Understanding the Earth from a thermodynamic systems perspective

Axel Kleidon
Max-Planck-Institute für Biogeochemie
akleidon@bgc-jena.mpg.de

11 October 2019
IISER Pune

Understanding the Earth System

Image: NASA

Why do things happen? Are the general operating principles for the planet?

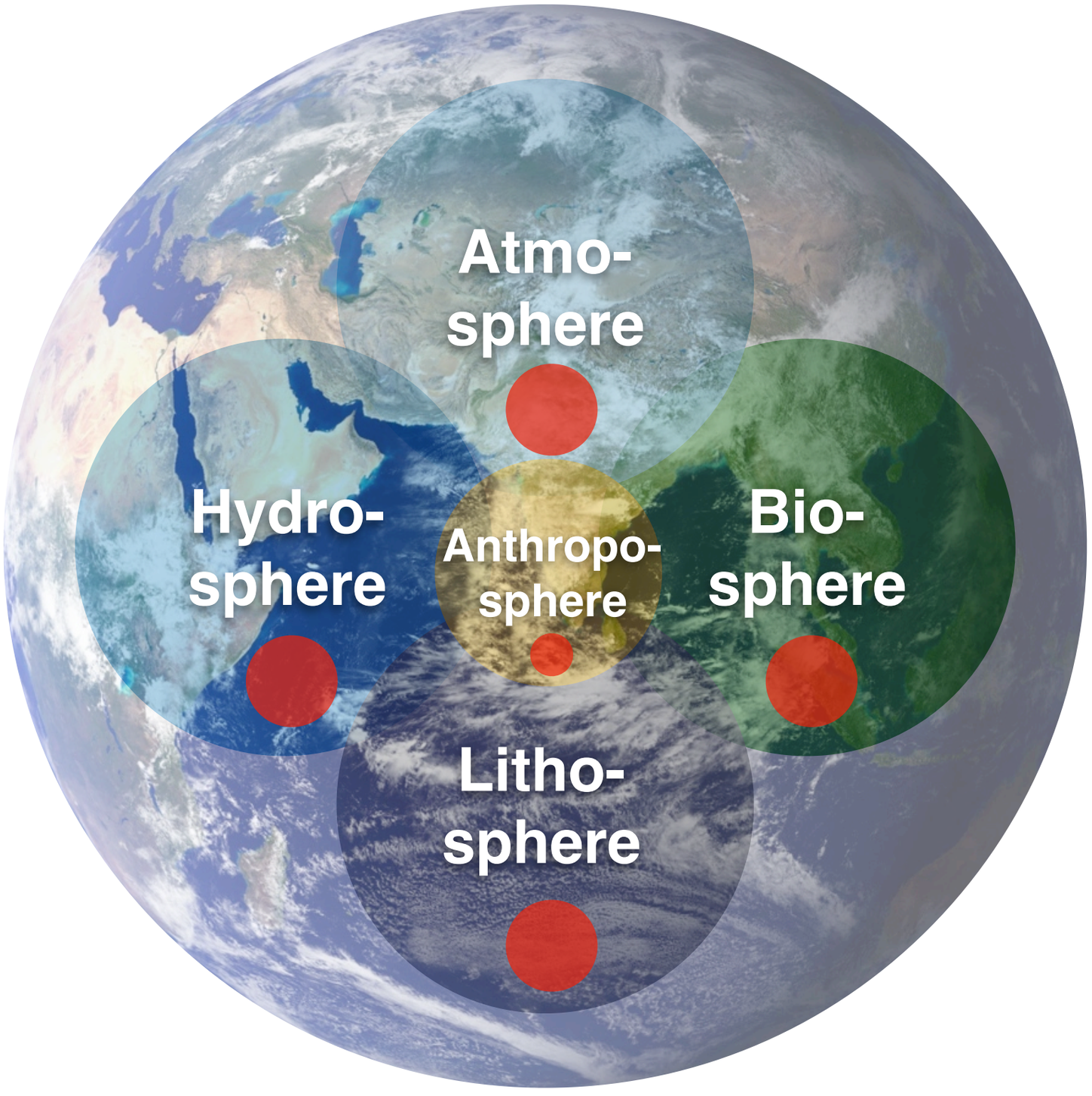
How can we understand and estimate climate change from first principles?

What is the role of life? Does it regulate the planetary environment?

What is the role of humans in the system? What sets the limits to human activity? How is the future going to look like?

Thermodynamics in an Earth system context provides a basis for the answers

Thermodynamics of the Earth System



Within Earth's spheres, there are pockets in which **thermodynamics** is routinely applied.

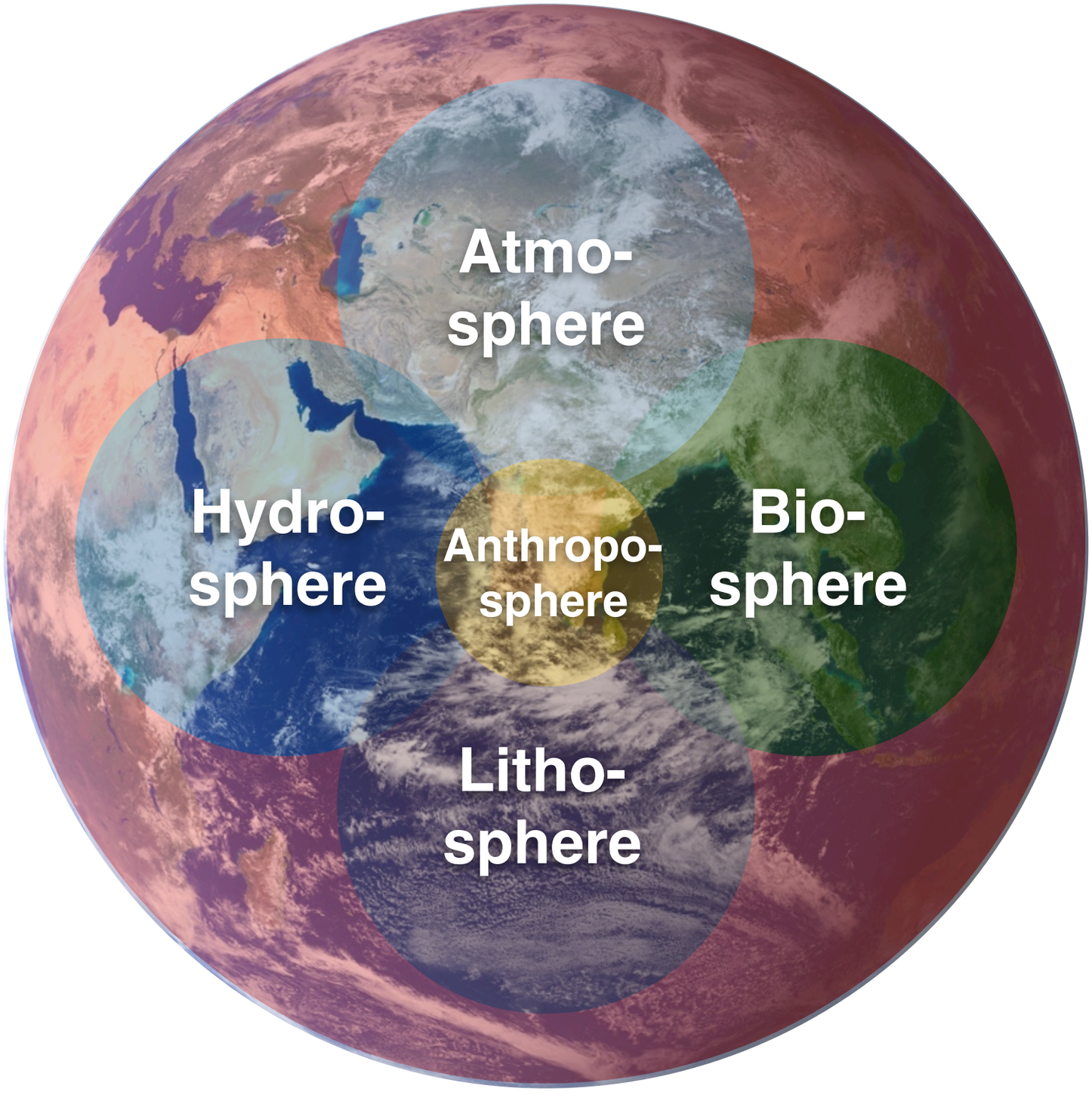
Examples:

Adiabatic conditions in atmospheric sciences

Aqueous geochemistry in hydrology

Power plants in human technology

Thermodynamics of the Earth System



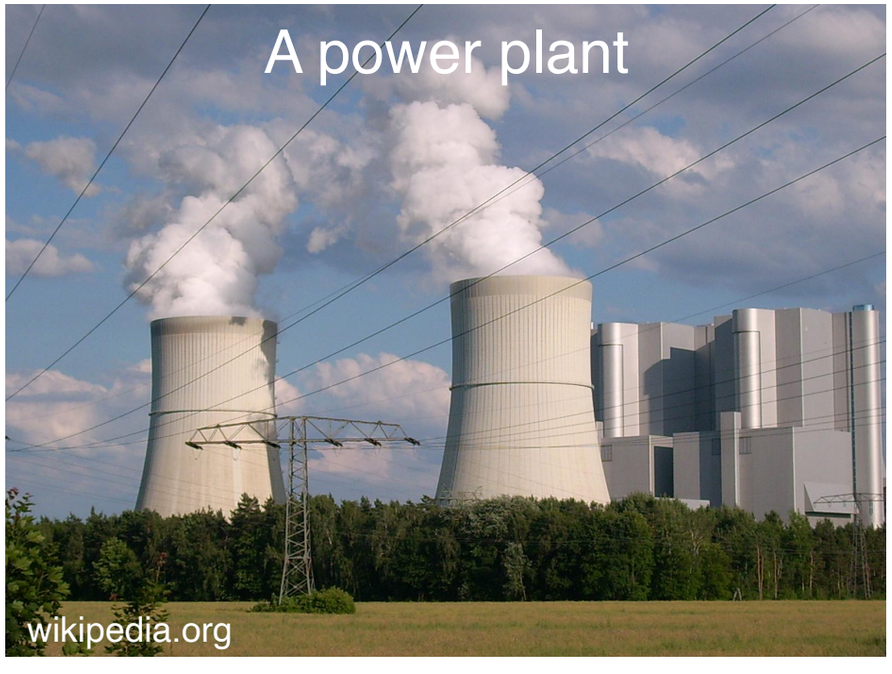
How can we apply **thermo-dynamics** to the **whole Earth system**?

What else do we need to know?

What are we going to learn from this approach?

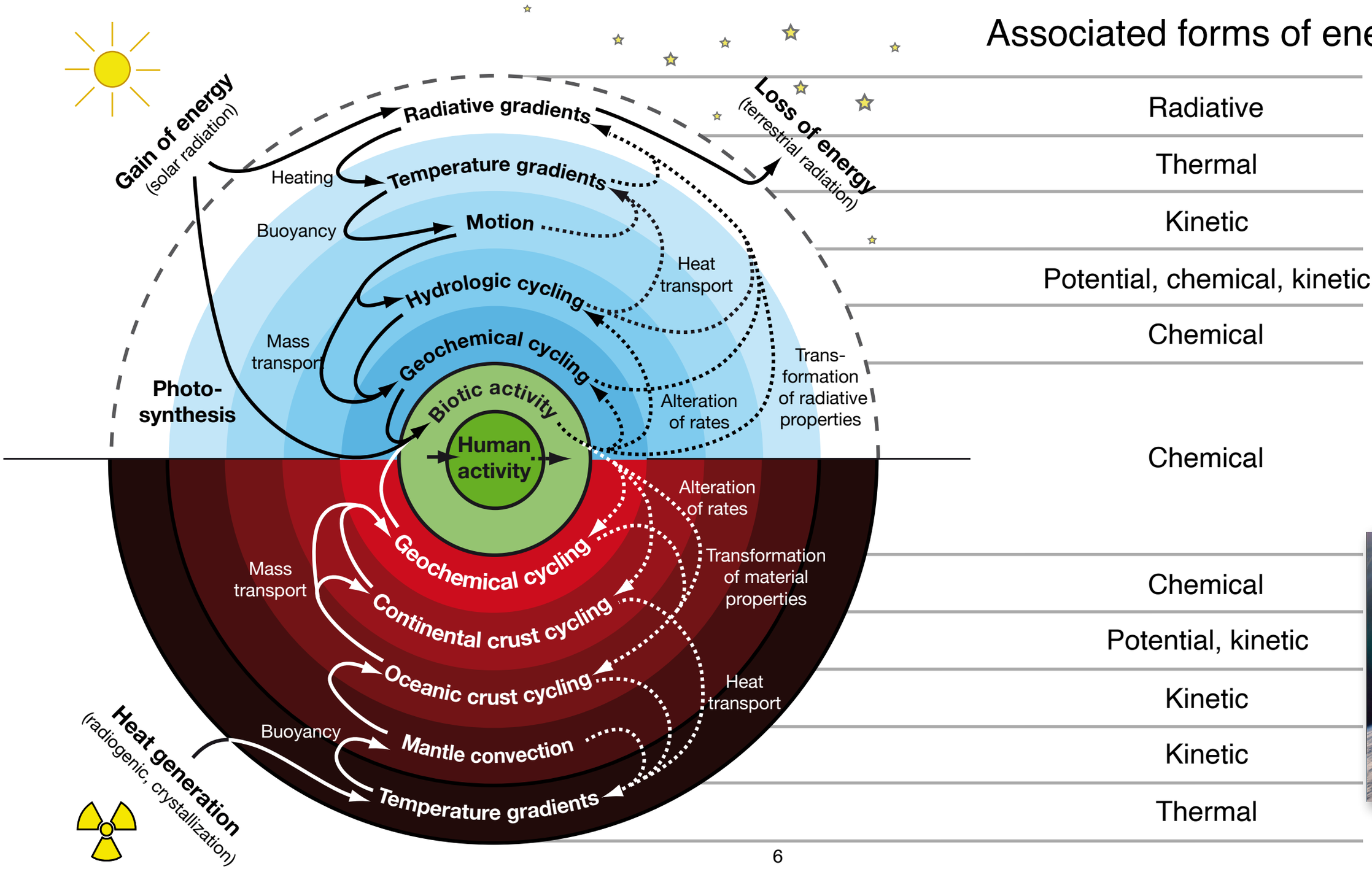
Thermodynamics of the Earth System

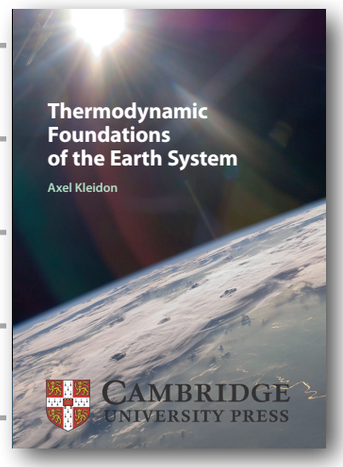
Everything relates to energy conversions



