Modelling the Earth System

Antonello Provenzale
antonello.provenzale@cnr.it
Institute of Geosciences and Earth Resources, Pisa
National Research Council of Italy

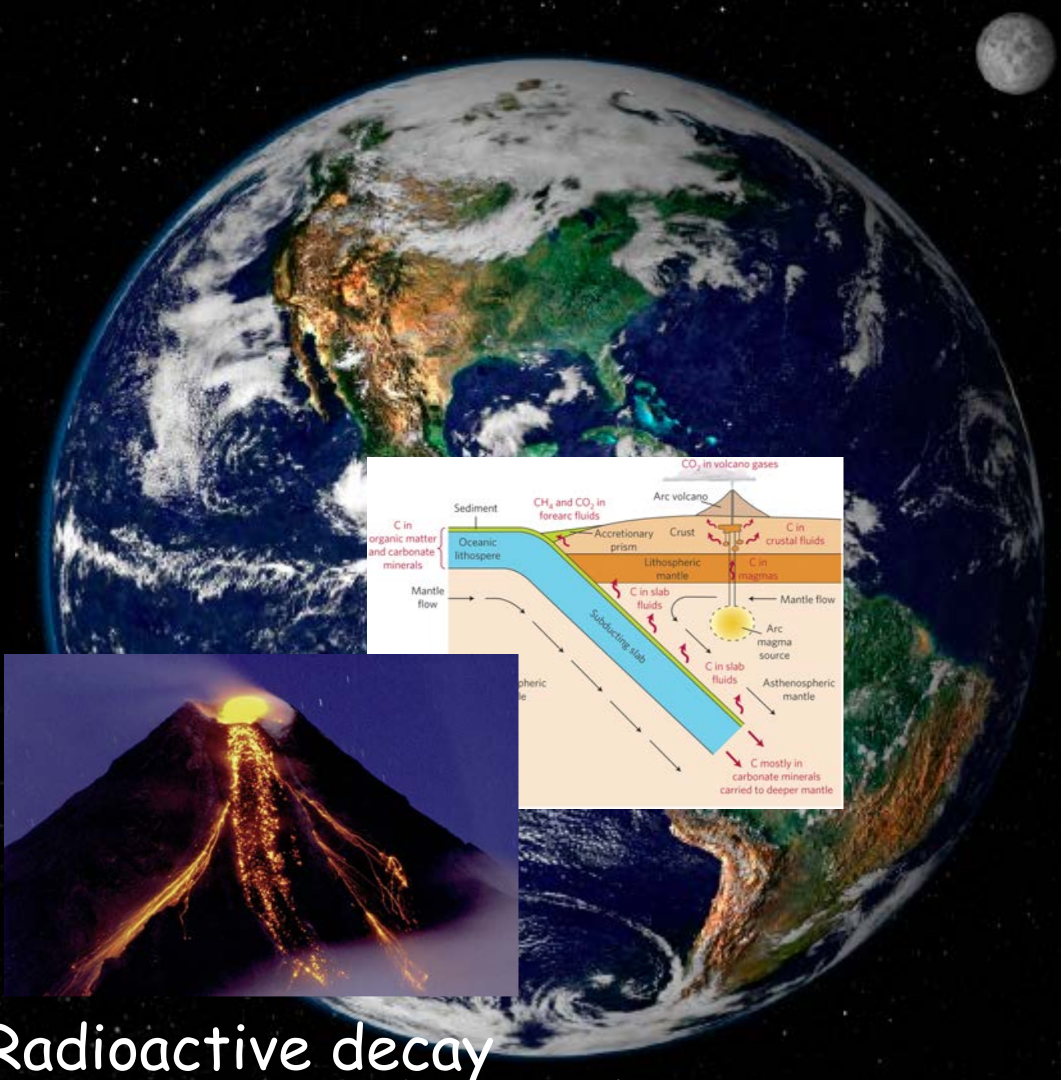
ESRIN School, 4-5 August 2016

Modelling the Earth System

1. Climate processes and conceptual models
2. Climate models and downscaling
3. Geosphere-biosphere interactions and ecosystems

The Earth System is a complex nonlinear system

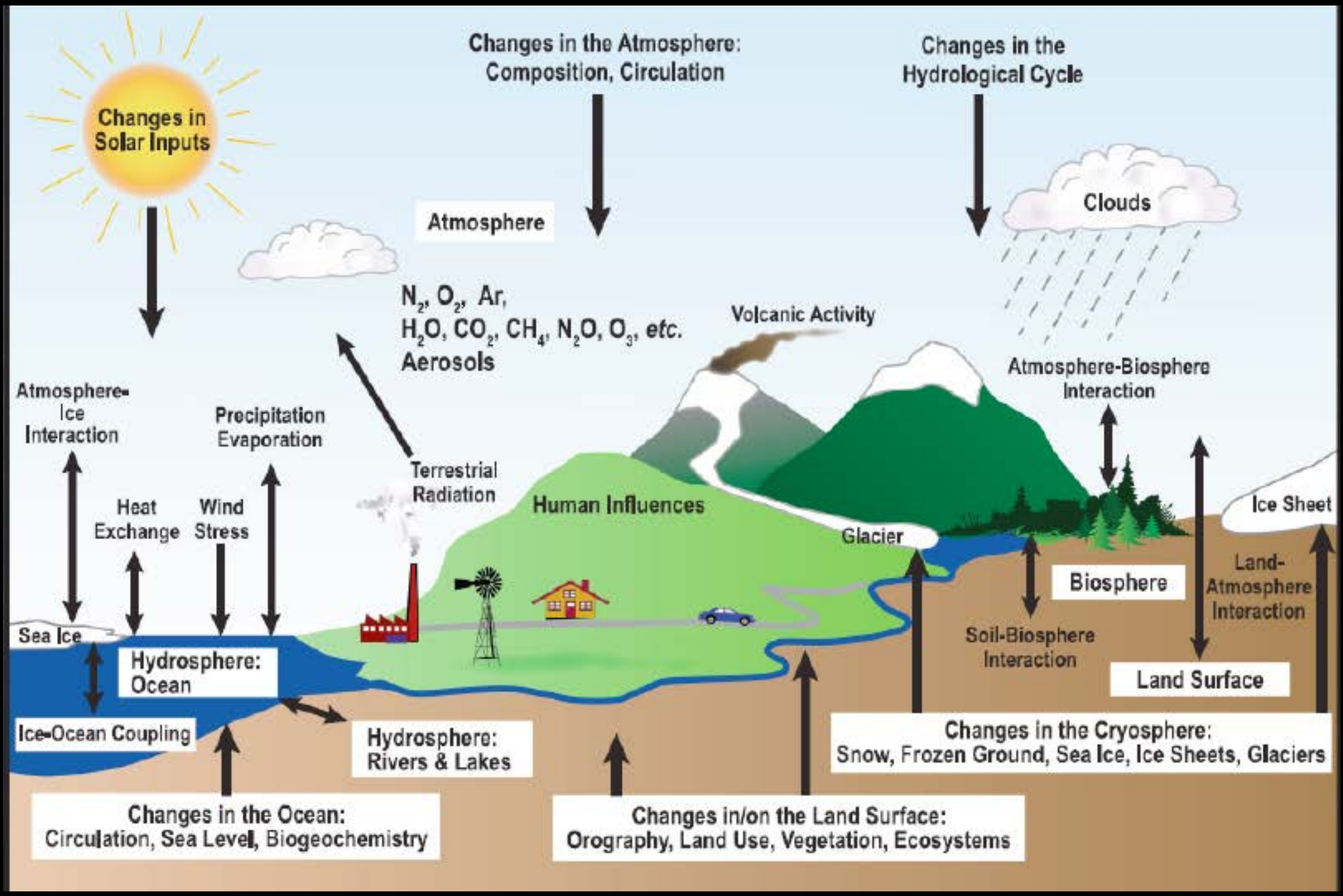
Solar forcing



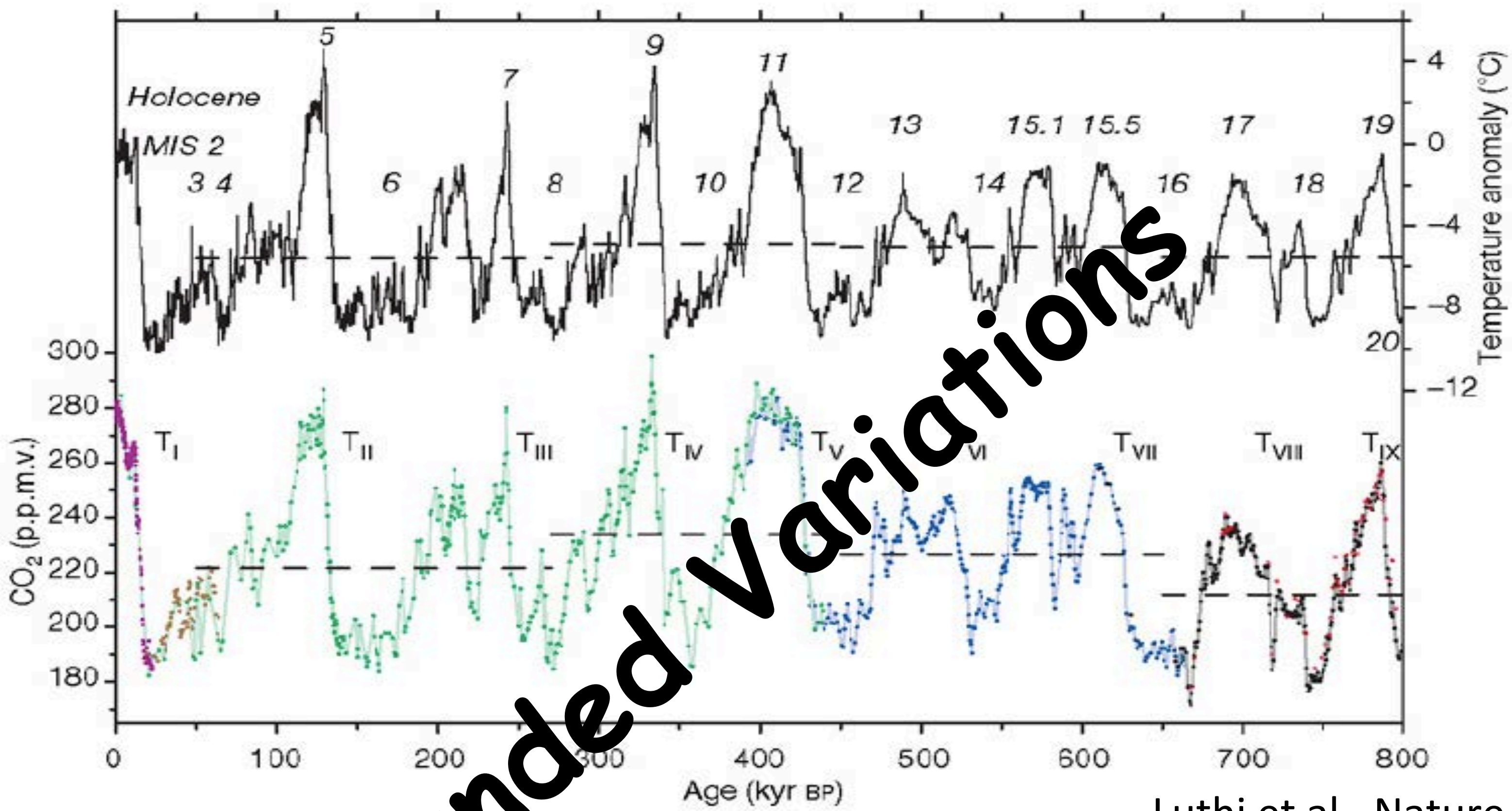
Infrared emission

Radioactive decay
(+ condensation in the core)

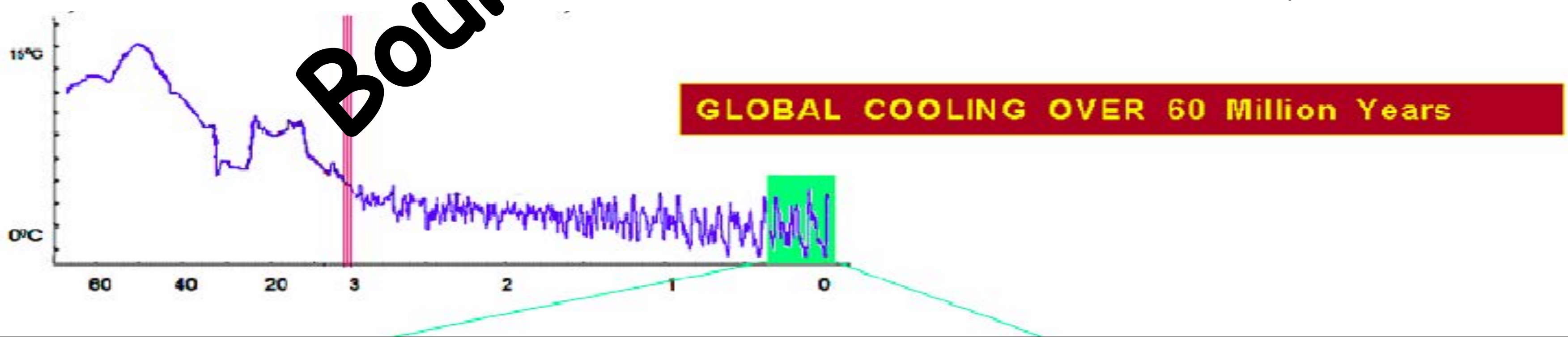
Climate:
the statistical state of the Earth System



Earth's climate varies on all time scales



Luthi et al., Nature 2008



A touch of climate physics:

Energy Balance

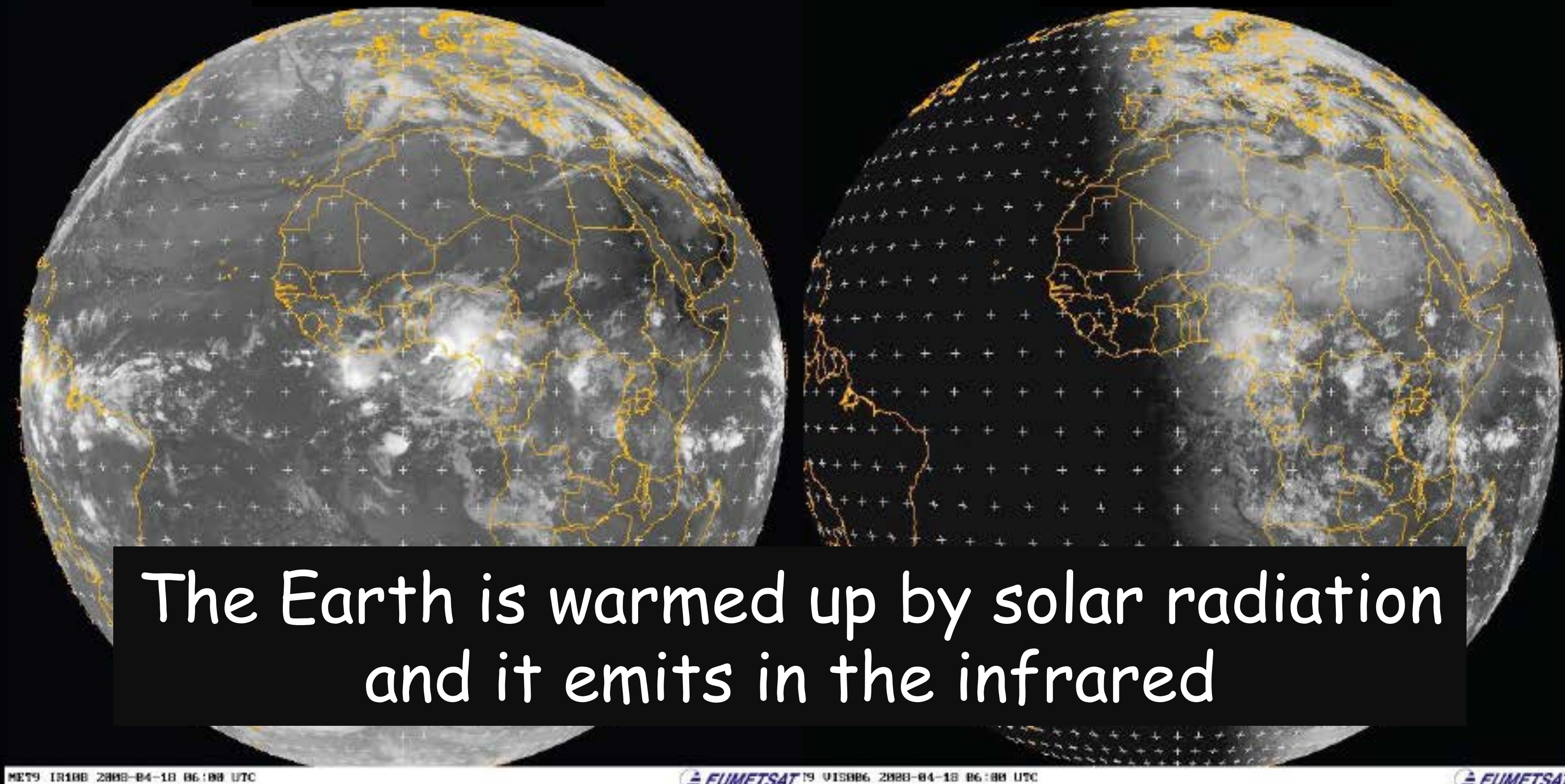
Meridional Transport

Climate reductionism and feedbacks

Global and regional climate models

METEOSAT 2° Generation
18/4/2008 06:00 UTC

INFRARED VISIBLE



The Earth is warmed up by solar radiation and it emits in the infrared

www.eumetsat.int

The main energy source of Earth's climate is solar radiation.

