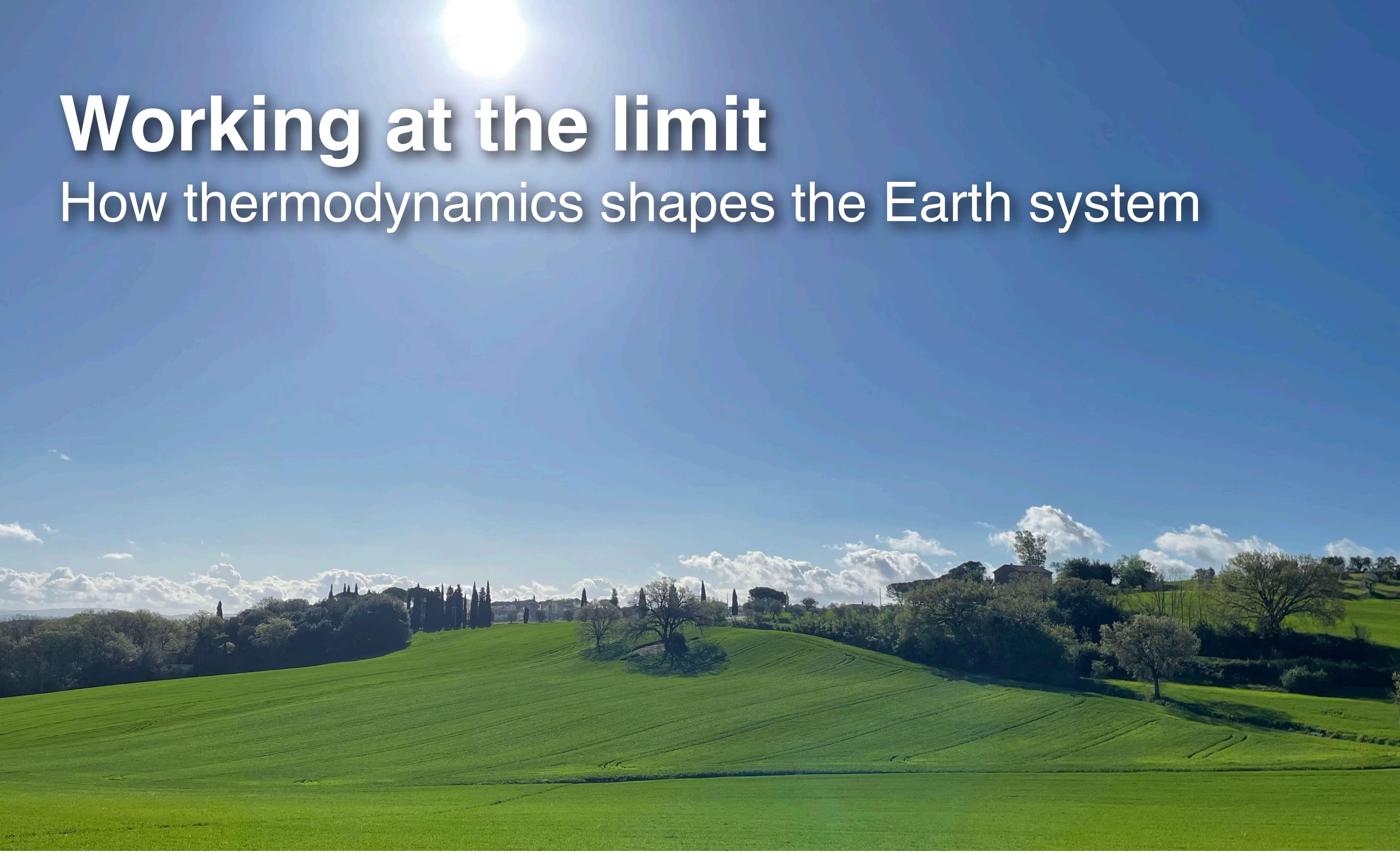
Working at the limit

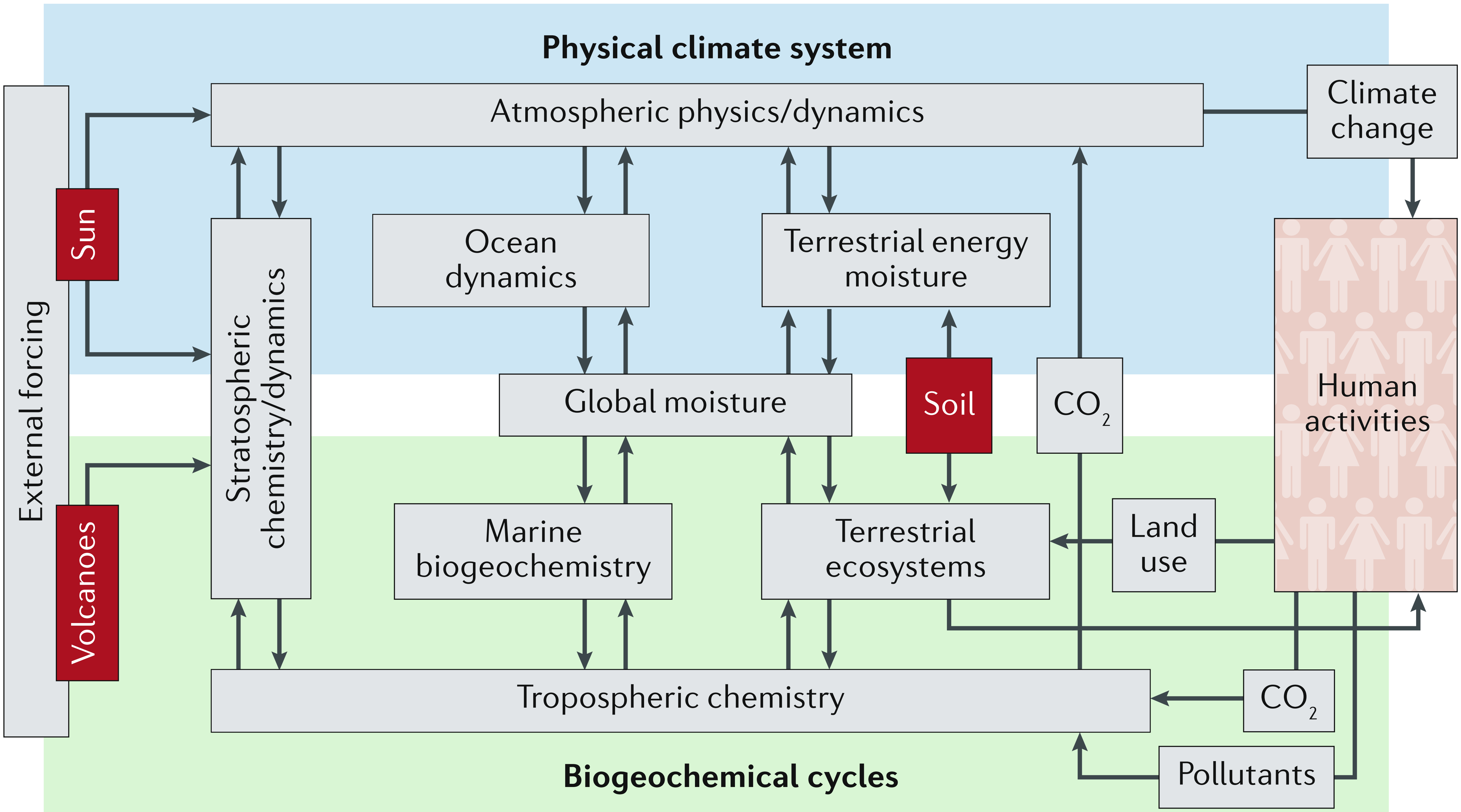
How thermodynamics shapes the Earth system



India Tour
April 2023

Axel Kleidon
Max-Planck-Institute for Biogeochemistry
http://gaia.mpg.de - akleidon@bgc-jena.mpg.de

The “Bretherton Diagram” of Earth System Science



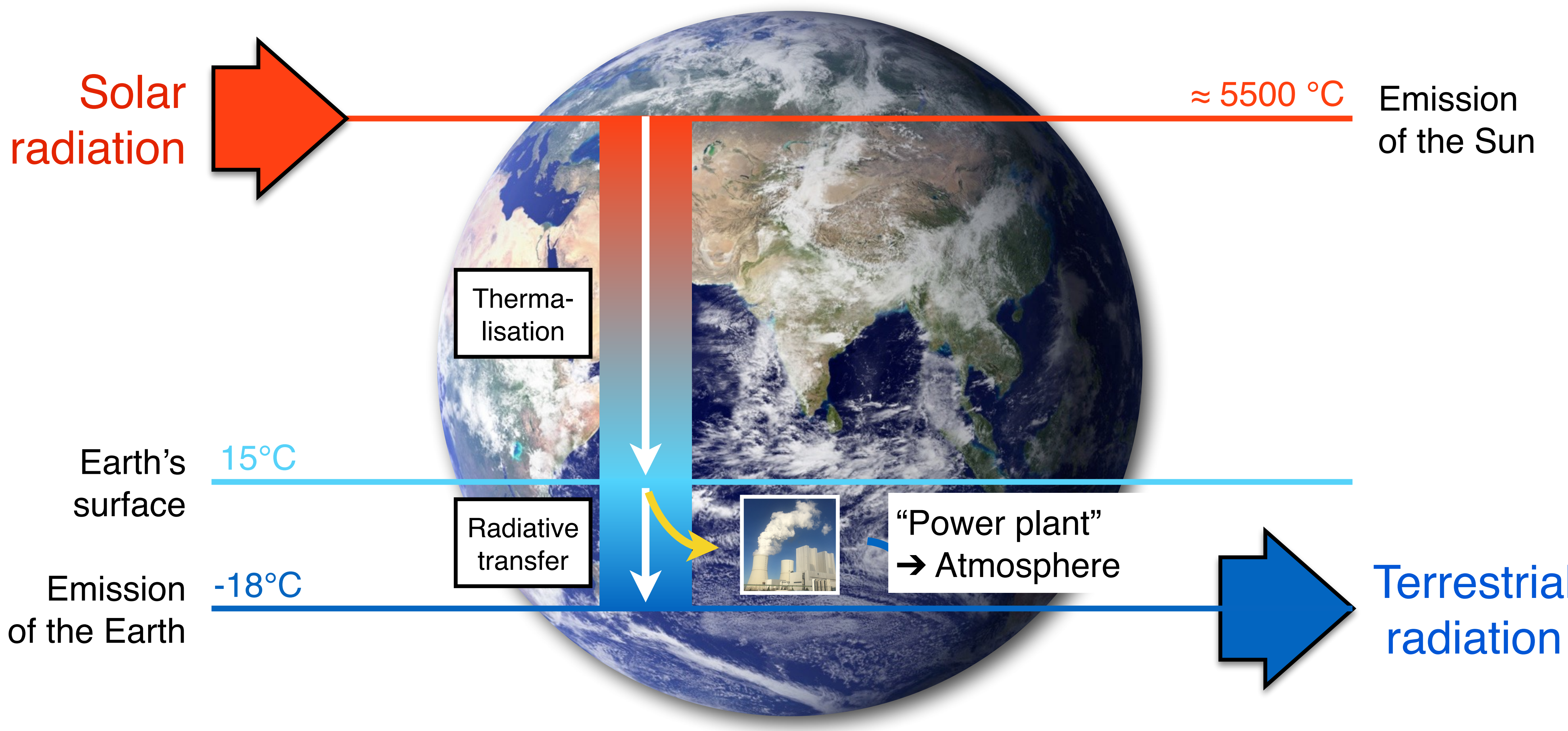
Steffen et al. (2020); based on NASA (1986)

Why do things happen on Earth?

- ➔ Entropy and the "Second Law"
- ➔ Direction for the Earth system
- ➔ Sets limits for energy conversions
- ➔ Constrains *work* to run dynamics
- ➔ *Working at the limit*
- ➔ Climate, hydrology, vegetation
- ➔ Basis for Earth system science,
  (renewable energy, sustainability, planetary evolution)

Image: NASA

Thermodynamics of the Planet

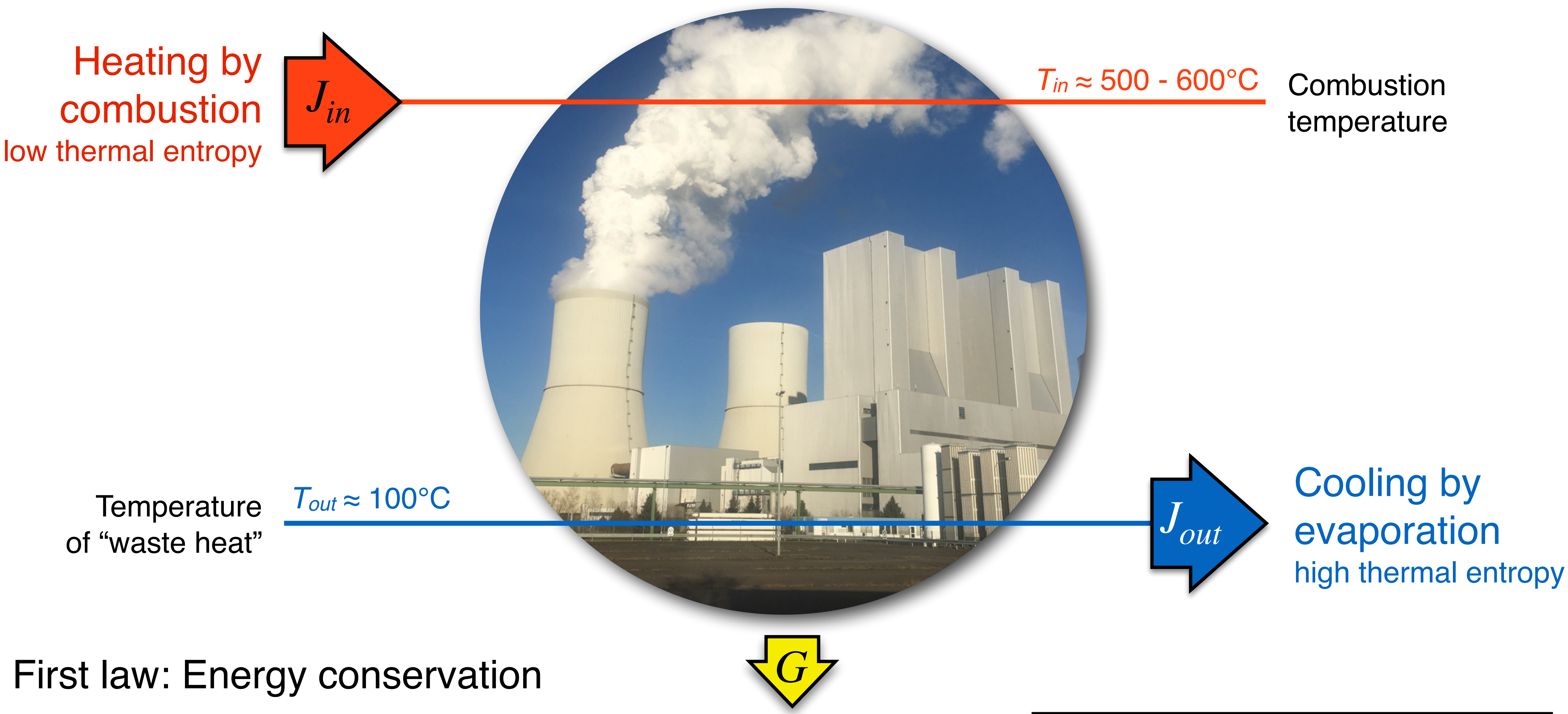


Low radiative entropy — Entropy production → High radiative entropy

Short wavelengths — Long wavelengths

Few energetic photons — Many less-energetic photons

Setting Limits to Free Energy



Free energy
(no entropy)