Thermodynamics of the Earth System

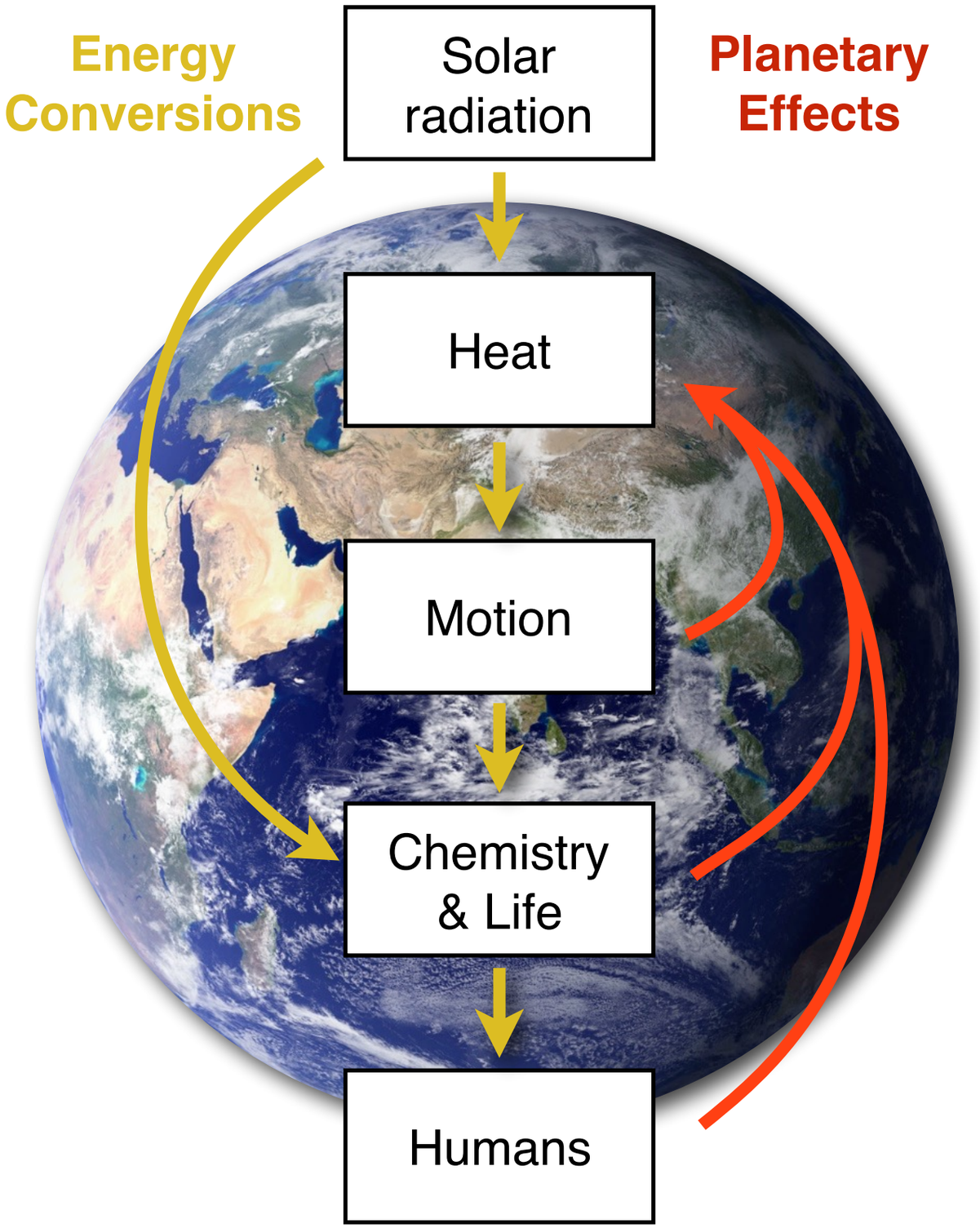
Energy conversions are connected and alter the system





Kleidon (2012), Kleidon (2016)

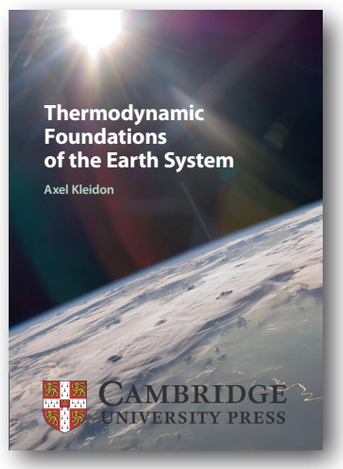
Thermodynamics of the Earth System



Earth system processes evolve to their thermodynamic limits

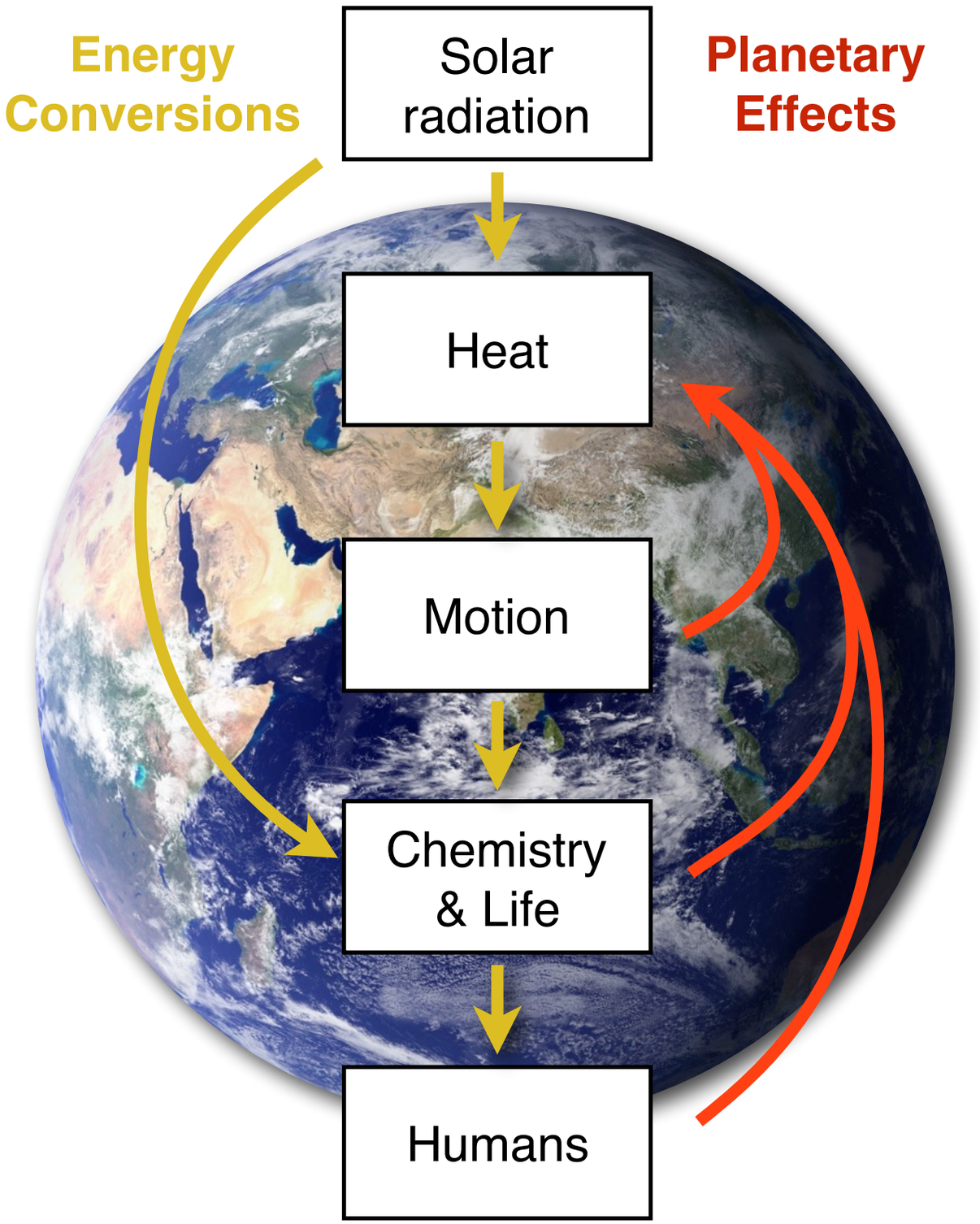
Because Earth system functioning operates at its limits, it becomes predictable

Life pushes these limits to yield more power



Kleidon (2016)

Thermodynamics of the Earth System



Basics in Thermodynamics

Application to Climate

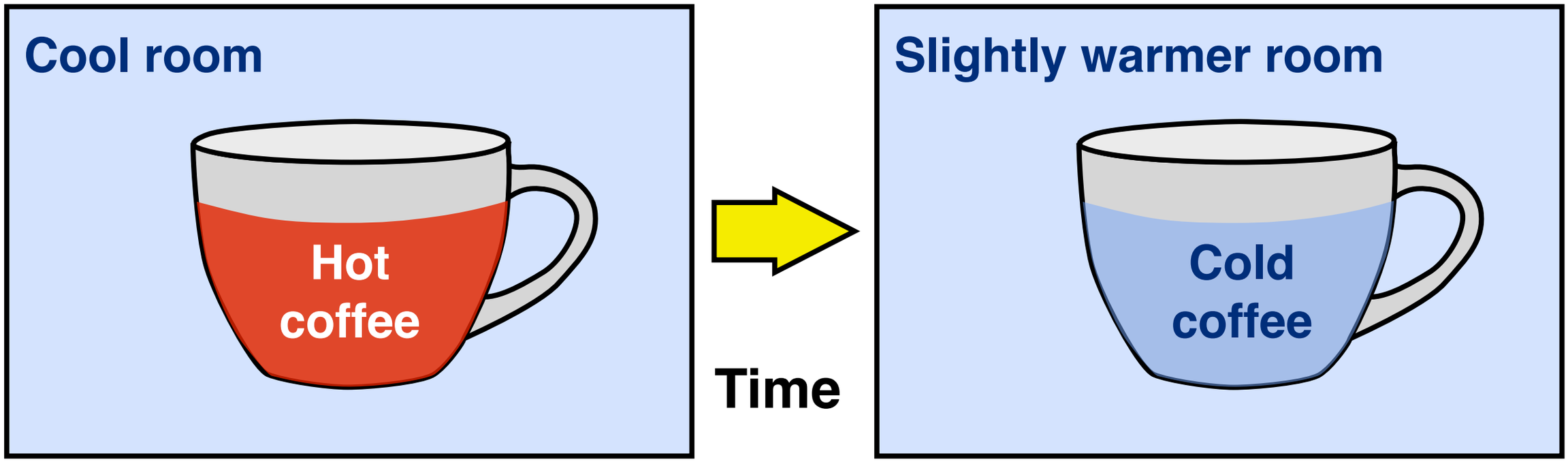
Application to Geochemistry

Application to Humans

Summary and Outlook

Thermodynamics

Thermodynamics happens every day!