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

first principle of Thermodynamics

$$dE + dL = dQ$$

For the Earth as a point in the empty space

$$dE \approx C_V dT \quad , \quad dL = 0$$

C_V specific heat at constant volume

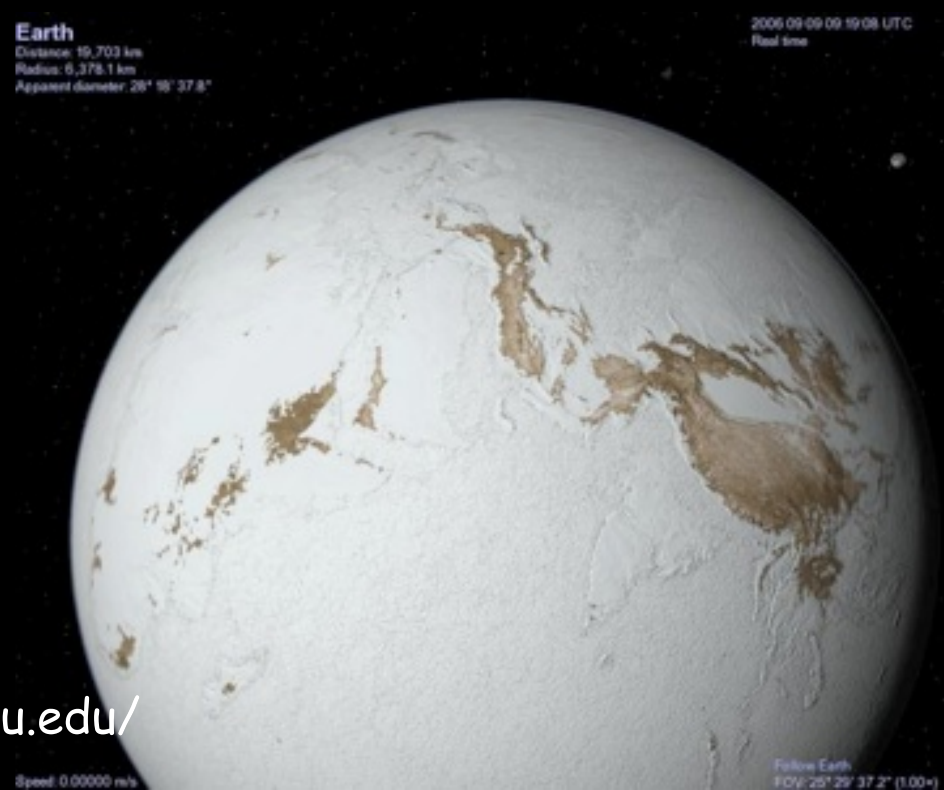
$$C_V \frac{dT}{dt} = P_{in} - P_{out}$$

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

If we look for a stationary state

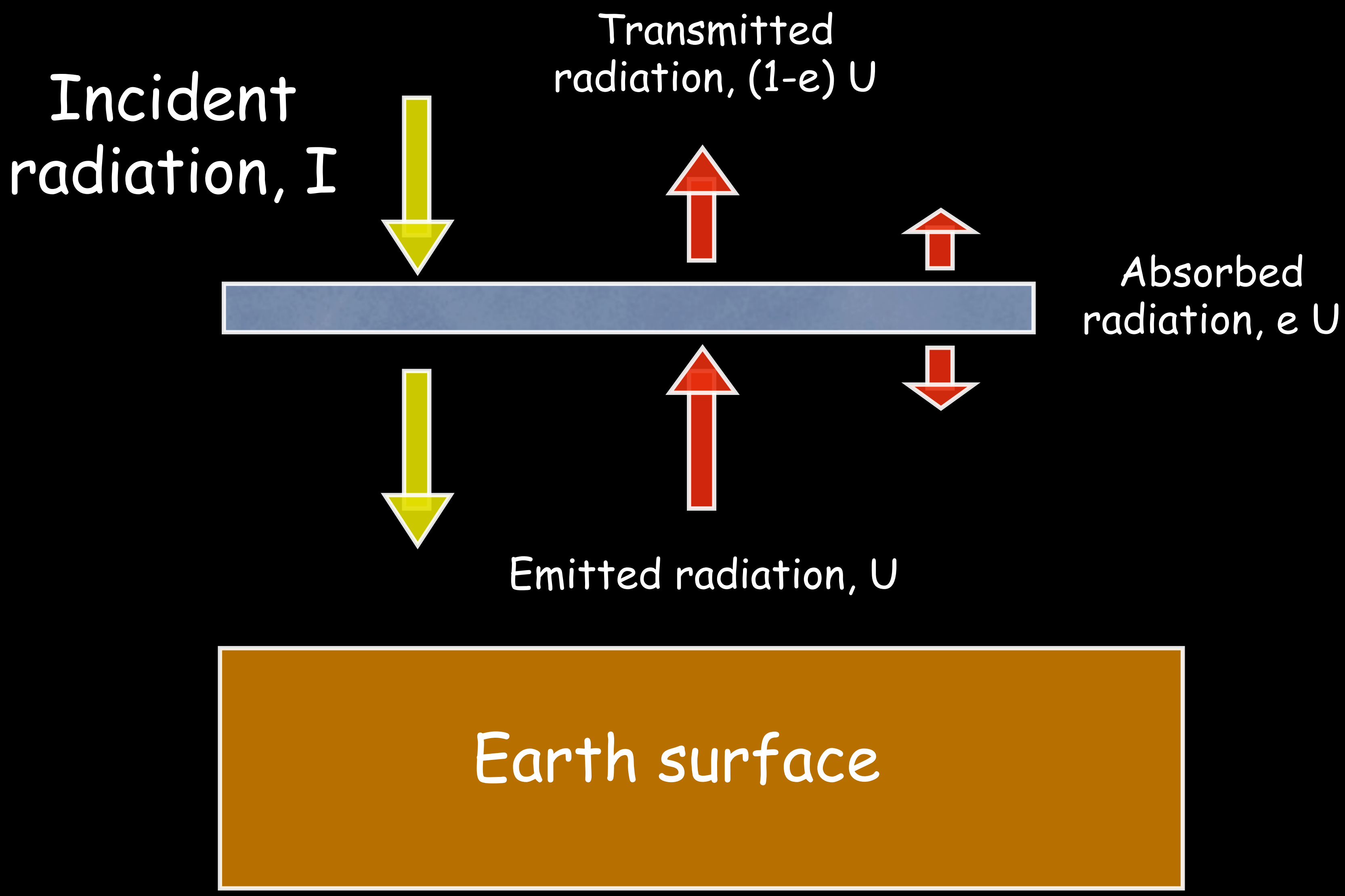
$$\frac{1}{4} S\,(1-\bar{\alpha}) - \sigma\,T^4 = 0$$

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



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

Role of the fluid envelope: greenhouse effect



Energy balance without greenhouse effect

$$\sigma T^4 = U = I$$

Greenhouse balance with greenhouse effect

$$I + \frac{e}{2}U = U$$

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

Spettro di radianza in onda lunga: REFIR-PAD, Teresina; Brasile, 30 giugno 2005

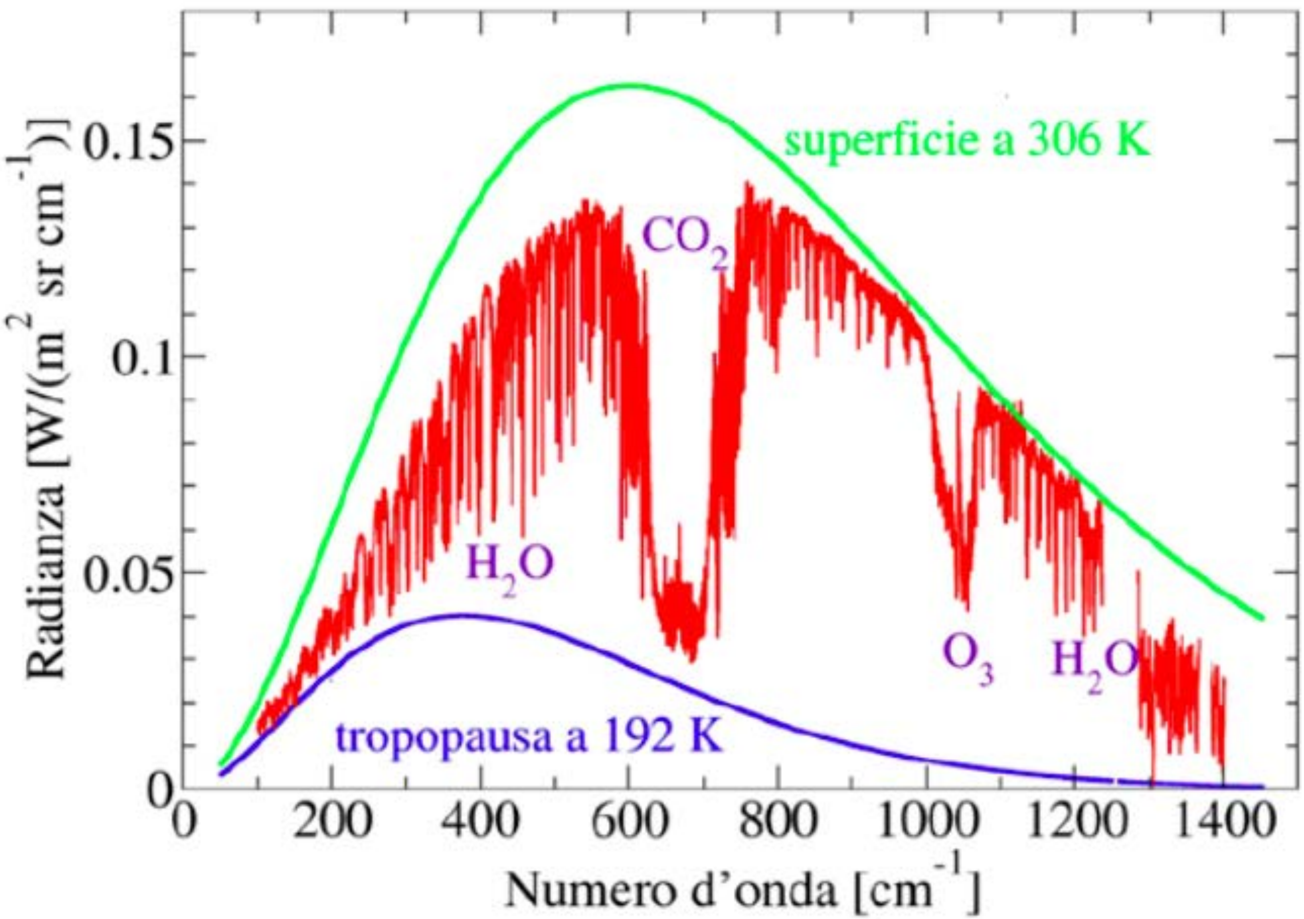


Figura 1a. Spettro di radianza in onda lunga (in Watt per m^2 per steradiante per cm^{-1}) con cui la Terra si raffredda disperdendo energia verso lo spazio, misurato da ricercatori dell'Istituto di Fisica Applicata del CNR con un esperimento effettuato in Brasile da pallone stratosferico a 34 km di quota. Curva verde: emissione di corpo nero della superficie terrestre a 306 K (gradi Kelvin) (circa +32.85 °C); curva blu: emissione di corpo nero della tropopausa a 192 K (circa -81.15 °C); curva rossa: radianza misurata nell'esperimento. Si tratta della prima misura spettralmente risolta di tutta la radianza includendo anche le componenti a grande lunghezza d'onda. Si nota, in particolare, il contributo dei principali gas che causano l'effetto serra. (Riadattata da Palchetti et al., *Atmos. Chem. Phys* 2006.)

Effetto serra: REFIR-PAD, Teresina; Brasile, 30 giugno 2005

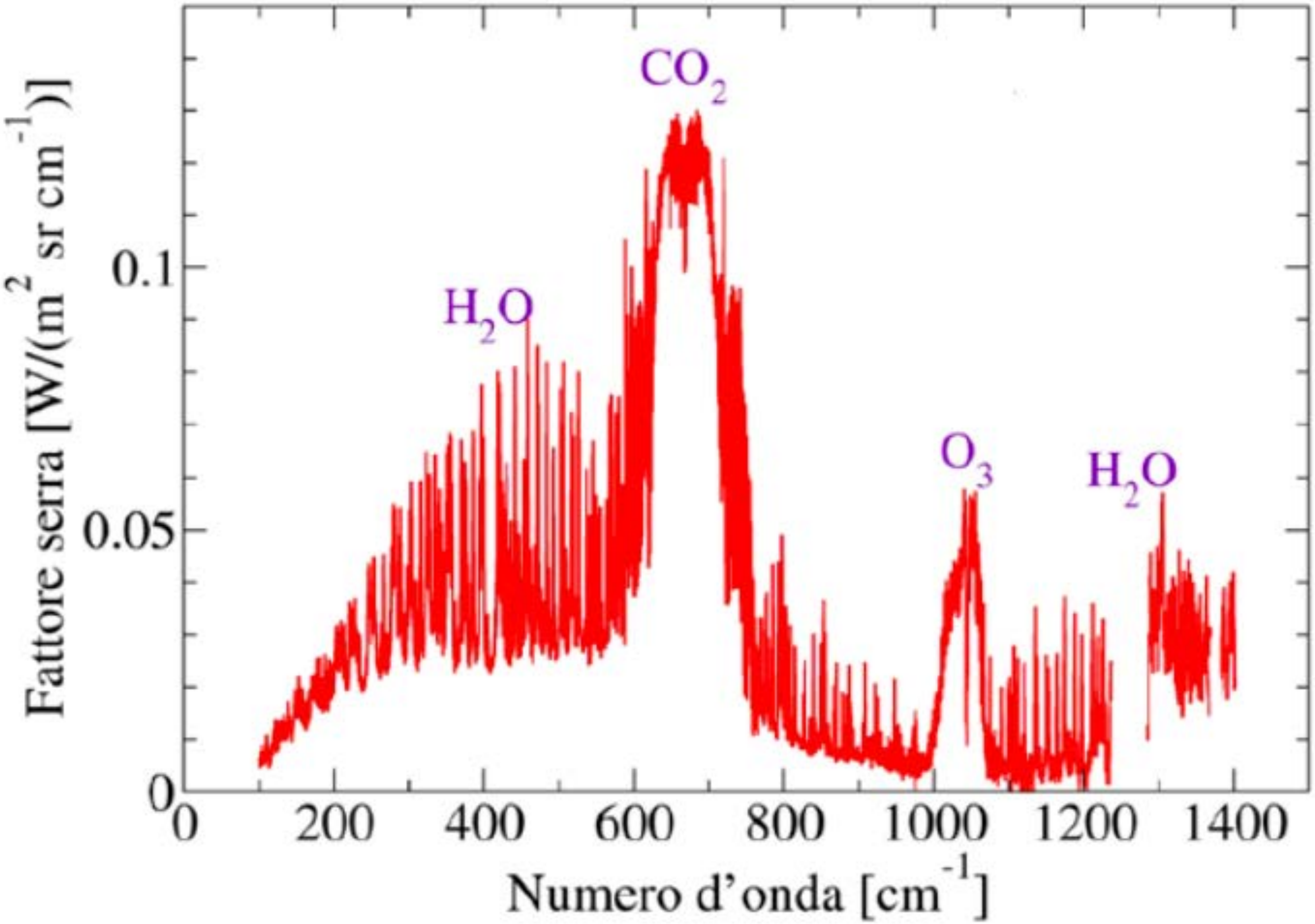
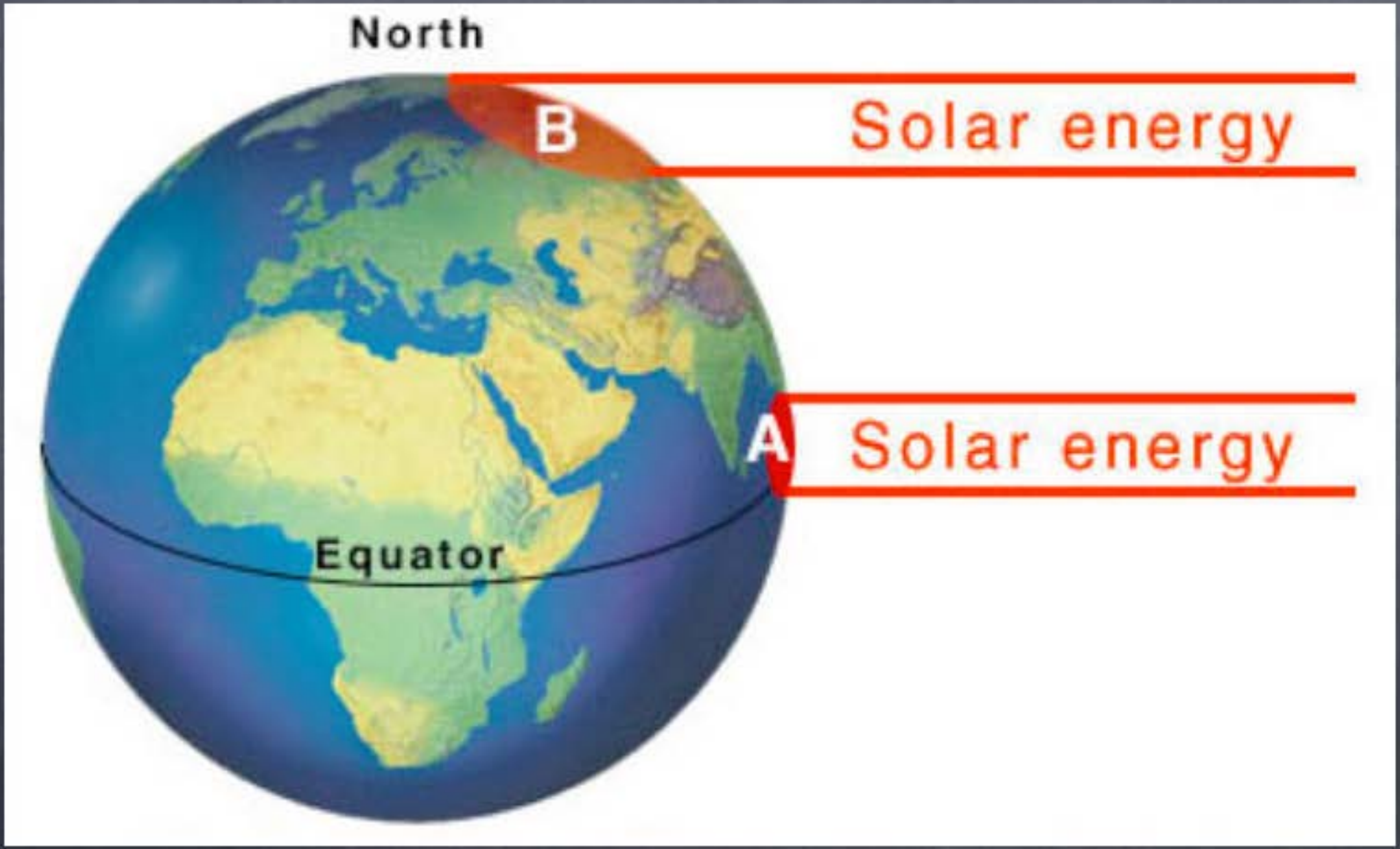


Figura 1b. Quantificazione dell'effetto serra, ottenuta dalla differenza fra l'emissione della superficie terrestre (curva verde in figura 1a) e l'emissione misurata in stratosfera (curva rossa in figura 1a). Le misure sono state effettuate da ricercatori dell'Istituto di Fisica Applicata del CNR con un esperimento effettuato da pallone stratosferico. (Riadattata da Palchetti et al., *Atmos. Chem. Phys* 2006.)

