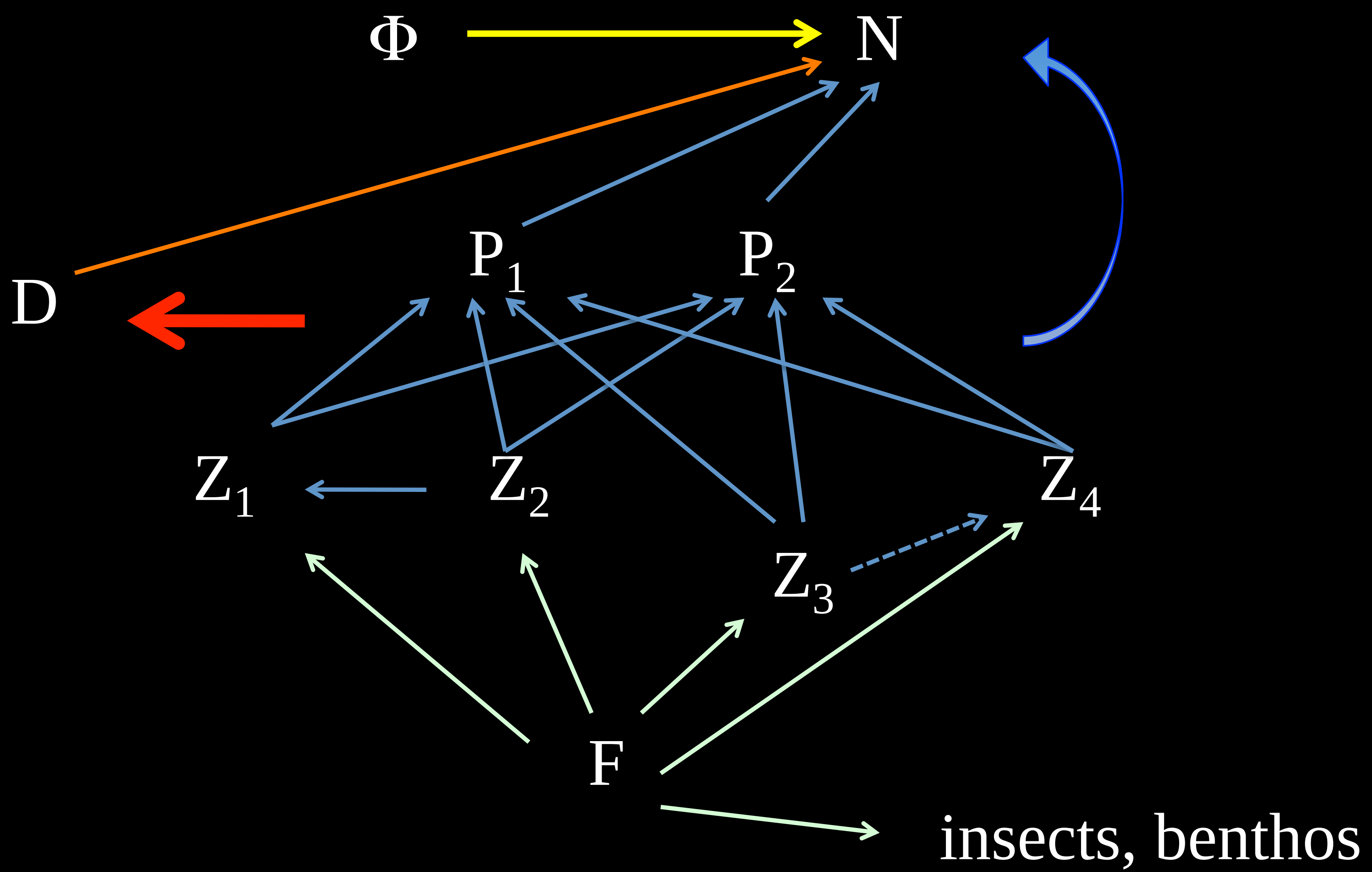


A “realistic” model ?

A “realistic” model ?

Zooplankton	Average body length (μm)		Average dry weight (μg)		Number of lakes where found (2006 – 07)	
	No fish	Fish	No fish	Fish	No fish	Fish
Rotifers	119	119	0.15	0.15	6	6
Copepod nauplii	254	251	0.47	0.41	6	6
Copepodites	763	691	3.17	2.54	6	6
Arctodiaptomus alpinus	1236	1257	13.03	13.58	6	5
Cyclops abyssorum	1267	1249	17.33	16.57	6	5
Eucyclops serrulatulus	–	740	–	4.21	0	1
Daphnia middendorffiana	2103	–	47.04	–	4	0
Daphnia gr. longispina	1307	1002	14.14	6.42	5	5
Alona quadrangularis	699	652	5.85	4.30	3	2
Acroperus harpae	327	592	1.23	2.05	1	1
Chydorus sphaericus	352	323	1.78	1.32	2	5

Structure of the model (in summer)



The problem of parameter values: optimal model size?

Param.	Explanation	Value	Units	References
V_U	optimal ultrapl. P uptake rate	65	d^{-1}	[11], Tab. 4.2, [36], Tab. 5
κ_U	half-sat. c. for ultrapl. P uptake	0.5	μmol–P L^{-1}	[11] Tab. 4.2, [36], Tab. 5
Q_U	ultraplankton P:C molar ratio	1/70	mol–P/mol–C	[15, 35, 37]
r_{oi}	organic to inorg. P recycling rate	2.5	d^{-1}	[15] (pp. 258–259)
Φ	allochthonous phosphorus input	0.0007	μmol–P L^{-1} d^{-1}	[15] (p. 270), using $\bar{z} = 6.3$ m
g_U	GE for ultraplankton	0.30		[40, 41]
g_0	GE for ciliates	0.68		[42]
g_1	GE for rotifers	0.55		[29]
g_2	GE for copepods	0.34		[29]
g_3	GE for cladocerans	0.83		[29]
g_F	GE for *S. fontinalis*	0.75		[43, 44]
q_0	ciliate P:C molar ratio	1/82	mol–P/mol–C	[42]
q_1	rotifer P:C molar ratio	1/111	mol–P/mol–C	[45]
q_2	copepod P:C molar ratio	1/114	mol–P/mol–C	[35]
q_3	cladoceran P:C molar ratio*	1/85	mol–P/mol–C	[46]
q_F	*S. fontinalis* P:C molar ratio	1/62	mol–P/mol–C	[47]
m_U	ultrapl. mort. rate (lysis and cell death)	1/3	d^{-1}	[15] (pp. 366, 508), [48]
d_0	ciliate mortality rate	1/7	d^{-1} L (μmol-C)$^{-1}$	[15] (p. 402, Tab.16-3), [49]
d_1	rotifer mortality rate	1/14	d^{-1} L (μmol-C)$^{-1}$	[50, 51, 52]
d_2	copepod mortality rate	1/53	d^{-1} L (μmol-C)$^{-1}$	[53, 54]
d_3	cladoceran mortality rate	1/24	d^{-1} L (μmol-C)$^{-1}$	[55, 56, 57, 58]
d_F	*S. fontinalis* mortality rate	1/1825	d^{-1} L (μmol-C)$^{-1}$	[59]
α_U	ultrapl. constant in sinking rate (Stokes' law)	1240	μm^{-1} d^{-1}	[11] (at 10^{o}C)
$\bar{z}$	average depth of water column	6.3	m	[9]
τ	time scale of P loss to sediment	90	d	[29]
p	parameter in predation function (??)	1		
γ	parameter in predation function (??)	3.605		

Trophic web in the ocean

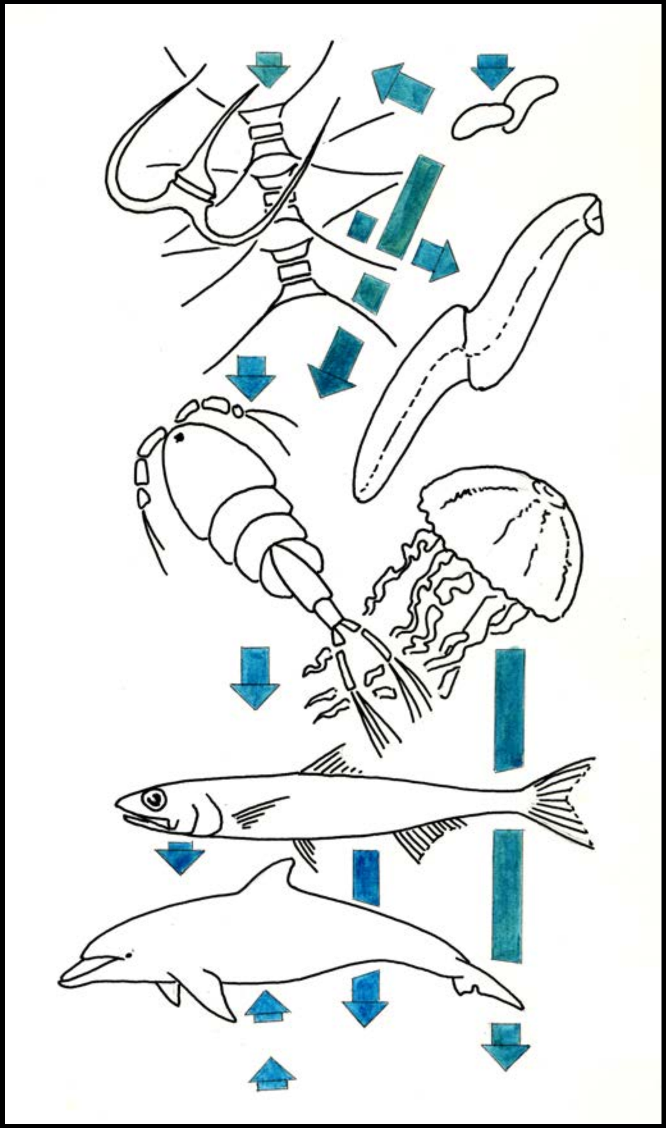
Nutrients
(N, P, Fe)