First law: Energy conservation

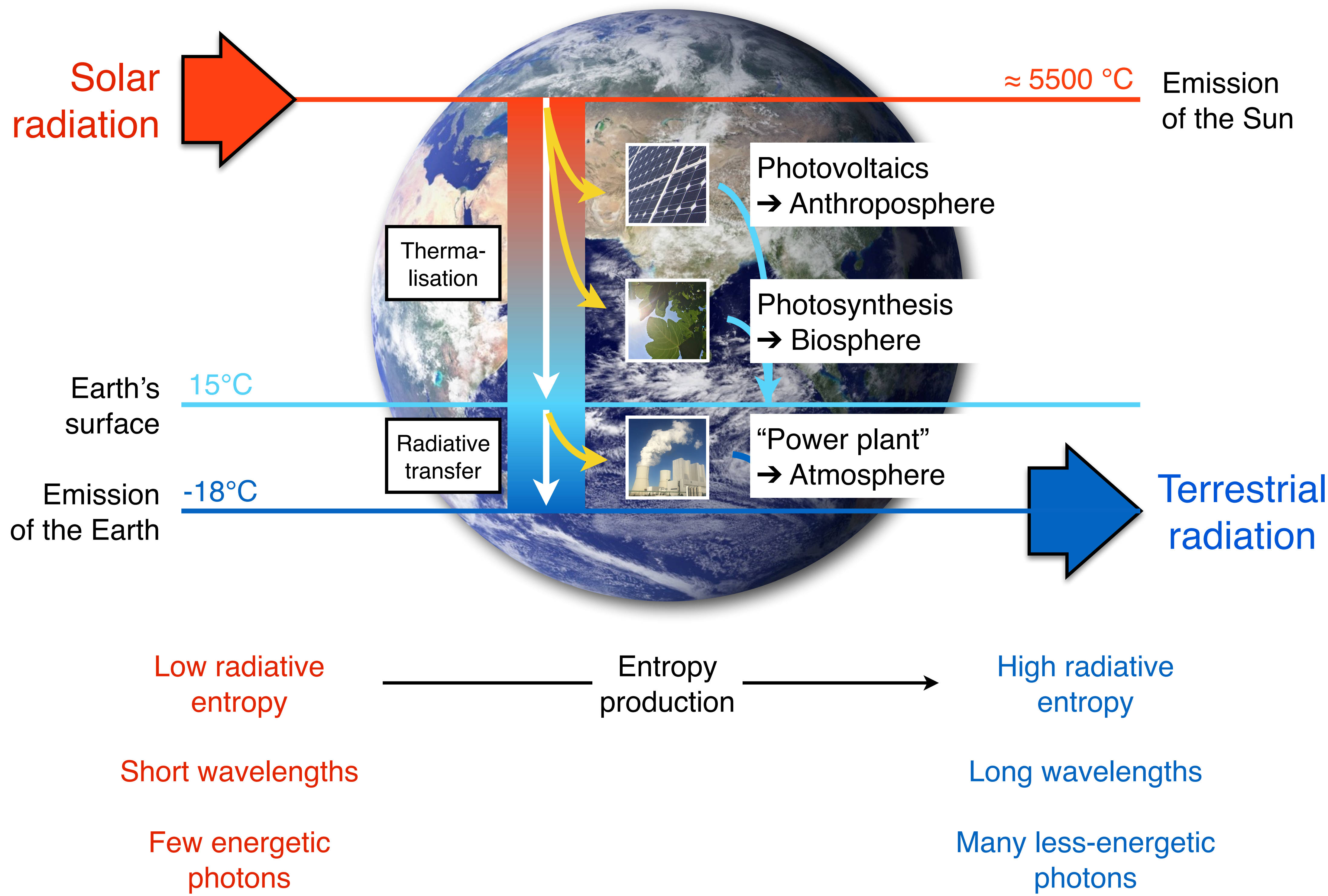
$$J_{in} = J_{out} + G$$

Second law: Entropy increase

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

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

Thermodynamics of the Planet



Outline

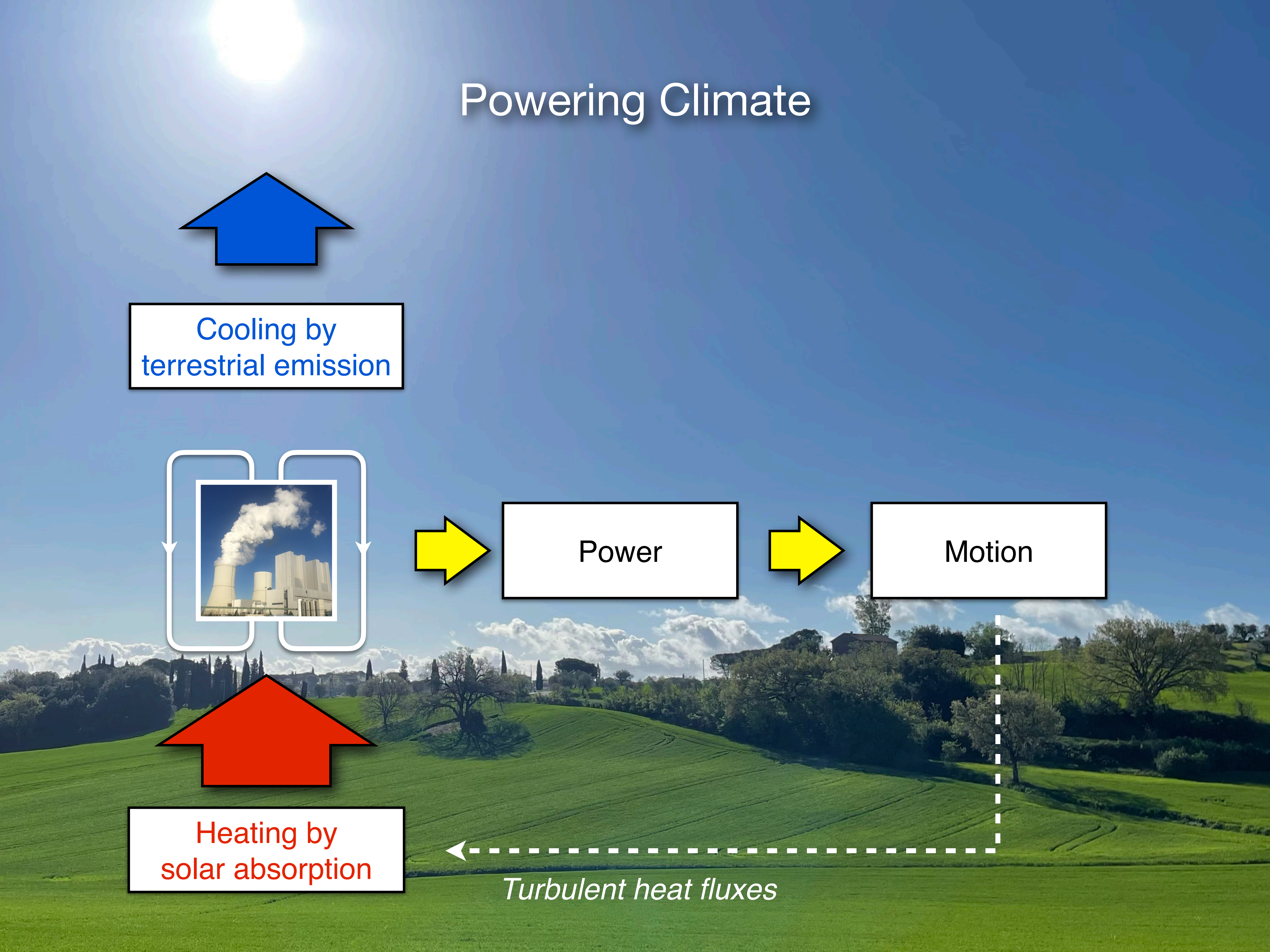
1. Powering climate
   How thermodynamics constrains motion and determines temperatures

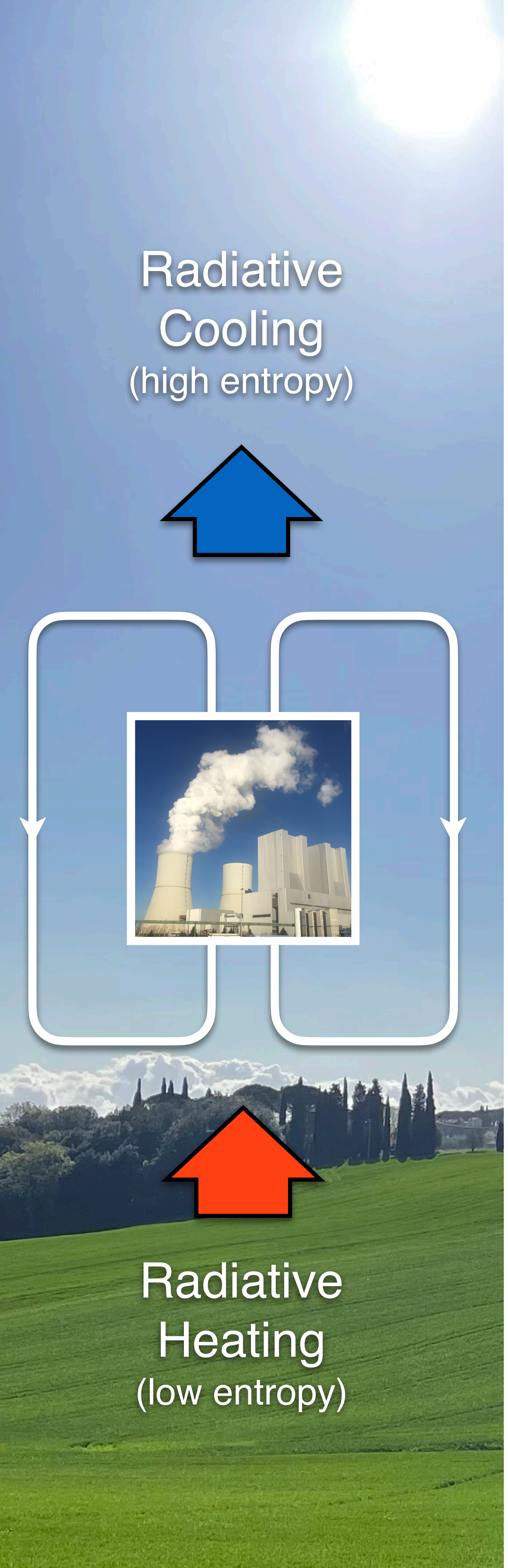
2. Powering cycling
   How thermodynamics shapes evaporation and hydrologic cycling

3. Powering life
   How thermodynamics constrains photosynthesis indirectly and how vegetation can push its limits

4. Powering human societies
   Energy and future sustainability

5. Summary


Powering Climate
Cooling by terrestrial emission
Power
Motion
Heating by solar absorption
Turbulent heat fluxes

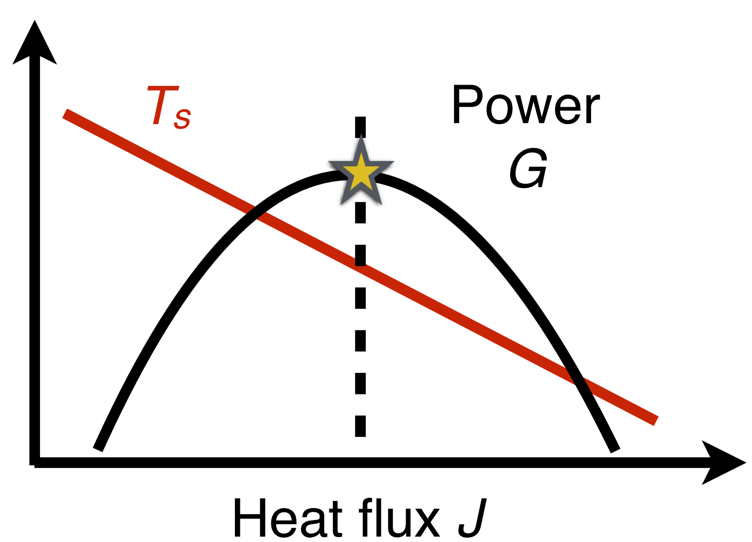


Working at the Limit

Thermodynamic limit:

$$G = J \cdot \frac{T_s - T_r}{T_s}$$

Maximum power limit:



Top-of-atmosphere budget:

$$R_{l,toa} = \sigma T_r^4 \approx \overline{R_{s,tot}}$$

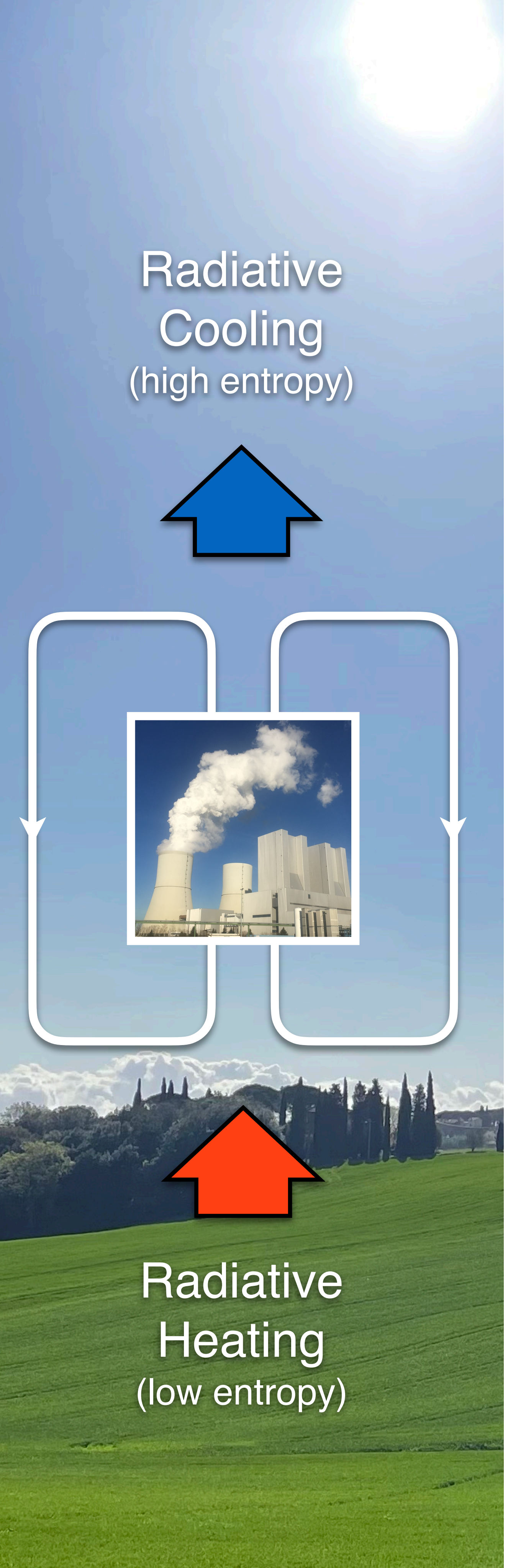
$$T_s - T_r \approx \frac{R_s - R_{l,0} - J}{k_r}$$

Surface energy budget:

$$R_s + R_{l,d} = \sigma T_s^4 + J$$

For simplicity: $J = H + LE$

Kleidon & Renner (2013), Ghausi et al. (in review)