Beyond a point-wise Earth: latitudinal dependence

Solar energy is not evenly distributed on Earth



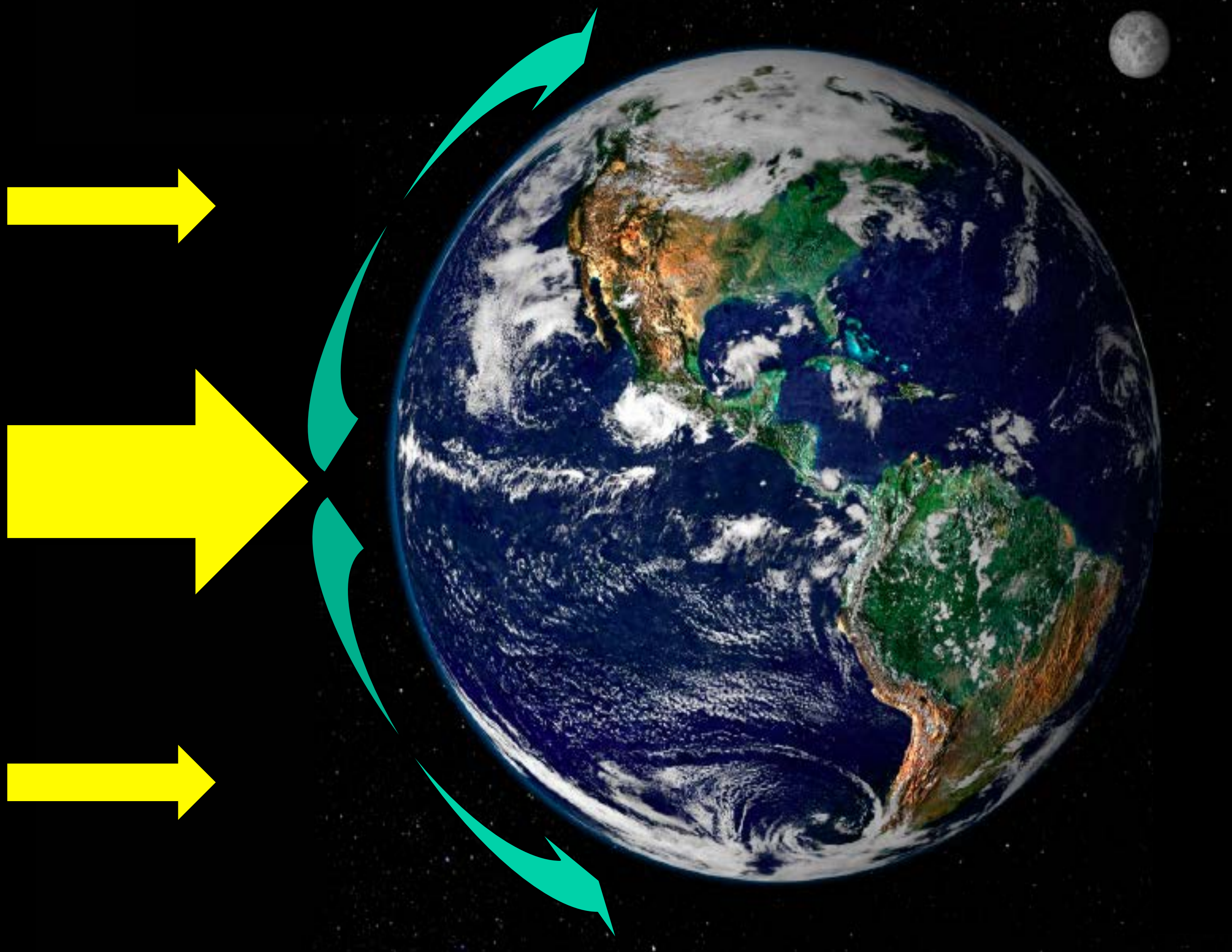
Local equilibrium at latitude ϕ

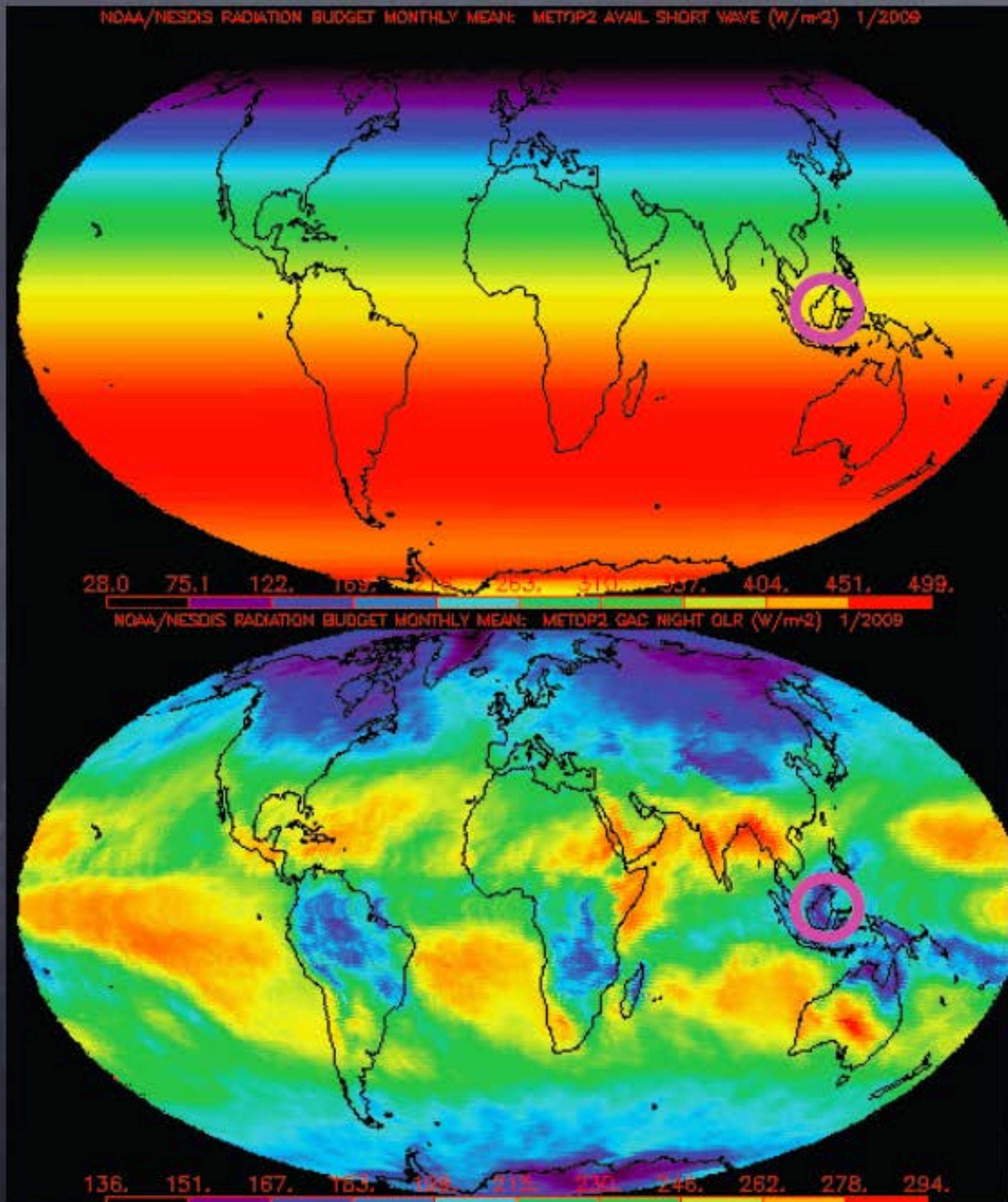
$$T_{loc} = \left[\frac{1}{4\sigma} (1 - \bar{\alpha}) \, f(\phi) \right]^{1/4}$$

$$T_{eq} \approx 270 \, K$$

$$T_{NP} \approx 170 \, K \qquad T_{SP} \approx 150 \, K$$

Tropics get more solar heating than the Poles: Heat transport from Equator to Poles





IN

solar

~410 W/m^2

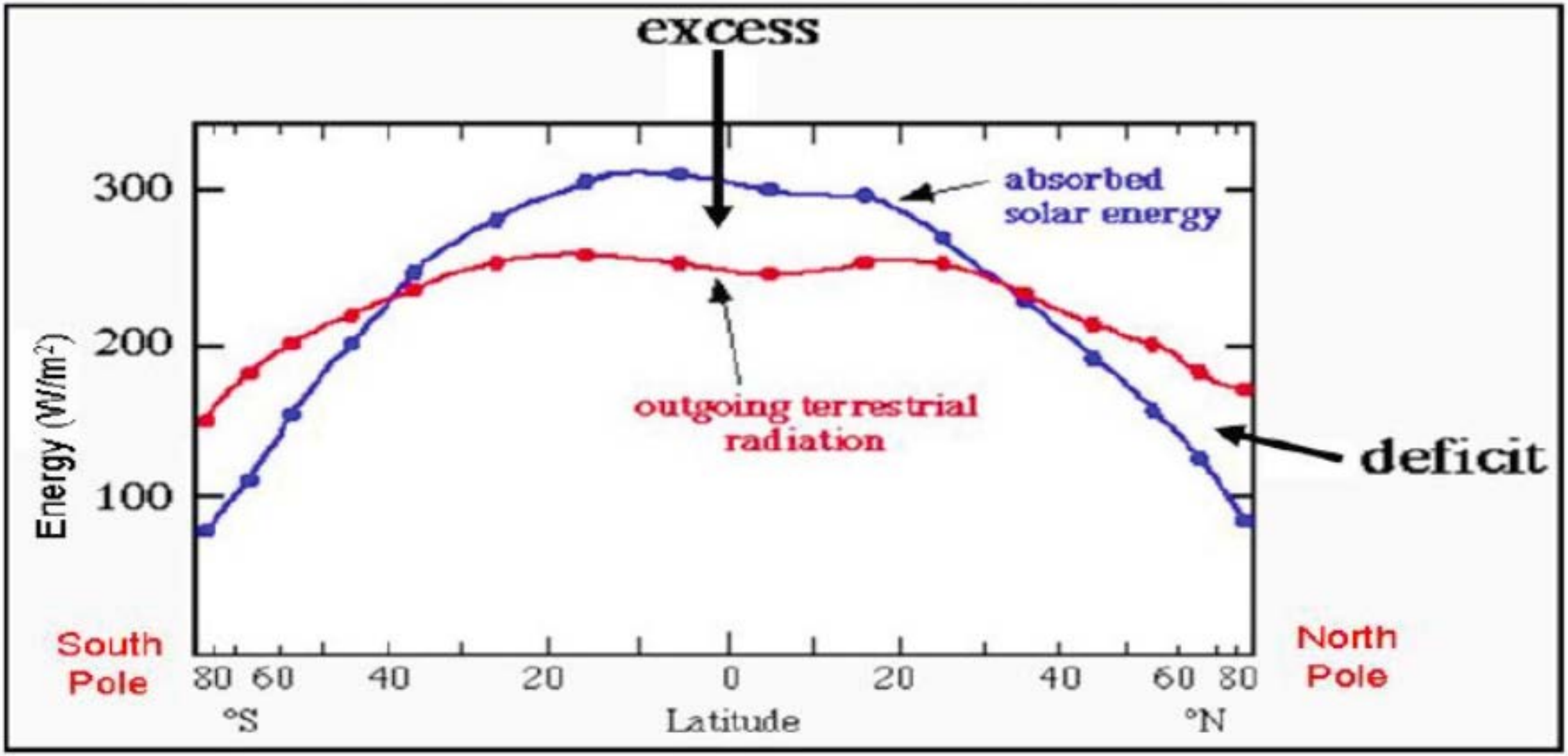
Energy does not go out from where it came in

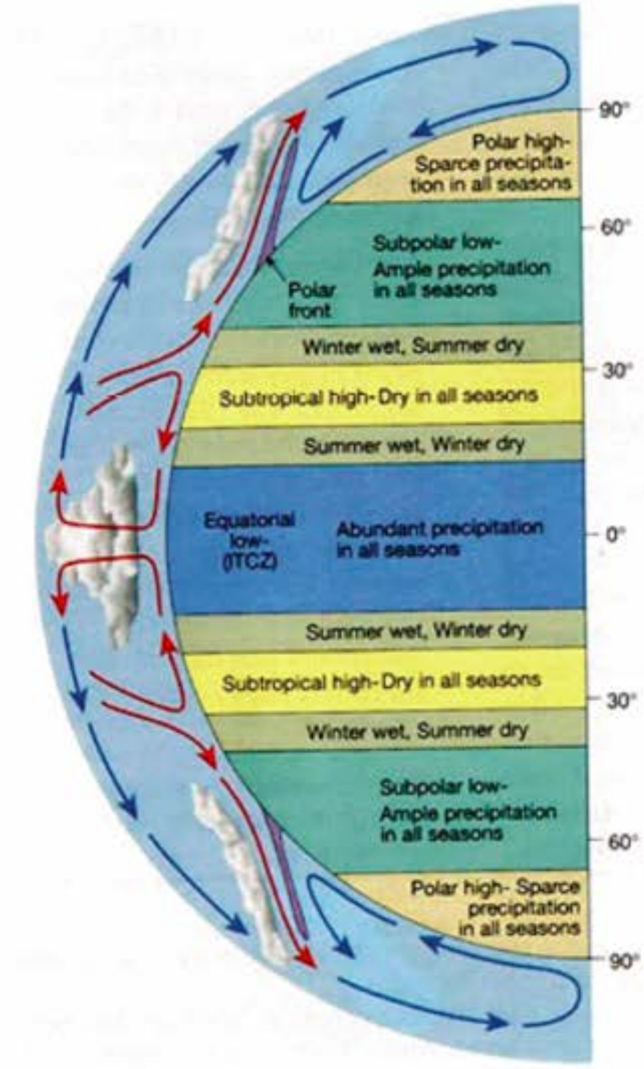
~170 W/m^2

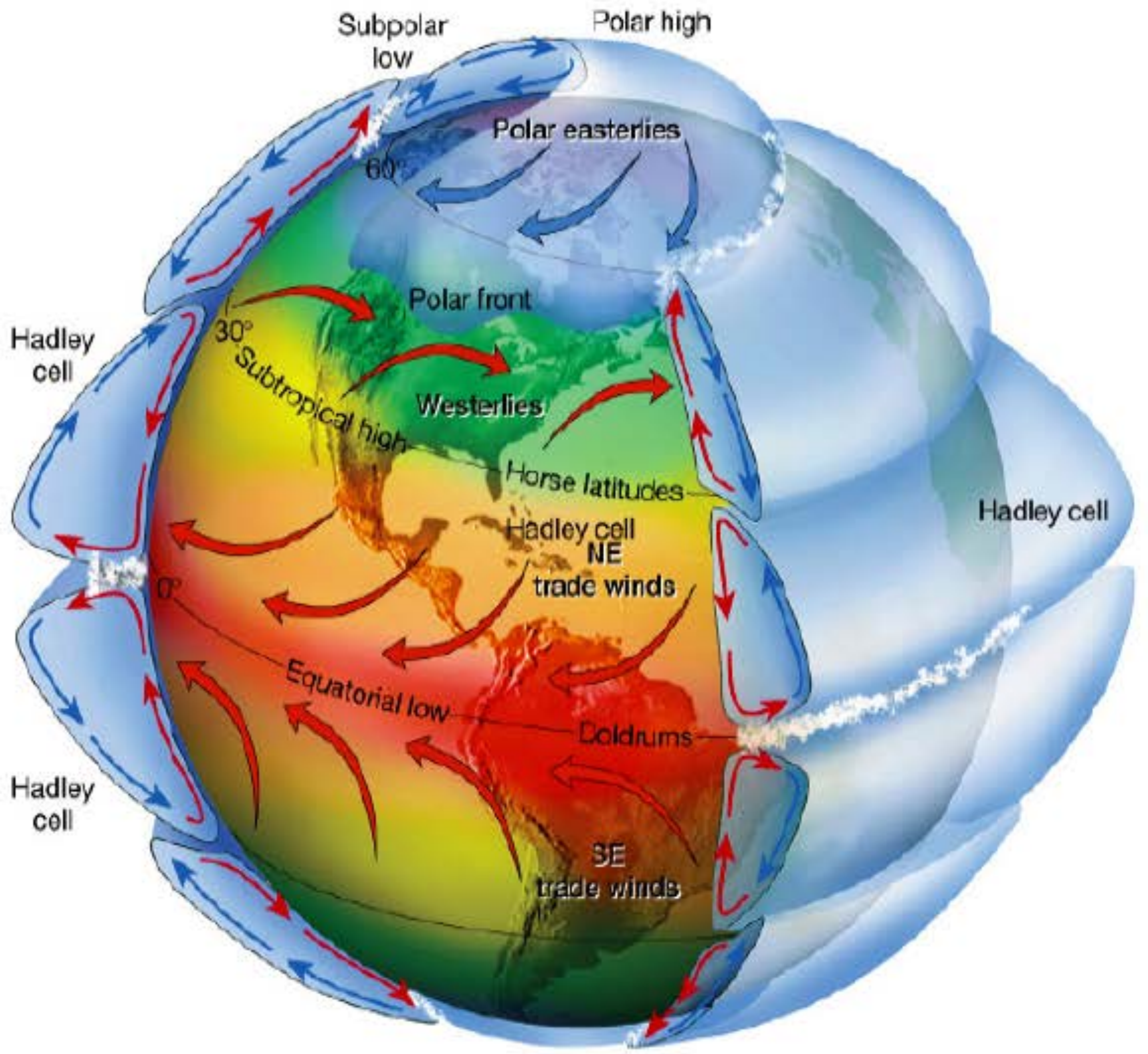
OUT

infrared

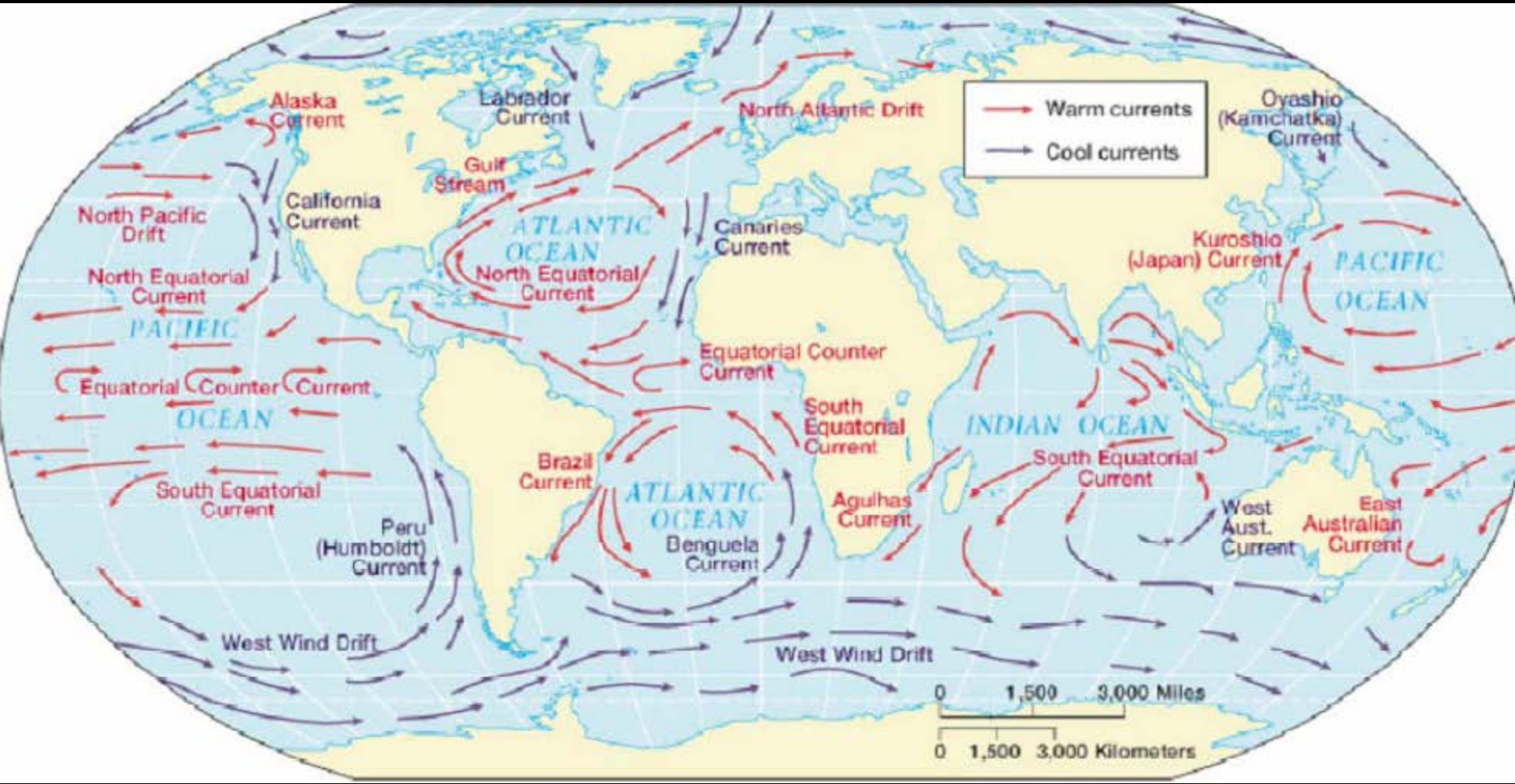
An important effect of the fluid envelope: unbalance between absorbed and emitted radiation