Phytoplankton
(primary producers)

Zooplankton

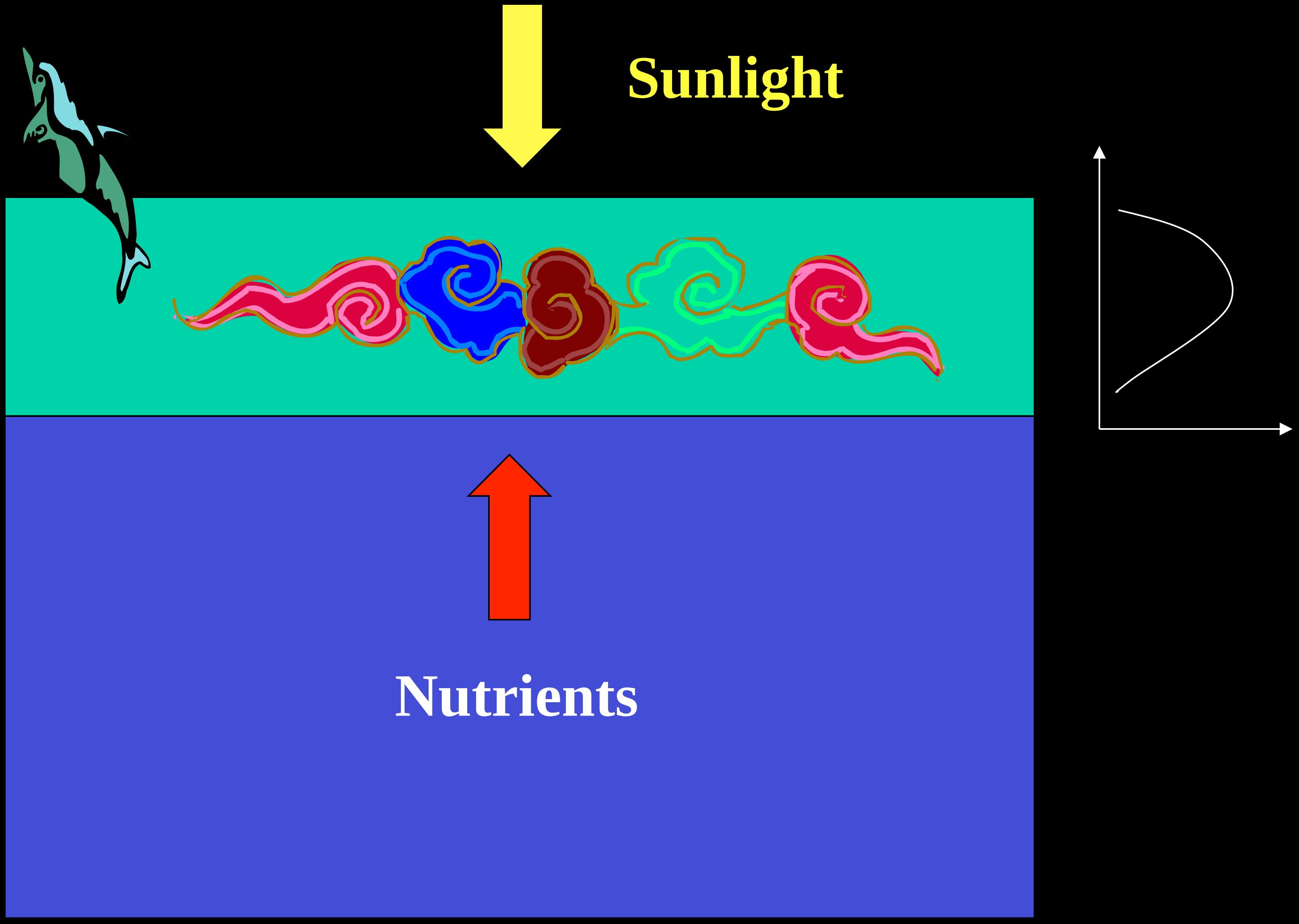
grazers (fish)