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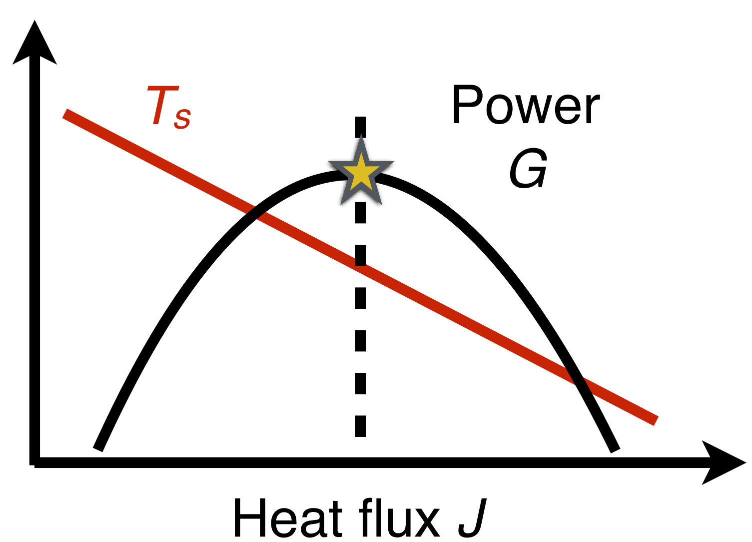
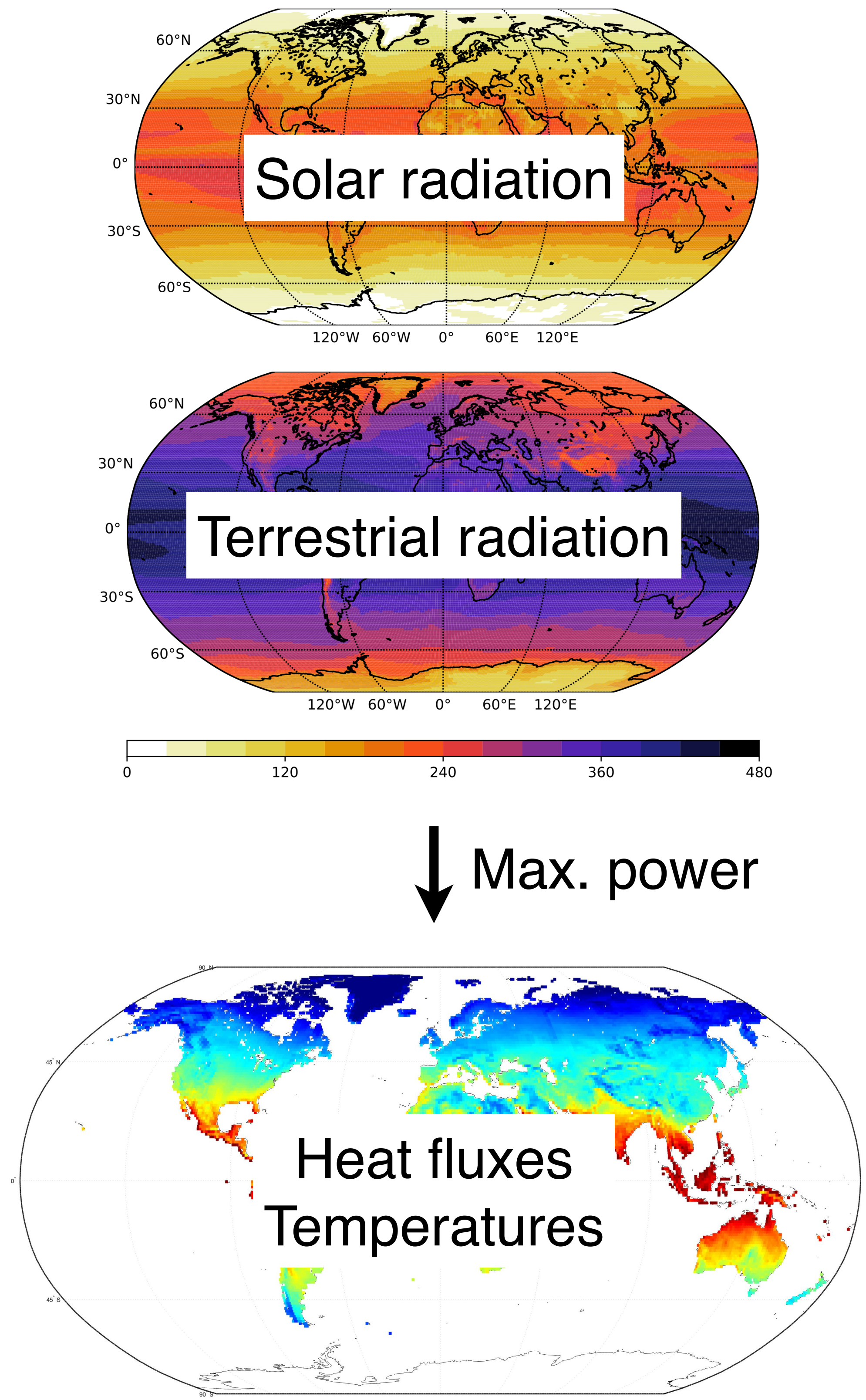
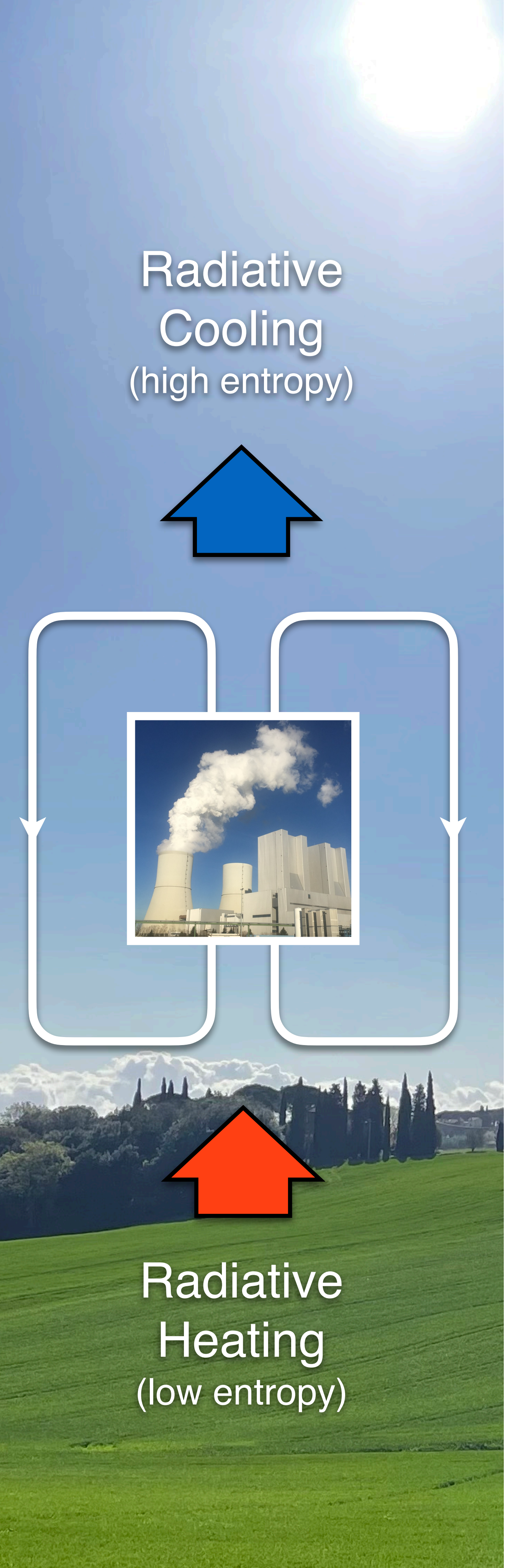


NASA-CERES datasets



Kleidon & Renner (2013), Ghausi et al. (in review)



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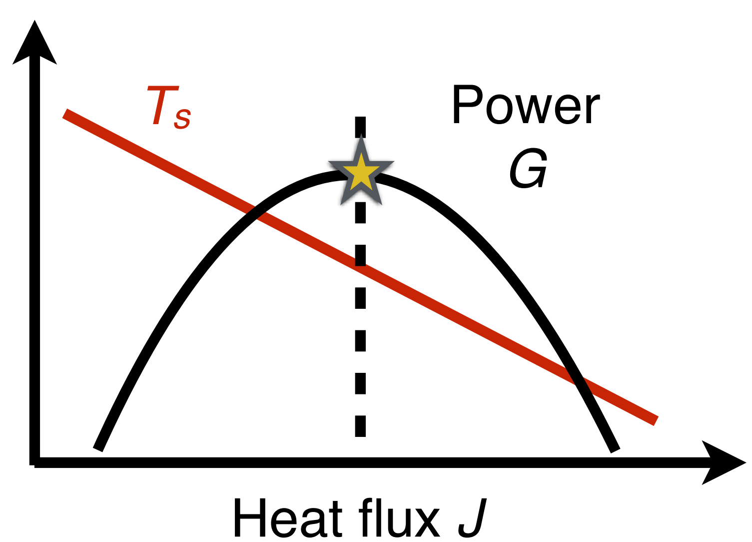
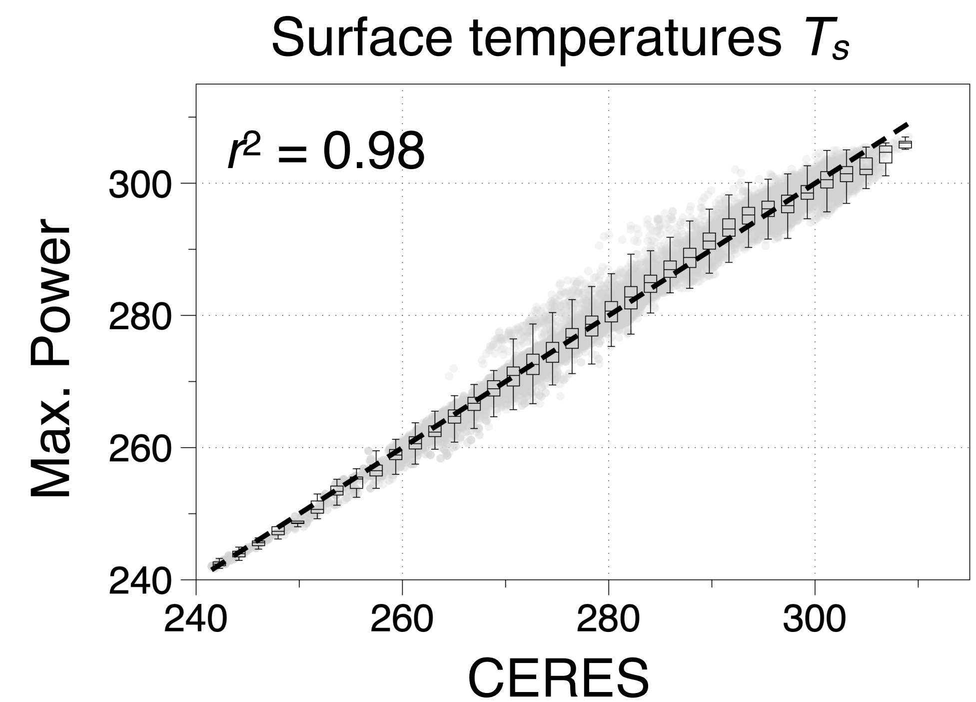
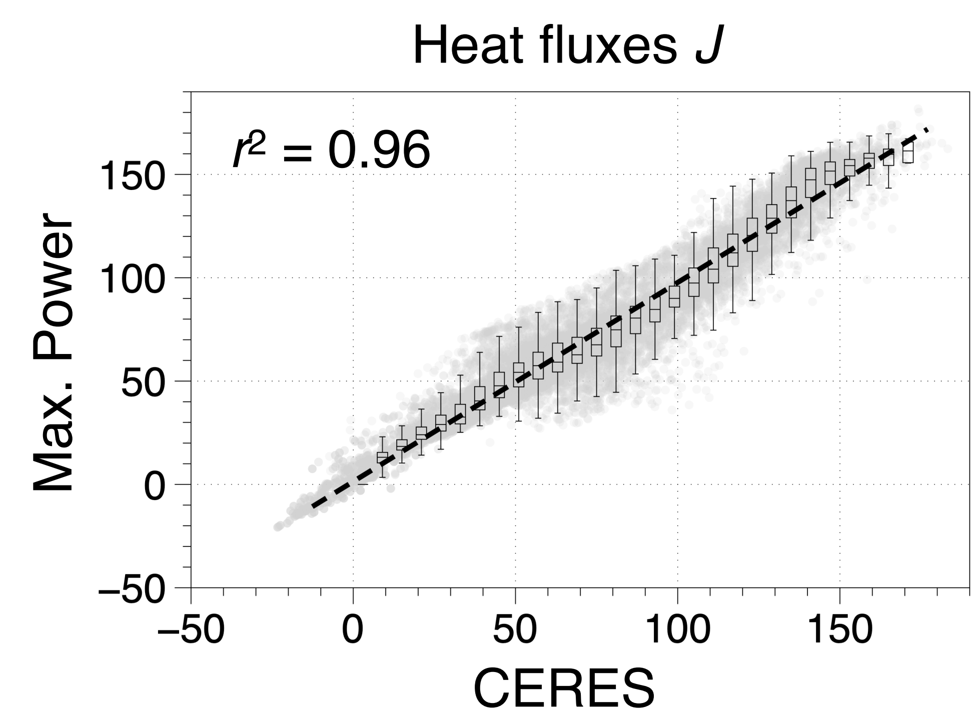
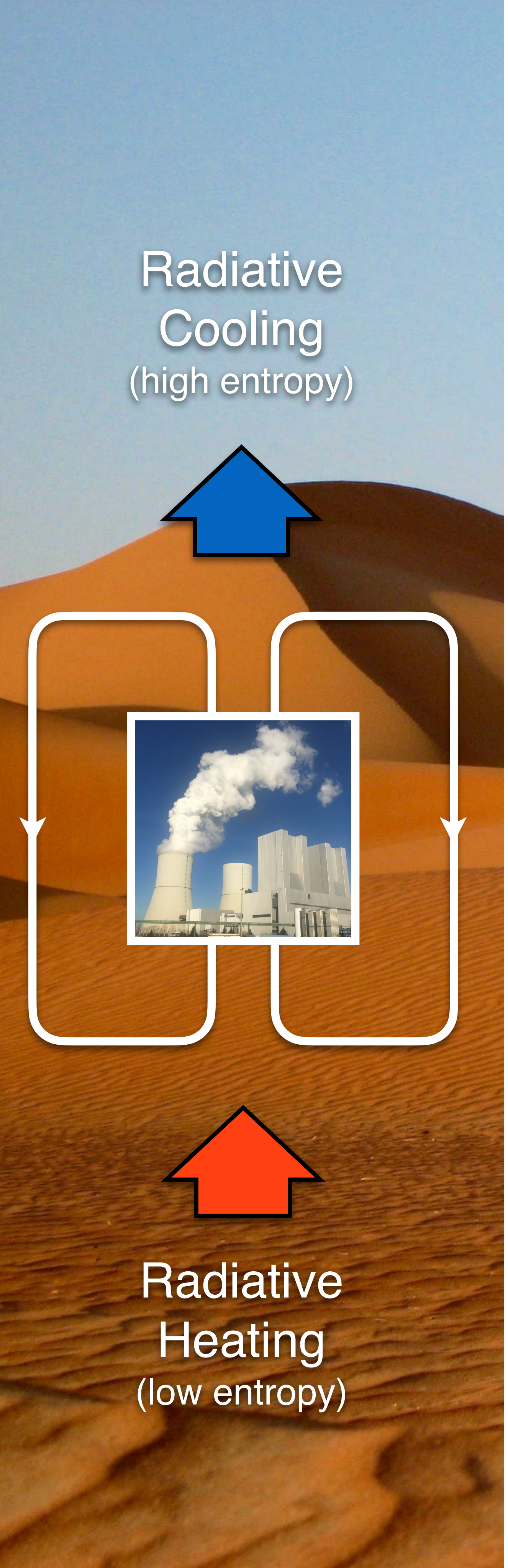


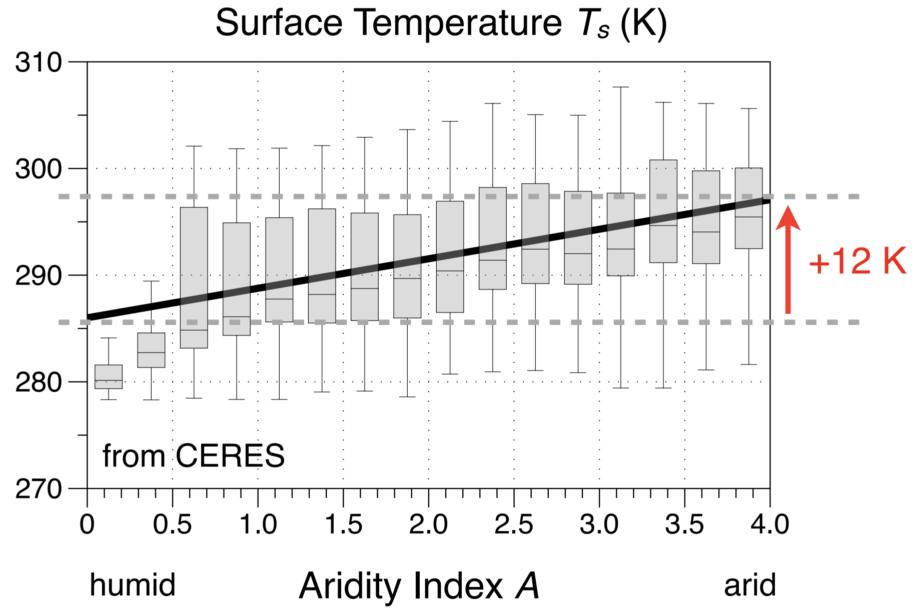


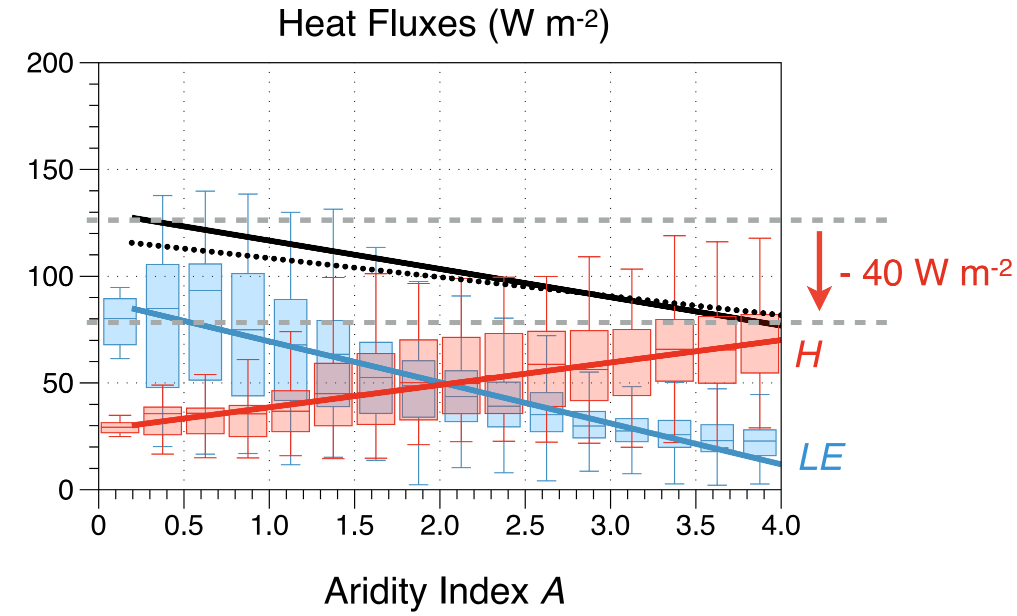


Kleidon & Renner (2013), Ghausi et al. (in review)