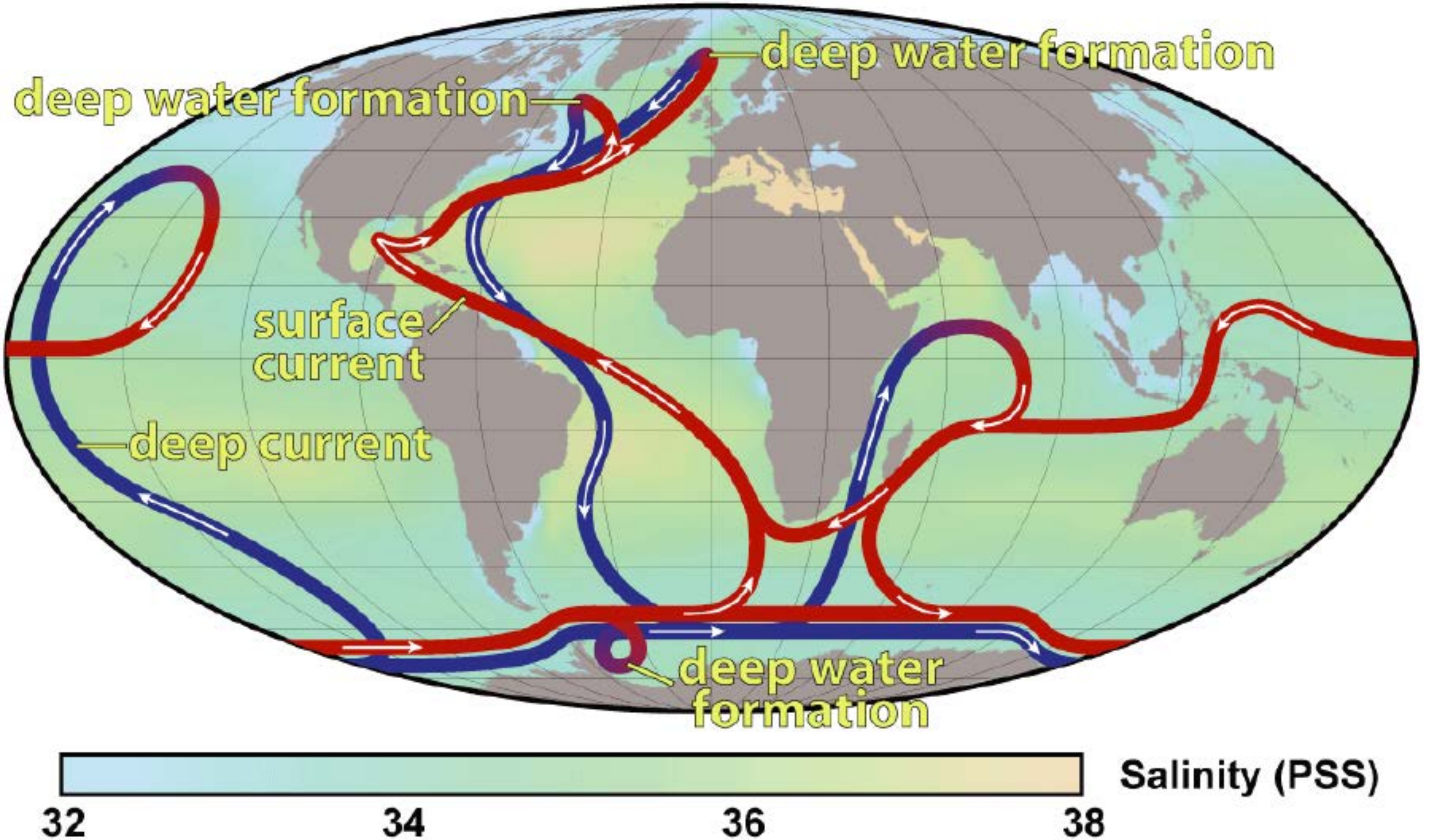




Atmospheric circulation



Wind-driven ocean circulation



Thermohaline circulation

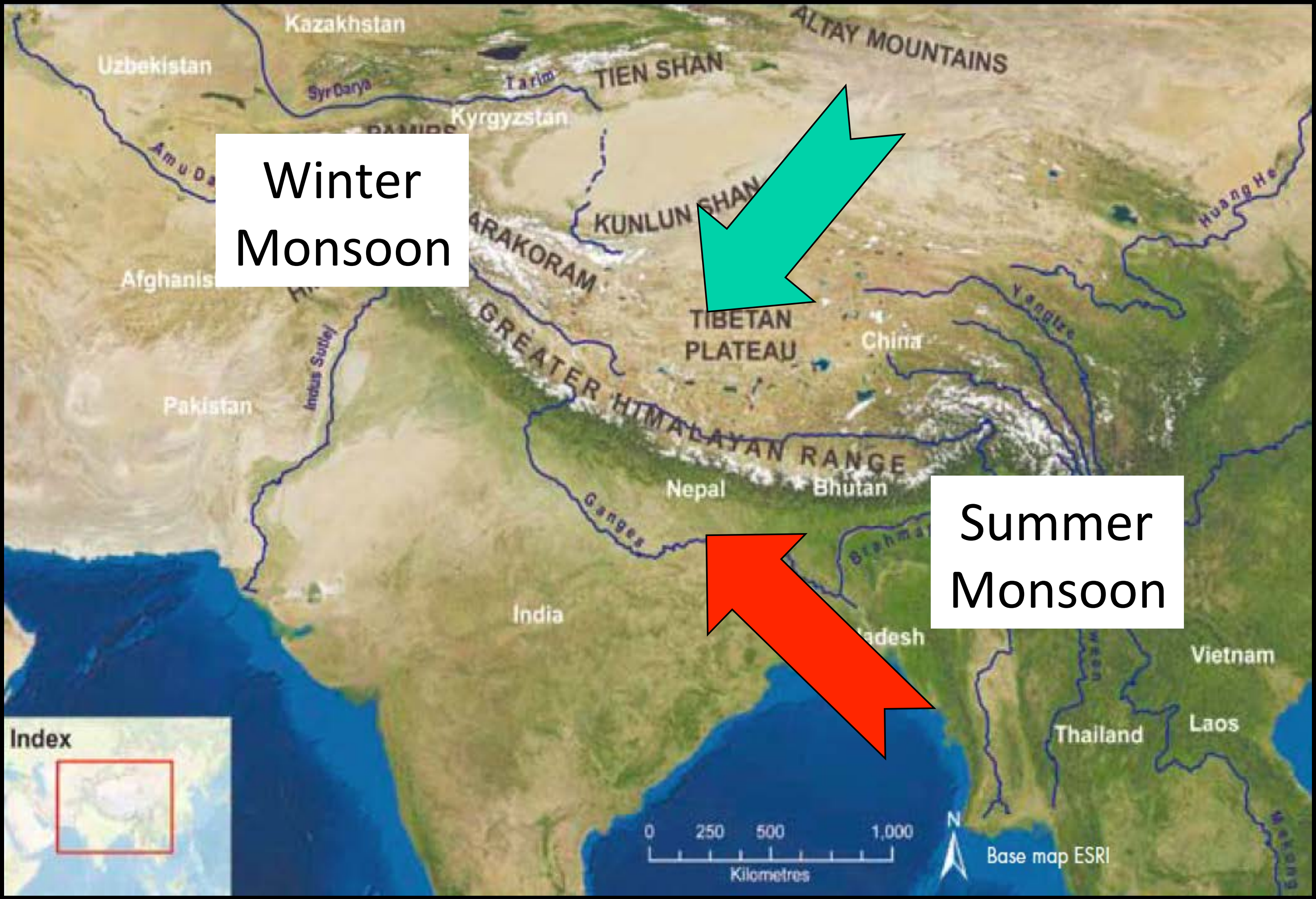
Mean state

versus

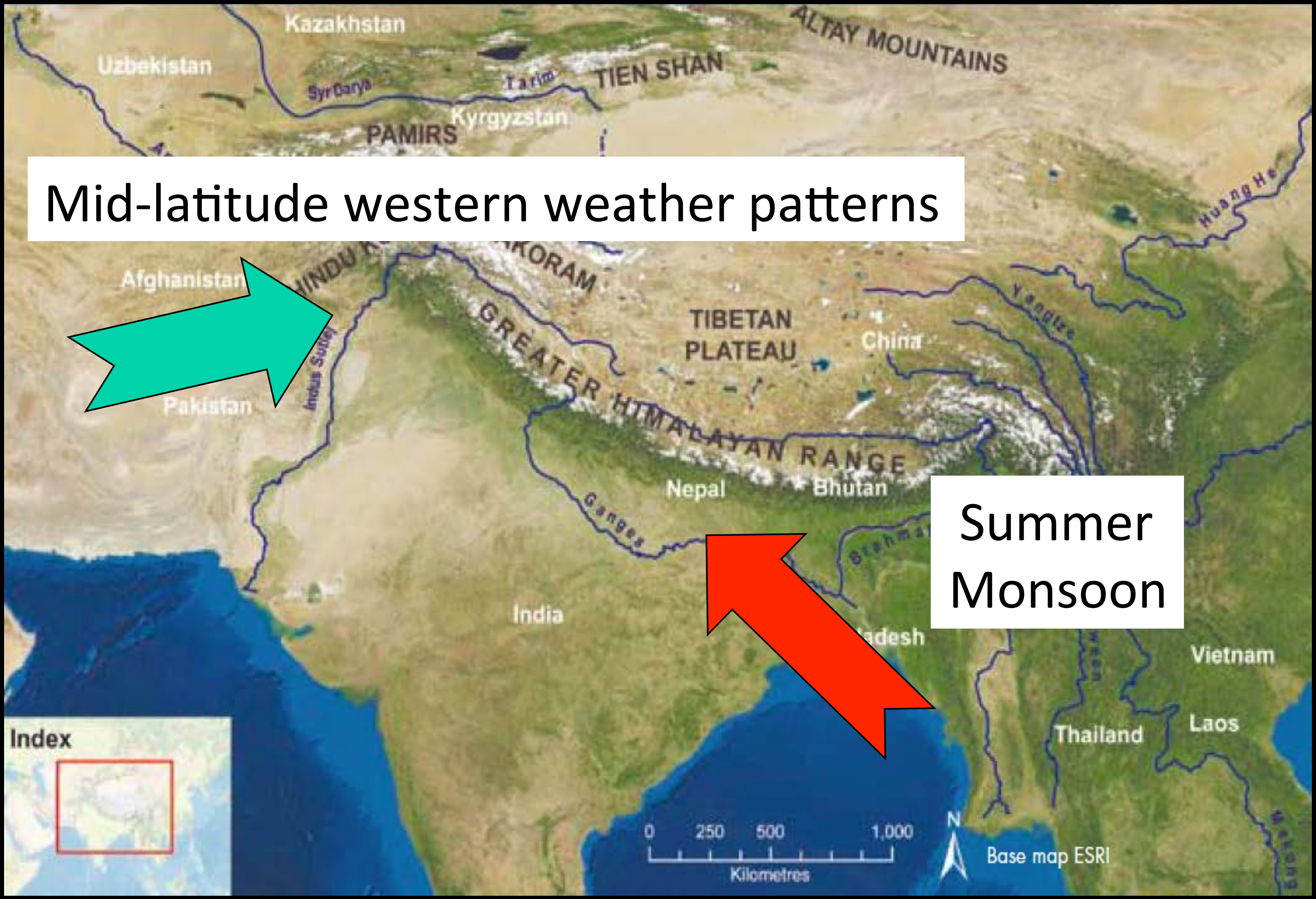
Spatial-temporal variability

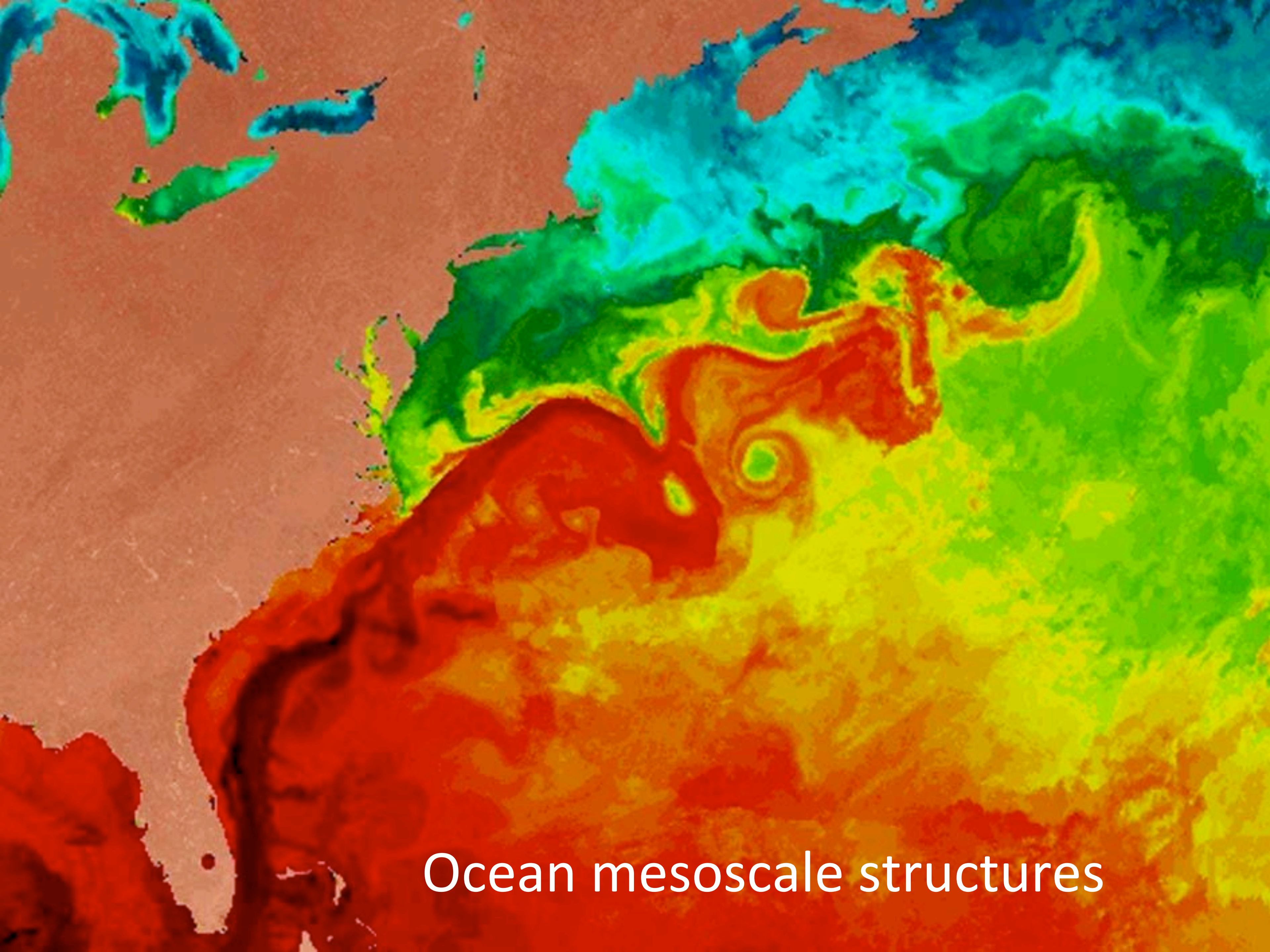
Atmospheric dynamics at midlatitudes: Mean circulation and transient eddies

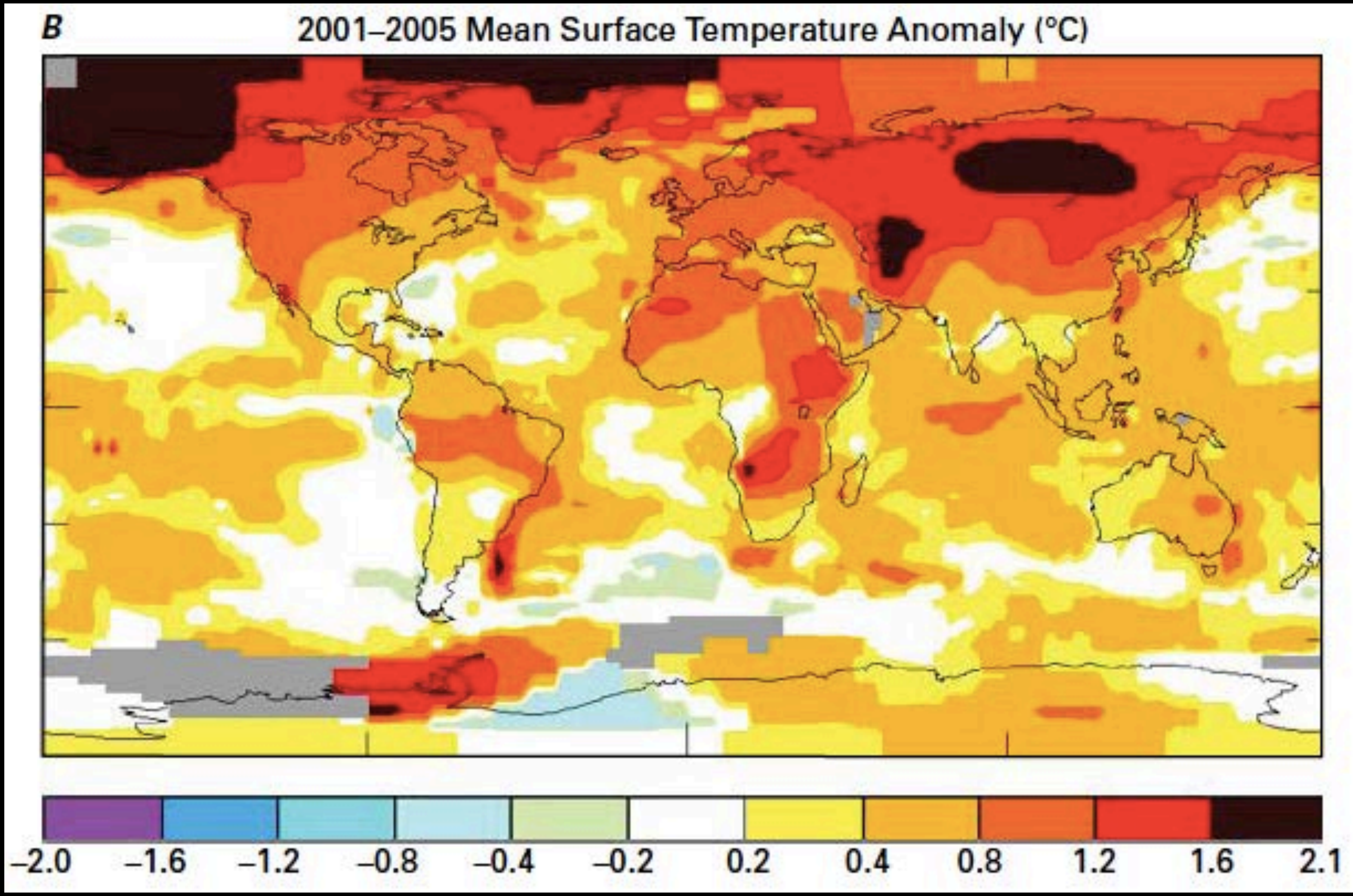
Monsoons


Winter Monsoon
Summer Monsoon
Kazakhstan
Uzbekistan
ALTAY MOUNTAINS
TIEN SHAN
Syr Darya
Tarim
Kyrgyzstan
Amu Da
KUNLUN SHAN
ARAKORAM
Afghanis
TIBETAN PLATEAU
China
Huang He
Yangtze
Indus Sutlej
Pakistan
GREATER HIMALAYAN RANGE
Nepal
Bhutan
Ganges
India
adesh
Vietnam
Thailand
Laos
Index
0 250 500 1,000
Kilometres
N
Base map ESRI