First law: Energy is conserved

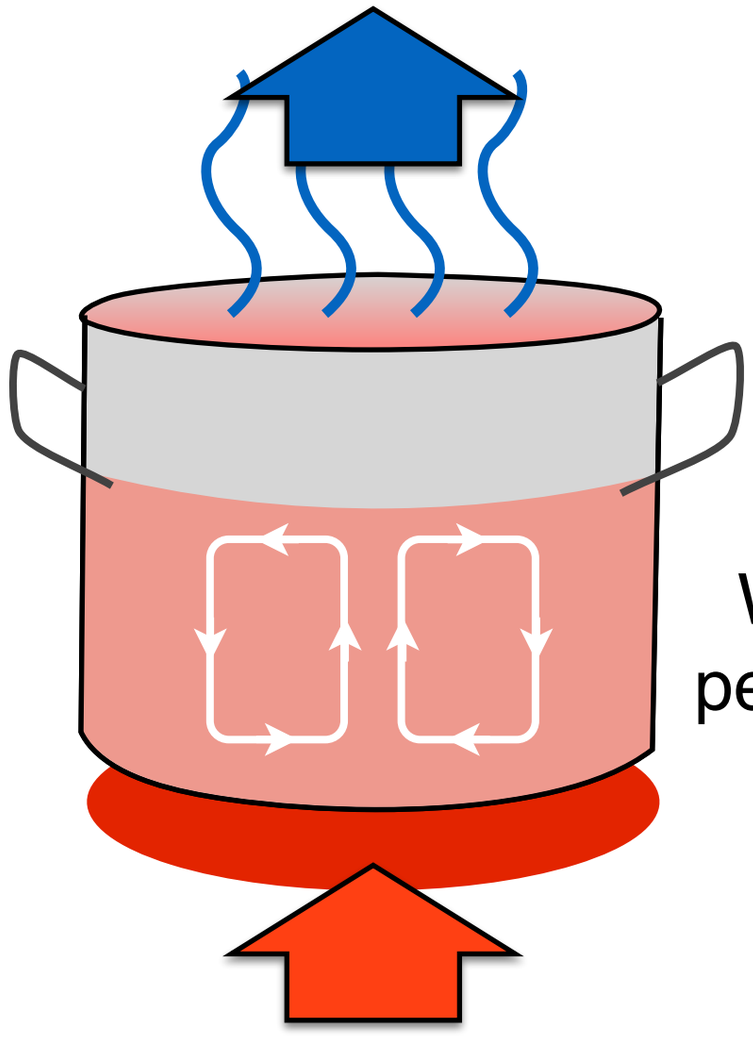
Second law: Energy is dispersed (increase of entropy)

Thermodynamics

Equilibrium Thermodynamics

Gradients are depleted

Non-equilibrium Thermodynamics



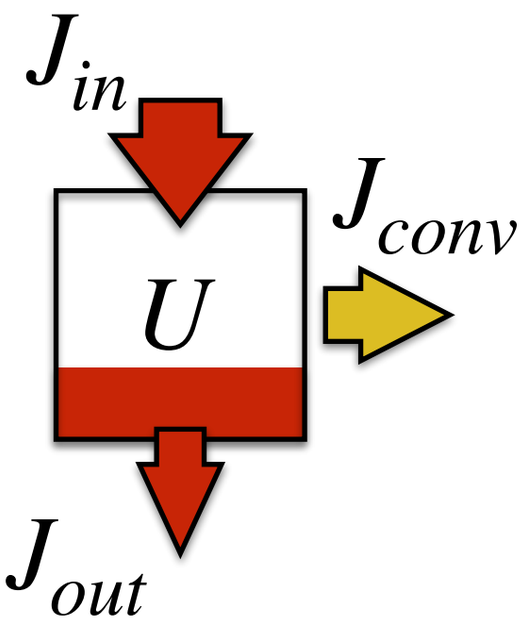
Gradients are maintained by energy input

Thermodynamics

Laws of thermodynamics are implemented in budgets

First law: Energy conservation => Energy budget

$$\frac{dU}{dt} = J_{in} - J_{out} - J_{conv}$$

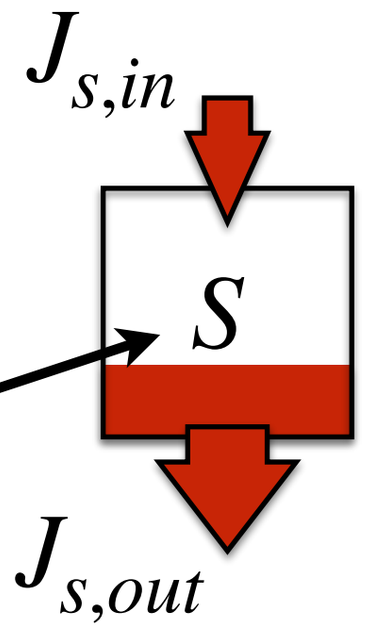


Second law: Entropy increase => Entropy budget

$$\frac{dS}{dt} = J_{s,in} - J_{s,out} + \sigma$$

Second law requires $\sigma \geq 0$

=> Entropy production by dissipative processes



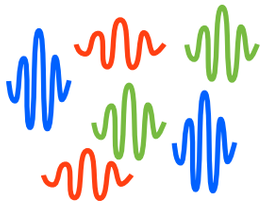
Thermodynamics

Entropy measures energy dispersal at microscopic scale

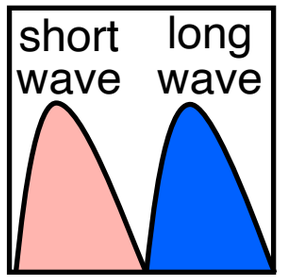
Microscopic World
(Photons, electrons, molecules)

Scaling →

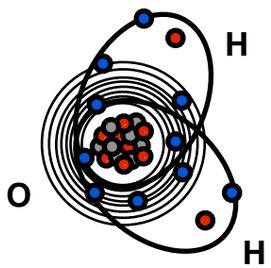
Macroscopic World
(Solids, liquids, gases)



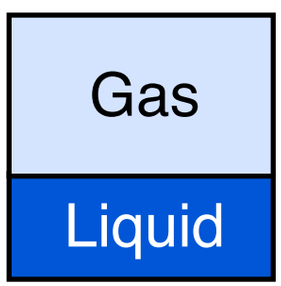
Photons ⋯⋯→



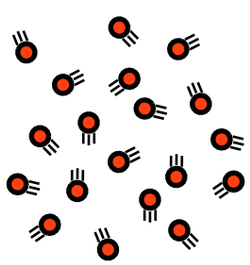
Radiative Entropy



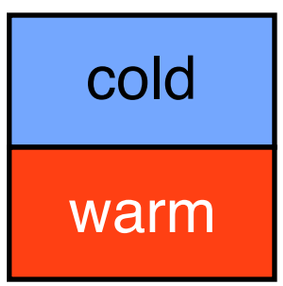
Electrons ⋯⋯→



Molar Entropy



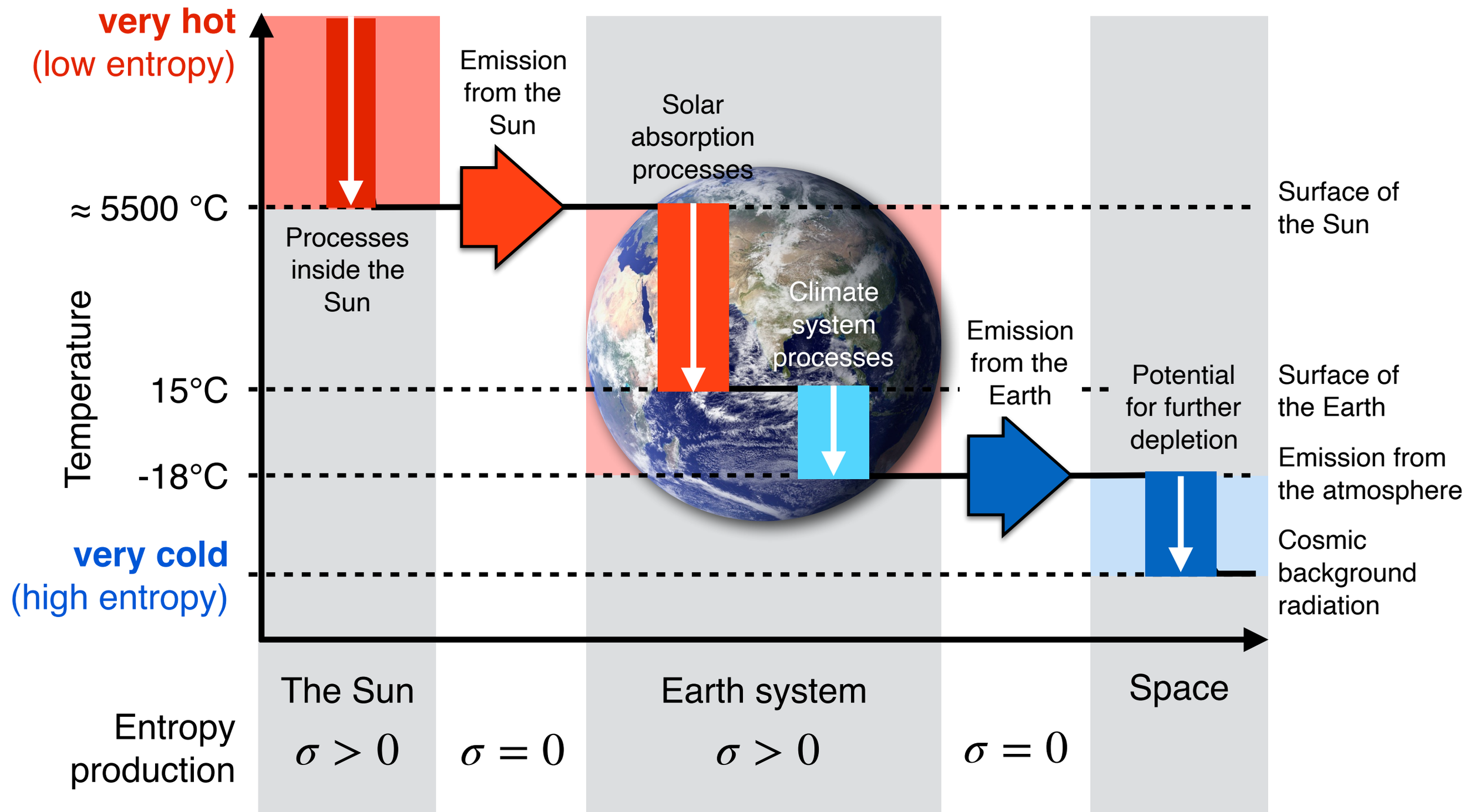
Molecules ⋯⋯→



Thermal Entropy

Thermodynamic Directions

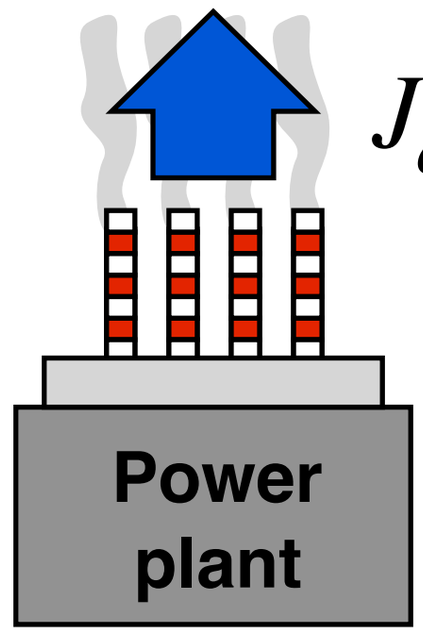
Increase of entropy governs energy conversions from Sun to Earth to Space



Thermodynamic Limits

Thermodynamics provides a constraint
on how much **work** can maximally be performed

Exhausts remove
heat at lower temperature



Power plant performs **work** through time ("power")

Combustion of fuels
adds heat

The Carnot limit

First law:
(energy conservation)

$$J_{in} = J_{out} + G$$

Second law:
(increase in entropy, $\sigma = dS_i/dt \geq 0$)

$$\frac{J_{in}}{T_{in}} - \frac{J_{out}}{T_{out}} + \sigma = 0$$

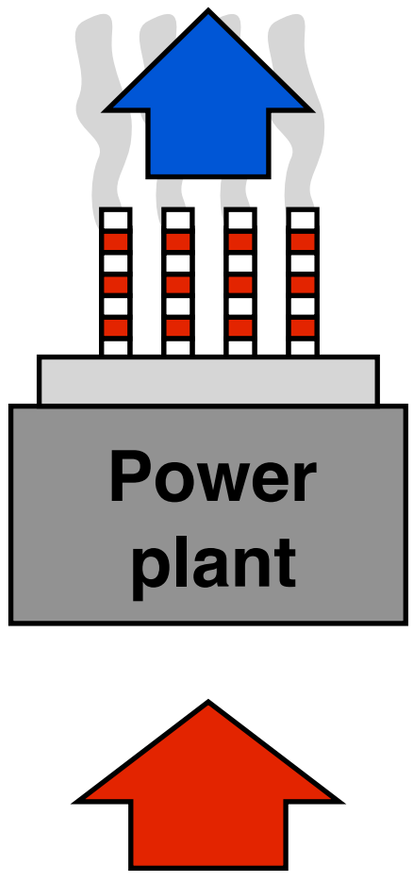
Combination yields limit on how much work per time can be performed (Carnot limit):

$$G \leq J_{in} \cdot \frac{T_{in} - T_{out}}{T_{in}}$$

Thermodynamic Limits

Thermodynamics provides a constraint
on how much **work** can maximally be performed

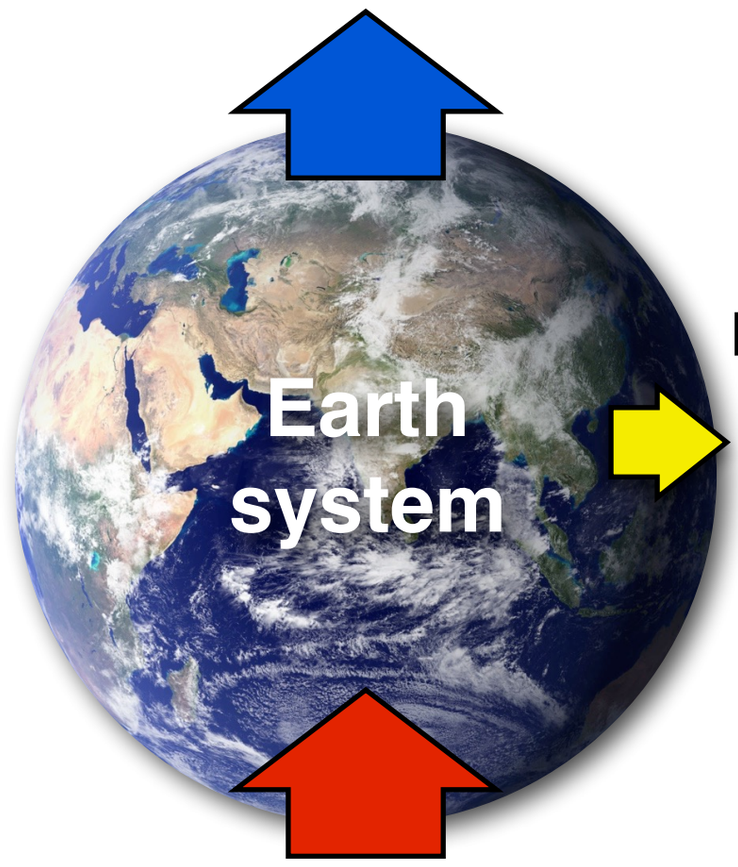
Exhausts remove
heat at lower temperature