Working at the Limit



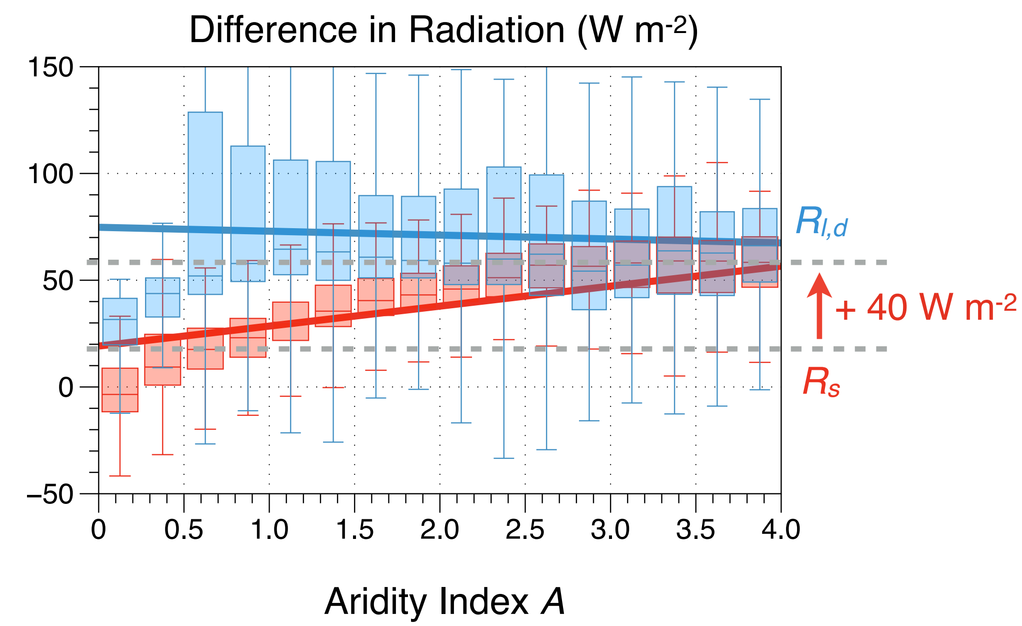




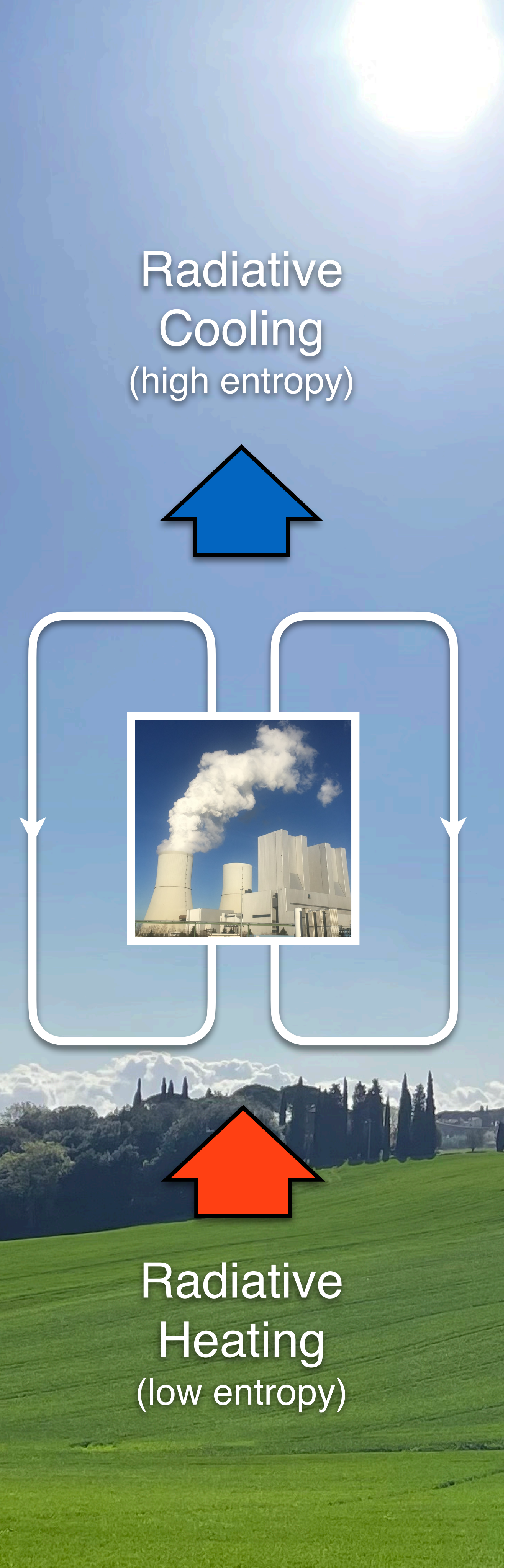
$$\Delta T_s = \frac{\Delta R_s + \Delta R_{l,d} - \Delta LE - \Delta H}{4\sigma T_{s,0}^3}$$

$\Delta T_s \approx +14$ K

mostly because of less clouds
and less efficient heat engine



Ghausi et al. (in review)



Powering Climate

- **Disequilibrium:** Spatiotemporal separation of absorption of solar radiation and emission to space
- **Heat engine:** Generates convective motion and turbulent heat fluxes; depletes disequilibrium
- **Working at the limit:** Heat fluxes deplete temperature difference, resulting in a maximum in power
- **Application:** Deserts are warmer because of less clouds and less efficient heat engine
- **Implication:** Surface temperatures are directly (and indirectly) mostly determined by radiation

Powering Cycling

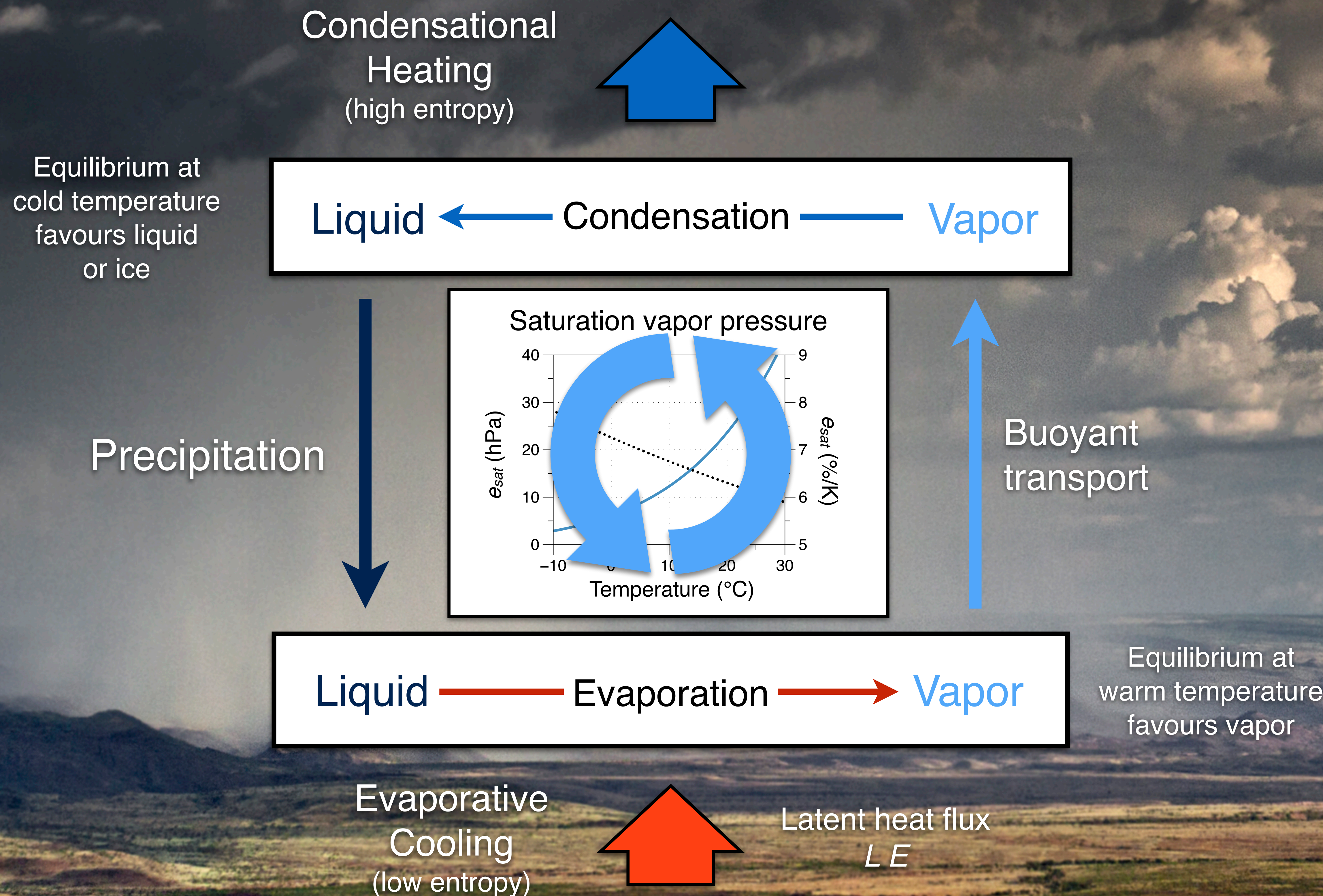


Image: Annett Junginger (distributed via imaggeo.egu.eu)

Partitioning of Surface Heating

Heating of air

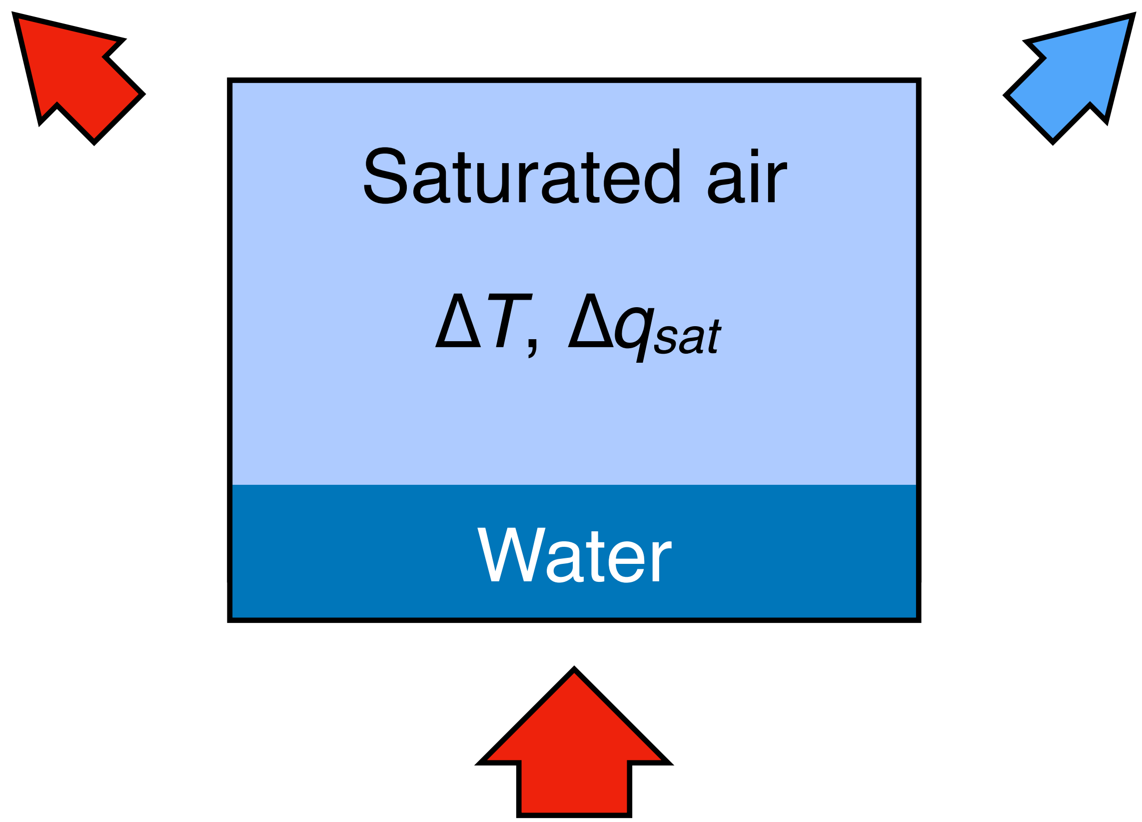
Increase in
thermal energy

$$\Delta U_{th} = c_p \rho V \cdot \Delta T$$

Moistening of air

Increase in
latent heat

$$\Delta U_{le} = L \rho V \cdot \Delta q_{sat}$$



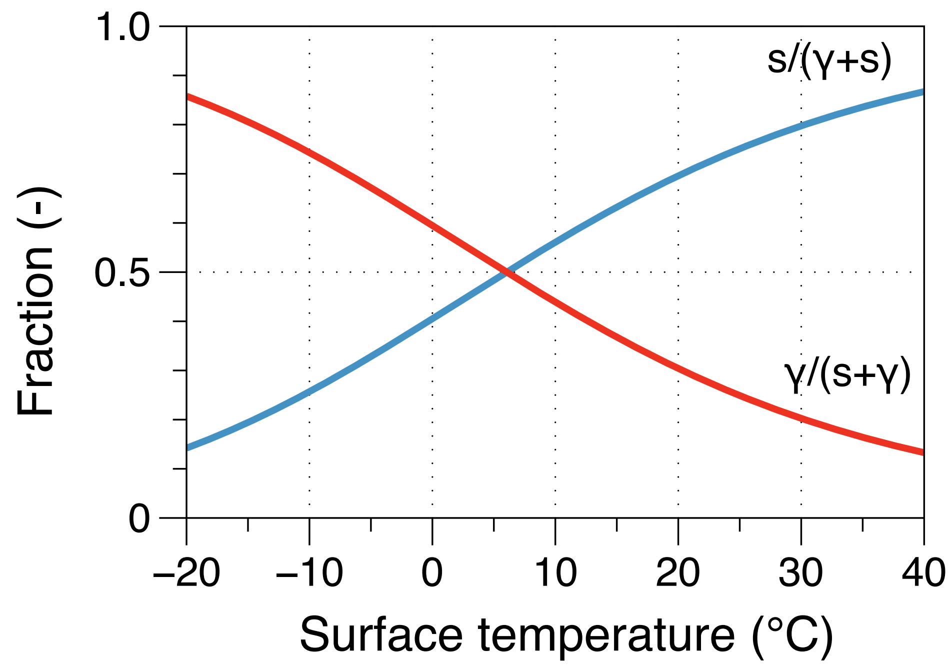
Energy added:
ΔU

"Equilibrium partitioning" of turbulent fluxes at the surface (Schmidt, 1915)

Heating of air

Increase in thermal energy

$$\Delta U_{th} = \frac{\gamma}{\gamma + s} \cdot \Delta U$$



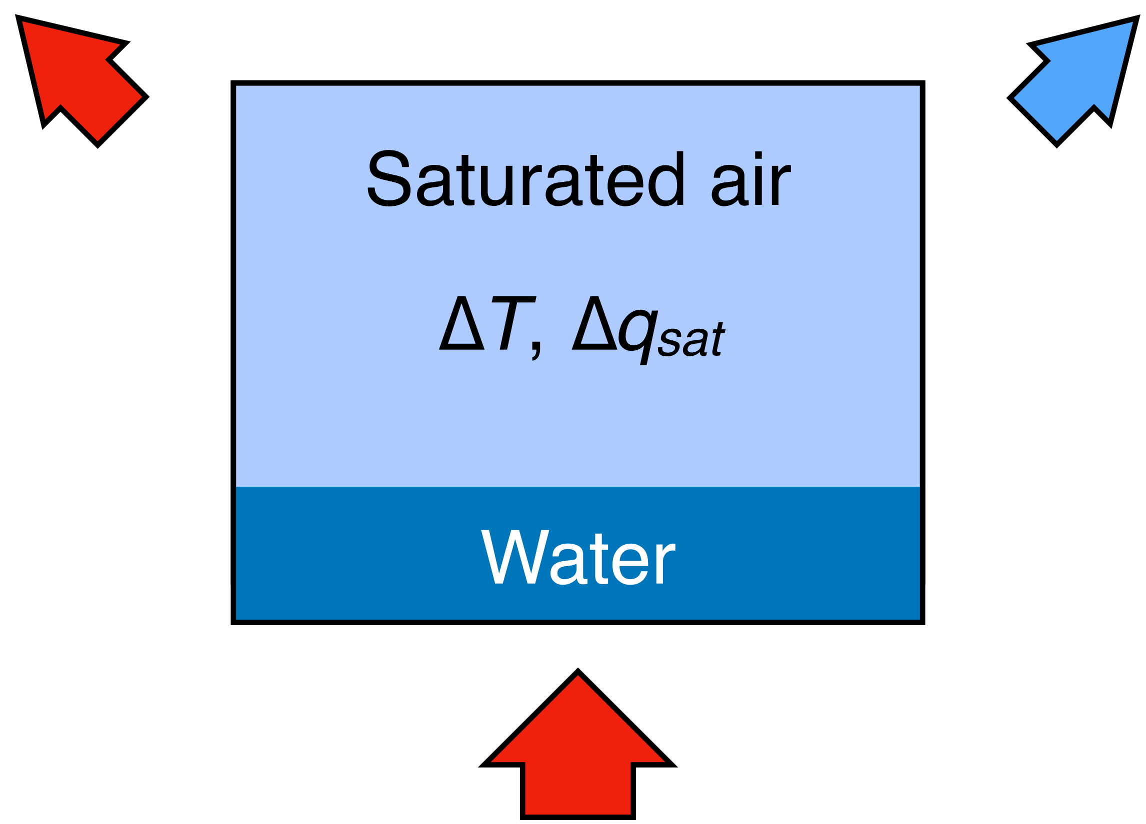
Moistening of air

Increase in latent heat

$$\Delta U_{le} = \frac{s}{\gamma + s} \cdot \Delta U$$

γ: psychrometric constant

s: slope of saturation vapour pressure, de_{sat}/dT ("Clausius-Clapeyron")