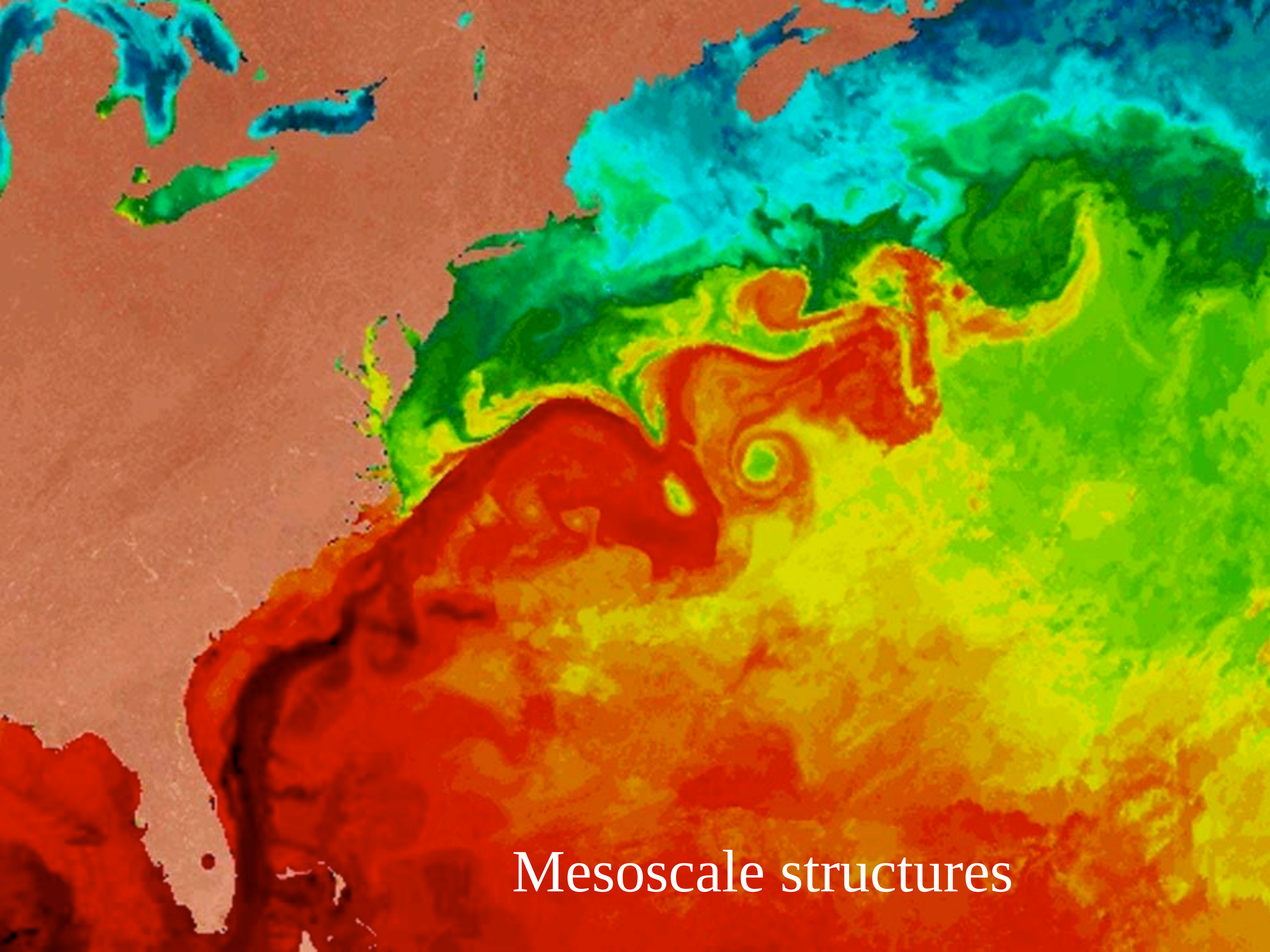
highest predators



bacteria

The structure of the upper ocean




Mesoscale structures

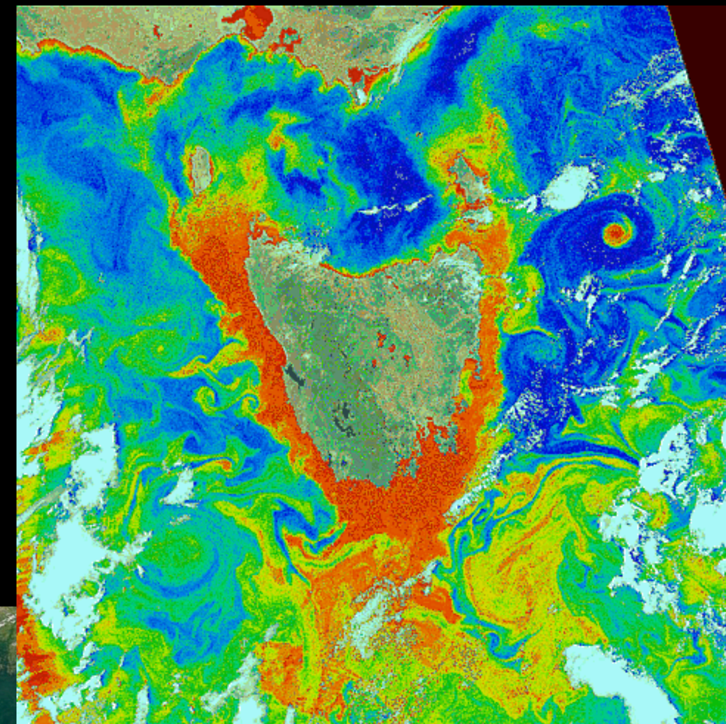
The problem of space: advection

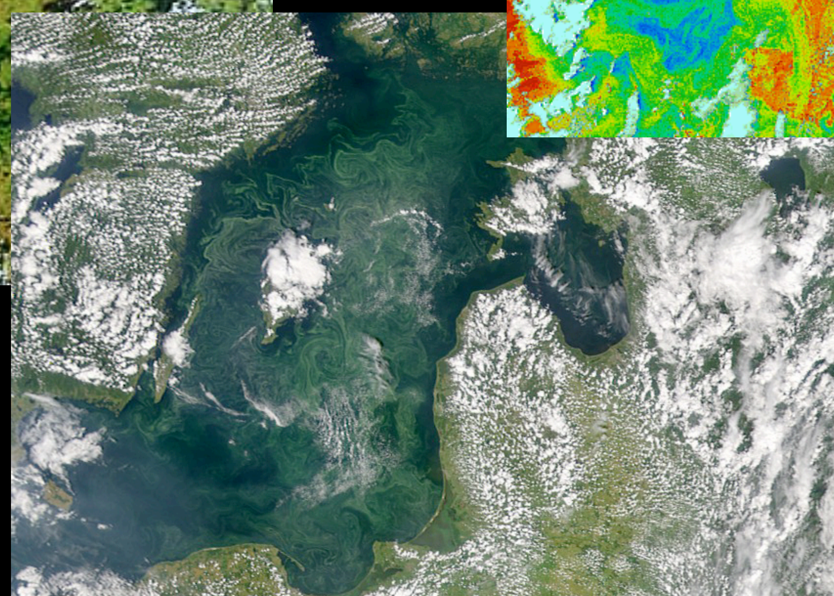
$$\frac{DN}{Dt} = \frac{\partial N}{\partial t} + \vec{u} \cdot \nabla N + w \frac{\partial N}{\partial z} = f(N,P,Z) + \mu_N \nabla^2 N$$

$$\frac{DP}{Dt} = \frac{\partial P}{\partial t} + \vec{u} \cdot \nabla P + w \frac{\partial P}{\partial z} = g(N,P,Z) + \mu_P \nabla^2 P$$

$$\frac{DZ}{Dt} = \frac{\partial Z}{\partial t} + \vec{u} \cdot \nabla Z + w \frac{\partial Z}{\partial z} = h(N,P,Z) + \mu_P \nabla^2 Z$$

The problem of space: advection





Role of the physical/chemical/geological environment

Geosphere – Biosphere interactions

from D. deB. Richter and S. A. Billings,
New Phytologist, 2015

Arthur Tansley (1935), who briefly but substantively defined the ecosystem to be the integrated biotic–abiotic complex:

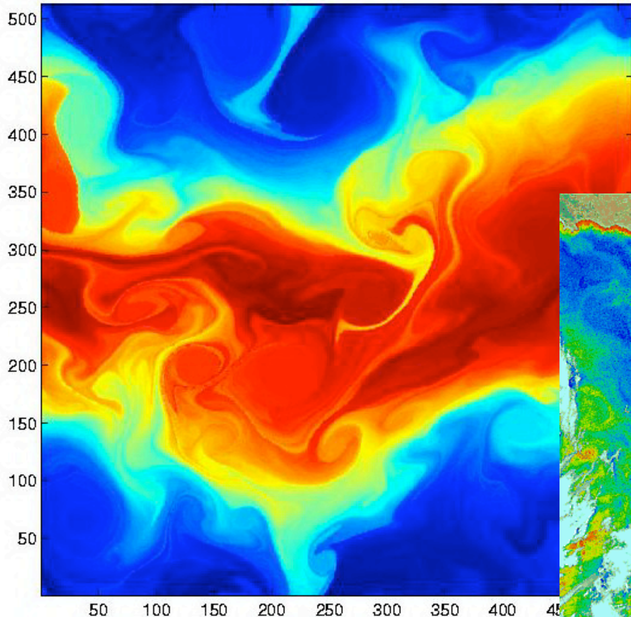
> the whole *system* (in the sense of physics), including not only the organism-complex, but also the whole complex of physical factors forming what we call the environment of the biome – the habitat factors in the widest sense.

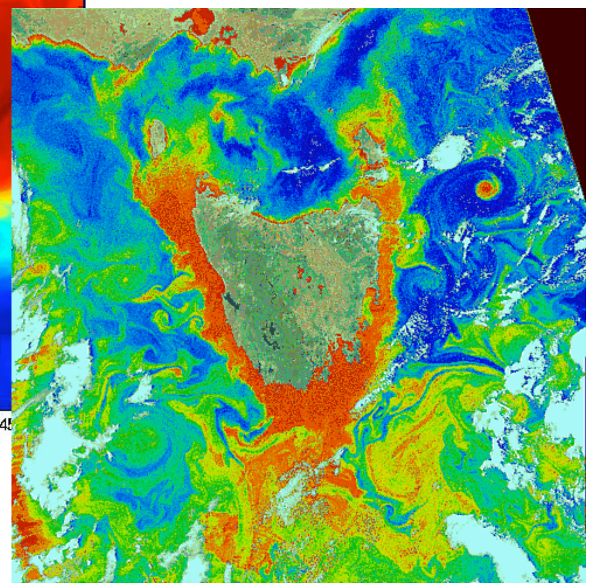
Significantly, as if to emphasize what he meant by 'the whole system', Tansley (1935) added:

> Though (as biologists) the organisms may claim our primary interest, when we are trying to think fundamentally we cannot separate them from their special environment, with which they form *one physical system* (italics ours).