Power plant
performs
work
through time
("power")

Combustion of fuels
adds heat

Emission of radiation
cools the Earth

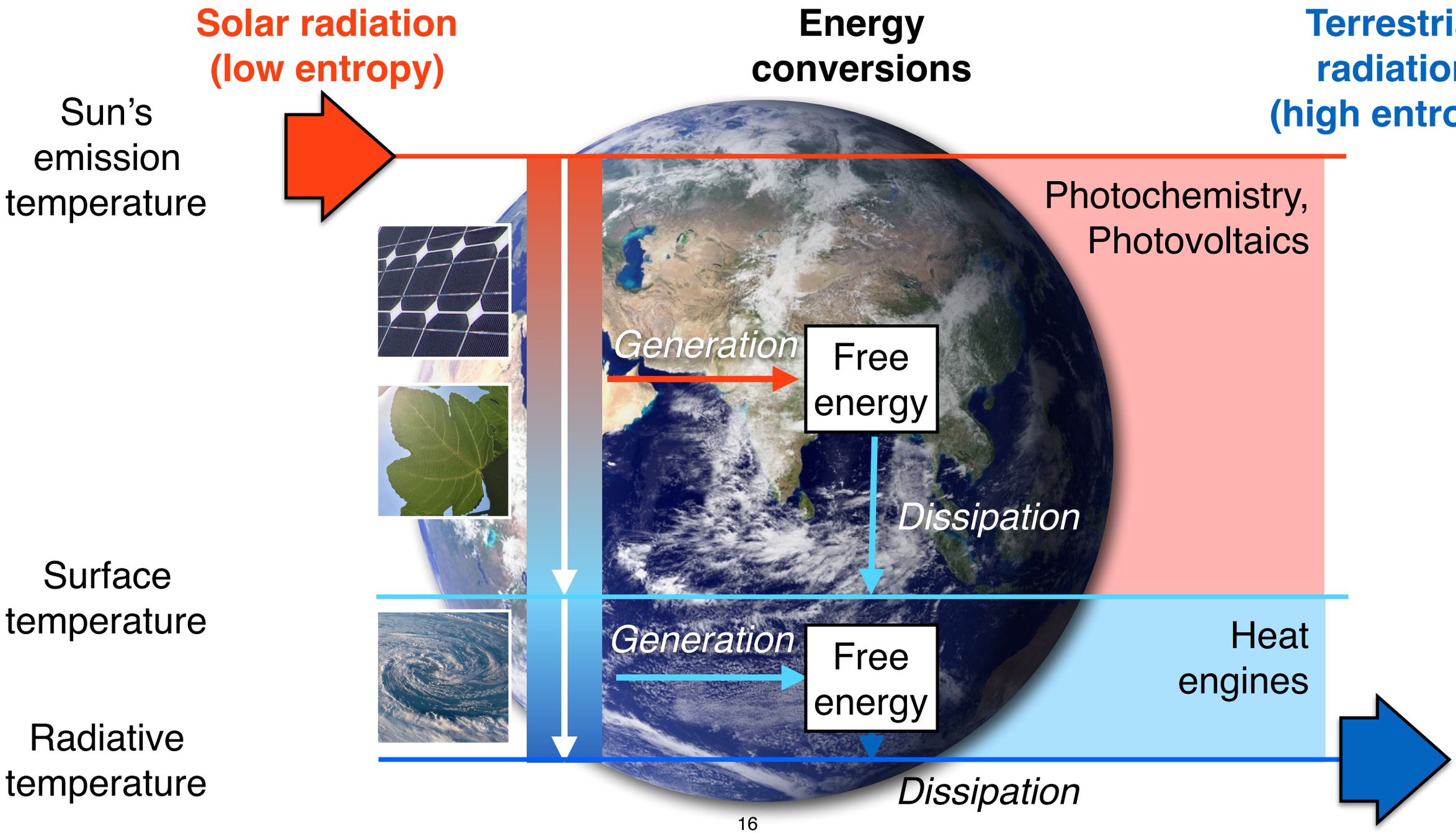


Earth system
processes
perform
work

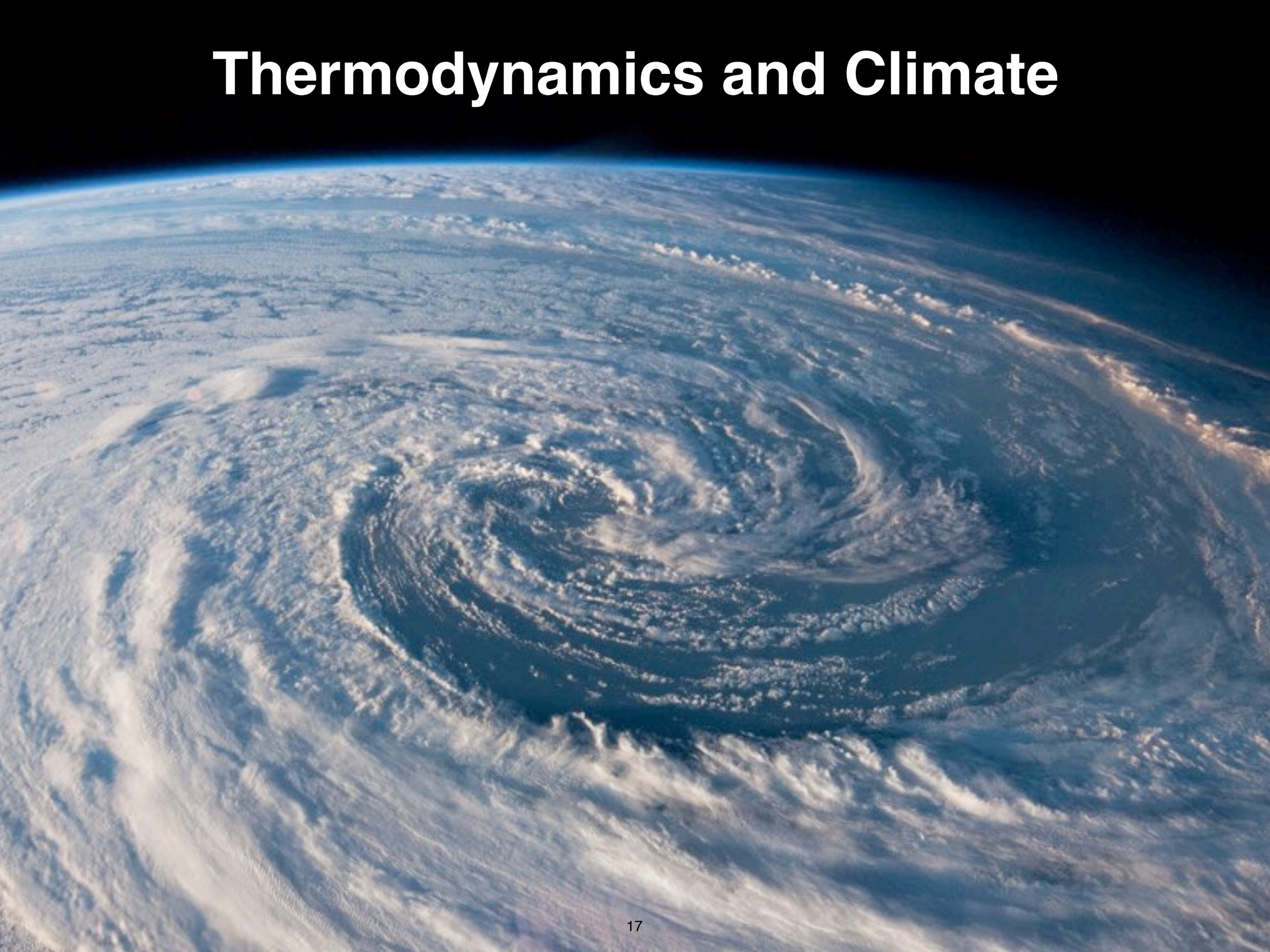
Sunlight
heats the Earth

Thermodynamics of the Earth System

Generating free energy for the dynamics of the Earth system

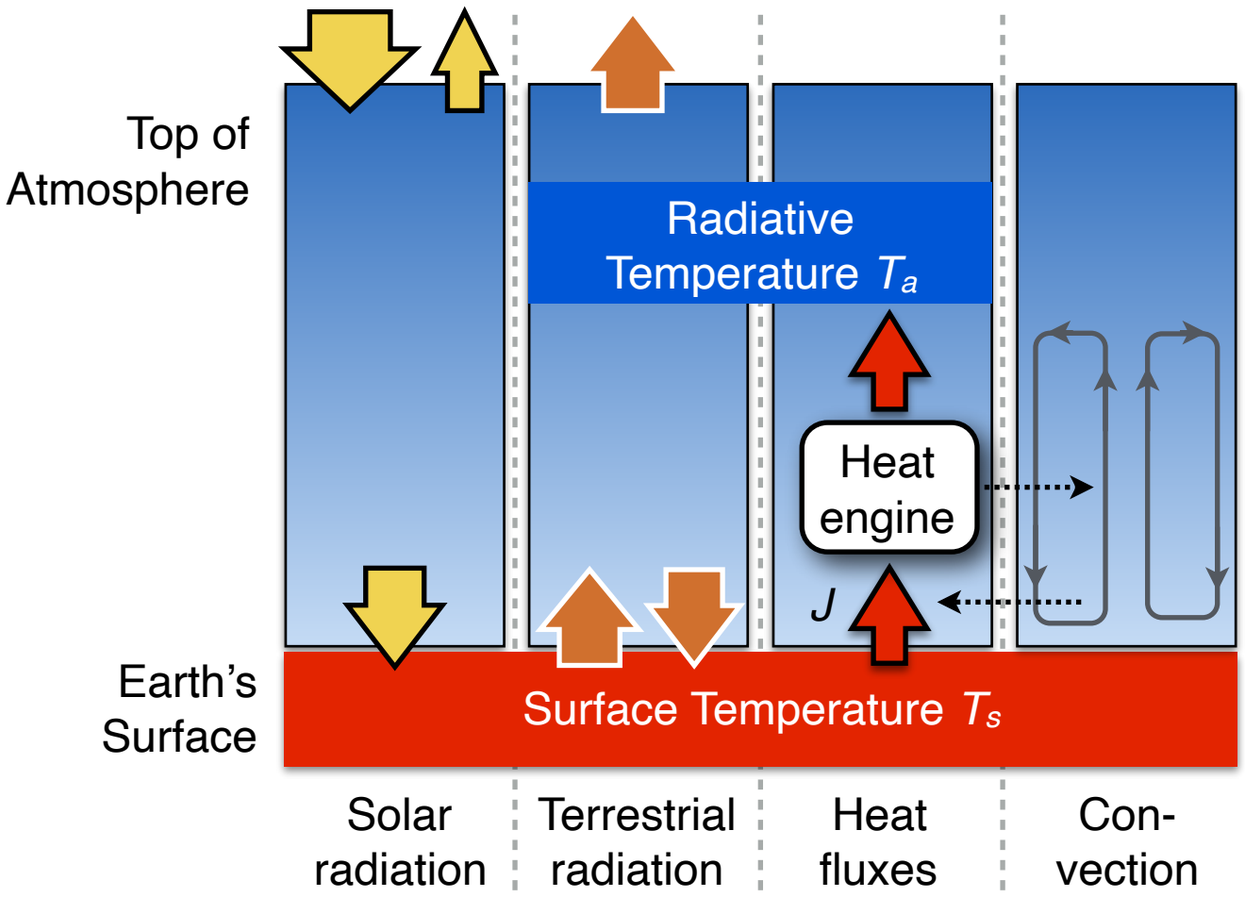


Thermodynamics and Climate



Thermodynamics and Climate

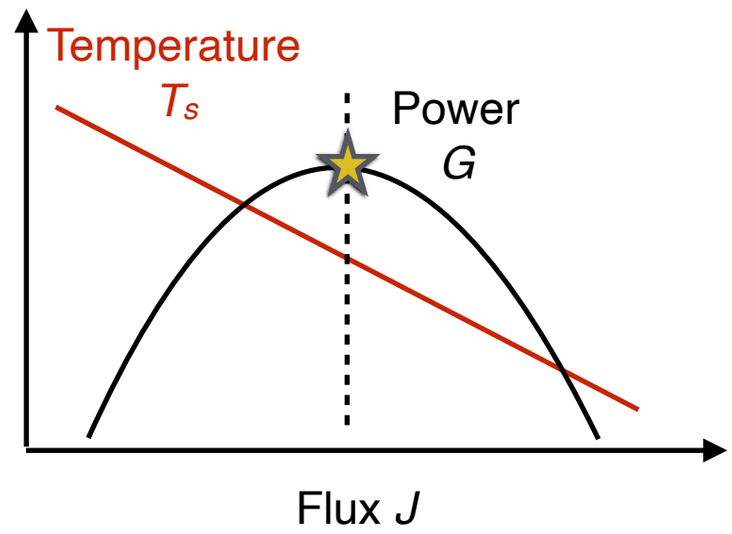
Limit on convection/motion is set by thermodynamics and interactions with the system boundary