Sensible Heat Flux

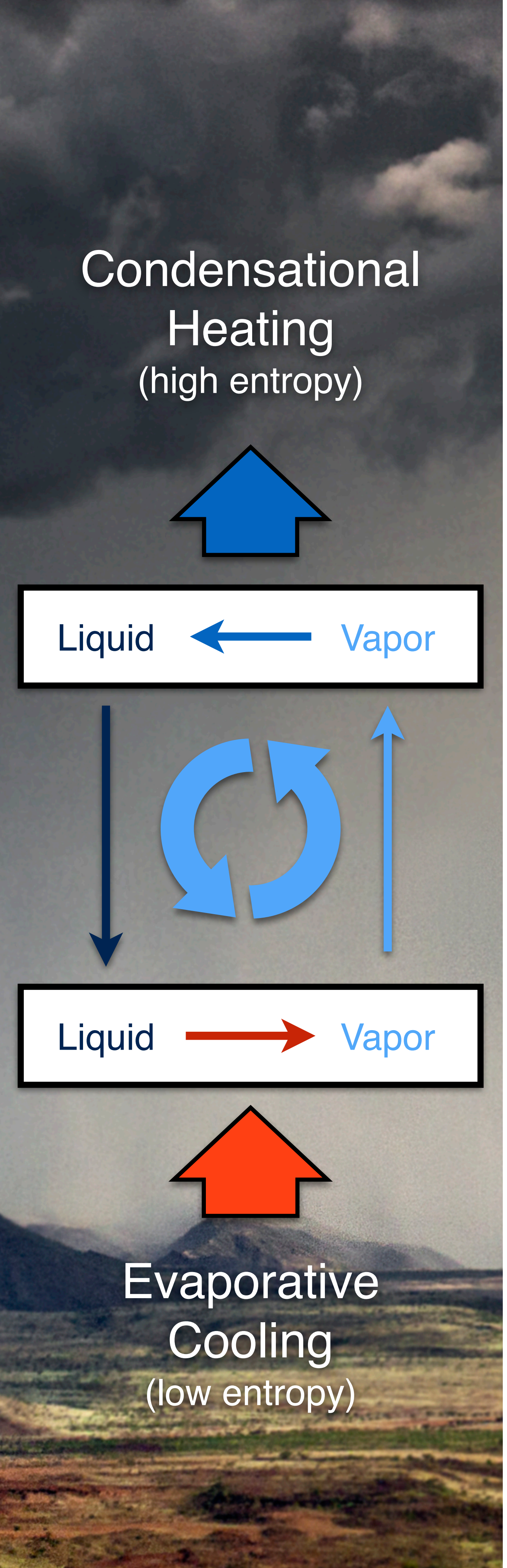
Latent Heat Flux

Equilibrium Evaporation

or

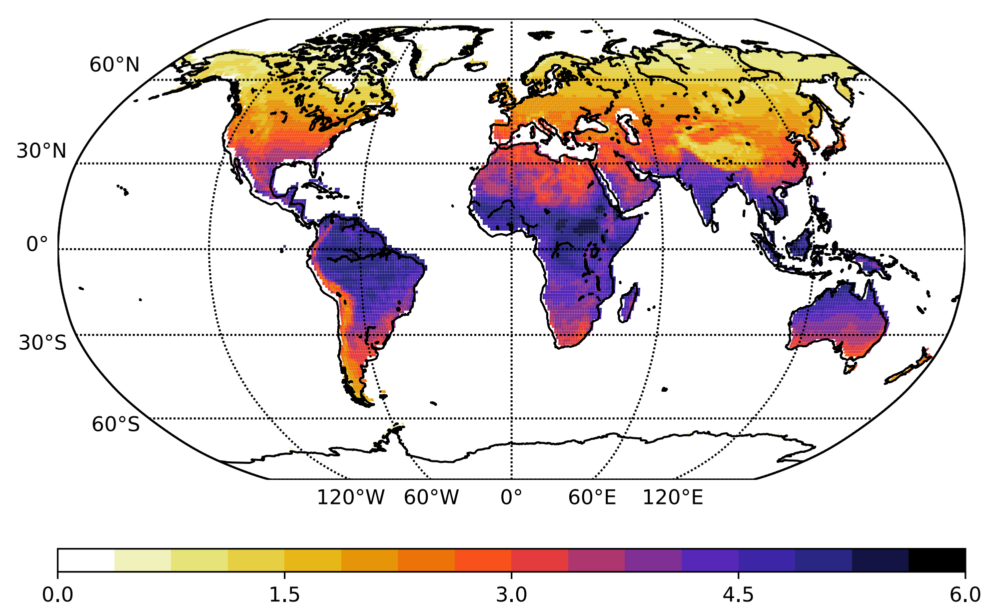
Potential Evaporation

Energy added: ΔU

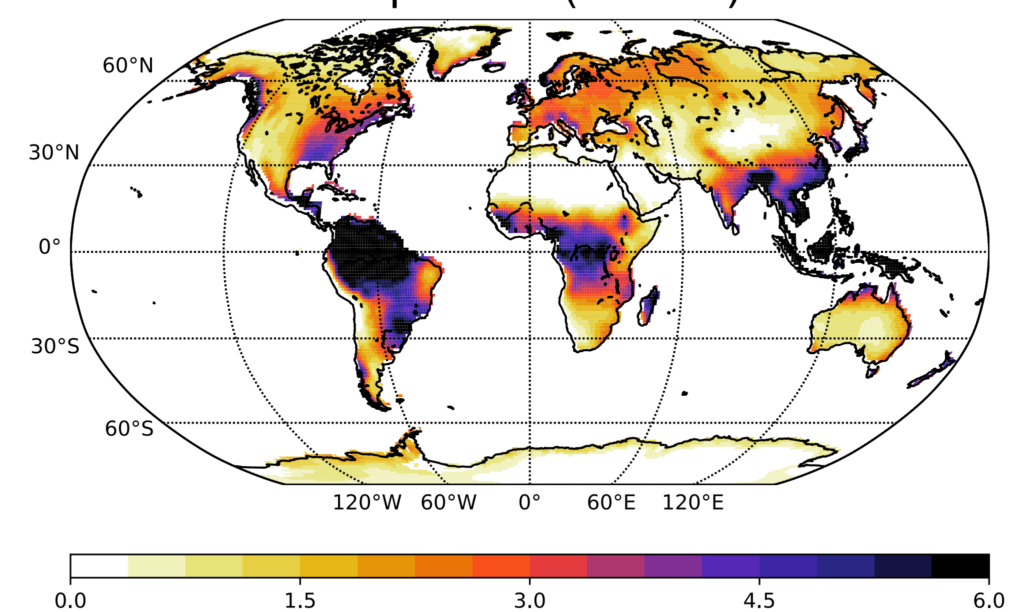


Working at the limit

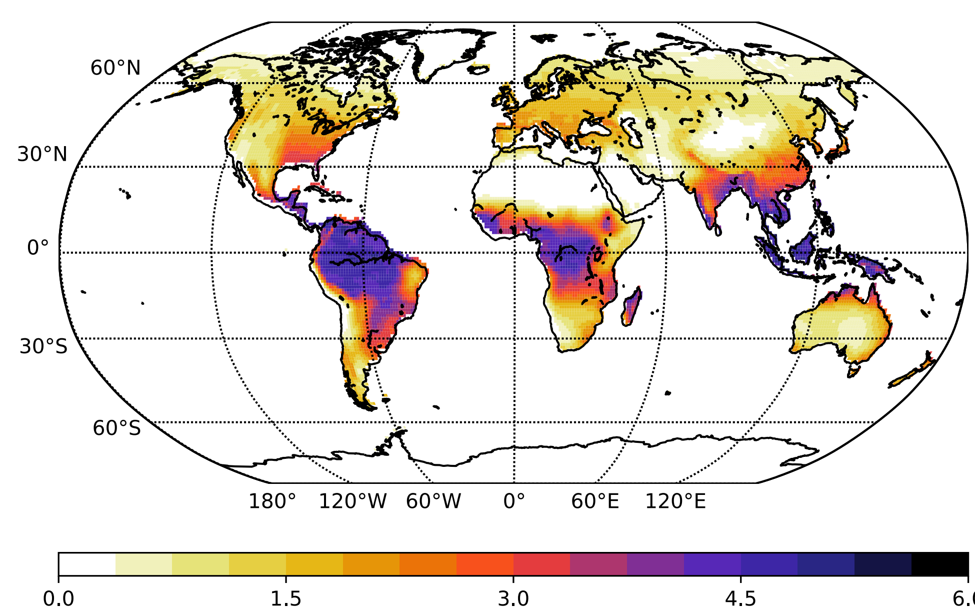
Potential Evaporation (mm d^{-1})

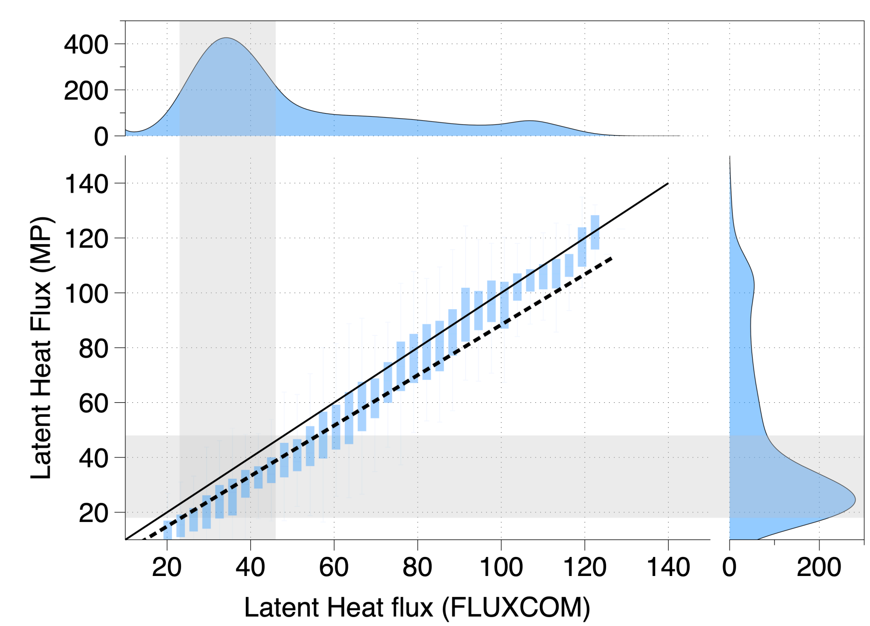


Precipitation (mm d^{-1})



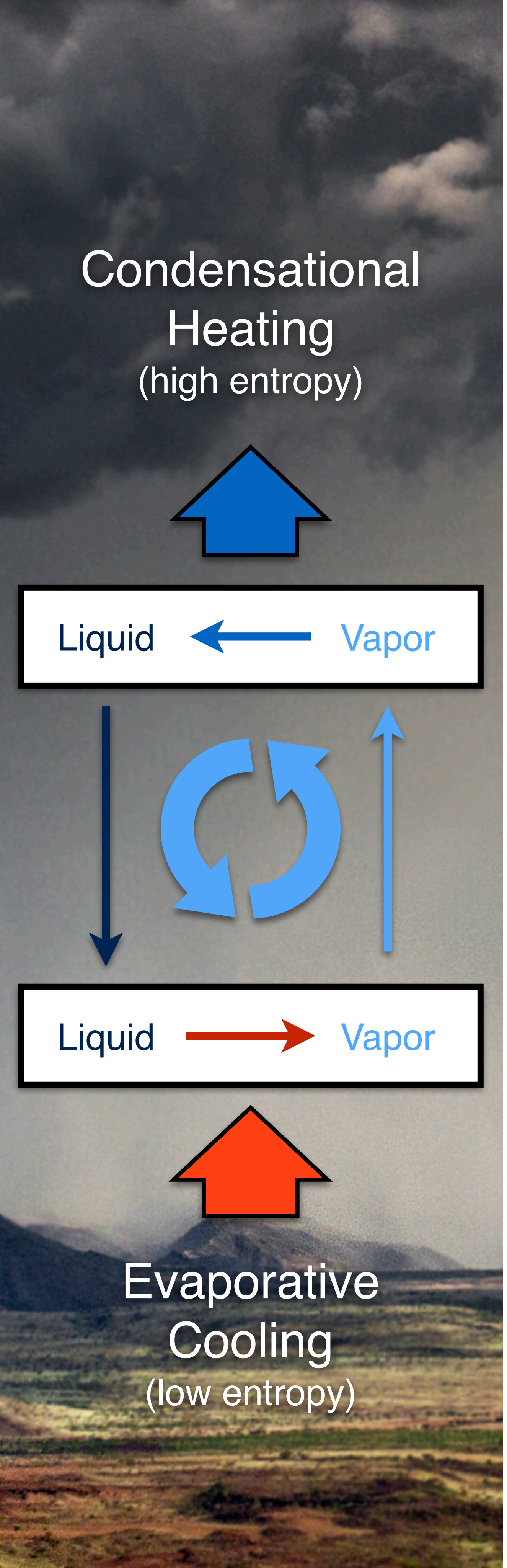
Actual Evaporation (mm d^{-1})