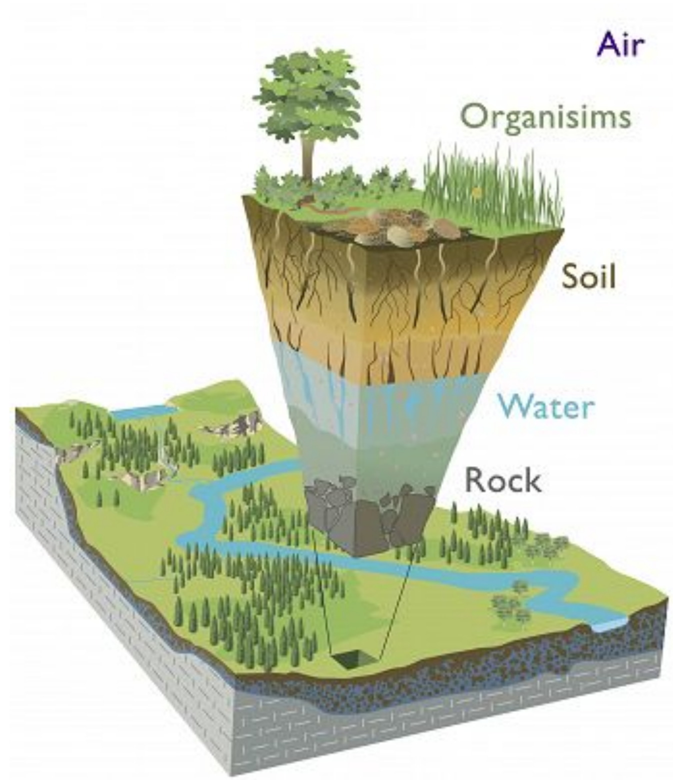
Ecosystems are complex adaptive systems

A focus on geosphere-biosphere interactions





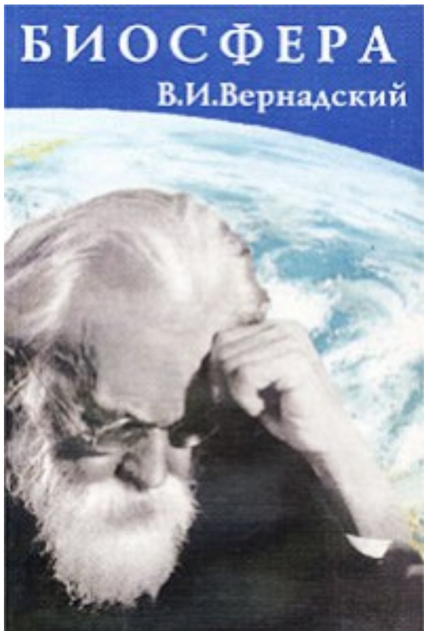
the **Earth's Critical Zone**



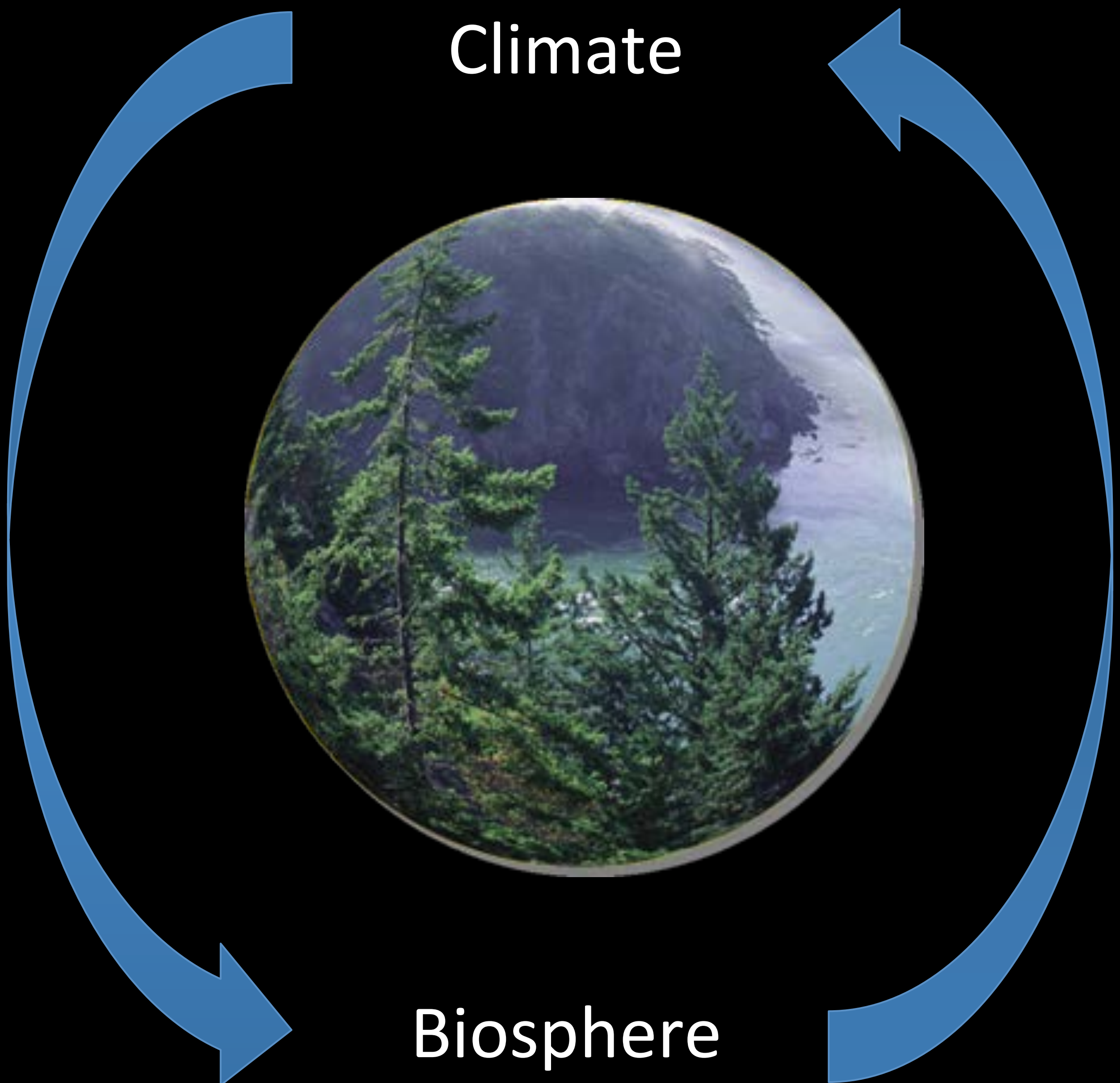
Circulation-ecosystem interactions

Biogeodynamical processes and biogeochemical cycles, fluxes and efficiencies

Two-way feedbacks between ecosystems and environment



Ecosystem engineers, niche construction, complex adaptive landscapes and global biogeochemical cycles


Climate
Biosphere

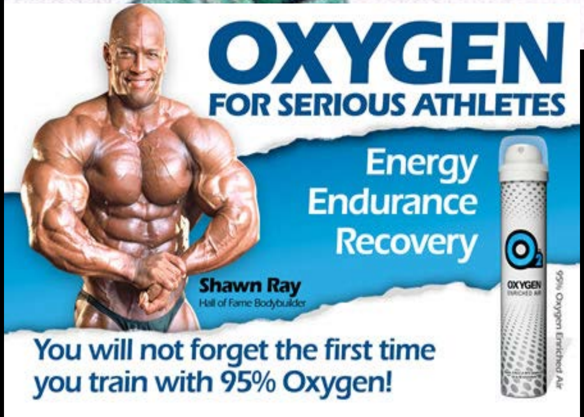
Biosphere dynamics
affect and possibly control climate
(V. Vernadsky, *Biosfera*, Leningrad 1926)

a conceptual challenge for XXI century physics:
understanding the interaction and coevolution
of climate and biosphere

These studies, rooted in thermodynamics and
statistical mechanics, chemistry and biology,
are an essential part of complex systems physics
and a central issue for the science of the coming decades.

The Great Oxydation Event
Oxygen production from Cyanobacteria

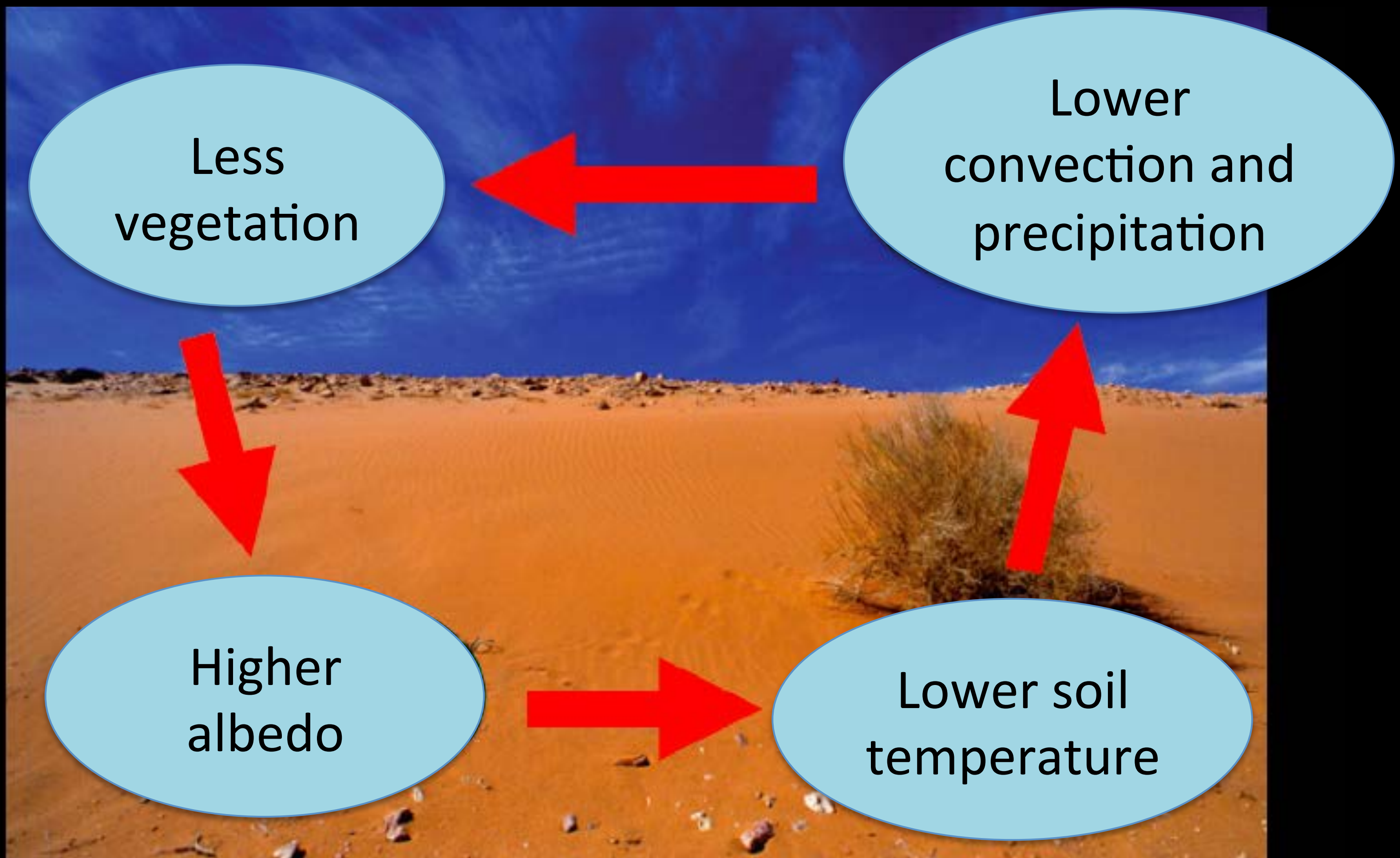
http://www.ucmp.berkeley.edu/bacteria/nostoc.gif