Monsoons and mid-latitude western weather patterns



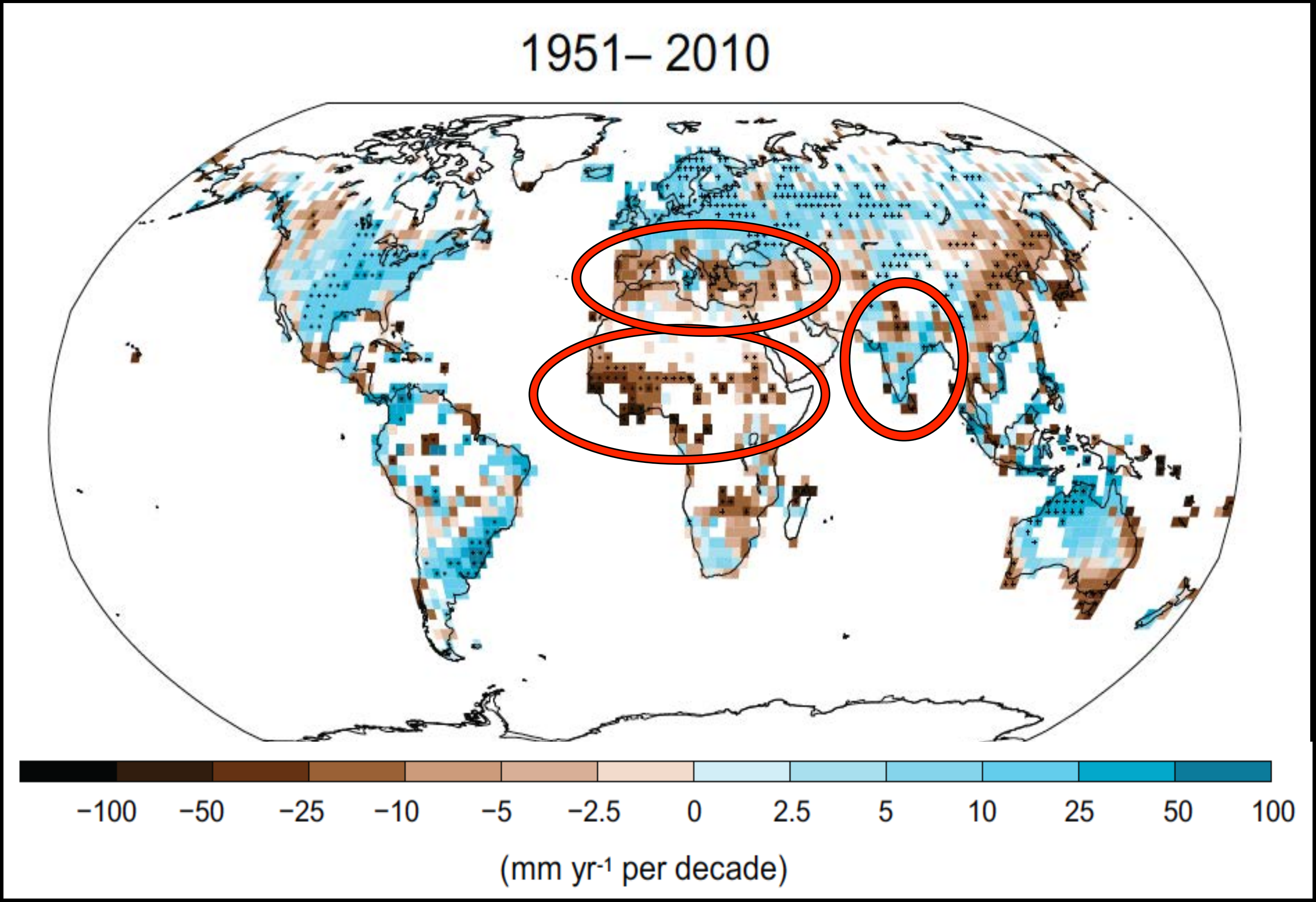

Ocean mesoscale structures



Past Climate Variability and Change in the Arctic and at High Latitudes
US Climate Change Science Program; from: Hansen et al. 2006

Climate change and climate variability are not spatially homogeneous

Precipitation changes: 1951-2010



IPCC 2013

(a) Observed climate change hot-spots - 7 indicators, $p_{95}(|\Delta_i|)$

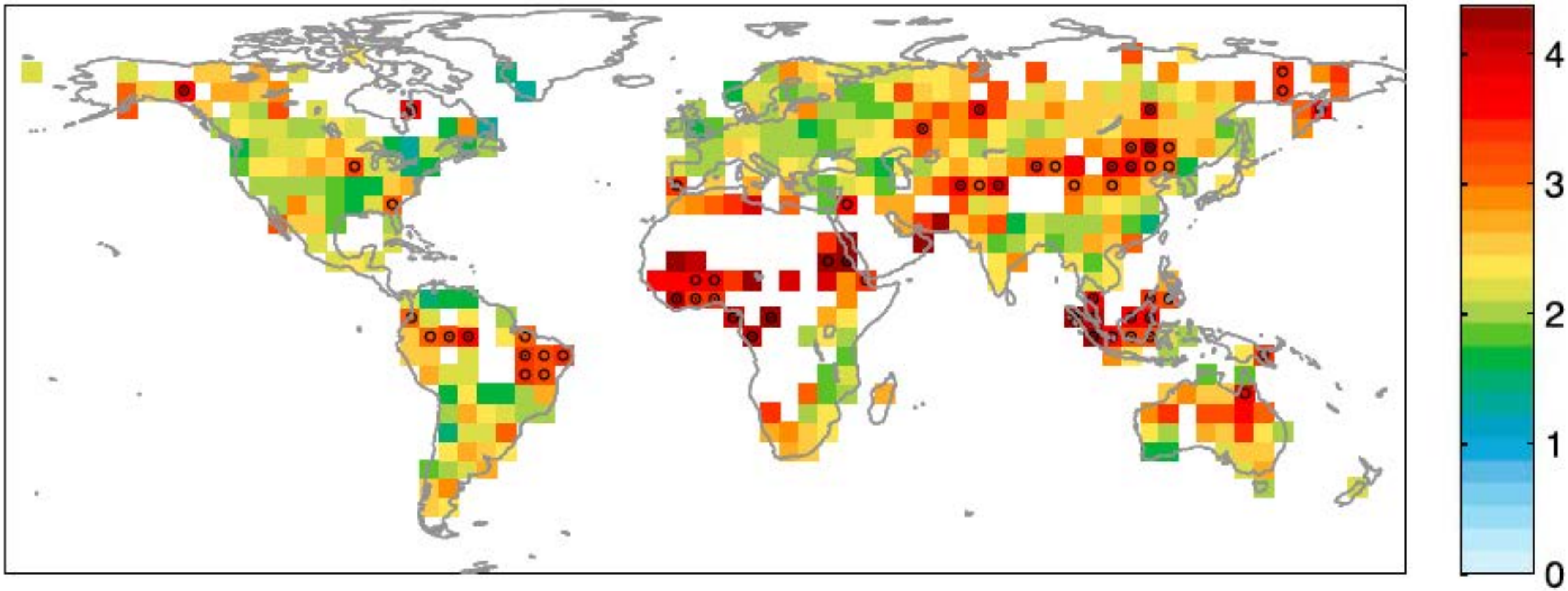
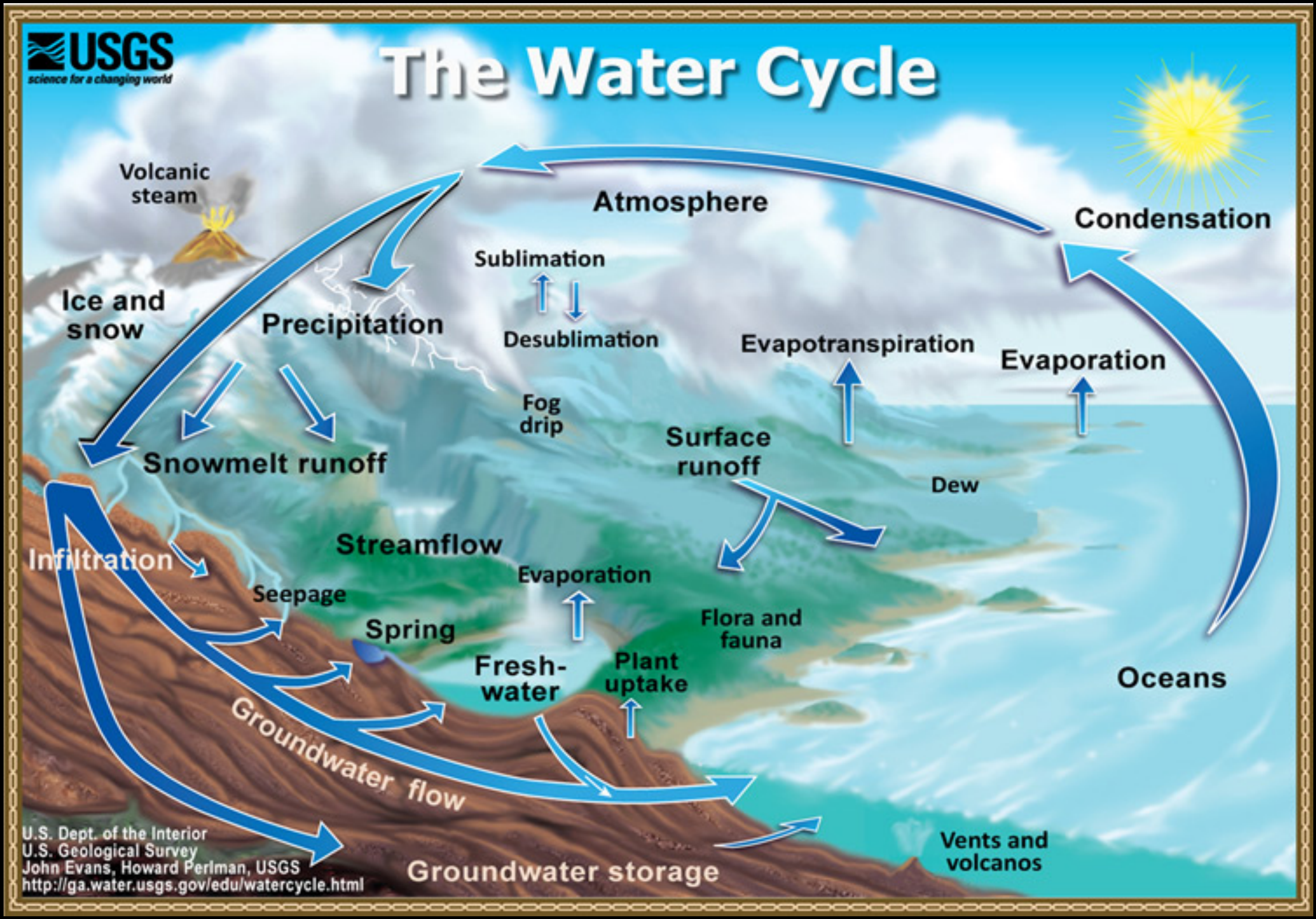


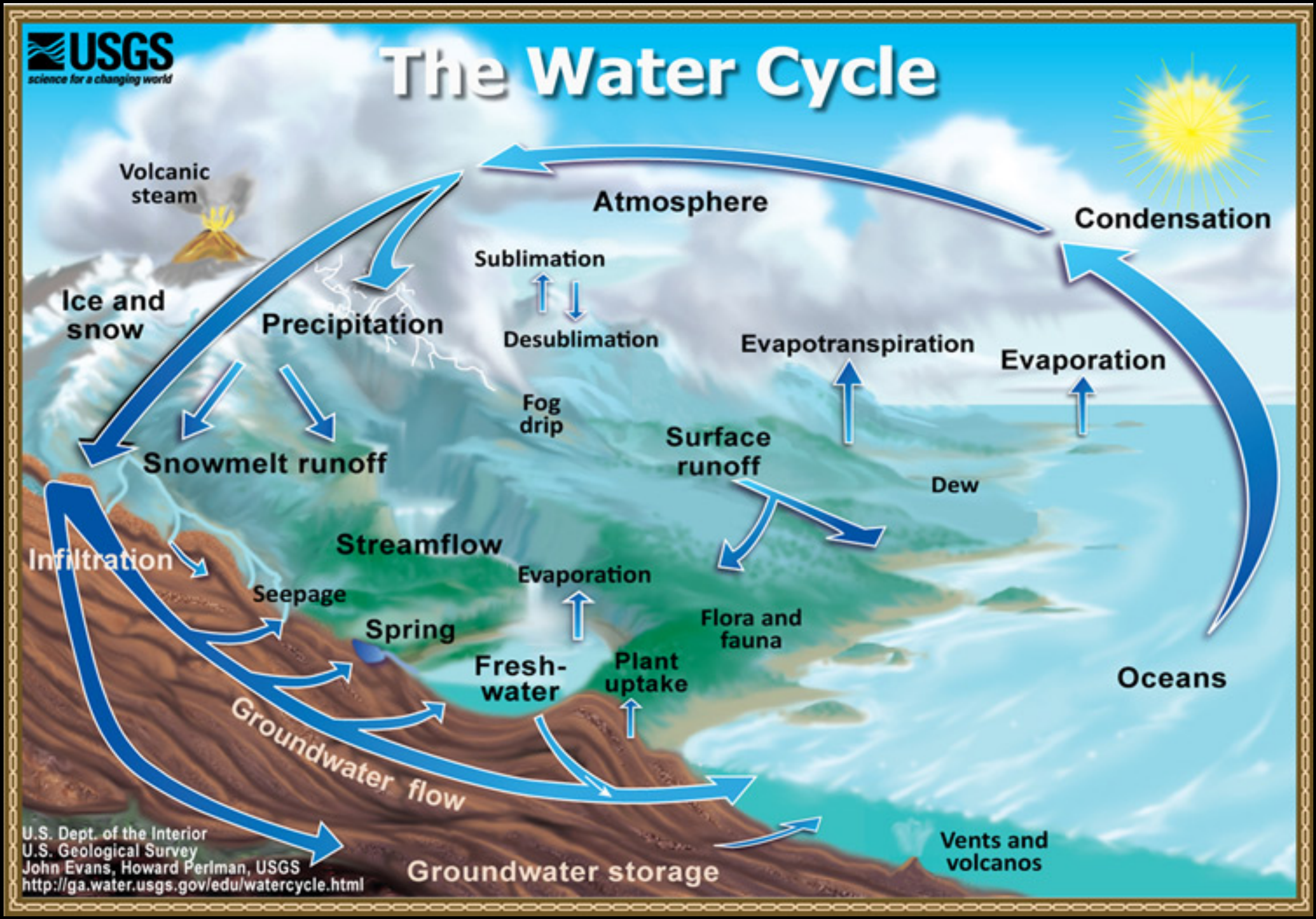
Figure 3. (a) Observed climate change hotspots at grid point scale using the seven indicators and the normalization factor $p_{95}(|\Delta_i|)$; (b) number of individual climate indicators that show significant change; (c) hotspots considering only four indicators (ΔT, ΔT_{var}, f_{hot}, and ΔP) and the normalization factor $p_{95}(|\Delta_i|)$; and (d) the same as Figure 3c but with the normalization factor $\max(|\Delta_i|)$ (the global maximum of the field). The data sets employed are $GISTEMP_{1200}$ and GPCC. Black points (empty circles) indicate significant hotspots at 95% (90%) level.

Turco et al. GRL 2015

Climate change hotspots

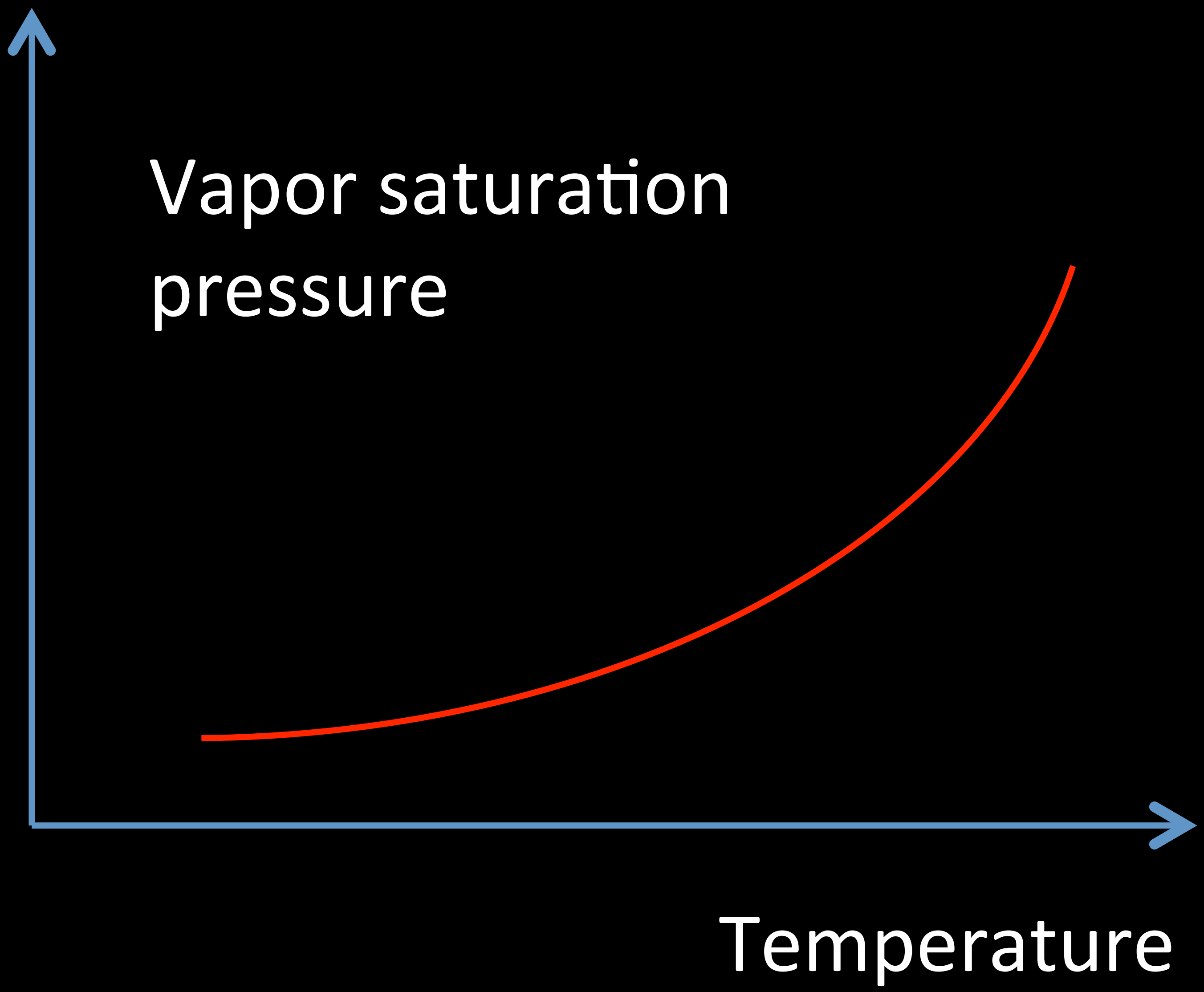


The hydrologic cycle

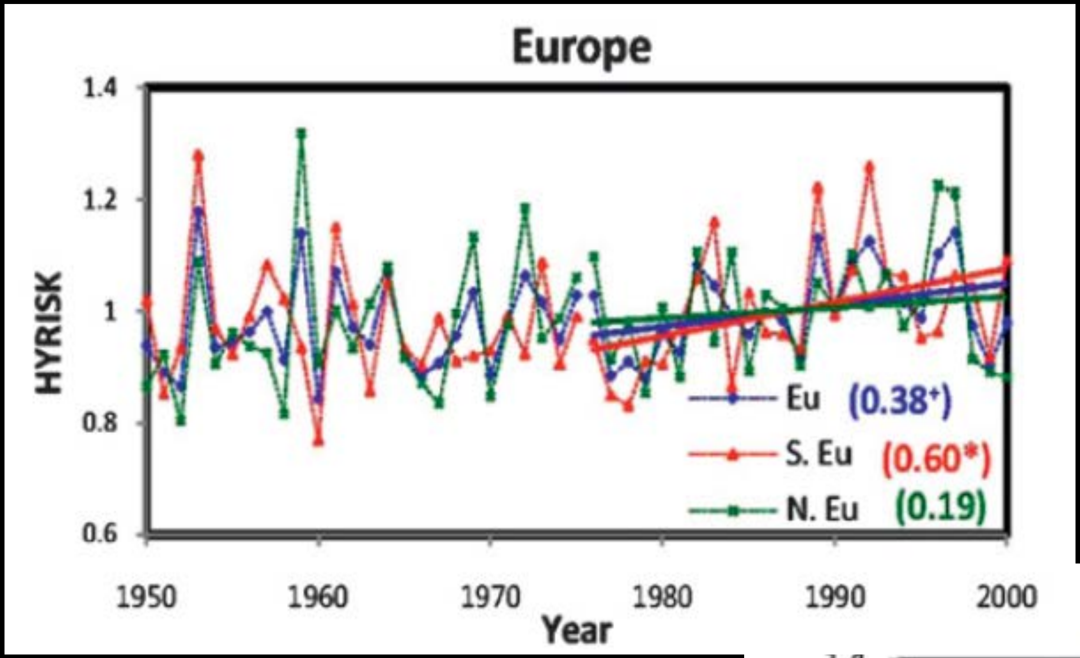


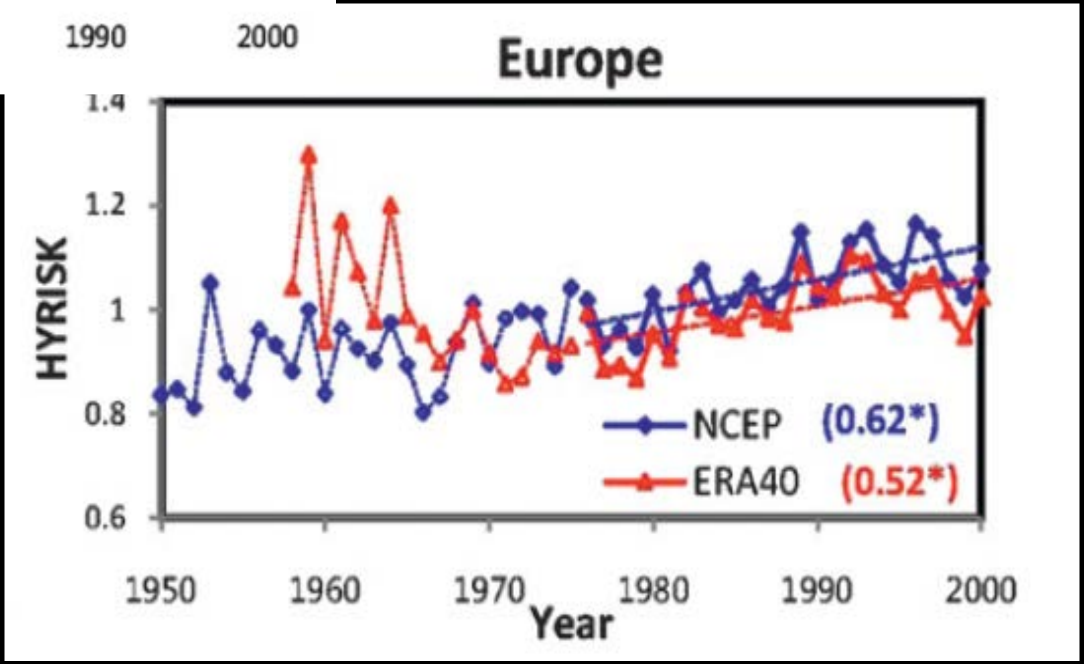
Does the hydrologic cycle become stronger in warm climates?