Carnot limit (thermodynamics):

$$G = J \, \frac{T_s - T_a}{T_s}$$

Maximum power limit results from trade-off between turbulent fluxes and surface temperature:



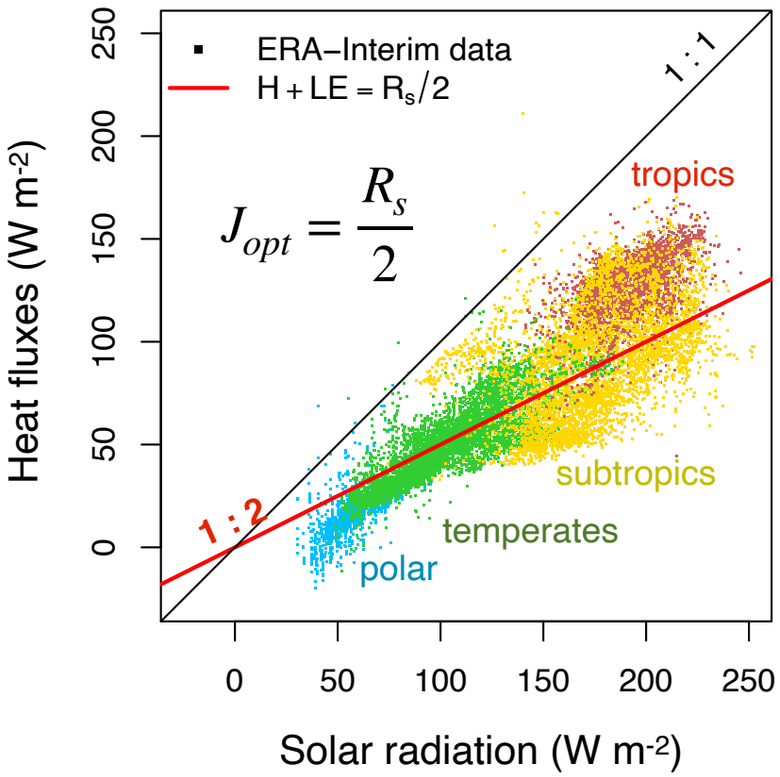
Kleidon and Renner (2013) *Hydrol. Earth Syst. Sci.*

Thermodynamics and Climate

Prediction from thermodynamic limit characterises mean turbulent fluxes over land very well!

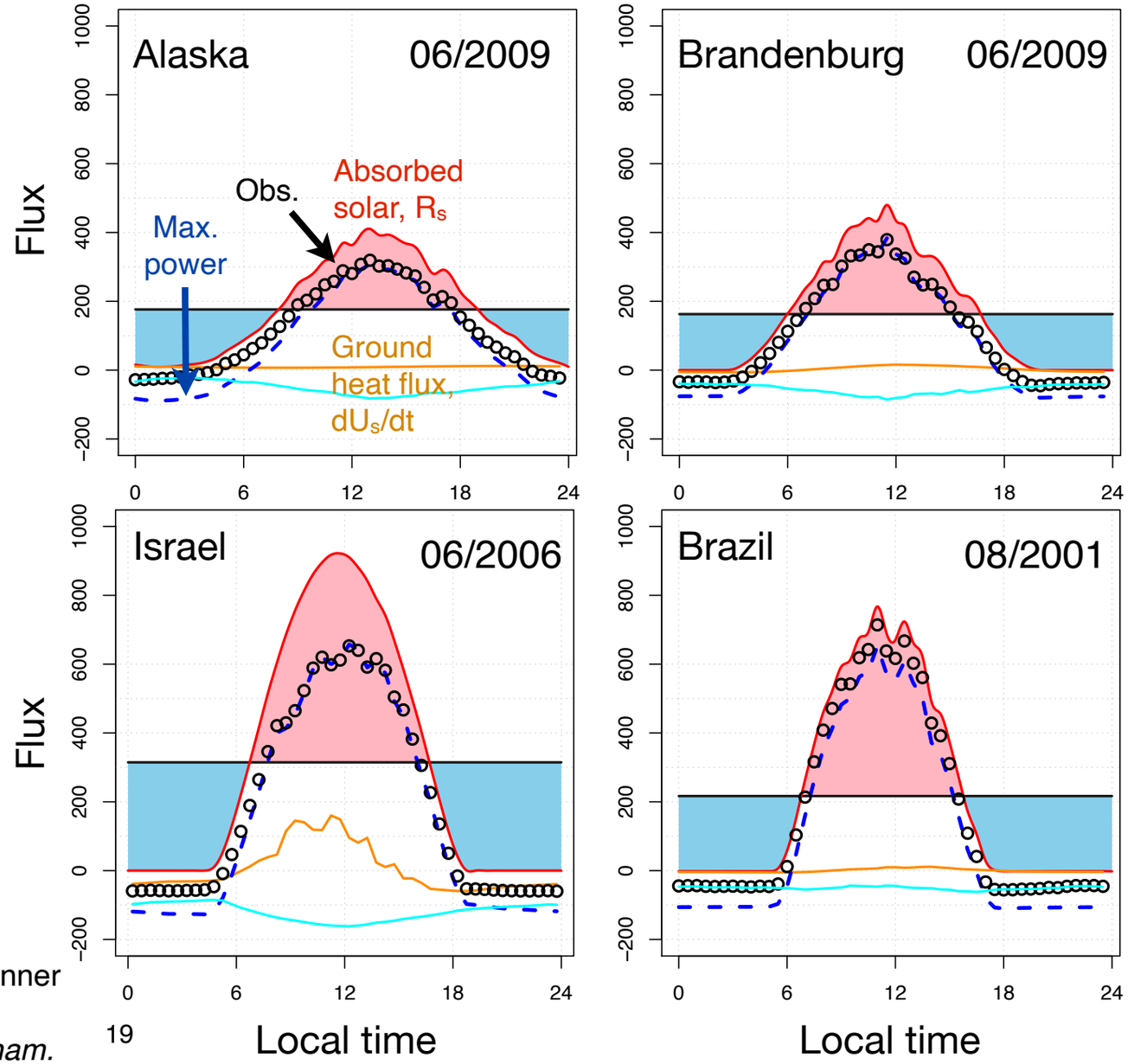
$$J_{opt} = R_s - \frac{R_{s,avg}}{2}$$

Climatological mean



Kleidon, Renner, Porada (2014)
Hydrol. Earth Syst. Sci.

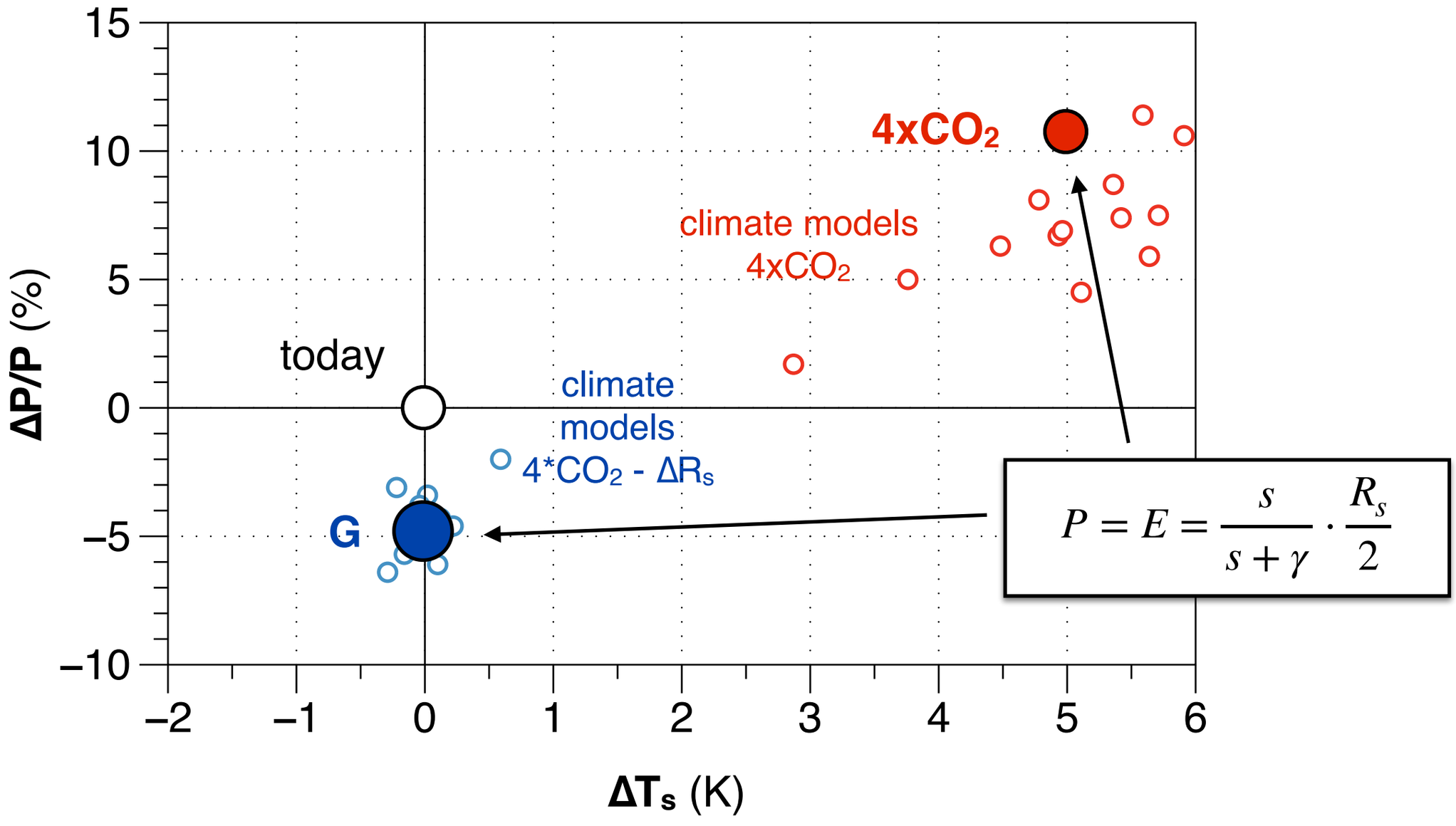
Diurnal variation



Kleidon and Renner (2018)
Earth Syst. Dynam.

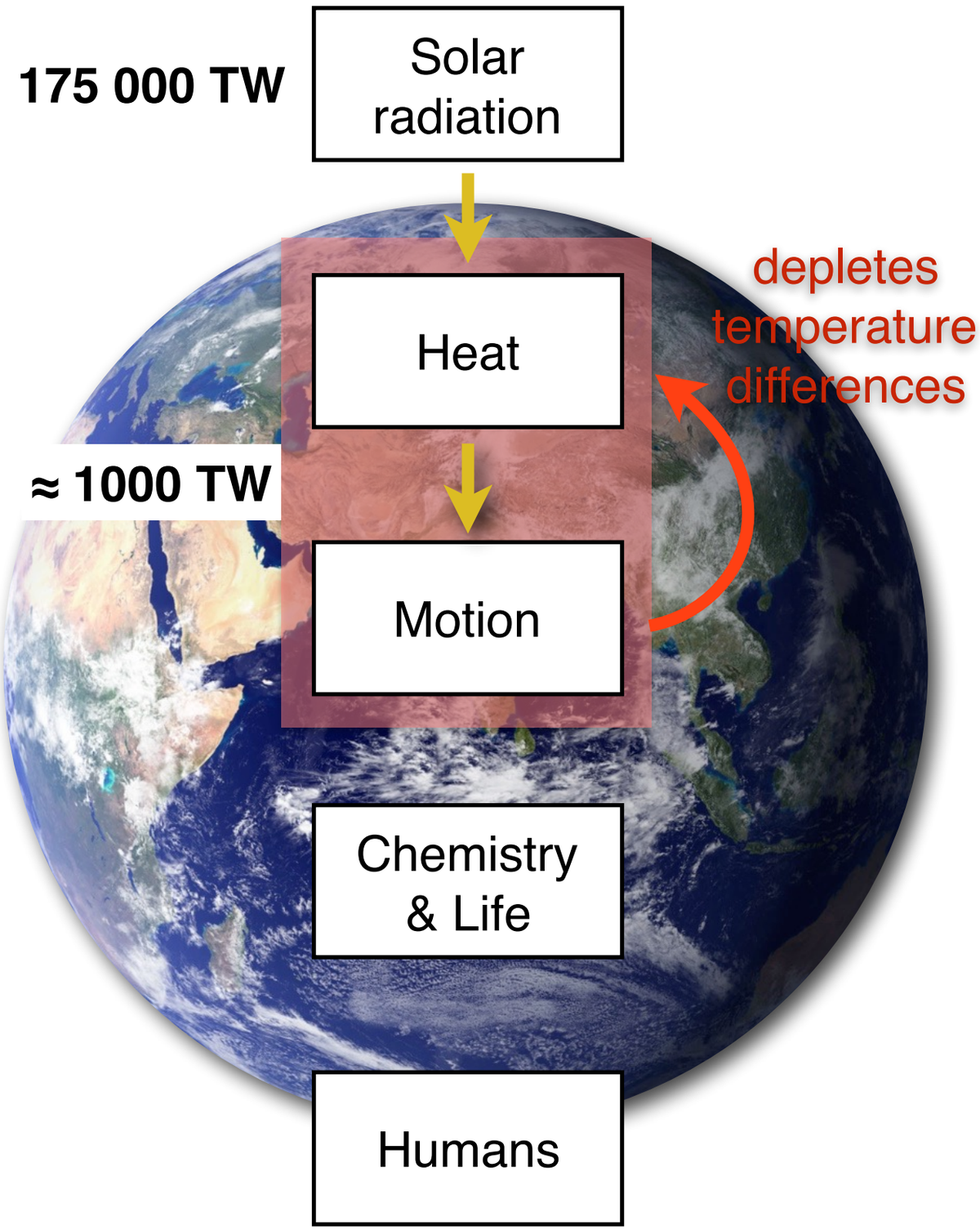
Thermodynamics and Climate Change

Example: Precipitation sensitivity
to global warming (4xCO2) and solar geoengineering (G)