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

A conceptual model approach: interaction between vegetation and climate

Albedo and the Charney mechanism (1975)



feedbacks in the vegetation-climate system

A classic example: the Charney mechanism (1975):

Reduction in vegetation

↓

Higher albedo

↓

Local cooling of the soil

↓

Higher atmosph. pressure, reduced convection

↓

Lower precipitation

A classic example: 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

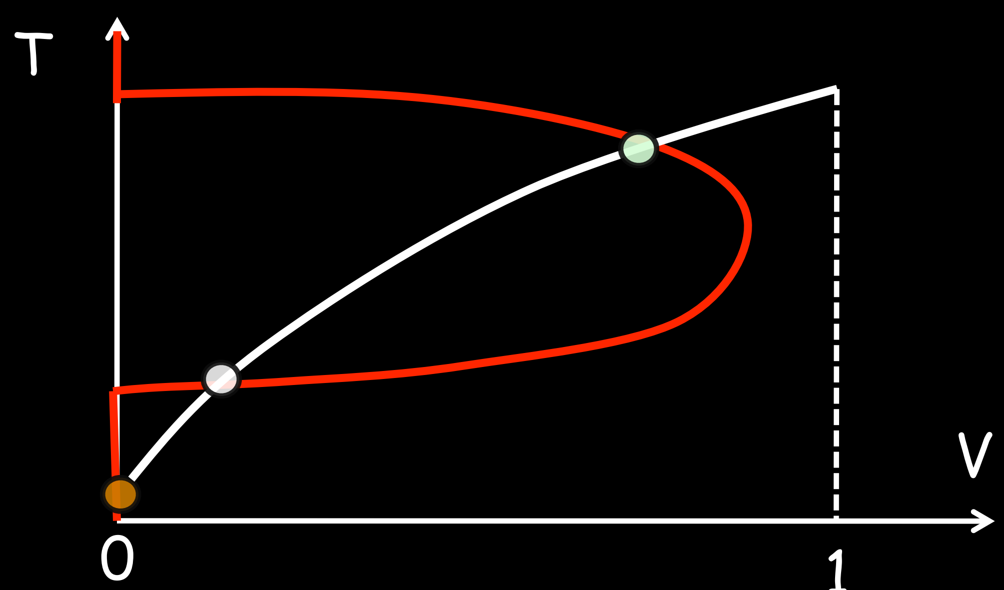
$$C_V \frac{dT}{dt} = \frac{S}{4}\left[1 - \alpha_V V - \alpha_B (1-V)\right] - \sigma T^4$$

First principle
of Thermodynamics

A classic example: the Charney mechanism (1975):

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

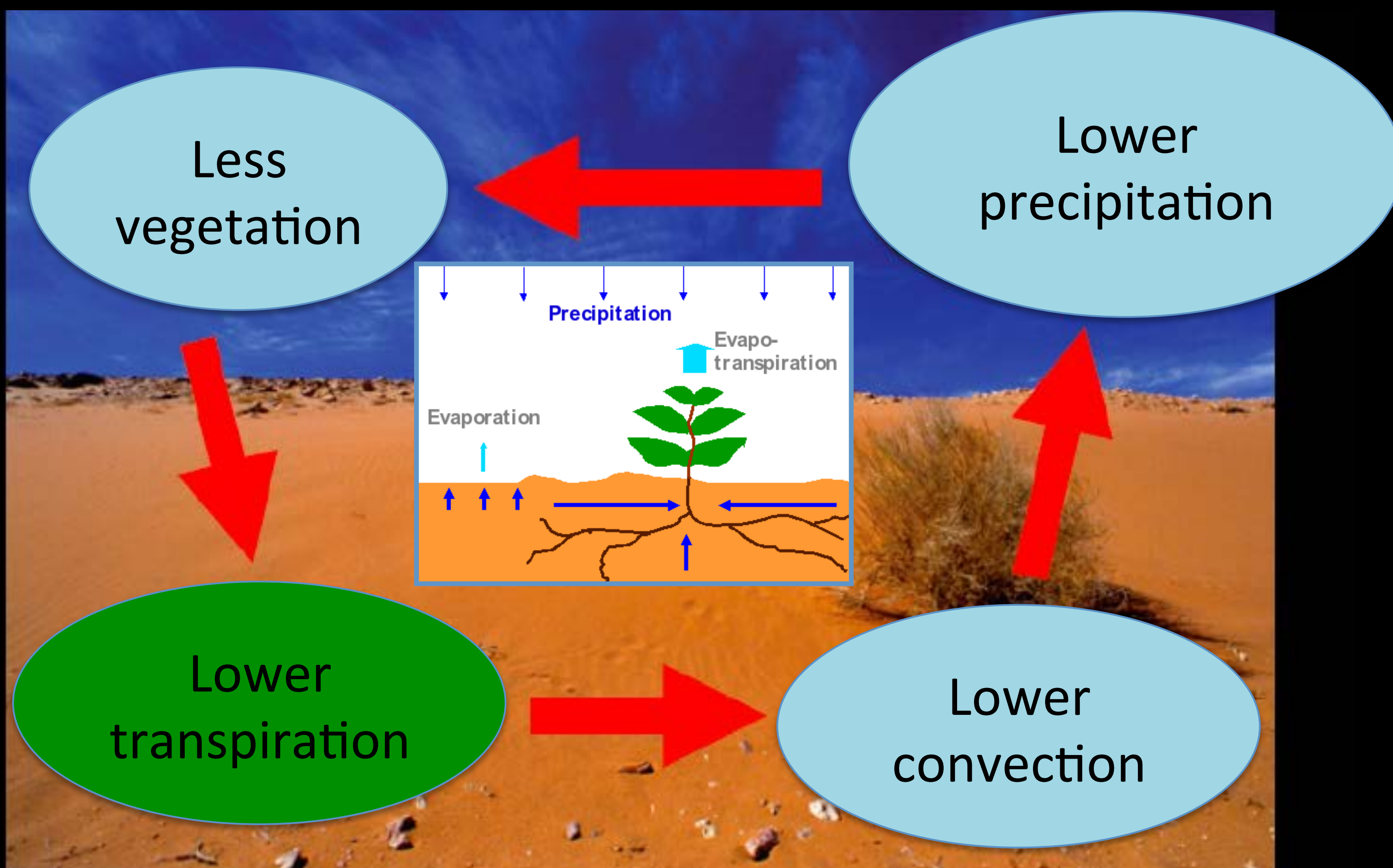
$$0 = \frac{S}{4}\left[1-\alpha_V V - \alpha_B(1-V)\right] - \sigma T^4 \quad \Rightarrow \quad T = \sqrt[4]{\frac{S}{4\sigma}\left[1-\alpha_V V - \alpha_B(1-V)\right]}$$