Clausius-Clapeyron and relative humidity



Intensity of the water cycle, HI-INT indicator

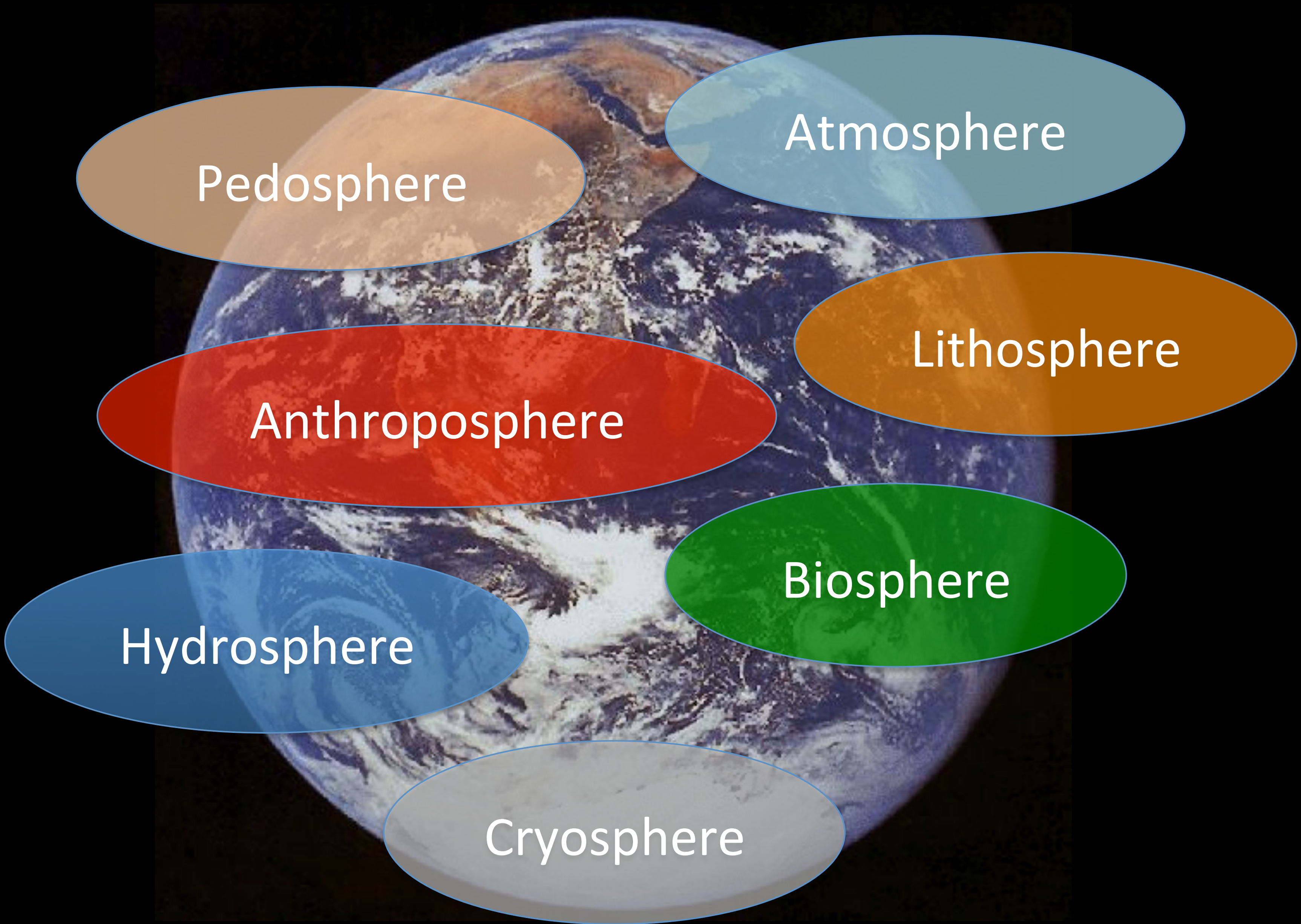




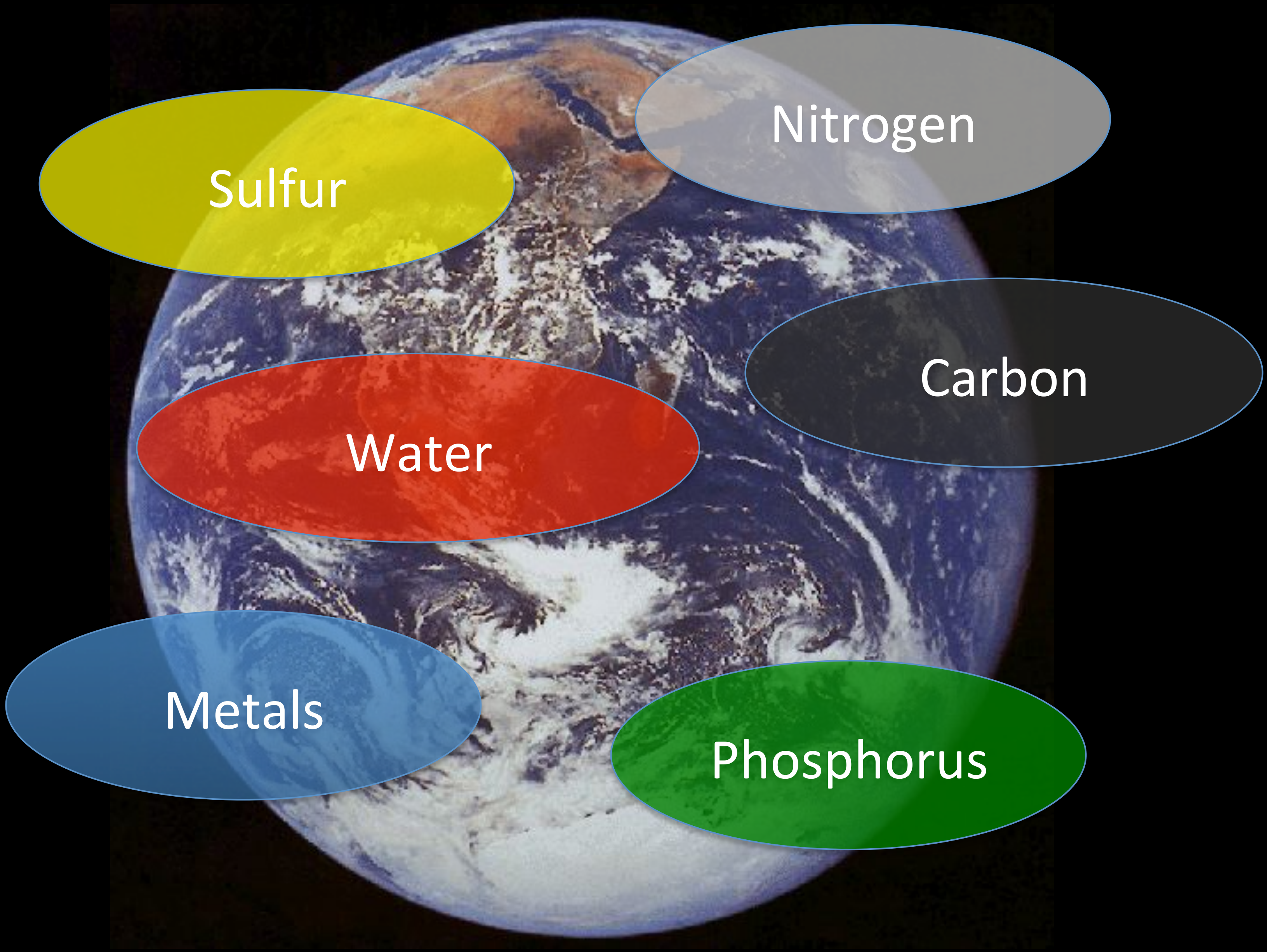
Giorgi et al.
J. Climate 2011

How can we model this extremely complex and complicated system?

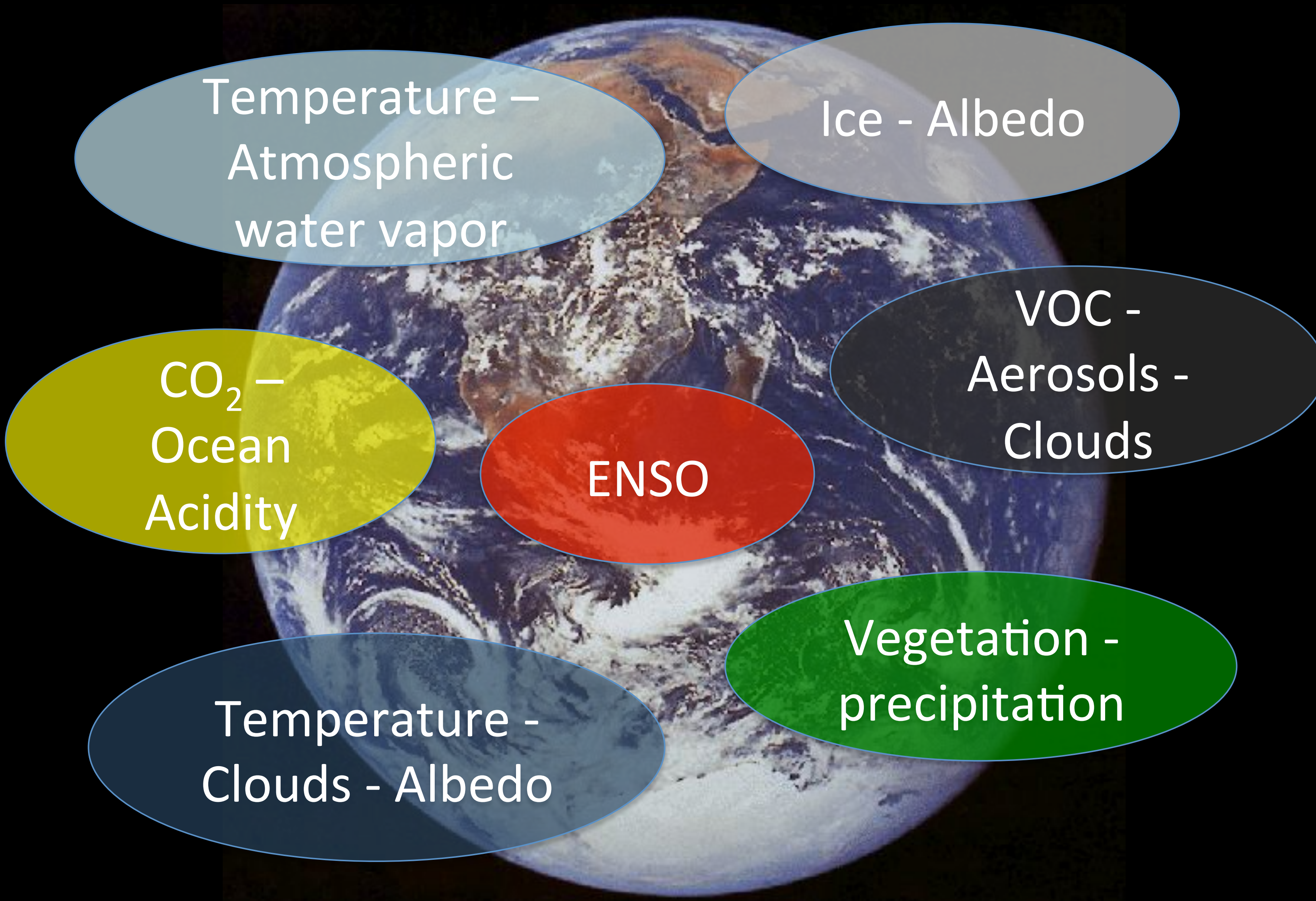
Reductionism I: the "spheres"