Kleidon and Renner (2013) *Earth Syst. Dynam.*
Kleidon, Kravitz, Renner (2015) *Geophys. Res. Lett.*

Thermodynamics and Climate



Motion operates near its thermodynamic limit

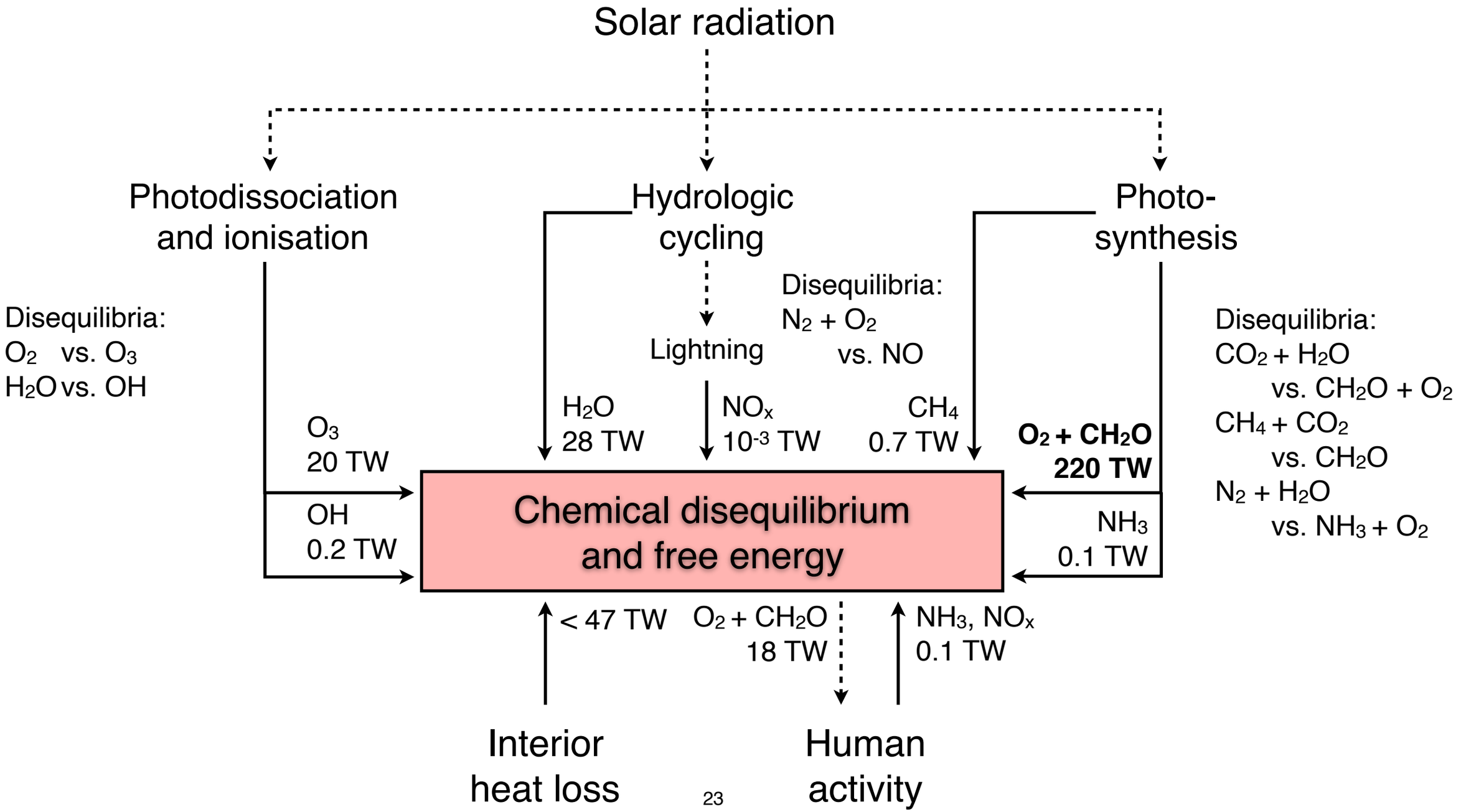
Turbulent fluxes can be estimated with an extremely simple approach

Interactions play a critical role in setting the limit

Thermodynamics, Geochemistry, and Life

Thermodynamics and Geochemistry

Biospheric activity is by far the largest contributor to chemical free energy generation on Earth

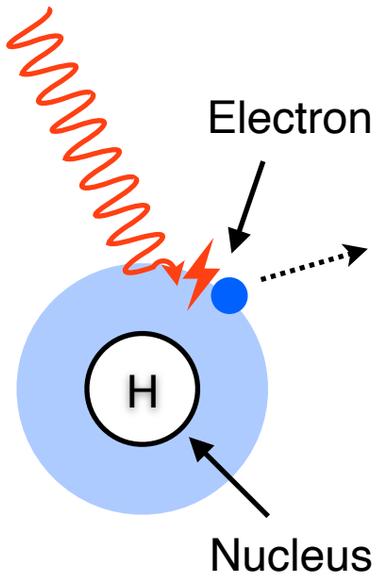


Disequilibrium by Absorption

Absorption of solar radiation can chemically alter molecules

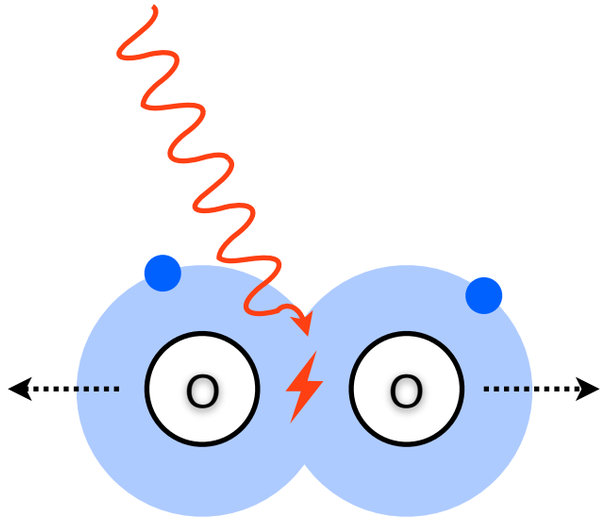
Ultraviolet Radiation

(More energetic radiation
(wavelengths shorter than visible light)



Photoionization
removes electrons
from nucleus

Example:
$H + 13.6\ eV \Longrightarrow H^+ + e^-$

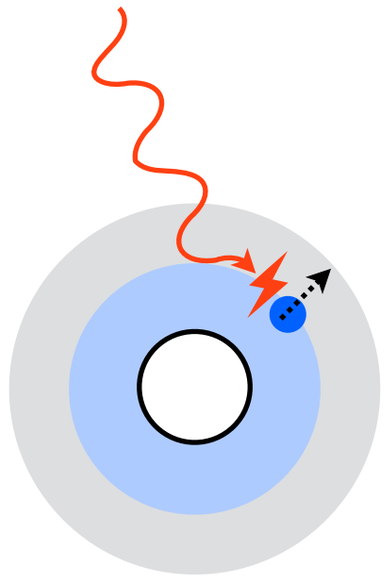


Photodissociation
breaks molecular
bonds

Example:
$O_2 + 5.2\ eV \Longrightarrow O + O$

Visible Light

Less energetic radiation
(visible light and near infrared)



Photoexcitation
brings electrons into
a more energetic state

Example:
$1/2\ H_2O + 8 \times 1.8\ eV \Longrightarrow 1/2\ O + H^+ + e^-$
(Photosynthesis)

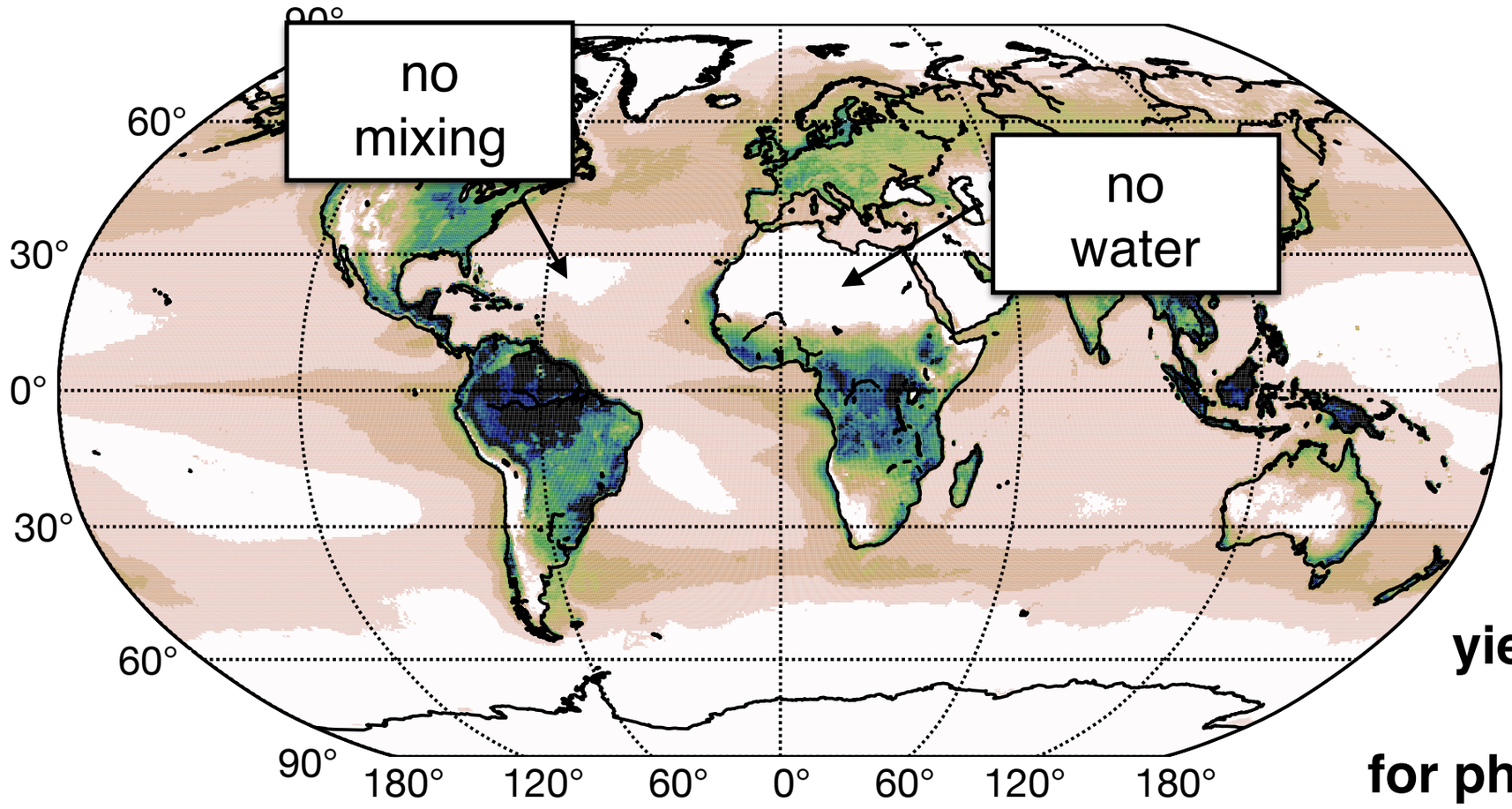
Photosynthesis

- 8 - 10 photons of 1.8 eV required to fix one CO_2
- Corresponds to an energy requirement of 1.4 MJ/mol C
- Energy content of sugar is 0.48 MJ/mol C
- Yields an efficiency of about 34%
- **but:** only 1/2 of solar radiation can be used => 17%
- **but:** observed efficiency < 3%!

Photosynthesis operates well below its thermodynamic limit.