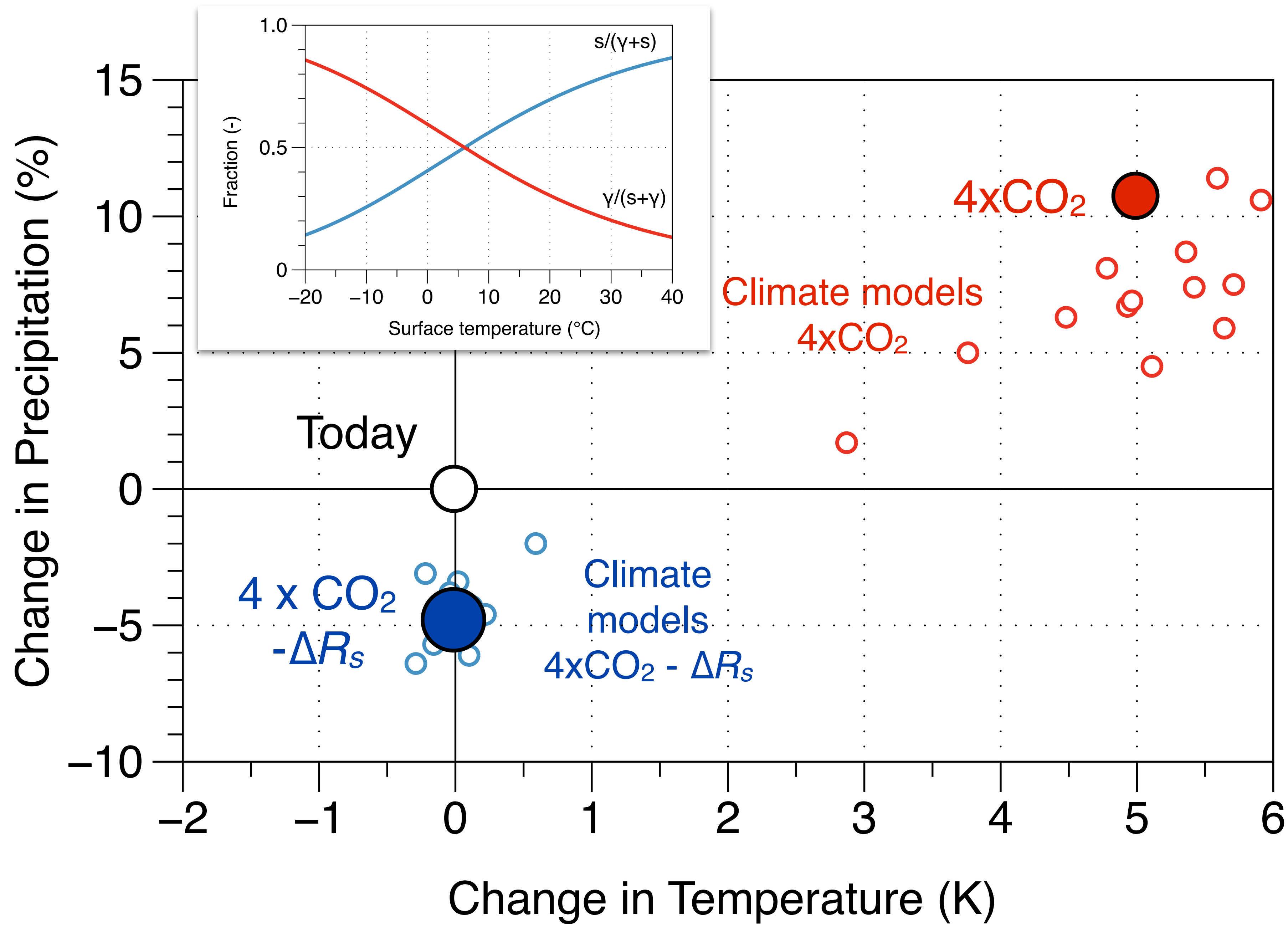




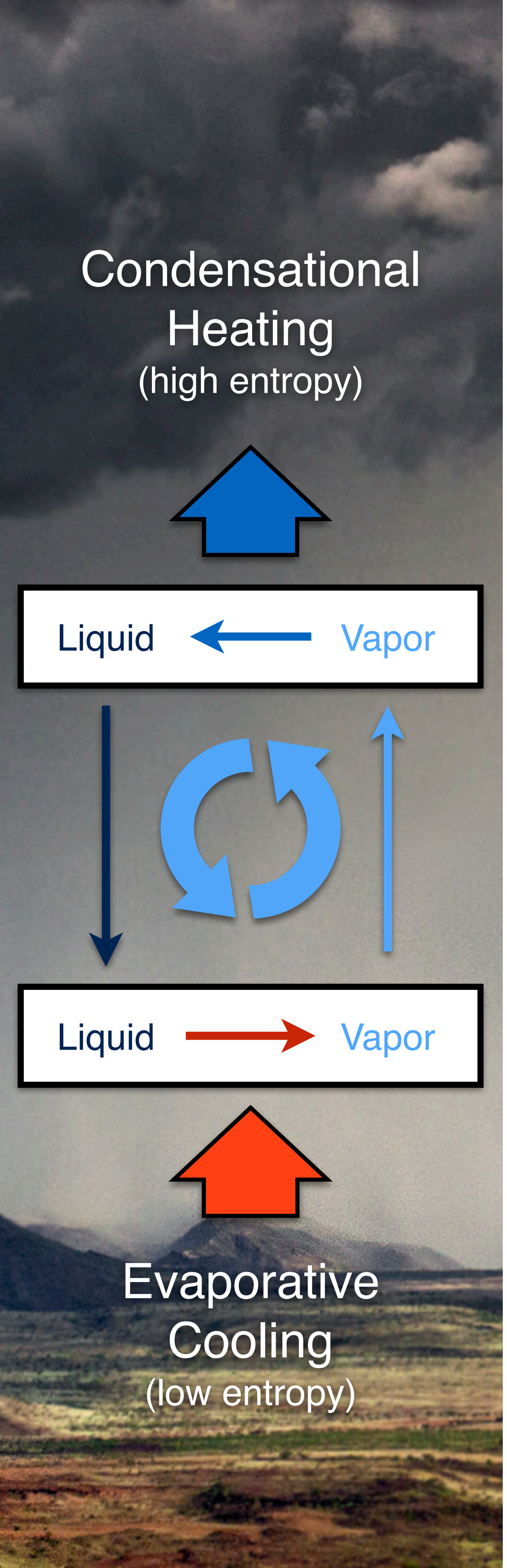
Kleidon (2021); Ghausi et al. (in review)

Hydrologic Cycling and Global Change





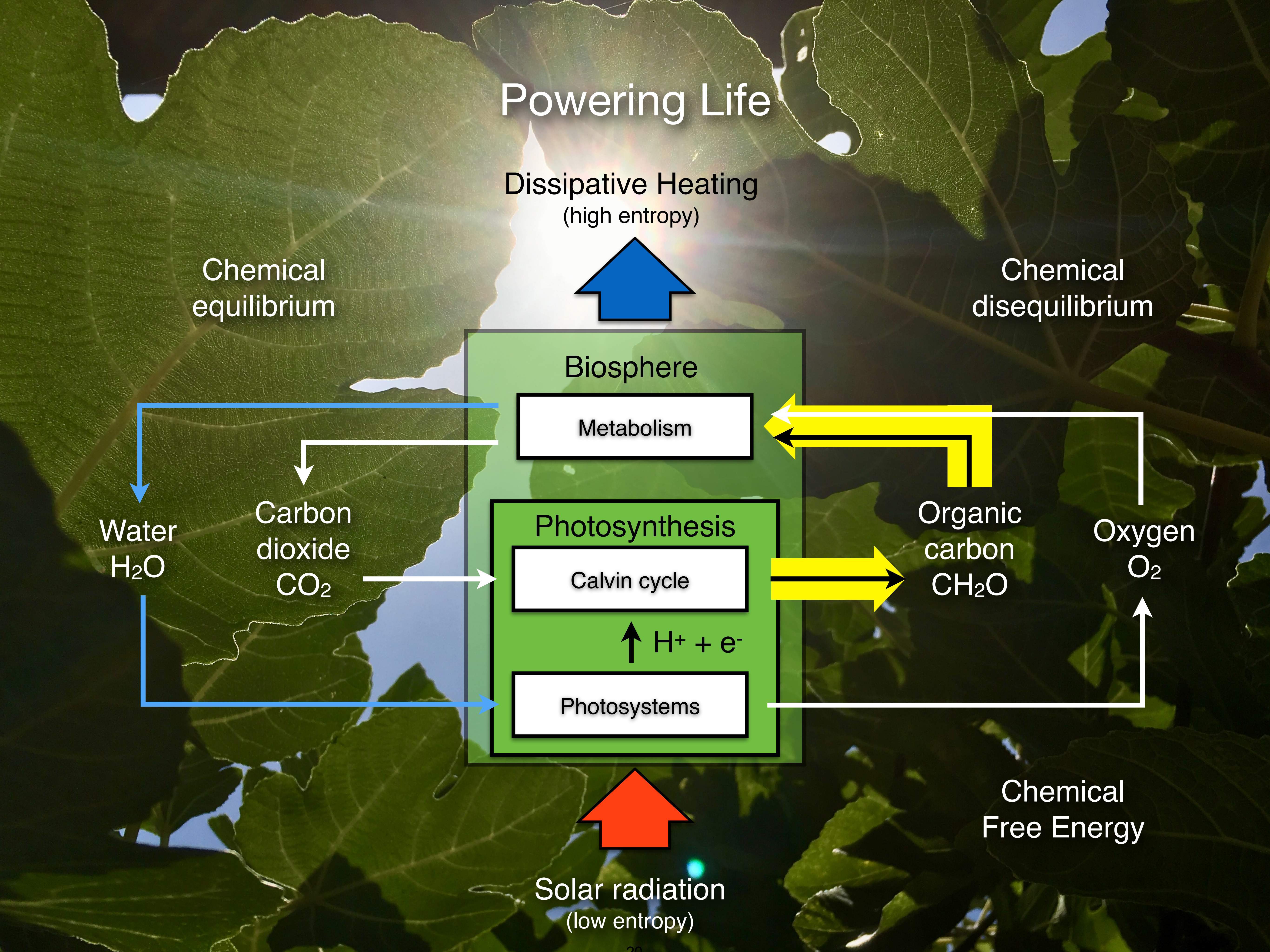
Kleidon and Renner (2013) *Earth Syst. Dynam.*
Kleidon, Kravitz, Renner (2015) *Geophys. Res. Lett.*

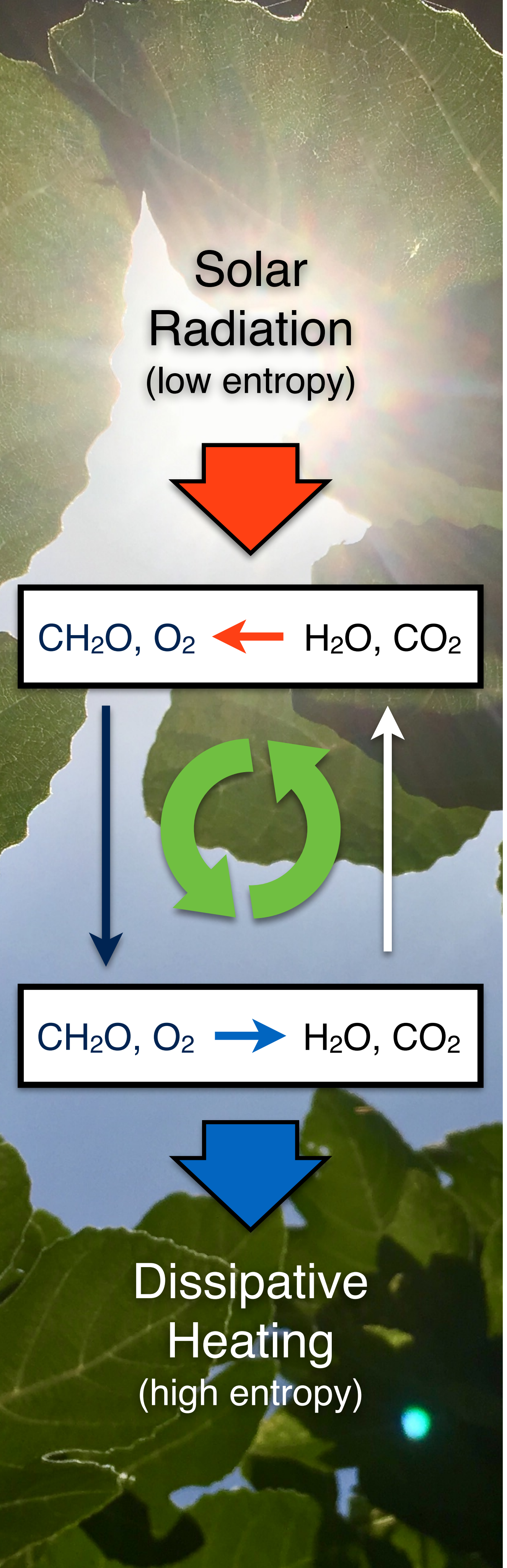


Powering Cycling

- **Disequilibrium:** Spatiotemporal separation of evaporation and condensation
  - Generated by dehumidification by precipitation
  - Depletion by evaporation
  - Requires vertical motion to operate
- **Working at the limit:** Indirect constraint by equilibrium partitioning combined with max. power heat fluxes
- **Application:** Sensitivity of hydrologic cycle to global warming reflects mostly the shift in equilibrium partitioning
- **Implication:** Rate of hydrologic cycling is set by thermodynamics