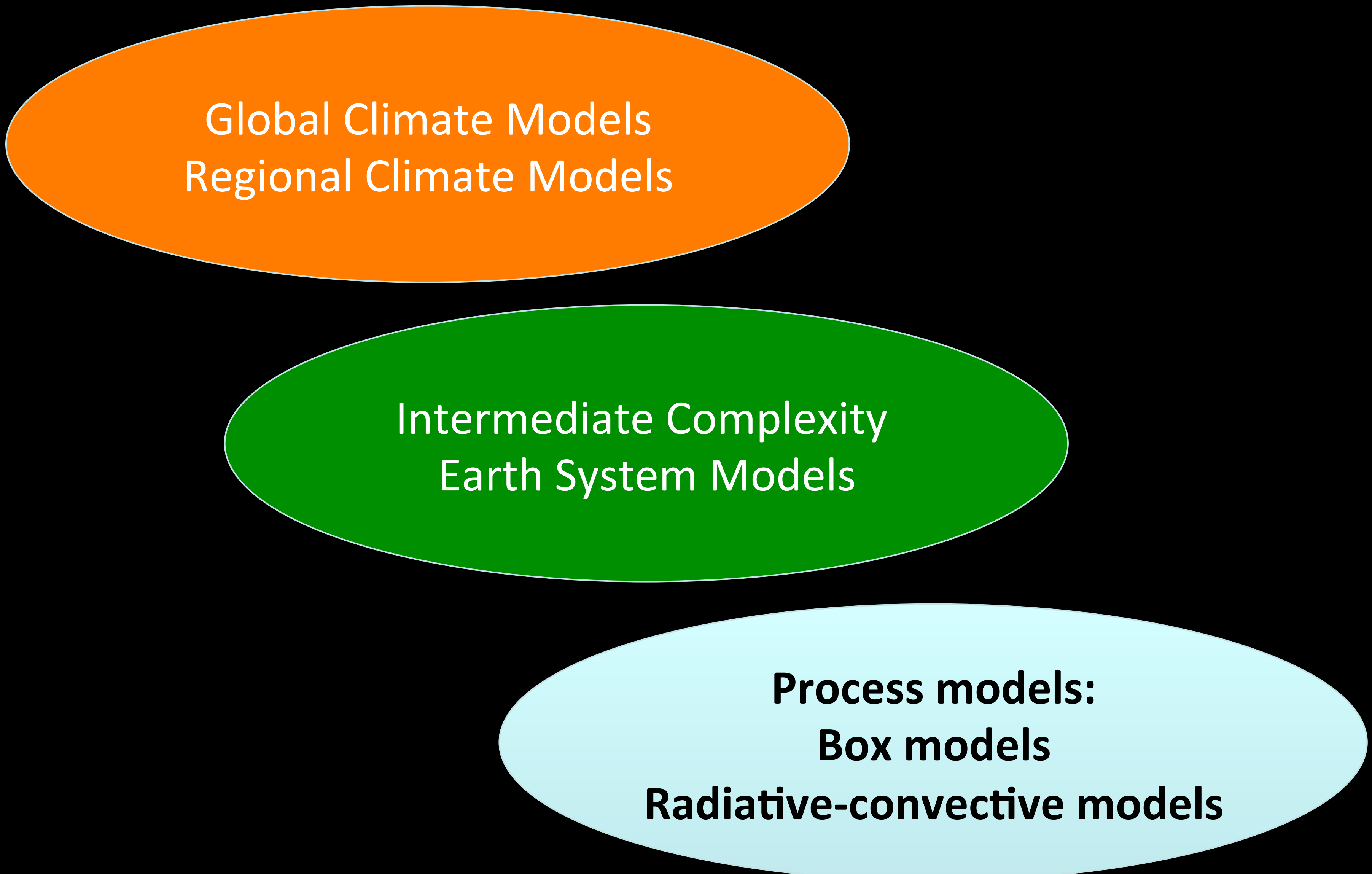
Reductionism II: biogeochemical cycles



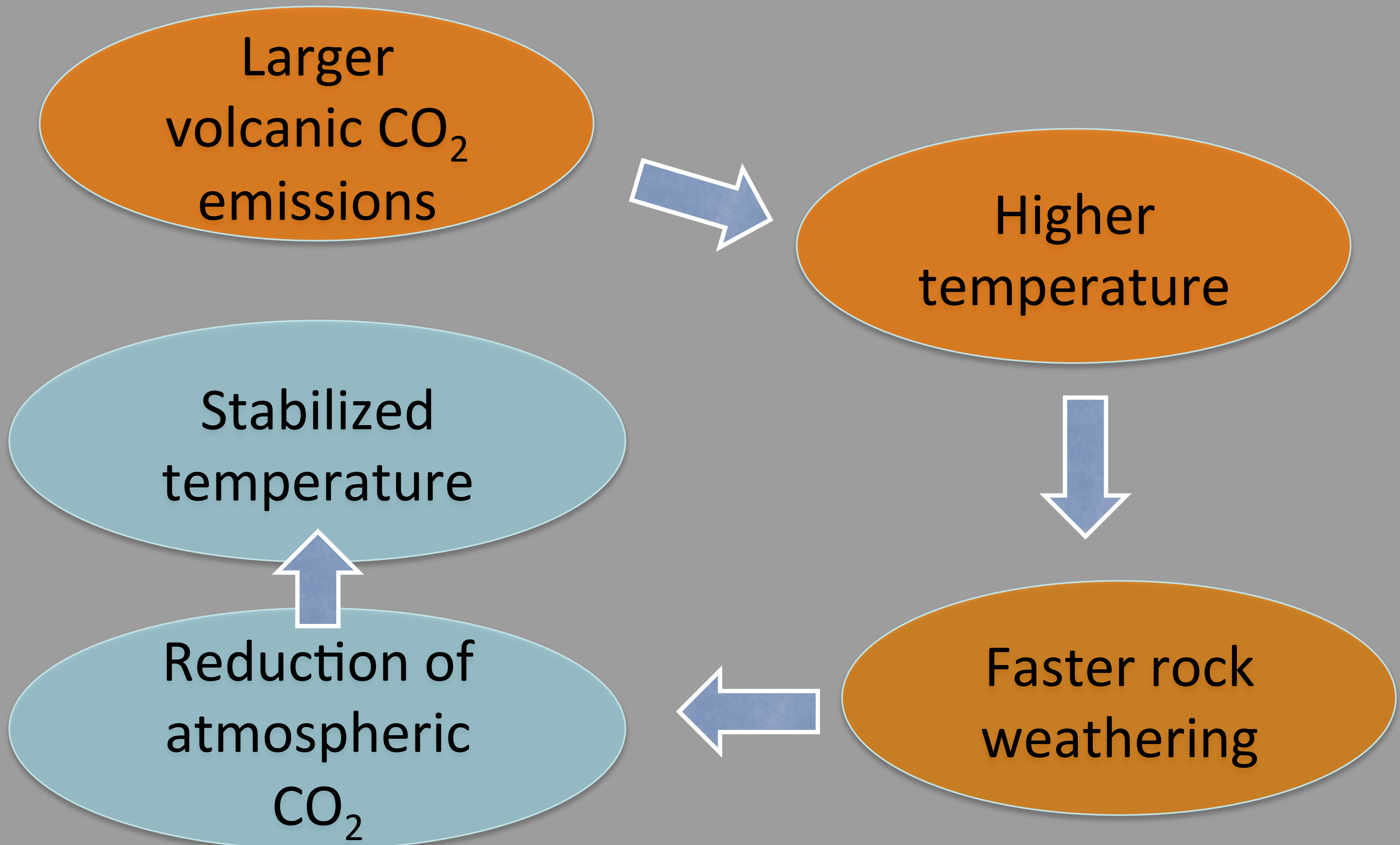
Reductionism III: process decomposition



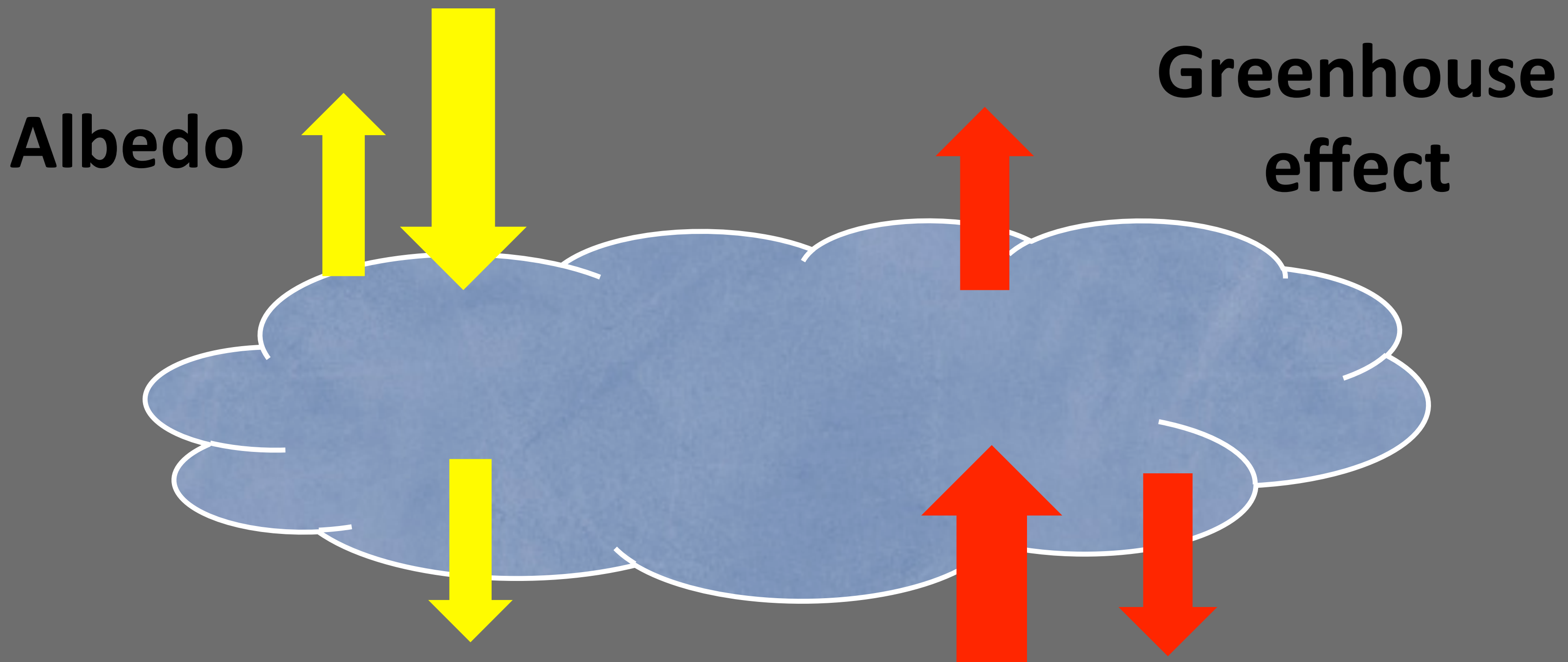
The climate modeling hierarchy



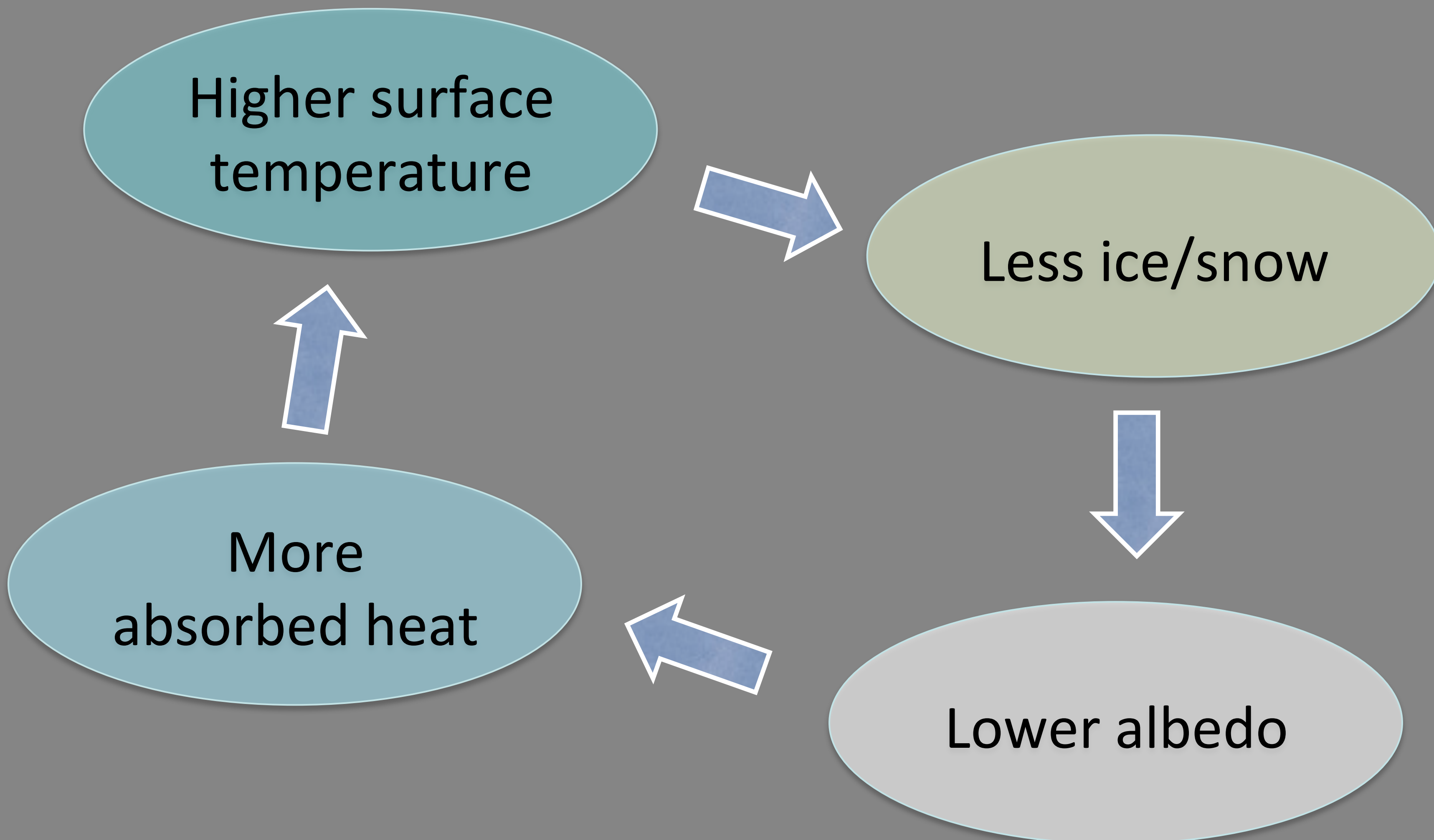
A stabilizing feedback: volcanic emissions and rock weathering



A complicated case:
Cloud – temperature feedback



A well-known positive feedback: ice-albedo



What determines the albedo of the Earth?

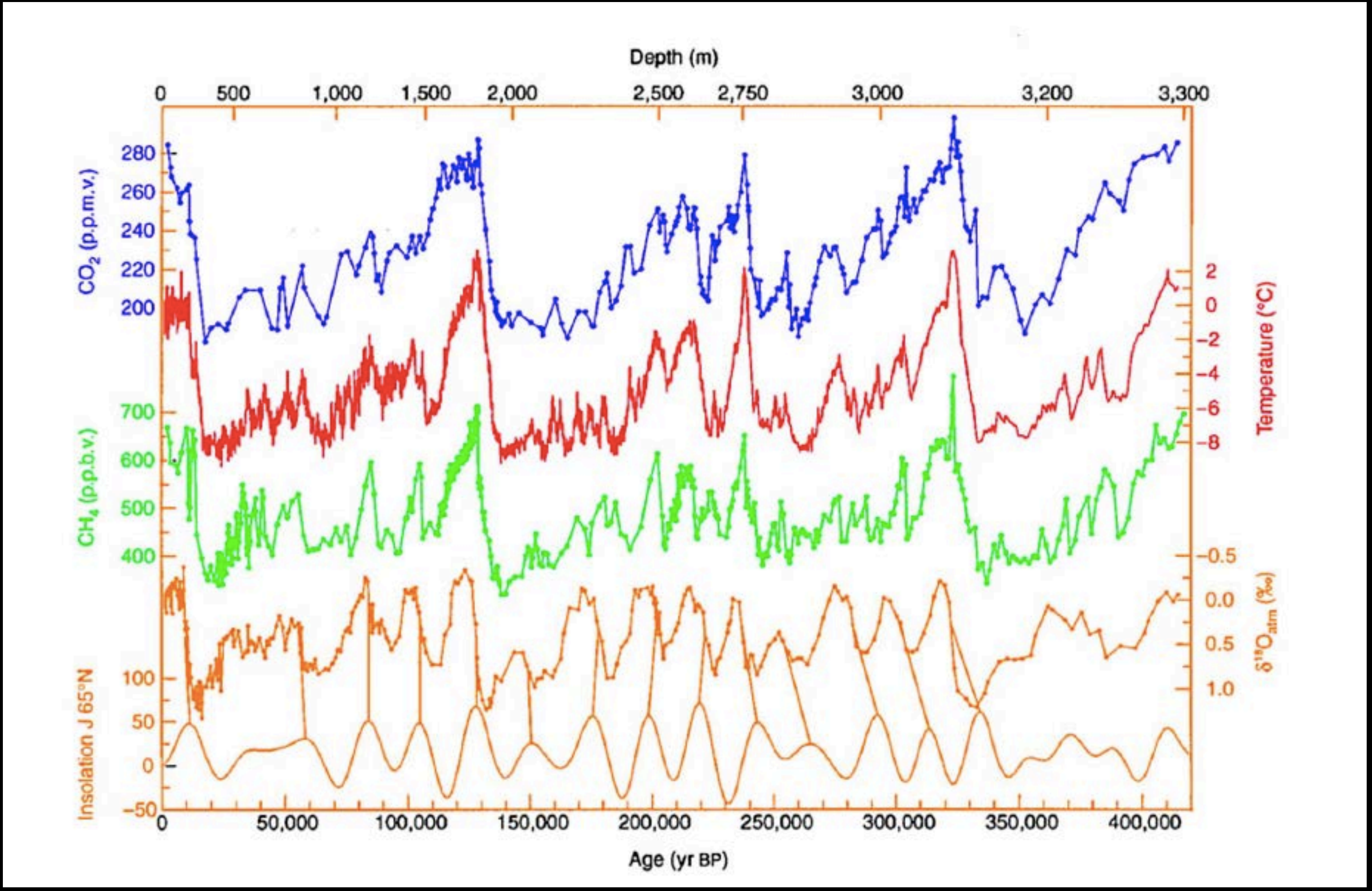
High albedo: snow and ice surfaces

High albedo: clouds

Medium albedo: desert sands, barren land

Low albedo: forests, ocean

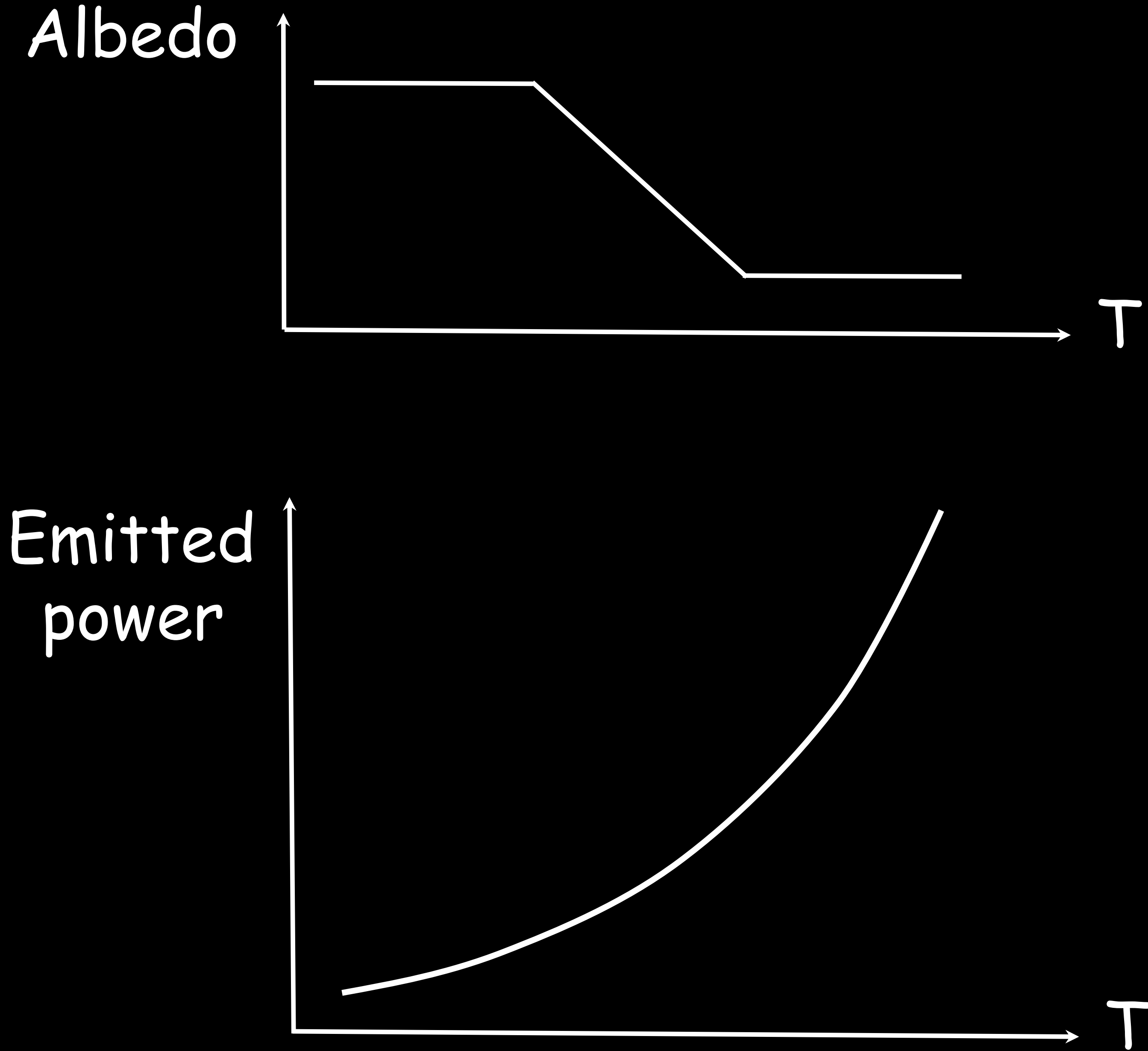
Quaternary glaciations and multiple equilibria of the climate system



Can we find a simple razionalization
of the two states (glacial and interglacial)
of the Earth's climate ?

Ice-albedo feedback:

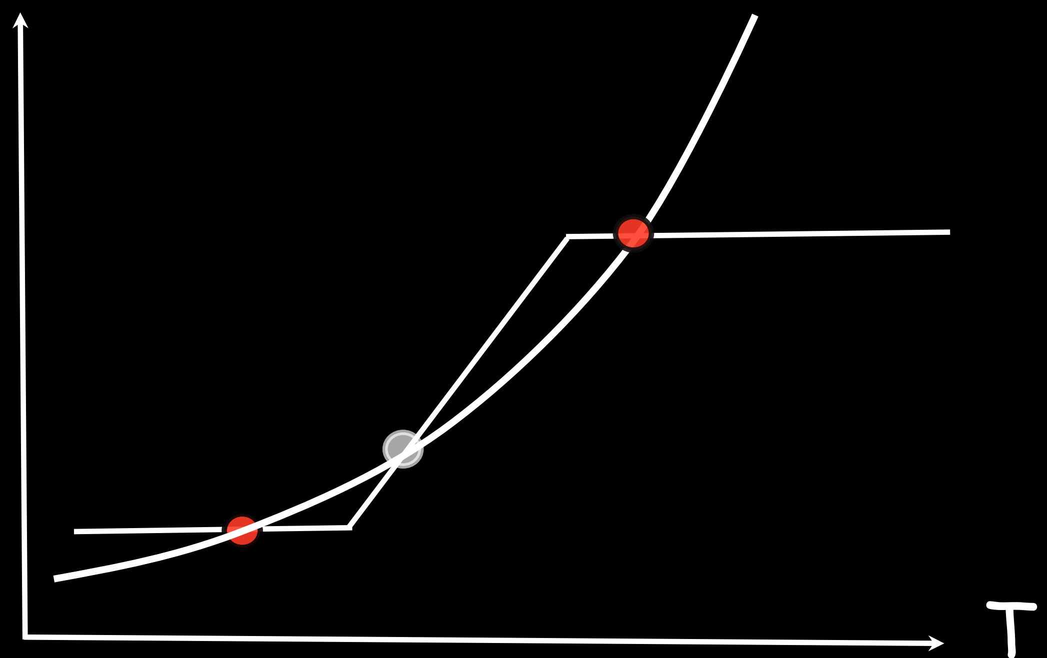
more ice, higher albedo
higher albedo, less absorbed heat
less absorbed heat, lower temperature
lower temperature, more ice