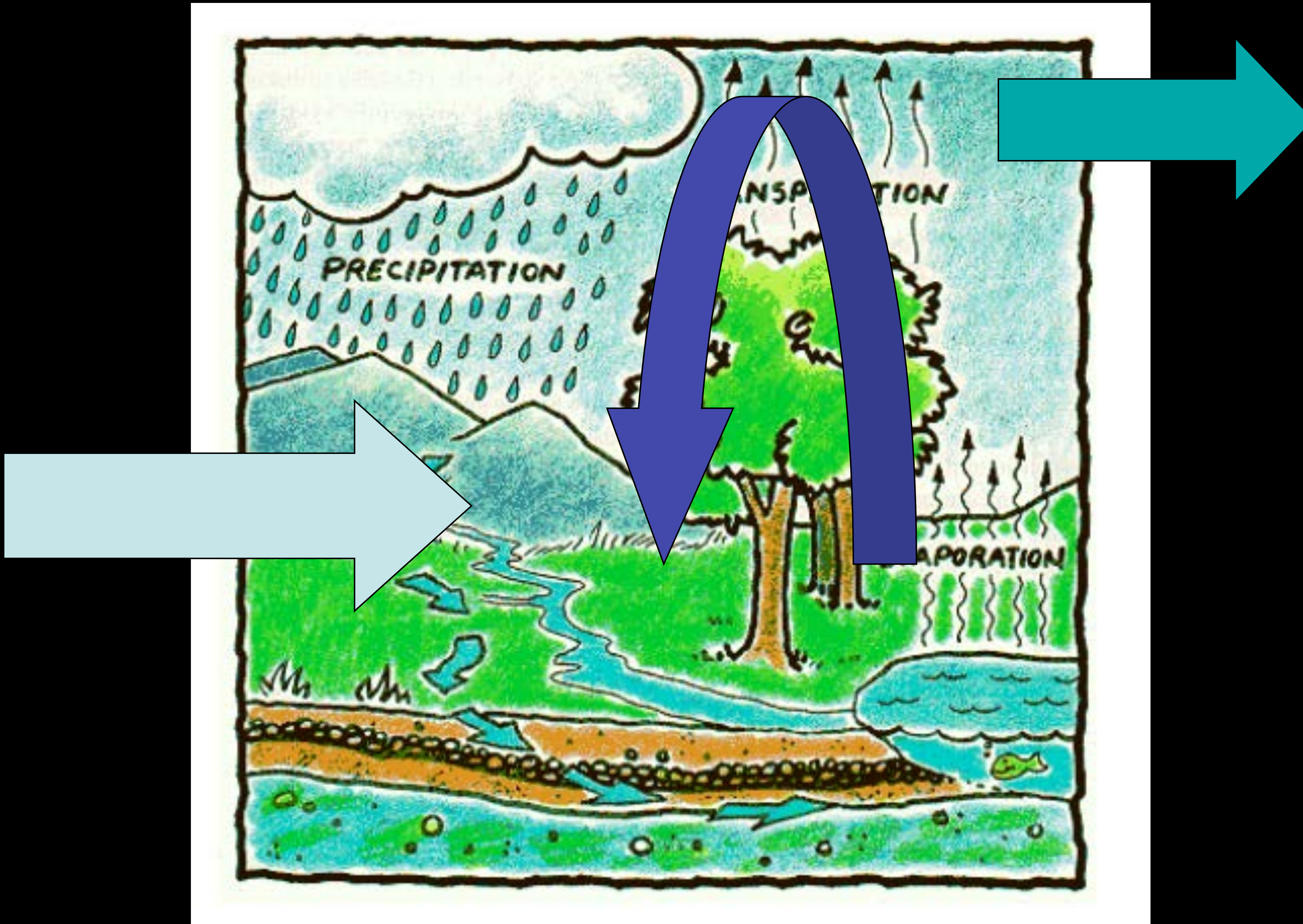


Brovkin et al JGR 1998

A conceptual model approach: interaction between vegetation and climate

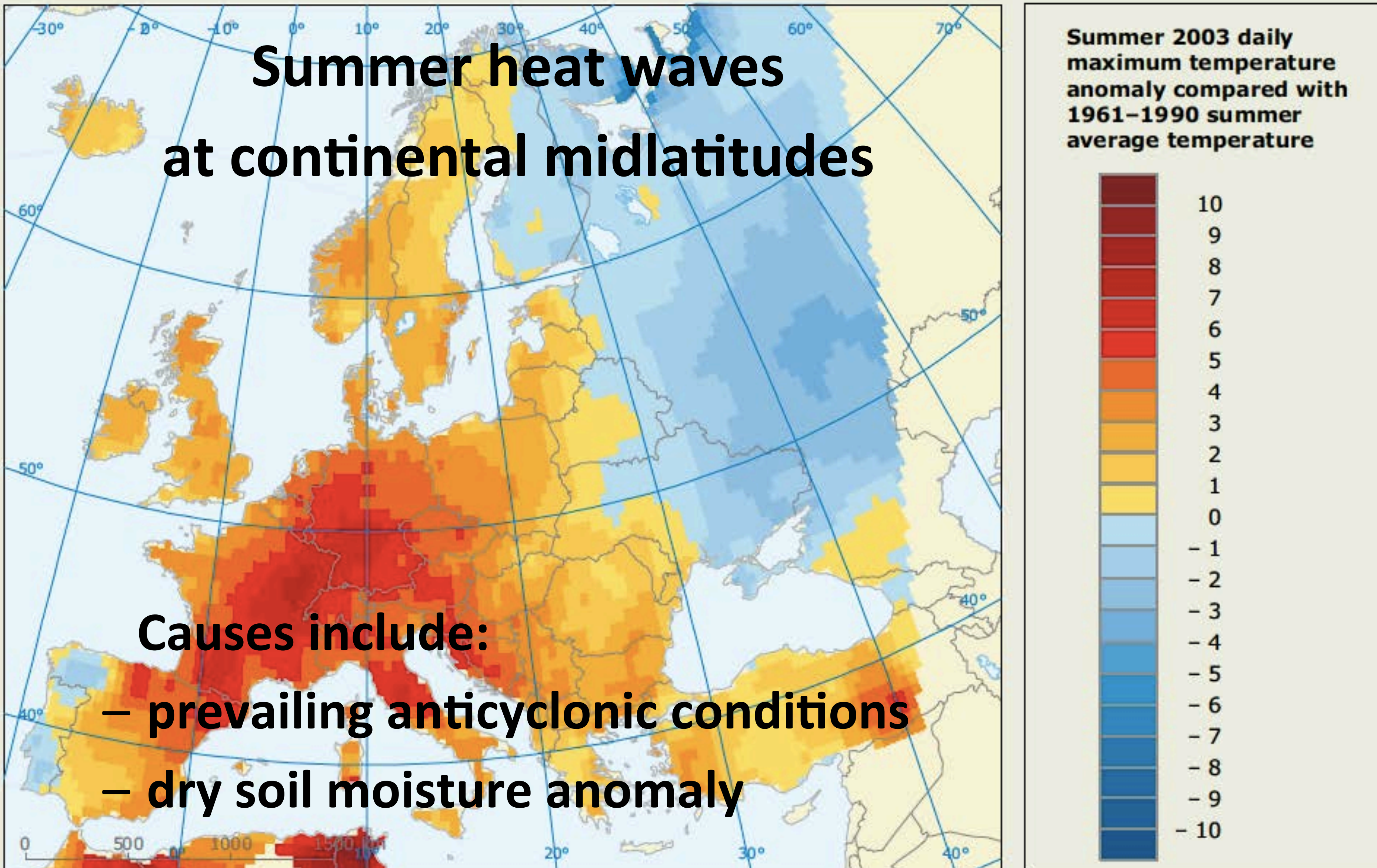
Plant transpiration and the hydrological cycle





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

Map 5.8 Summer 2003 (June–August) daily maximum temperature anomaly



Summer heat waves at continental midlatitudes

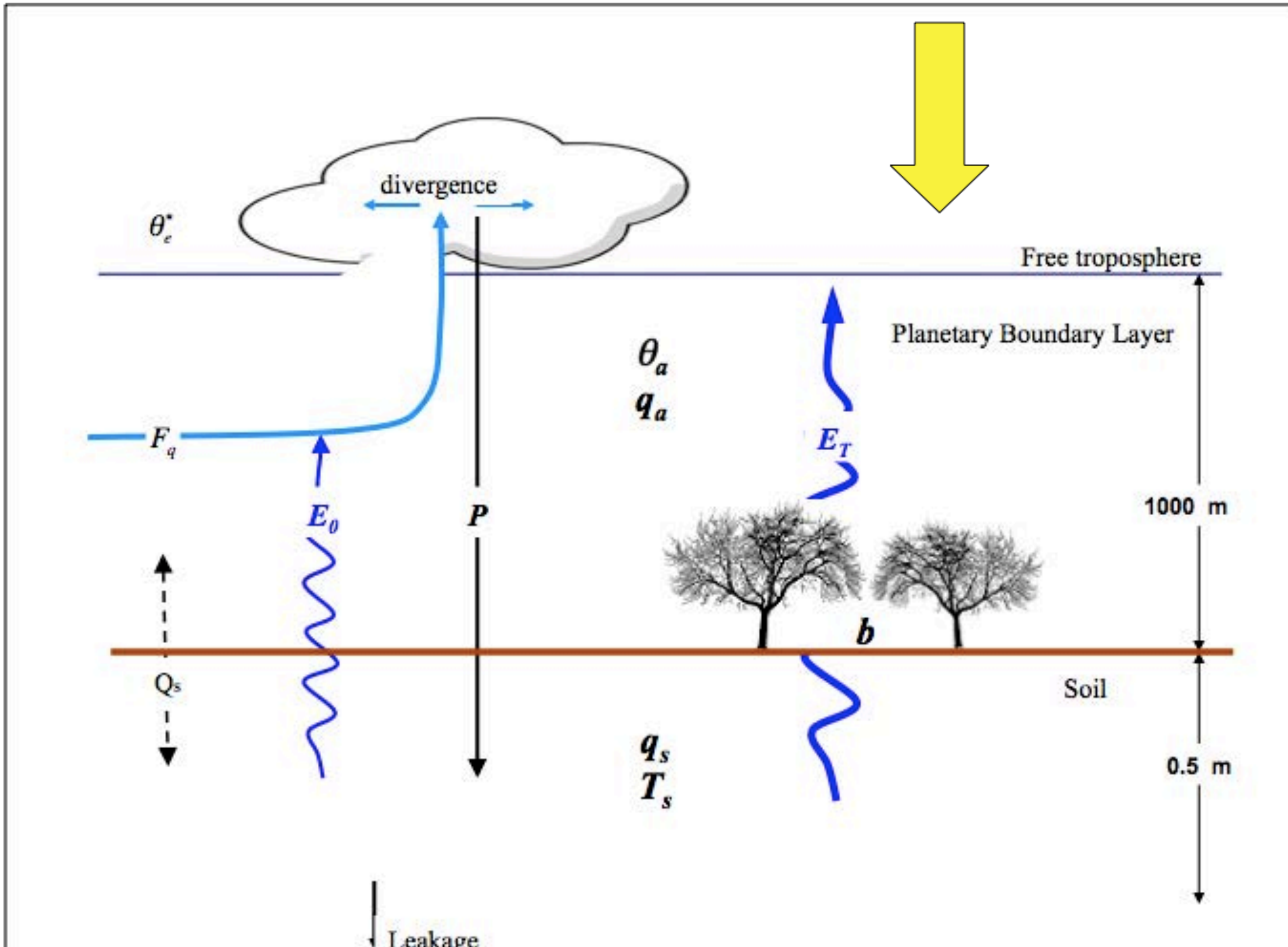
Causes include:

– **prevailing anticyclonic conditions**

– **dry soil moisture anomaly**

Source: The climate dataset is from the EU-FP6 project ENSEMBLES (http://www.ensembles-eu.org) and the data providers in the ECA&D project (http://eca.knmi.nl).

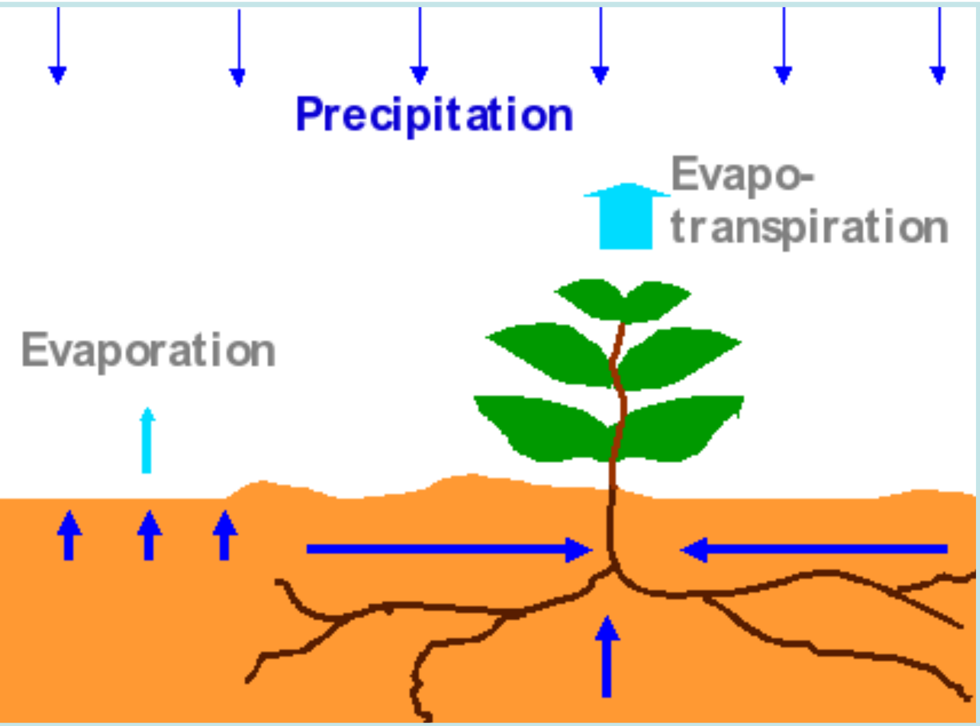
A simple box-model for the soil-vegetation-atmosphere interaction

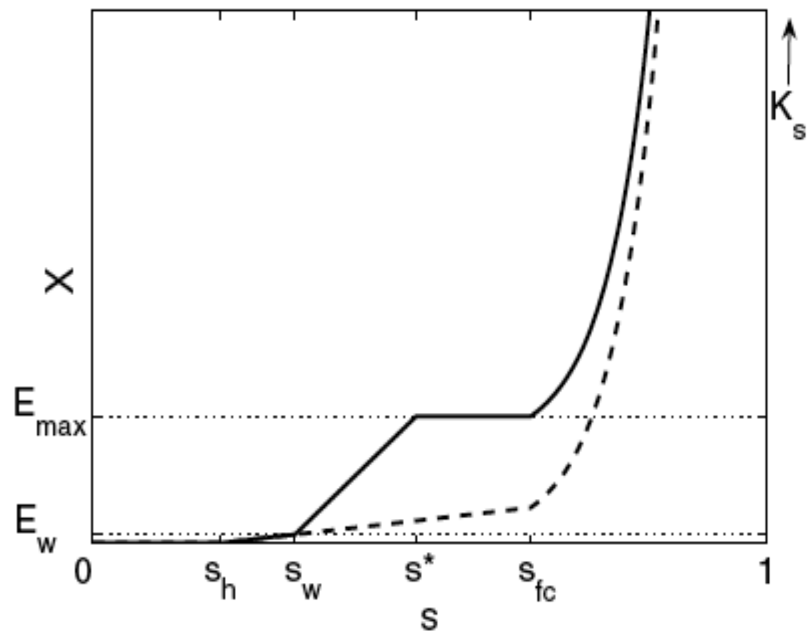


D'Andrea, AP, Vautard, De Noblet-Ducoudrè, GRL, 2006
Baudena, D'Andrea, AP, WRR, 2008

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

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

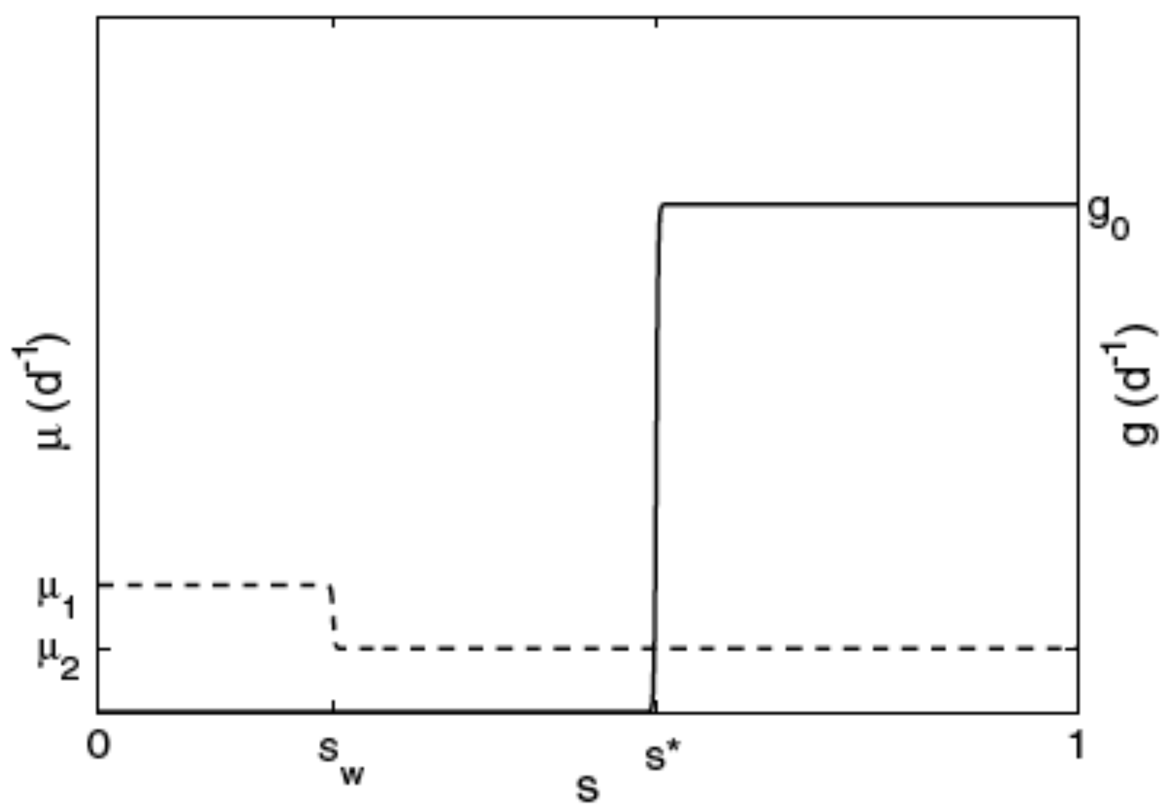
$$\alpha_0 = 0.35$$
$$\alpha_b = 0.14$$

As in Charney [1975]