Biotic Activity

Productivity of the biosphere is limited by physical mixing and exchange, which in turn is thermodynamically limited

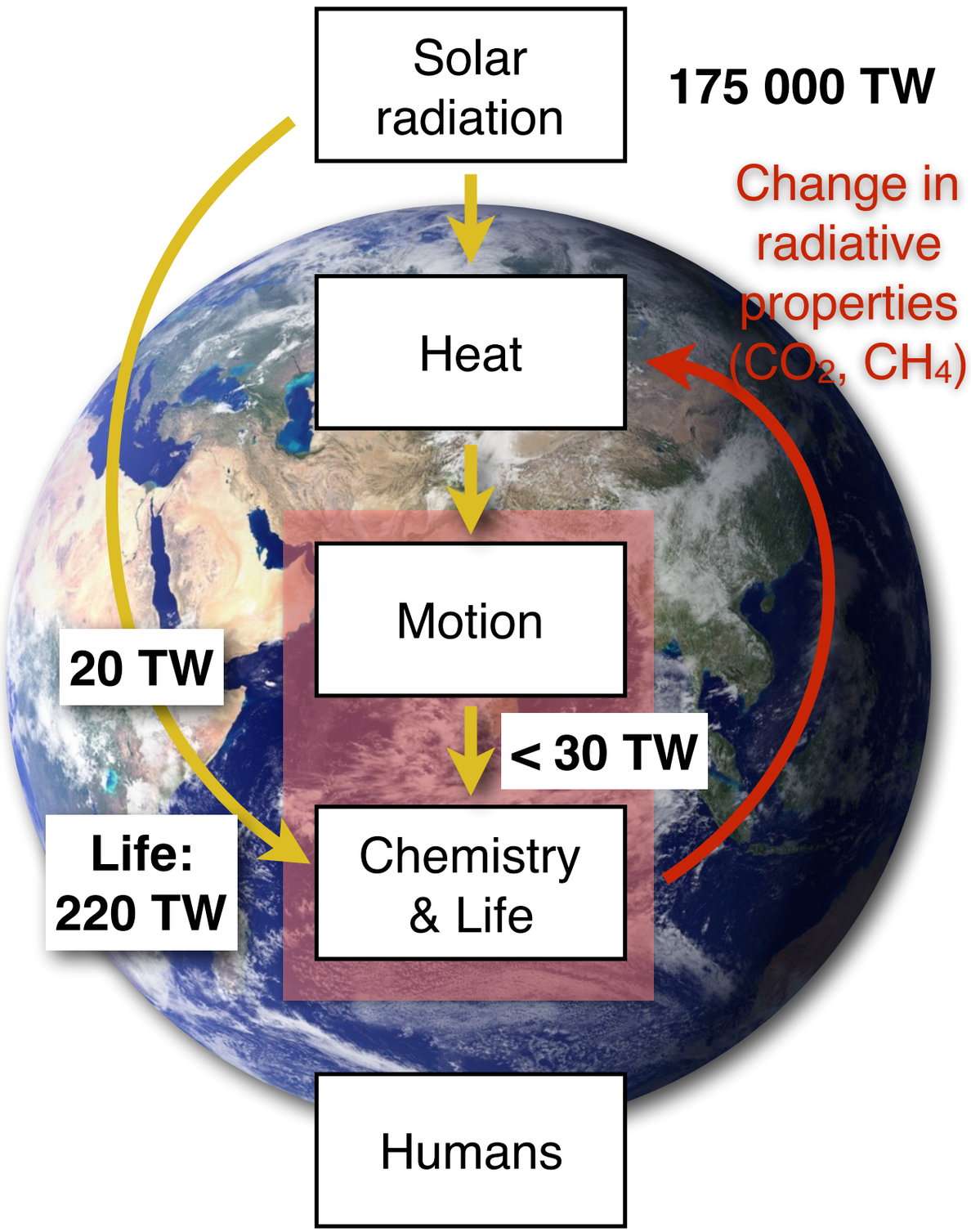


yields about 220 TW for photosynthesis

Net Primary Productivity (W m^{-2})

based on NASA MODIS data of the years 2002-2005

Thermodynamics and Geochemistry



Chemical free energy is generated by motion or absorption

Photosynthesis dominates chemical free energy generation

Biotic productivity is indirectly limited by thermodynamics through transport

Geochemical changes feed back to radiative changes, which may maximize productivity

Thermodynamics and Human Activity

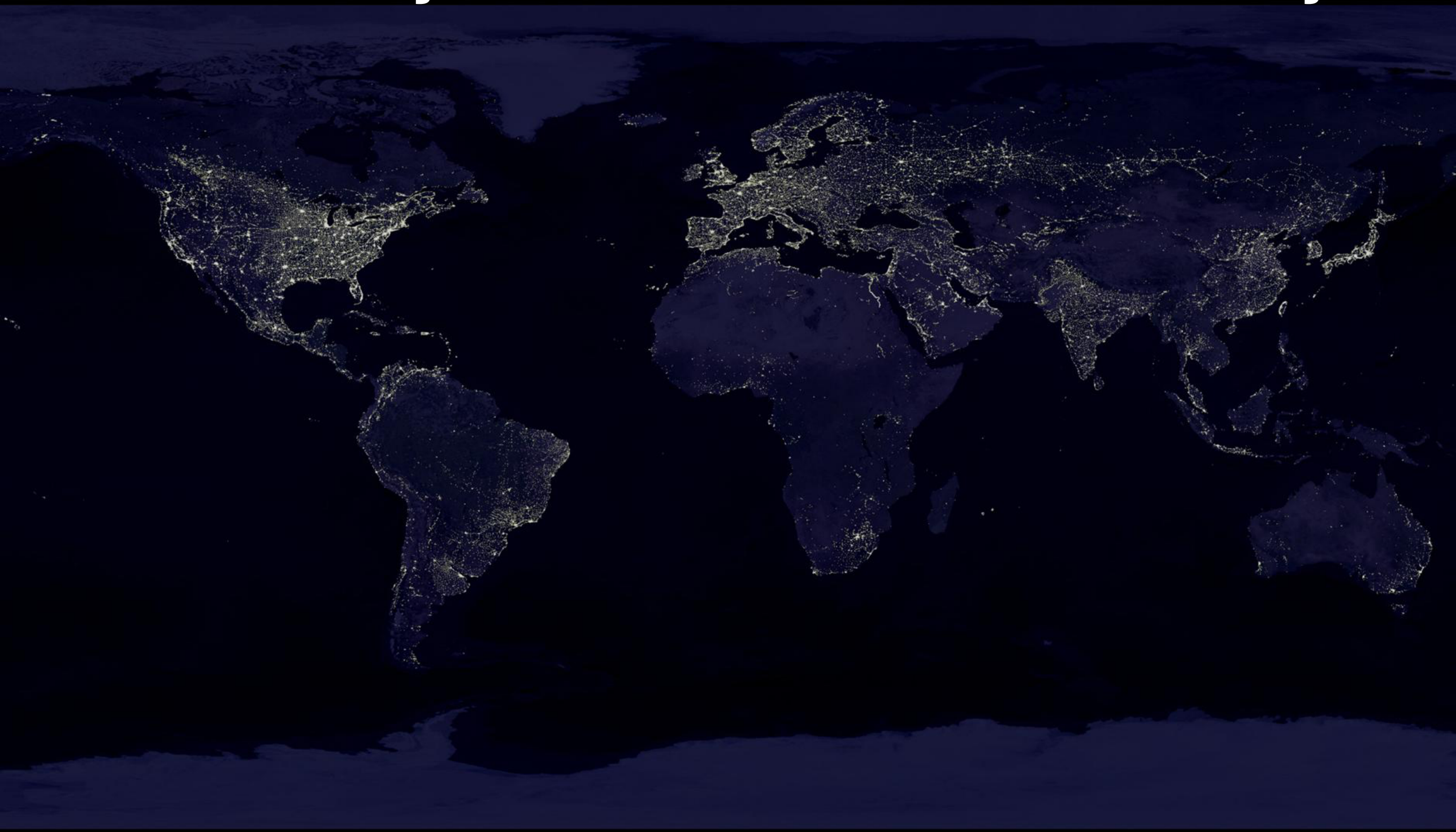


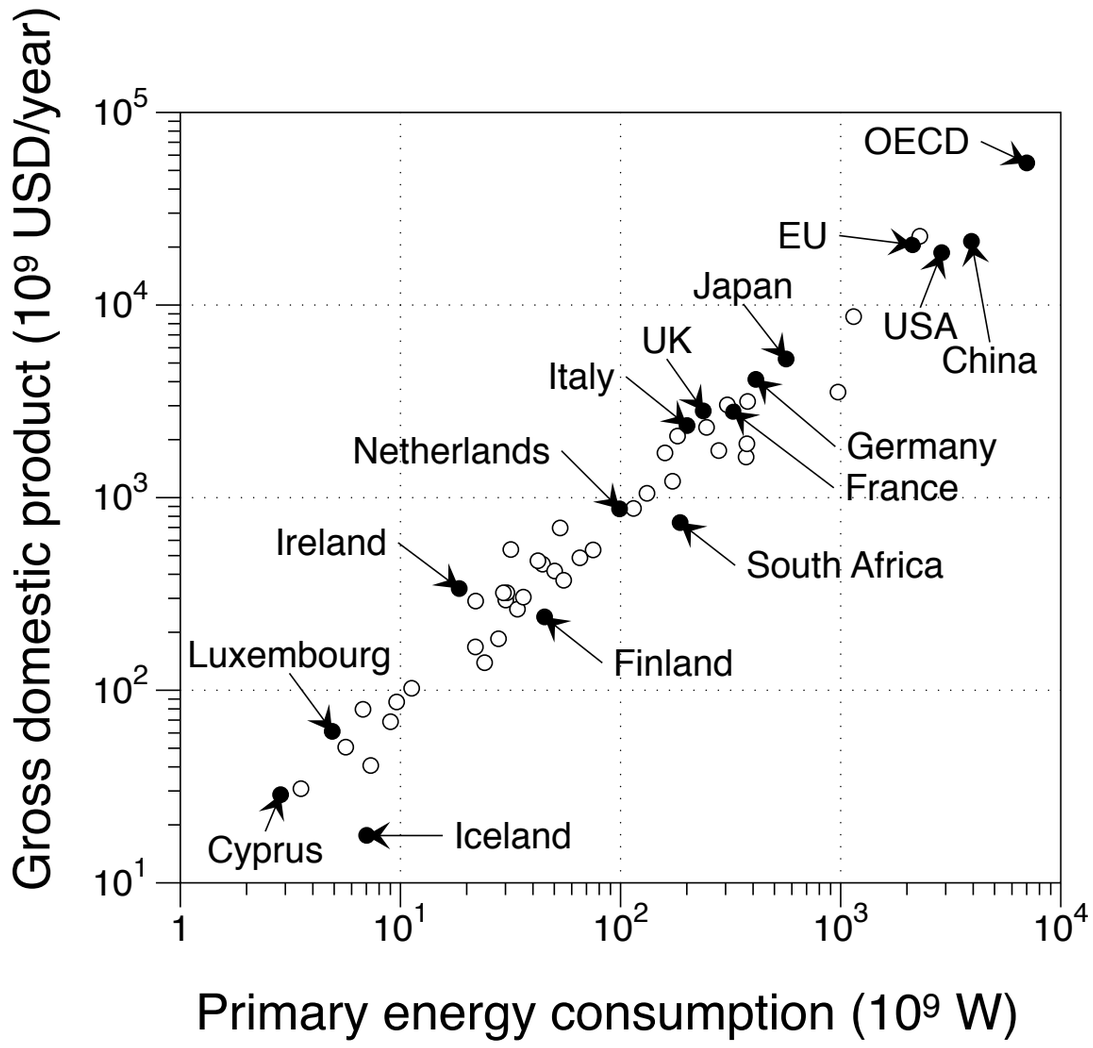
Image: NASA

Thermodynamics and Human Activity

Food = Calories = Energy

≈ 100 W/person

Economy = $$$ = Energy



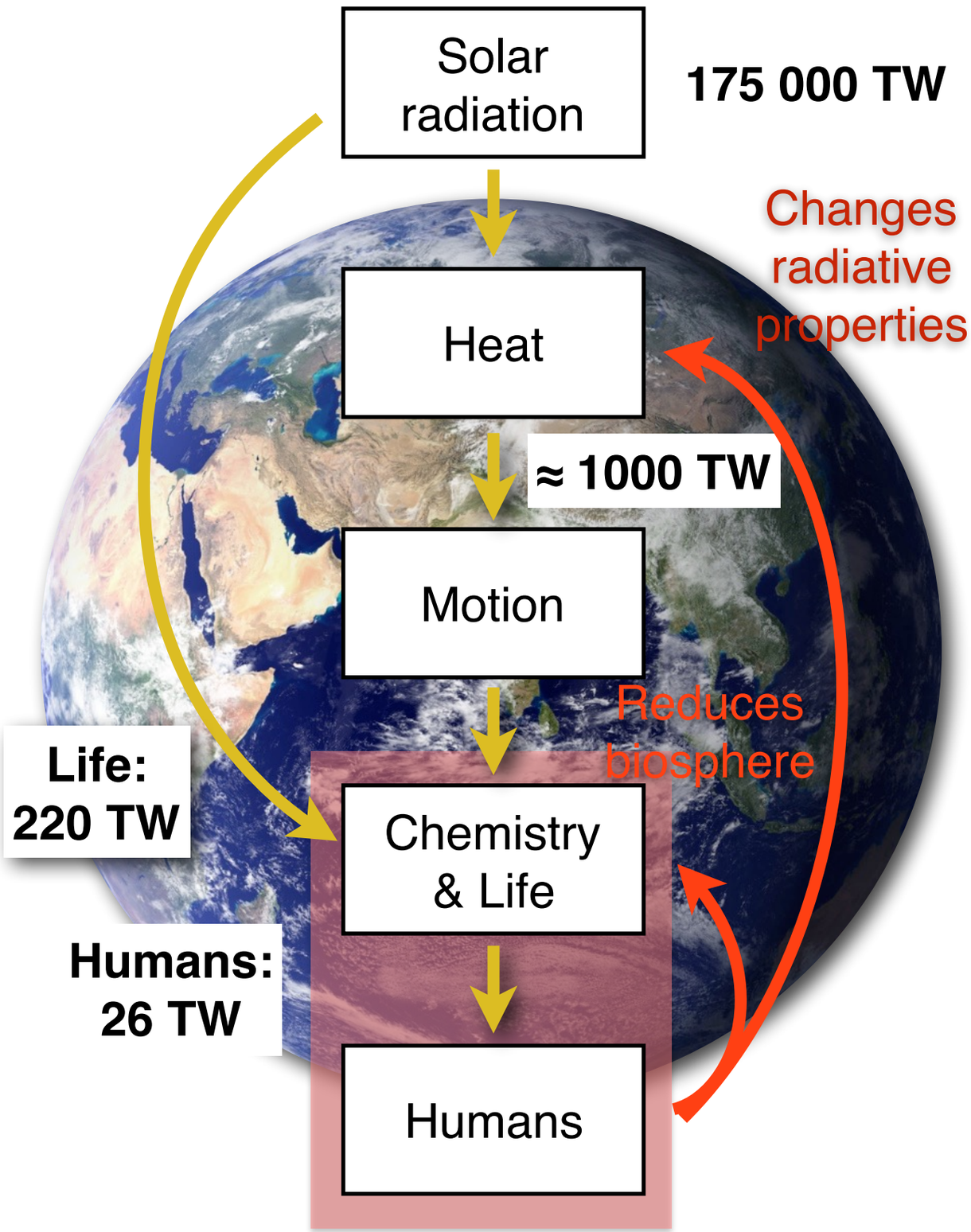
≈ 3300 W/person

≈ 7.5 USD/W

Image: wikipedia.org

Data source: data.oecd.org

Thermodynamics and Human Activity



Human energy consumption:

Food
(agriculture, uses photosynthesis)

≈ 8 TW

Socioeconomic activity
(fossil fuels, “buried sunshine”)

≈ 18 TW

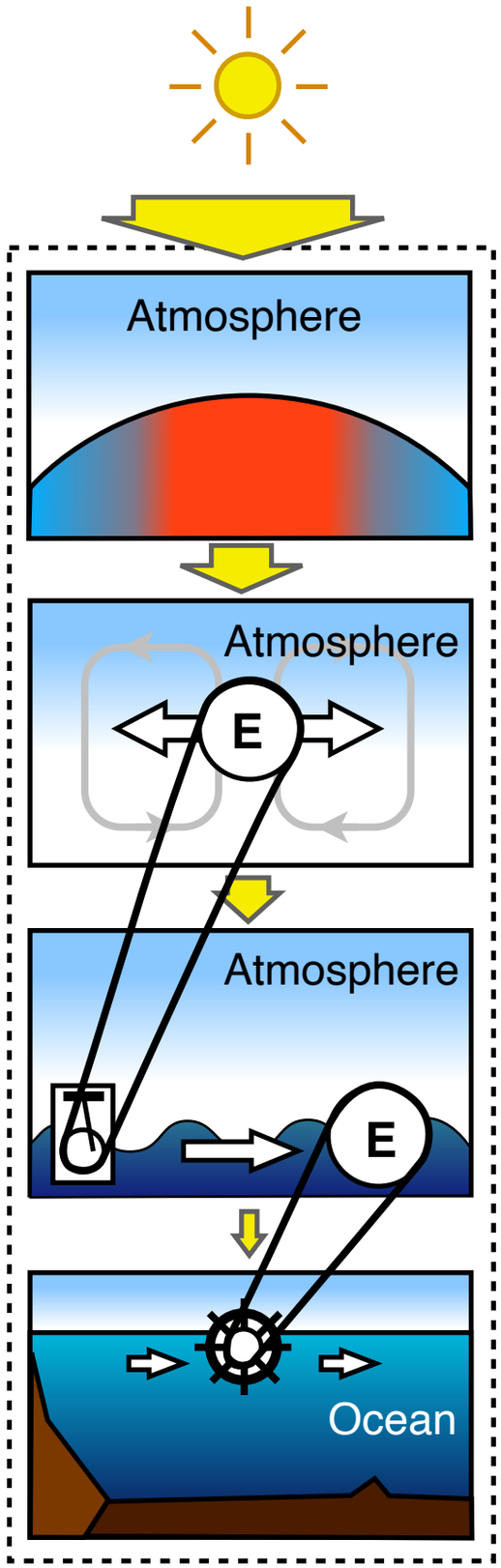
Similar magnitude as Earth system processes

Effects to the Earth system:

Reduction of natural ecosystems

Increase of atmospheric CO_2

Earth system process		Renewable energy
Incoming solar radiation	≈ 175000 TW	→ Solar power
	Absorption 70% *Differential heating* 40%	
Generation of heating differences by absorption	≈ 49000 TW	
	Conversion (max.) 2%	
Generation of atmospheric motion	≈ 1000 TW	→ Wind power
	Conversion (obs.) 6%	
Generation of ocean waves	≈ 60 TW	→ Wave power
	Conversion (obs.) 8%	
Generation of ocean currents	≈ 5 TW	→ Power from ocean currents



Efficiency of Photosynthesis

< 3 %

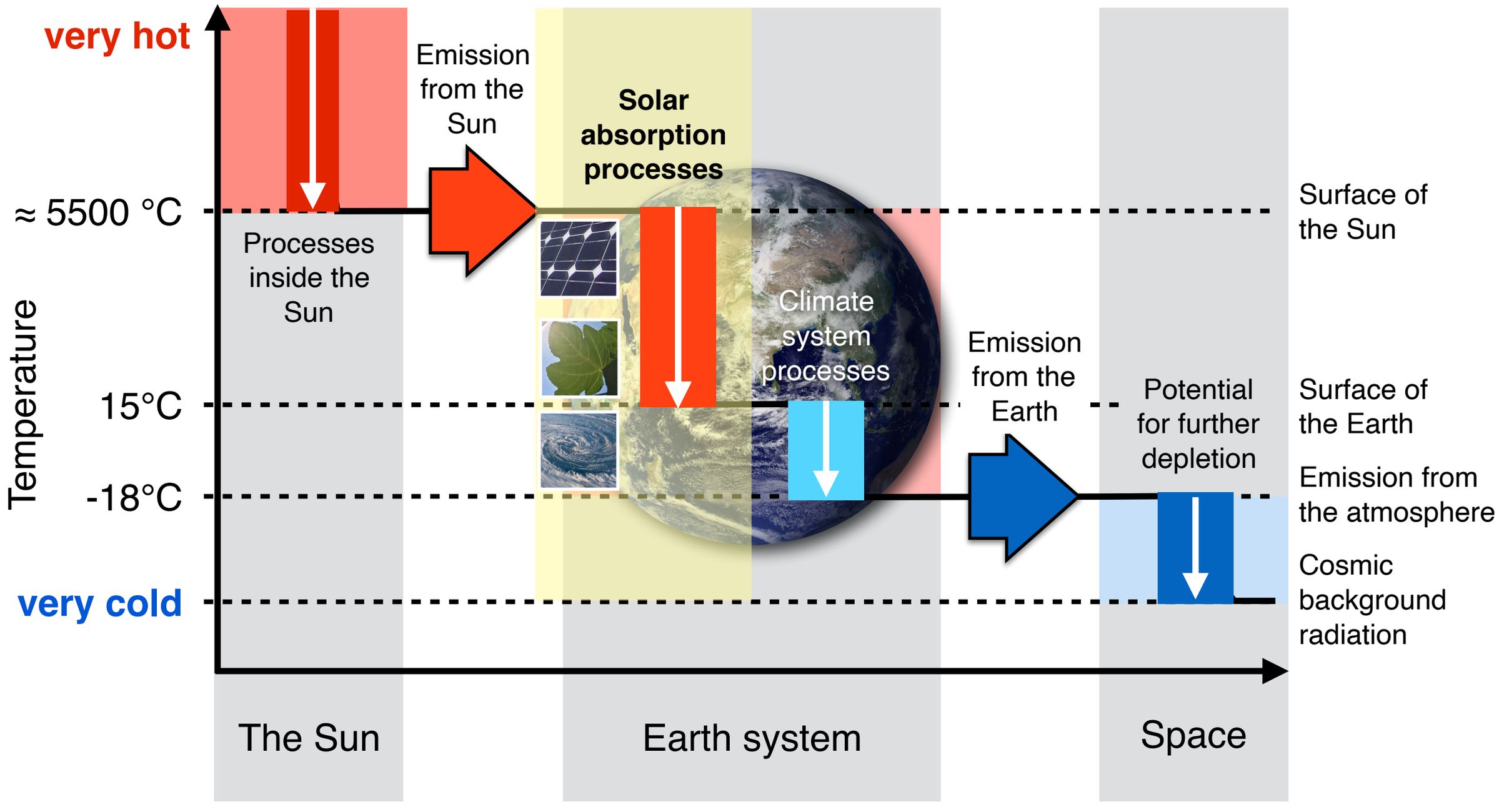
Efficiency of Photovoltaics

≈ 20 %

wikipedia.org
by Fernando Tomas
cc-by-2.0

Thermodynamic Directions

Human technology can get more free energy out of sunlight than photosynthesis or abiotic processes

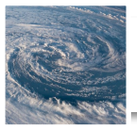


Thermodynamics, Planets, and Evolution

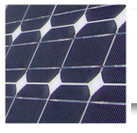
Types and magnitudes of work results in different types of planets

Type I	**Type II**	**Type III**	**Type IV**	**Type V**
Mercury	Venus, Mars	early Earth, Mars?	Earth	Earth 2200?

Free energy generated by:


Abiotic (Motion, Photochemistry)


Life (Photosynthesis)


Technology (Photovoltaics)

Increased generation

Frank, Kleidon, Alberti (2017) *Anthropocene*

Understanding Earth with Thermodynamics

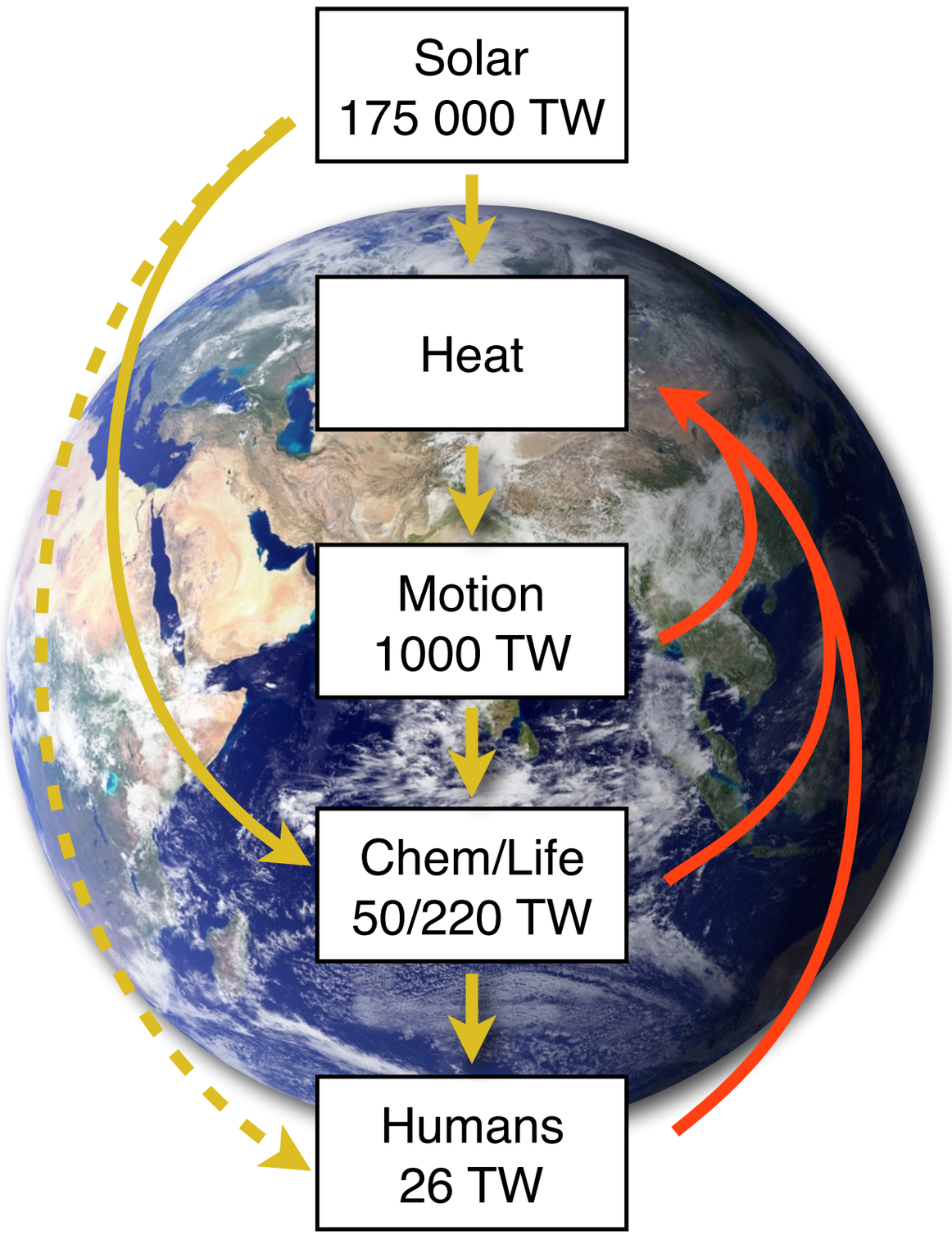


Image: NASA

Thermodynamics of Planet Earth
Entropy of radiation; entropy budget; thermodynamic limits; sequences of conversion

Atmosphere
Motion operates at its thermodynamic limit

Geochemistry
Life is the major producer of chemical energy; indirectly limited by transport; may maximize through changing radiative conditions

Anthroposphere
Major consumer of free energy; may increase free energy generation through technology (PV)