Powering Life





Thermodynamic Efficiency of Photosynthesis

8 - 10 photons of 1.8 eV

14.4 - 18 eV

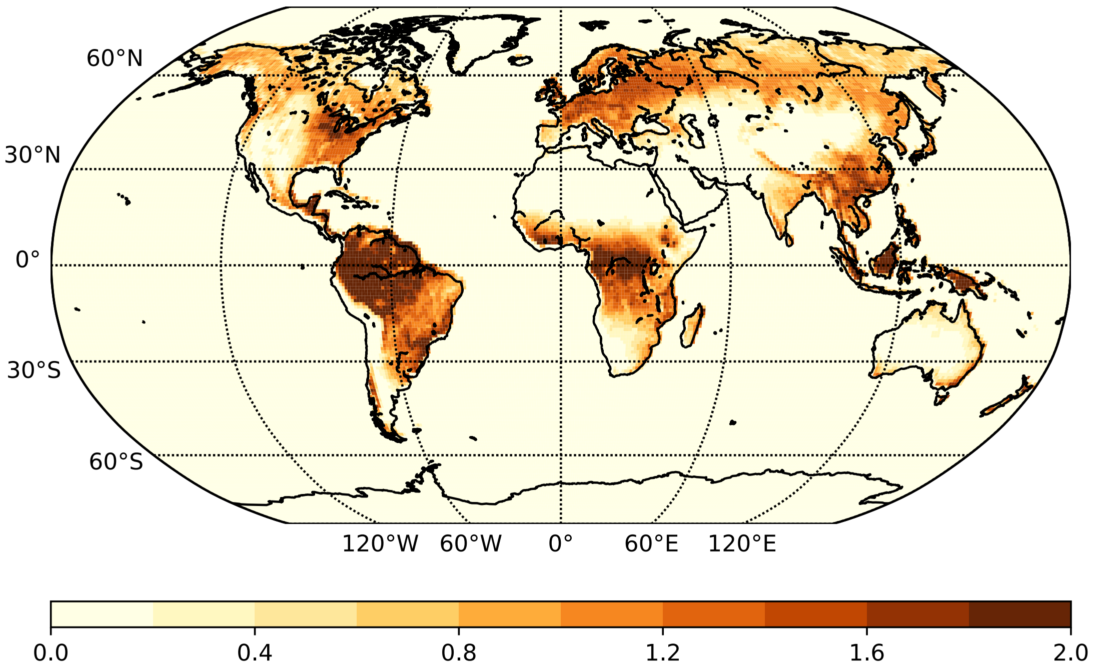
Compare to 13.6 eV for $H^+ + e^-$

1.4 MJ/mol C

Photosynthesis

0.48 MJ/mol C

Glucose



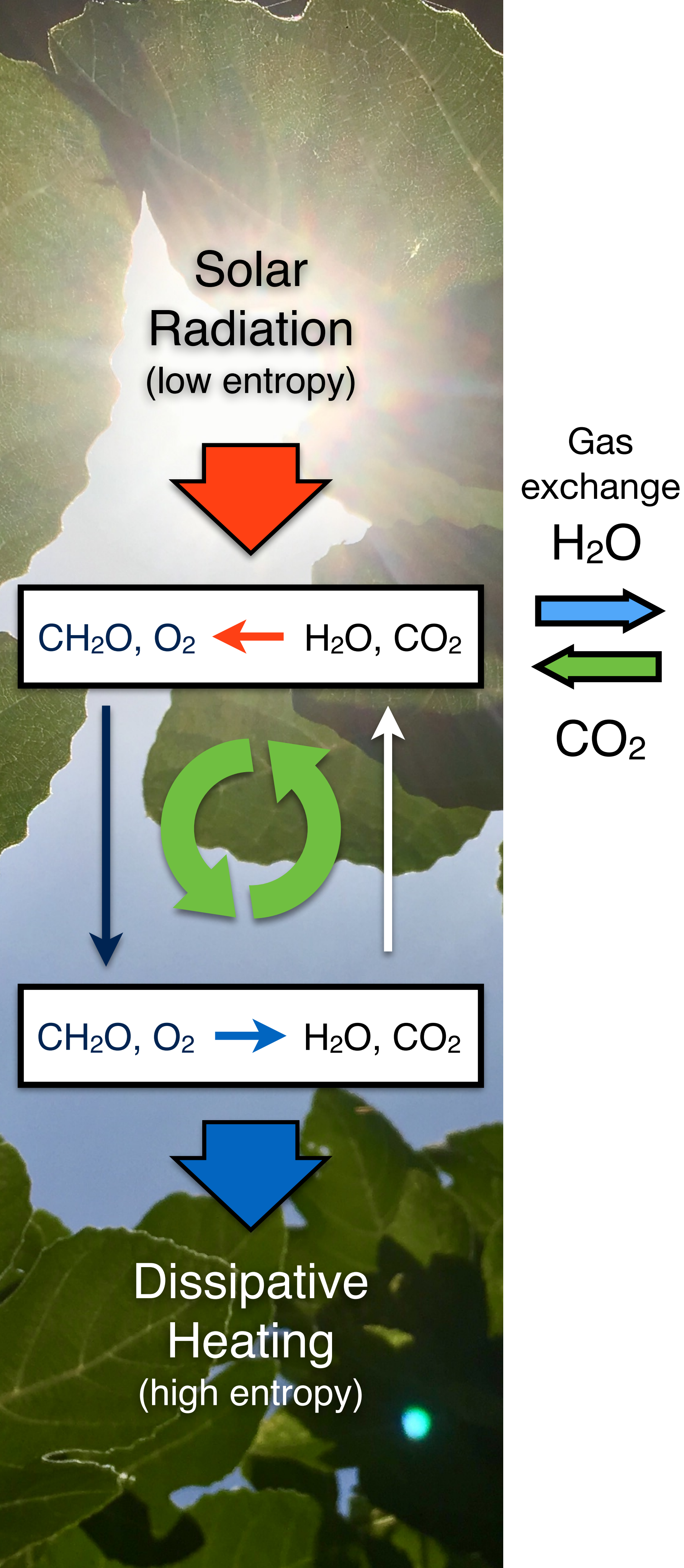
Data: NASA-CERES; CASA-GFED

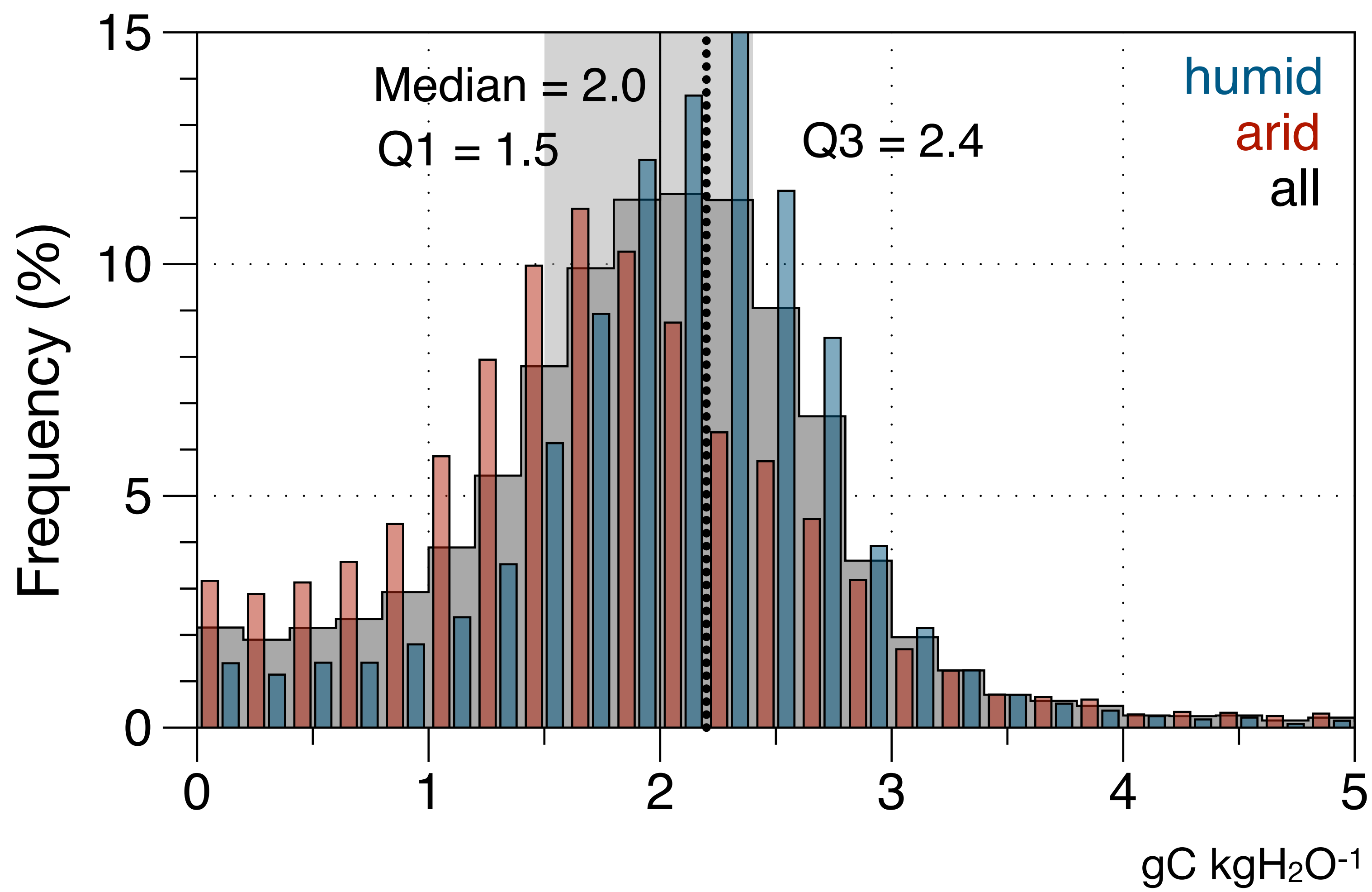
Efficiency	Efficiency
0.48/1.4 x 55% ≈ 17%	≈ 1-2%

Duysens (1962)
Radmer & Kok (1977)
Landsberg and Tonge (1980)
Hill and Rich (1983), …

Kleidon (2021) BBA Bioenergetics

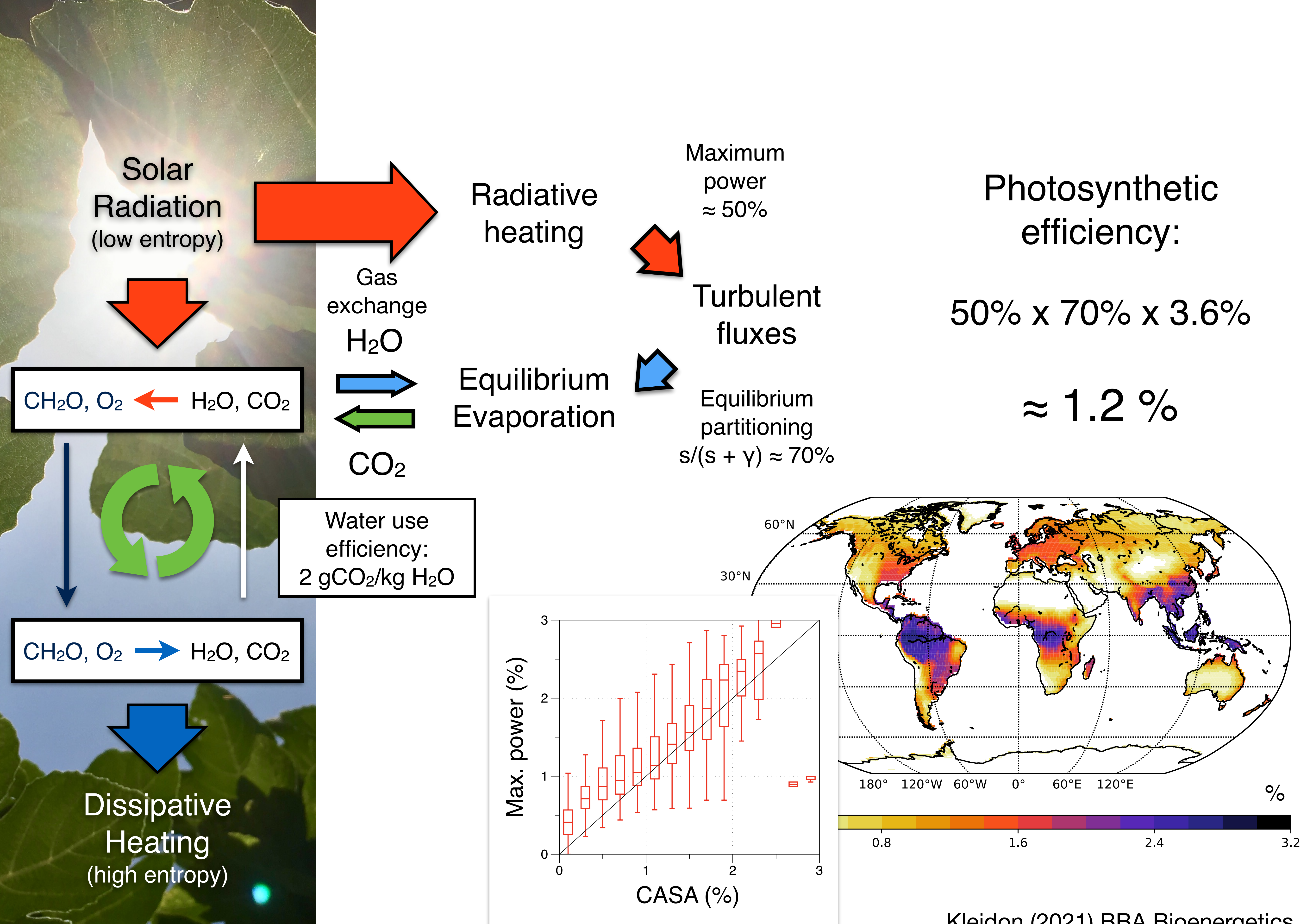
Water Use Efficiency





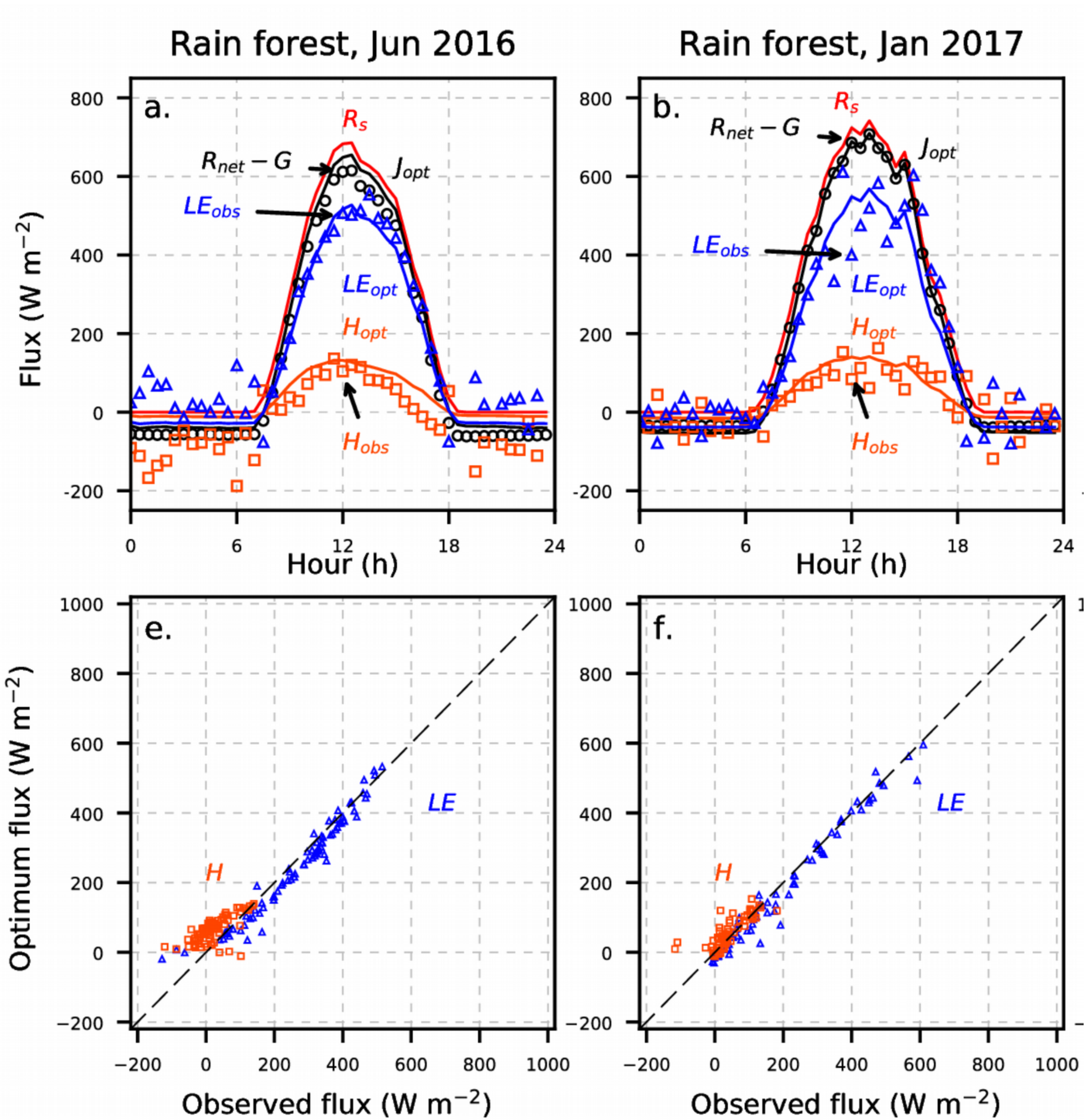
Kleidon (2021) BBA Bioenergetics

Data: CASA-GFED; GLEAM



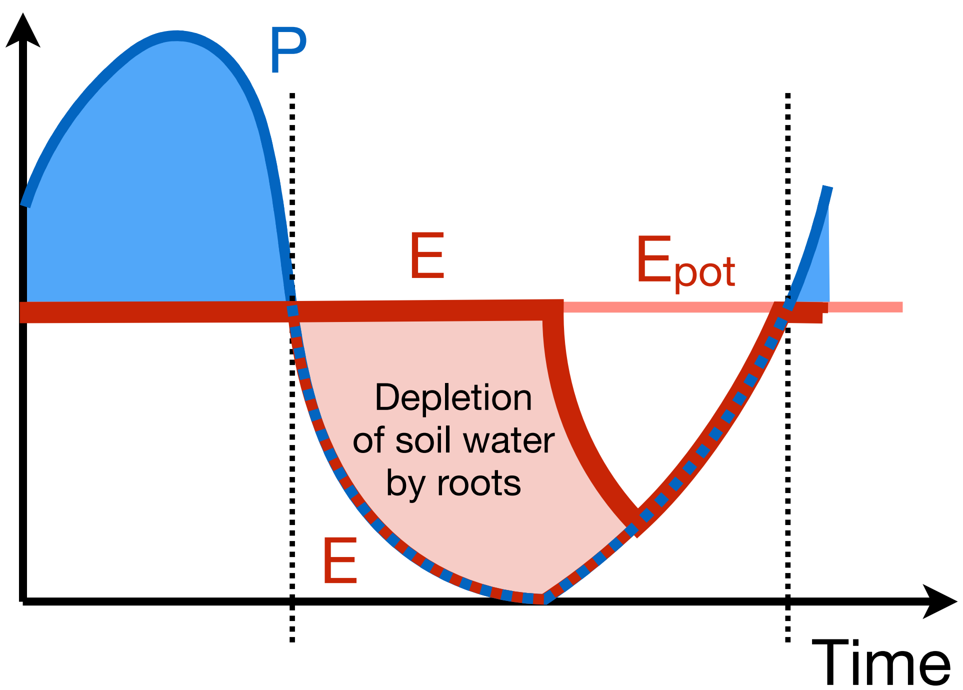
Kleidon (2021) BBA Bioenergetics

Data: NASA-CERES; CASA-GFED



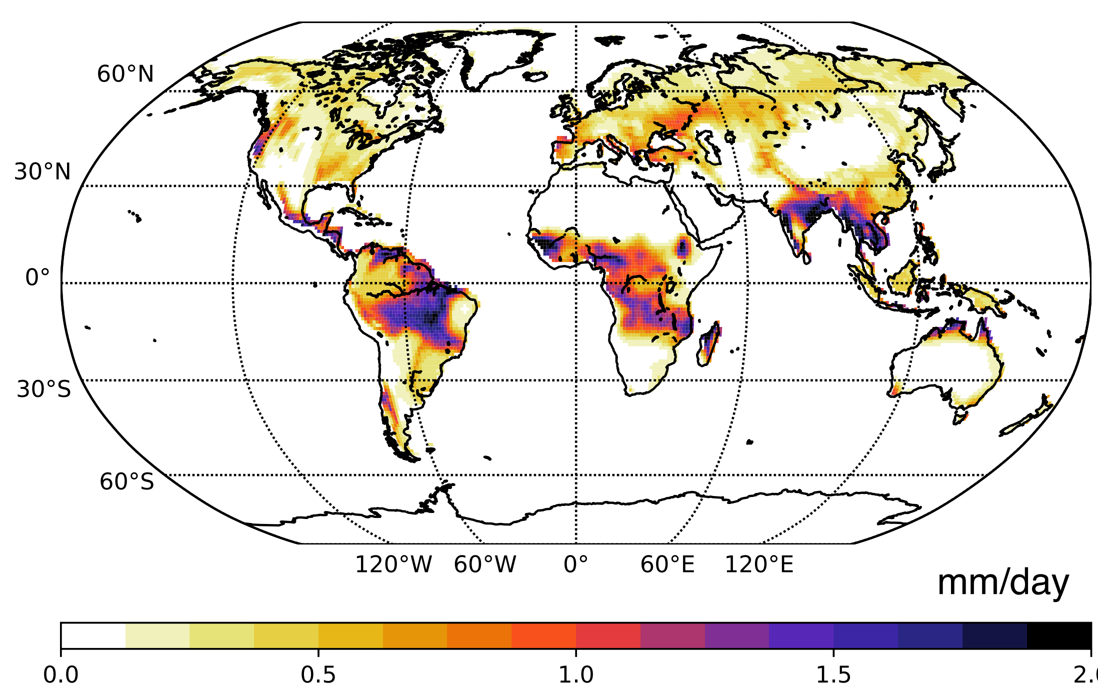
Conte et al. (2019) GRL

Pushing the Limit



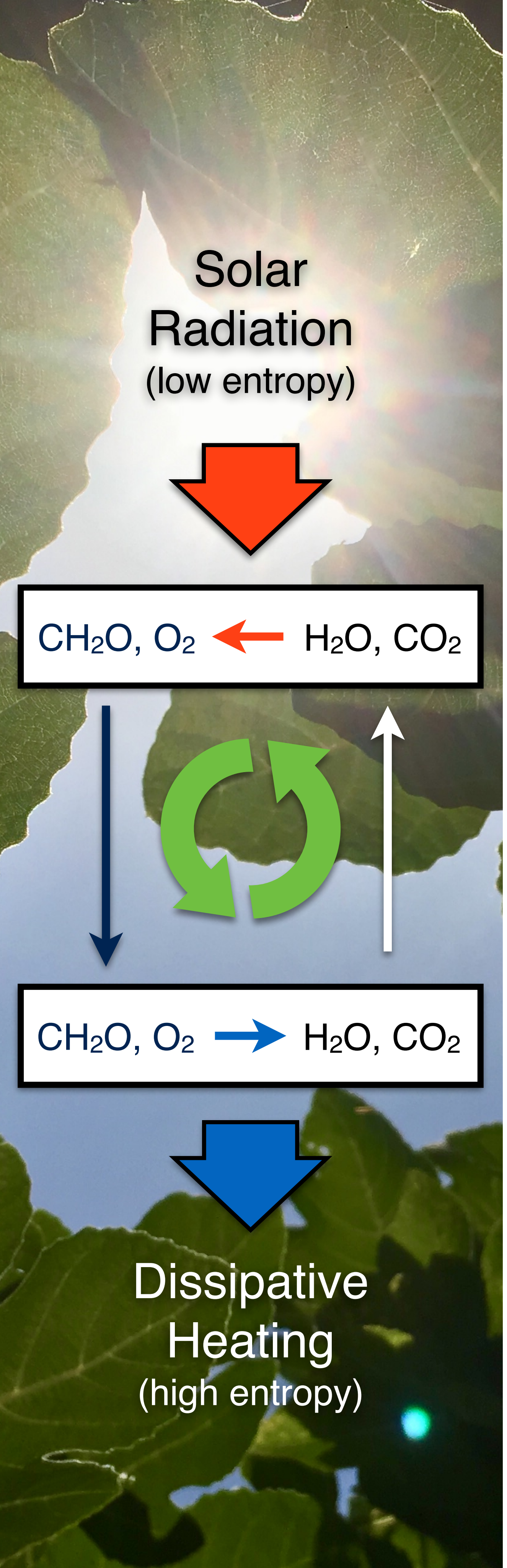
Root systems provide access to soil water storage, reducing the water deficit during dry seasons and enhancing evaporation