Albedo
T
Emitted power
T

first principle of Thermodynamics

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



equivalent to overdamped motion in a double potential well

A little step further: one-dimensional Energy Balance Models

Zonal averages
Diffusive meridional transport

$$C\frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left[D\left(1-x^2\right)\frac{\partial T}{\partial x}\right] + I = S\left(1-A\right)/4$$

$$I = g\,\sigma\,T^4$$

$$x = \sin\varphi.$$

What can be done with 1D EBM

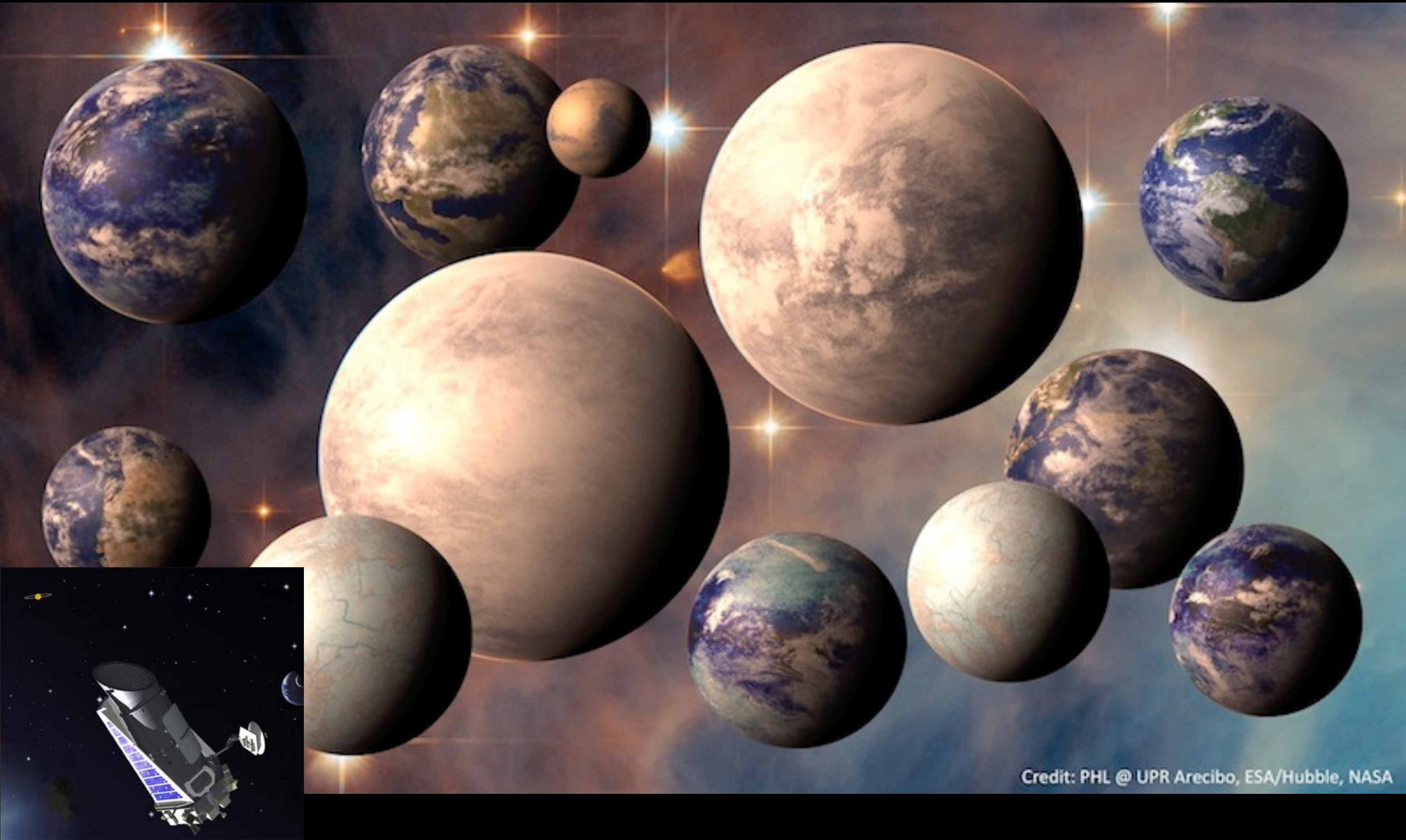
Explore specific processes:
e.g. effect of vegetation cover

Long (and ancient) paleo simulations

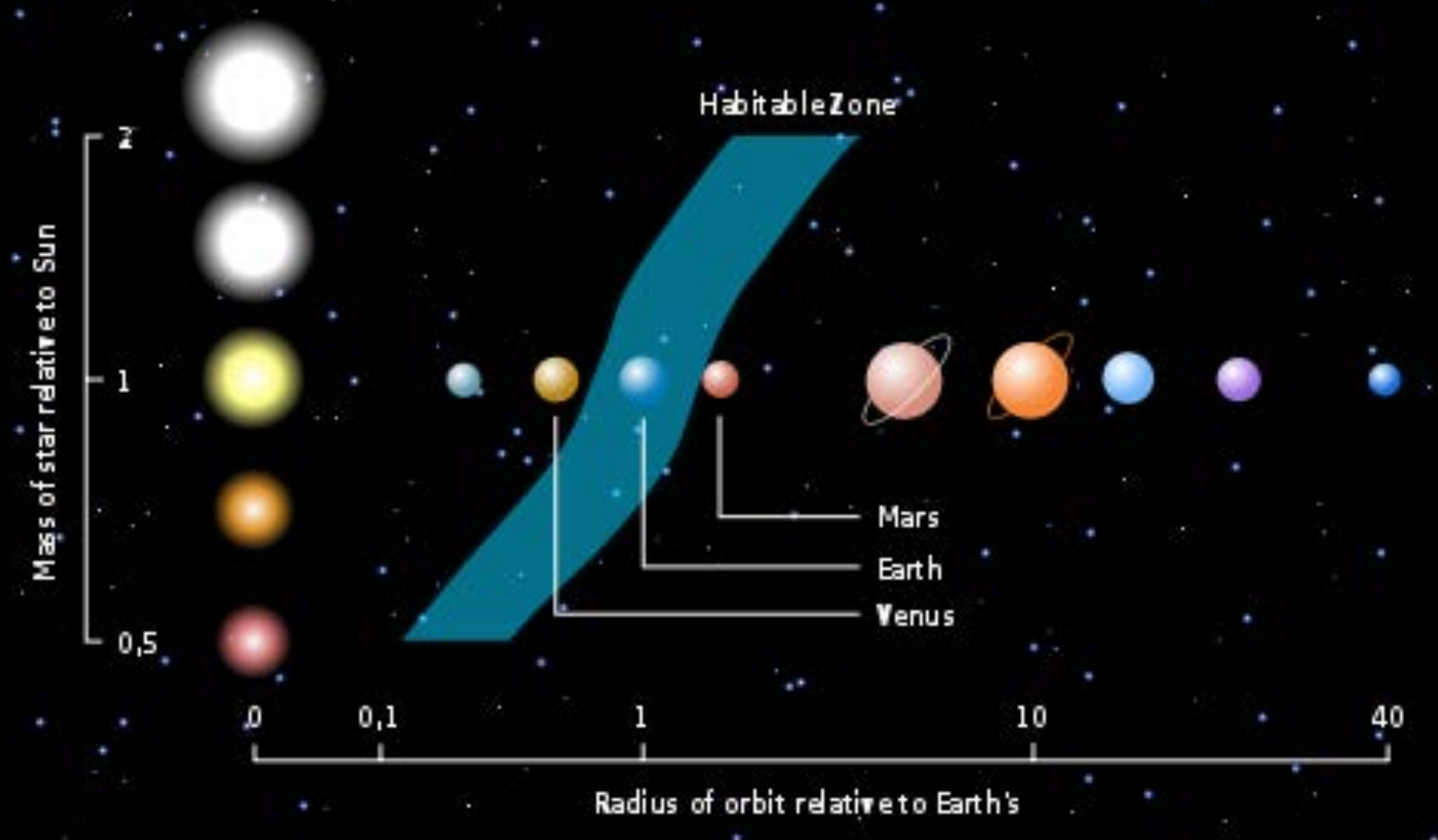
Explore exotic situations

Planetary habitability

A journey into deep space: planetary habitability



Planetary abitability



https://www.e-education.psu.edu/astro801/content/l12_p4.html

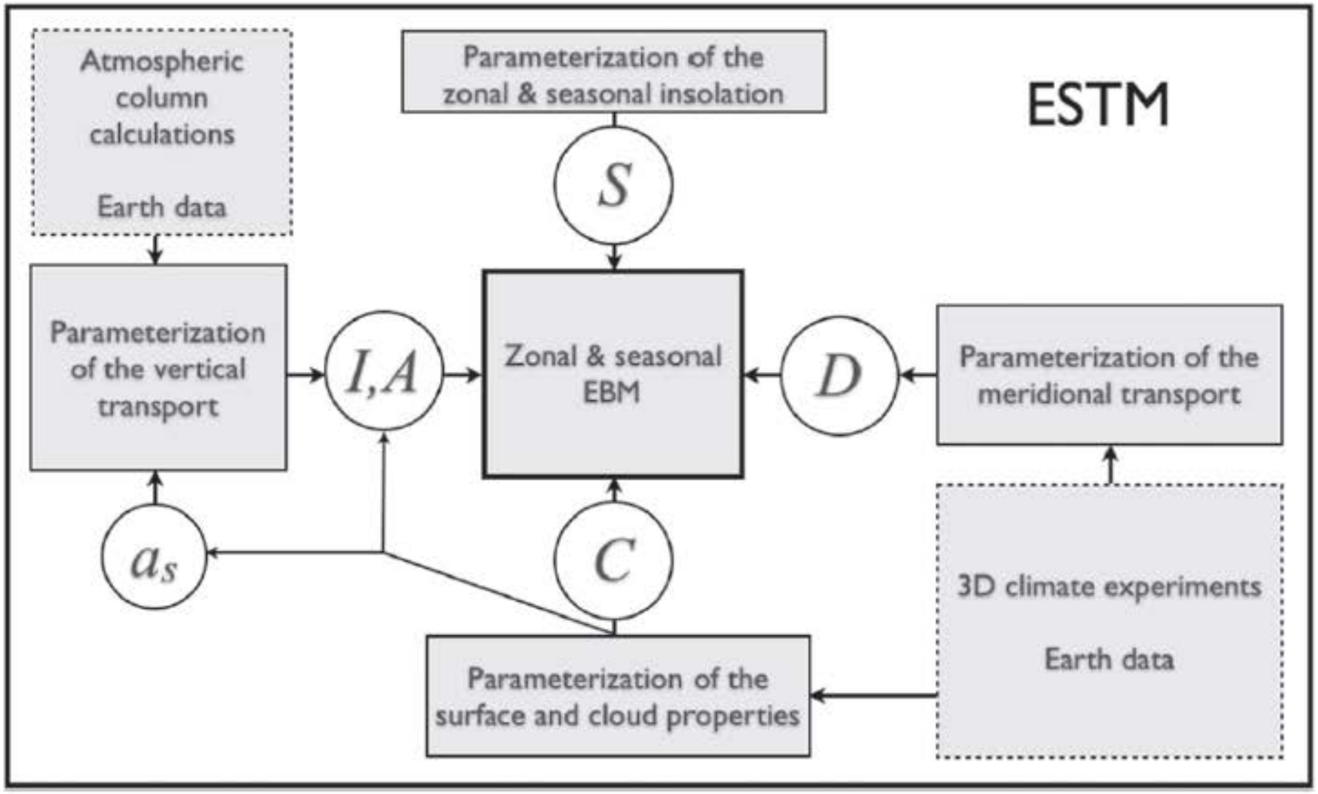
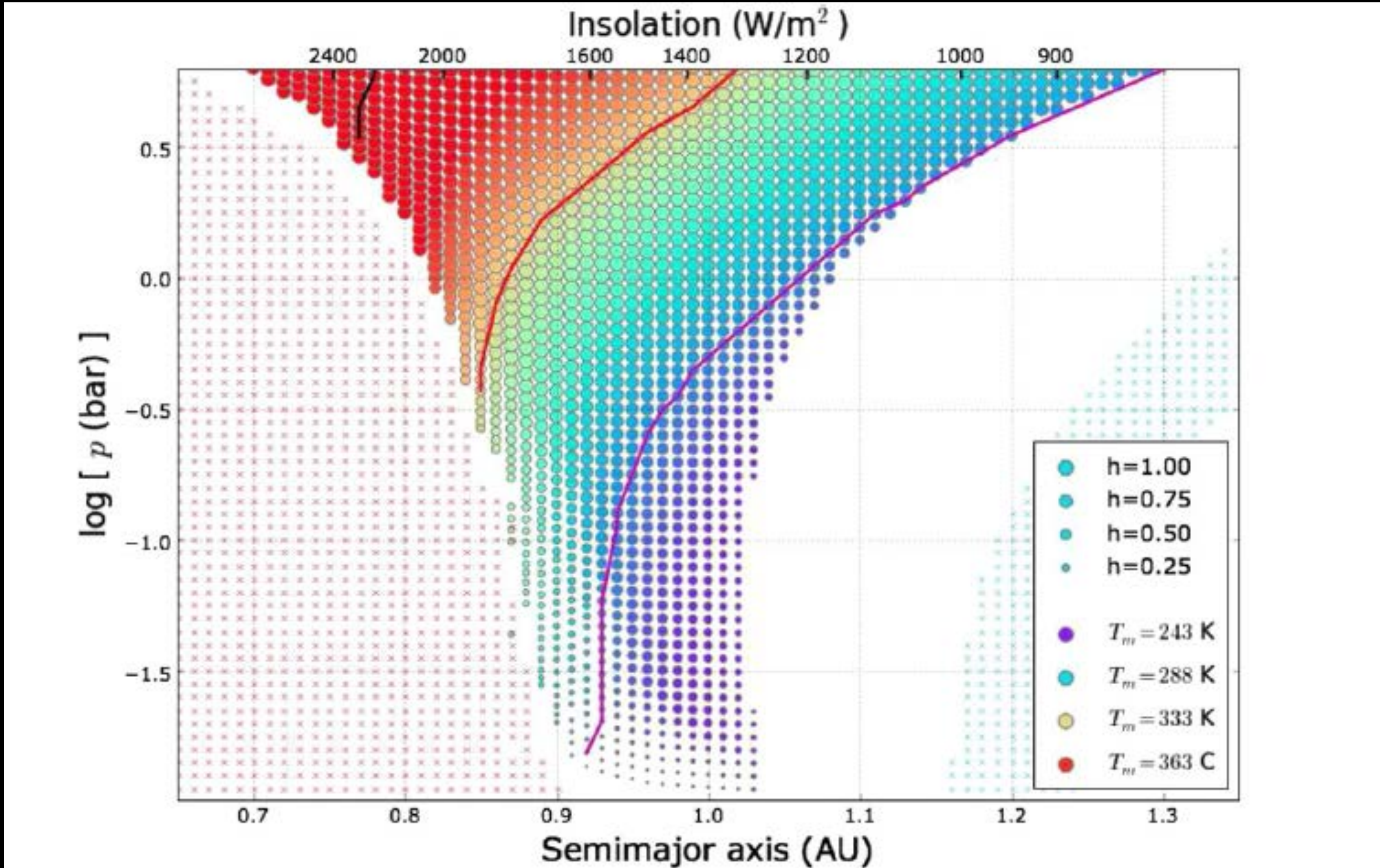


Figure 1. Scheme of the Earth-like planet surface temperature model (ESTM). The zonal and seasonal EBM (central box) is fed by physical quantities (circled symbols) described in Section 2. At variance with classic EBMs, the physical quantities are multi-parameter functions modeled with the aid of atmospheric column calculations (I and A) and 3D climate experiments (D).

MODELING THE SURFACE TEMPERATURE OF EARTH-LIKE PLANETS

Giovanni Vladilo[1,2], Laura Silva[1], Giuseppe Murante[1,3], Luca Filippi[3,4], and Antonello Provenzale[3,5]

The Astrophysical Journal, 804:50 (20pp), 2015 May 1

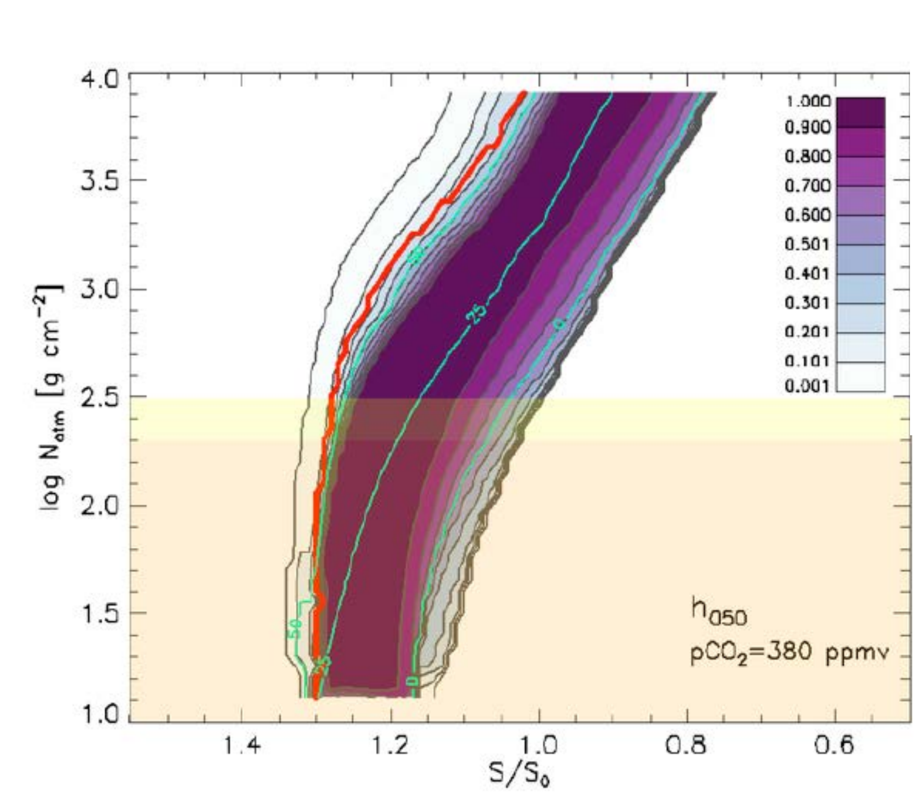


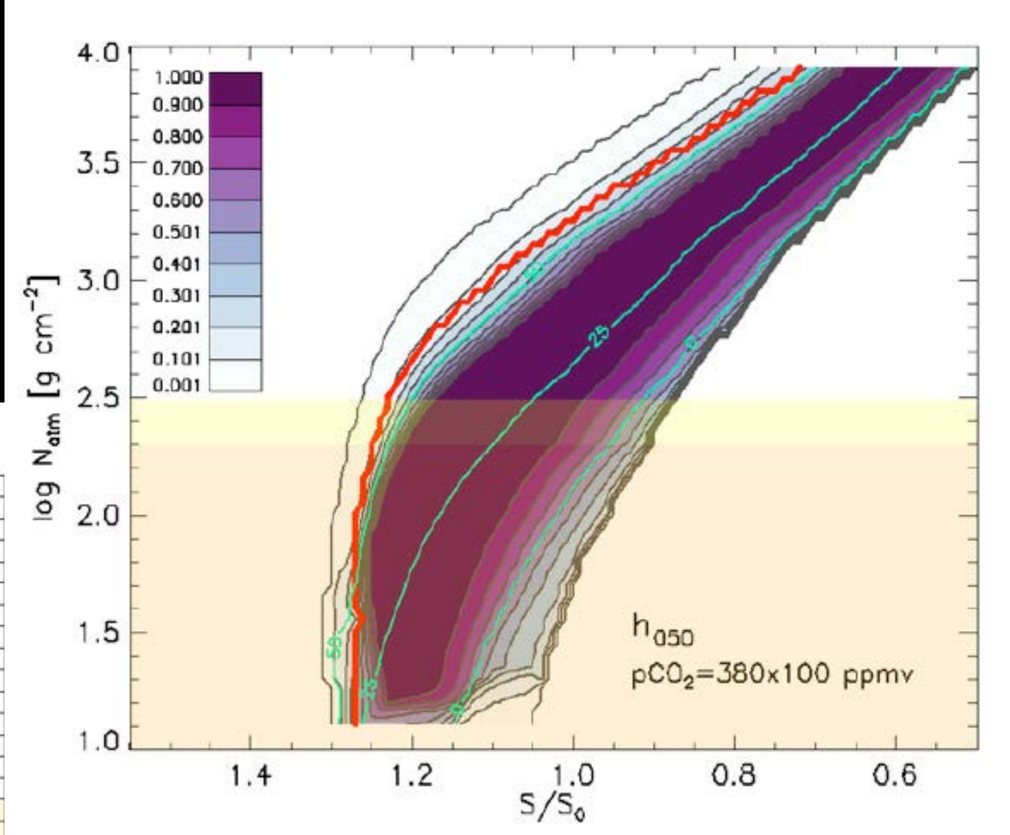
THE HABITABLE ZONE OF EARTH-LIKE PLANETS WITH DIFFERENT LEVELS OF ATMOSPHERIC PRESSURE

Giovanni Vladilo[1,2], Giuseppe Murante[1], Laura Silva[1], Antonello Provenzale[3], Gaia Ferri[2], and Gregorio Ragazzini[2]

The Astrophysical Journal, 767:65 (23pp), 2013 April 10

Looking for planetary habitability and complex life





From climate models to planetary habitability: temperature constraints for complex life

Laura Silva[1], Giovanni Vladilo[1], Patricia M. Schulte[2], Giuseppe Murante[1] and Antonello Provenzale[3]

International Journal of Astrobiology, Page 1 of 22
doi:10.1017/S1473550416000215

End of lecture 1

Next step: the “big models”

a.k.a. the “kitchen-sink” models

a.k.a. the dark side of climate science