Vegetation dynamics

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

$$\frac{\mathrm{d}b}{\mathrm{d}t} = gb(1-b) - \mu b.$$



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**

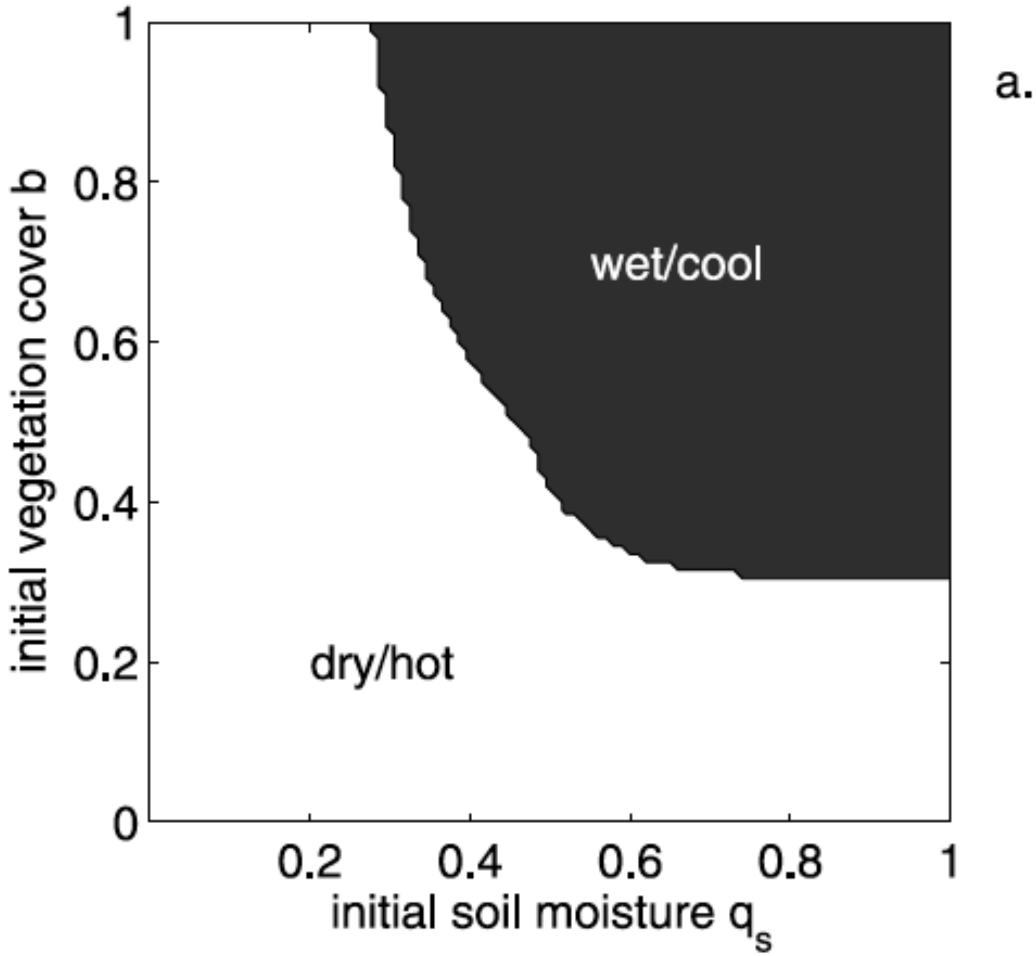
We assume that convection is instantaneous

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

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

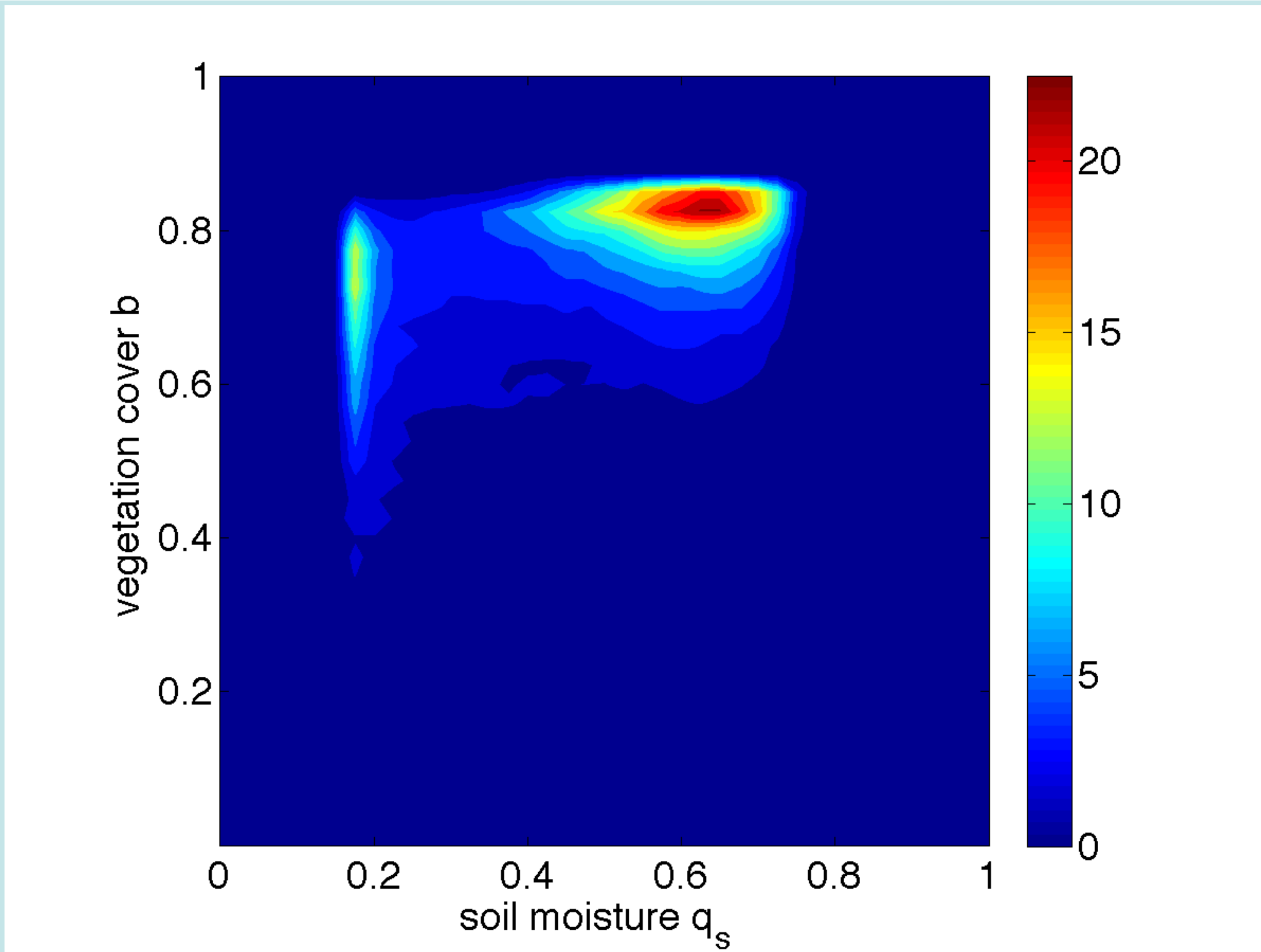
or: constant relative humidity in the PBL

Multiple equilibria of the soil-atmosphere system



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

Effects of stochastic variability in moisture flux



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

H2020 Project ECOPOTENTIAL: Improving future ecosystem benefits through Earth Observations

Starting date: 1st June 2015, Duration: 4 years

Coordinator: Antonello Provenzale

Institute of Geosciences and Earth Resources, National Research Council of Italy

Co-Coordinator: Carl Beierkuhnlein

Biogeography, BayCEER, University of Bayreuth, Germany

Project Manager: Carmela Marangi

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47 ECOPOTENTIAL Partners

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EURAC research

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Environment SYSTEMS

InBIO RESEARCH NETWORK
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Environmental and Water Agency of Andalusia
REGIONAL MINISTRY OF ENVIRONMENT AND SPATIAL PLANNING

UBO
université de bretagne occidentale

UNIVERSITÉ DE GENÈVE

What are we doing and key outputs:

- Focus on ecosystem functions/processes that **support specific ecosystem services**
- Make best use of EO data (satellite and in situ)
- Build data products and make them widely available
- Build models capable of including EO data
- Assess the current state and estimate the future evolution of ecosystems (processes/functions/services)
- Define policy options and the requirements of future protected areas
- Develop capacity building strategies
- Make all results available to the community, contributing to GEO and GEOSS (Virtual Laboratory)

ECOPOTENTIAL

This project is funded by the European Union

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 641762. *Copyright by Ecopotential Consortium.*

Working in partnership with 23 Protected Areas in Europe and beyond

Conceptual threads:

Propagation and estimate of uncertainties in future ecosystem projections

Role of changing extremes and intermittency compared with changing means

Ecosystem Services and their conceptual role in conservation and management. Benefits and dangers of the ES approach

How are (current and future) PAs identified and selected?

A grasp on Essential Variables: essential for what questions? How many do we need? Is it useful to define Essential Ecosystem Variables? (the example of rainfall)

Conclusions

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

Look at processes and mechanisms
(do not plunge wholeheartedly into the dark side…)

Paleoclimate and Earth System dynamics:
Understanding extreme and/or "different" climates as a testbed for our knowledge of climate processes

Unravel geosphere-biosphere interactions and how the biosphere makes our planet special


Thank you for your attention!