Enhancement by rooting zone storage



+12%

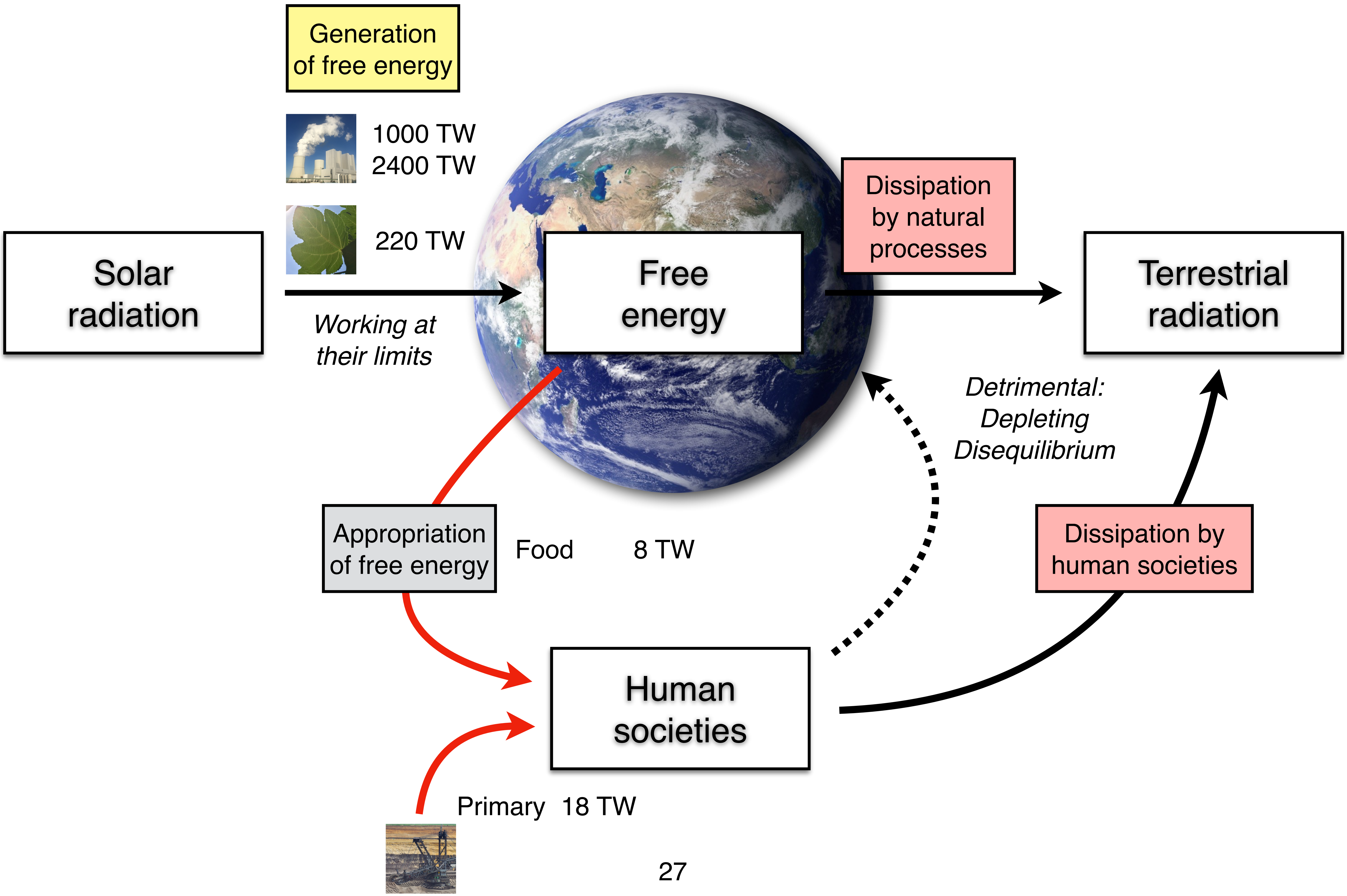
Kleidon (2023) INSEE



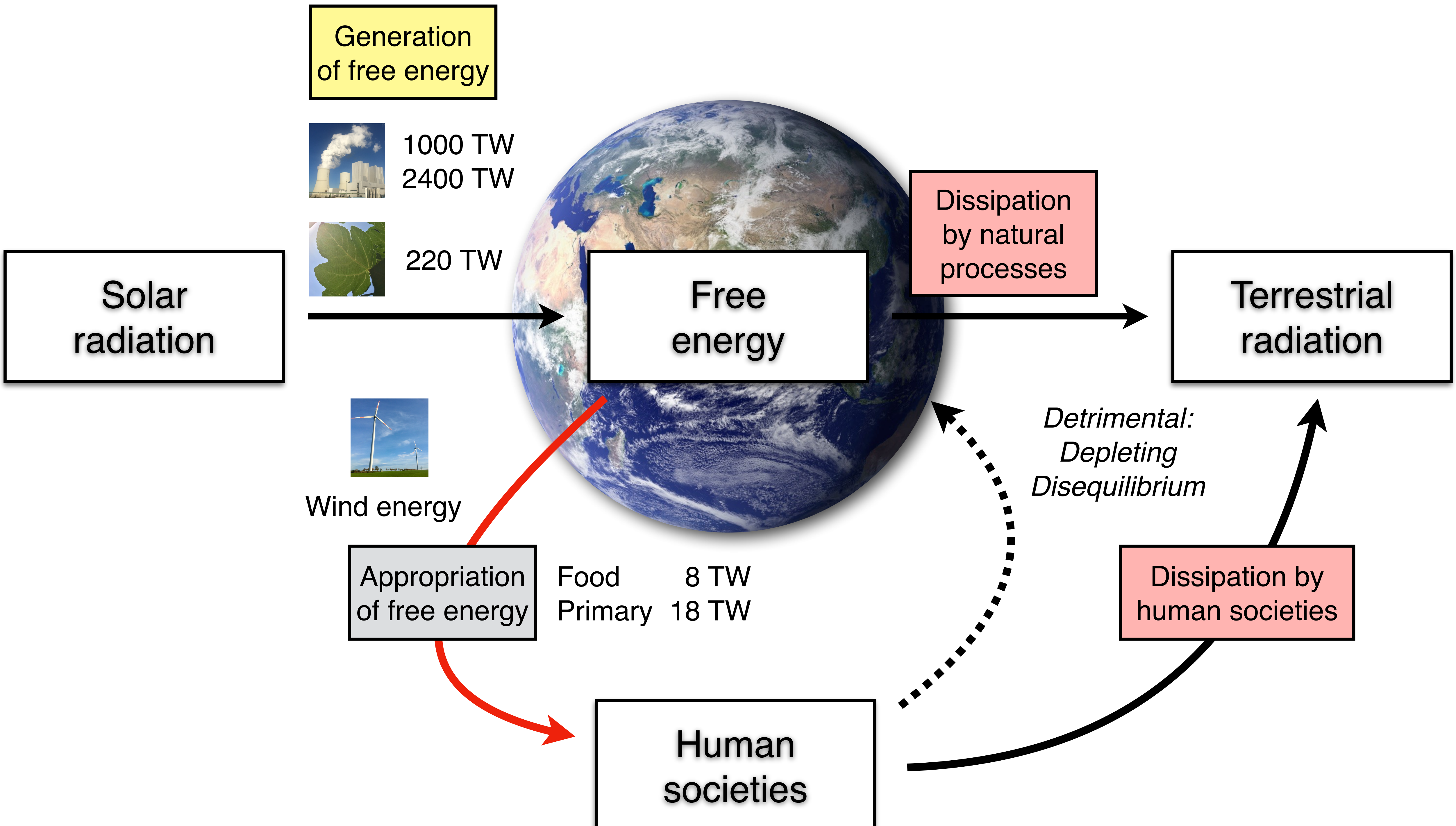
Powering Life

- **Disequilibrium:** Carbohydrates and oxygen
  - Generated by photosynthesis
  - Dissipated by metabolic activities of producers and consumers
- **"Photon" Engine:** Photosynthesis uses sunlight directly to perform work of splitting water and separate charges
- **Working at the limit:** Indirect bottleneck on gas exchange, linked to evaporation
- **Pushing the limit:** Root systems maximize ability to maintain gas exchange during dry episodes
- **Implication:** Biotic activity predictable by gas exchange constraint (radiation, precipitation)

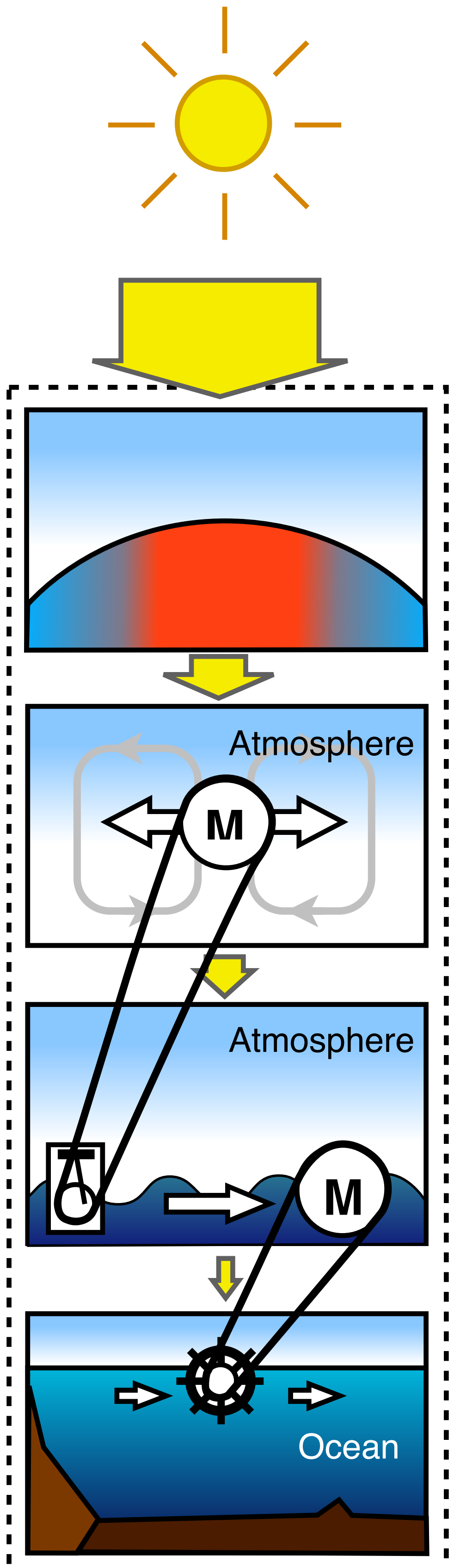
Powering Human Societies



Powering Human Societies



Follow the Energy



Radiation ≈ 175000 TW → Solar power

↓ Thermalisation
Differential heating

Thermal energy ≈ 49000 TW

↓ Atmospheric
heat engine

Kinetic energy ≈ 1000 TW → Wind power

↓ Ocean energy
input

Wave energy ≈ 65 TW → Wave power

↓

Kinetic energy ≈ 5 TW → Ocean power

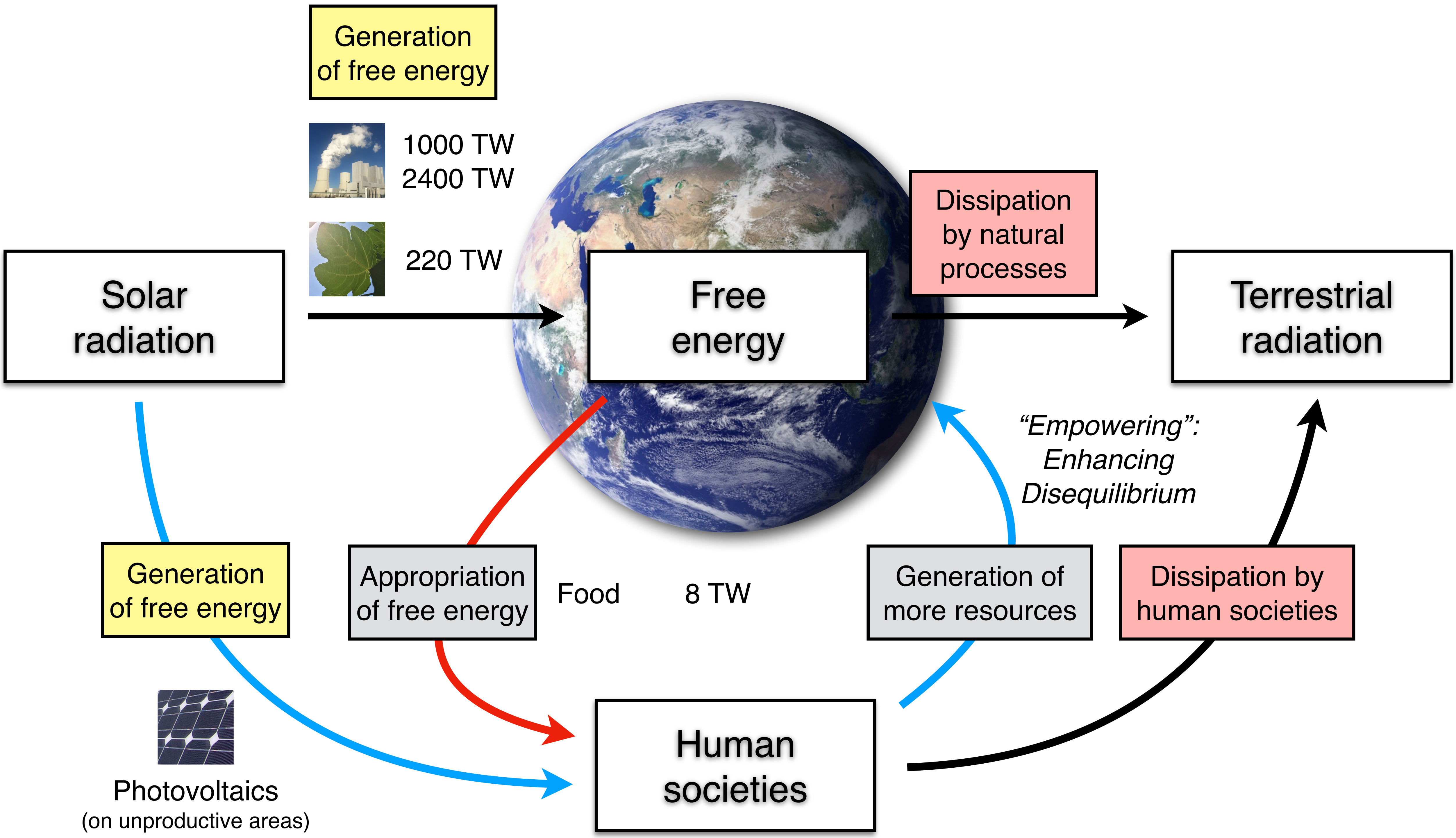
Geothermal ≪ 50 TW

Tidal ≈ 5 TW

Human energy demand ≈ 18 TW

Kleidon (2019) PhysIUZ

Powering Human Societies



Working at the limit

How thermodynamics shapes the Earth system

- **Entropy** sets fundamental **directions** and **limits** (beyond heat, includes interactions)
- Constrains the **work** needed to sustain dissipative dynamics (climate, life, human societies)
- Climate, hydrologic cycling, and biotic productivity at their **limits** ("maximum power", directly or indirectly)
- "**Simplicity**" in complex Earth system and global change
- Detrimental vs. beneficial effects of **human activity**
- **Evolutionary direction** for Earth's past and future?

Working at the limit

How thermodynamics shapes the Earth system

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