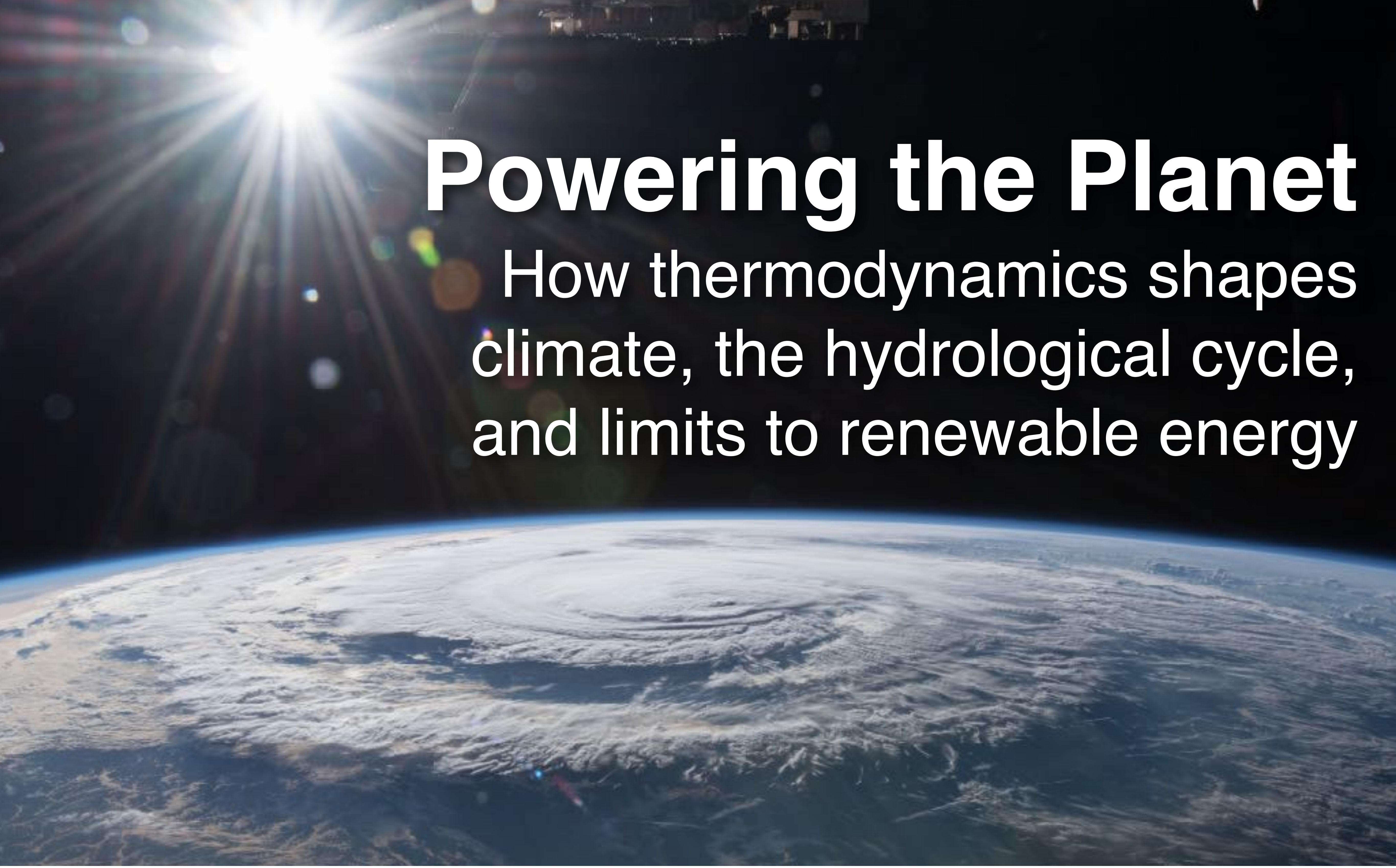


Powering the Planet

How thermodynamics shapes climate, the hydrological cycle, and limits to renewable energy

Aligarh Muslim University
March 2024

Axel Kleidon
Max-Planck-Institut für Biogeochemie
http://gaia.mpg.de ❖ earthsystem.org

Why do things happen on Earth?

➔ Entropy and the "Second Law"

➔ Direction for the Earth system

➔ Constrains *work* for dynamics

➔ *Working at the limit*

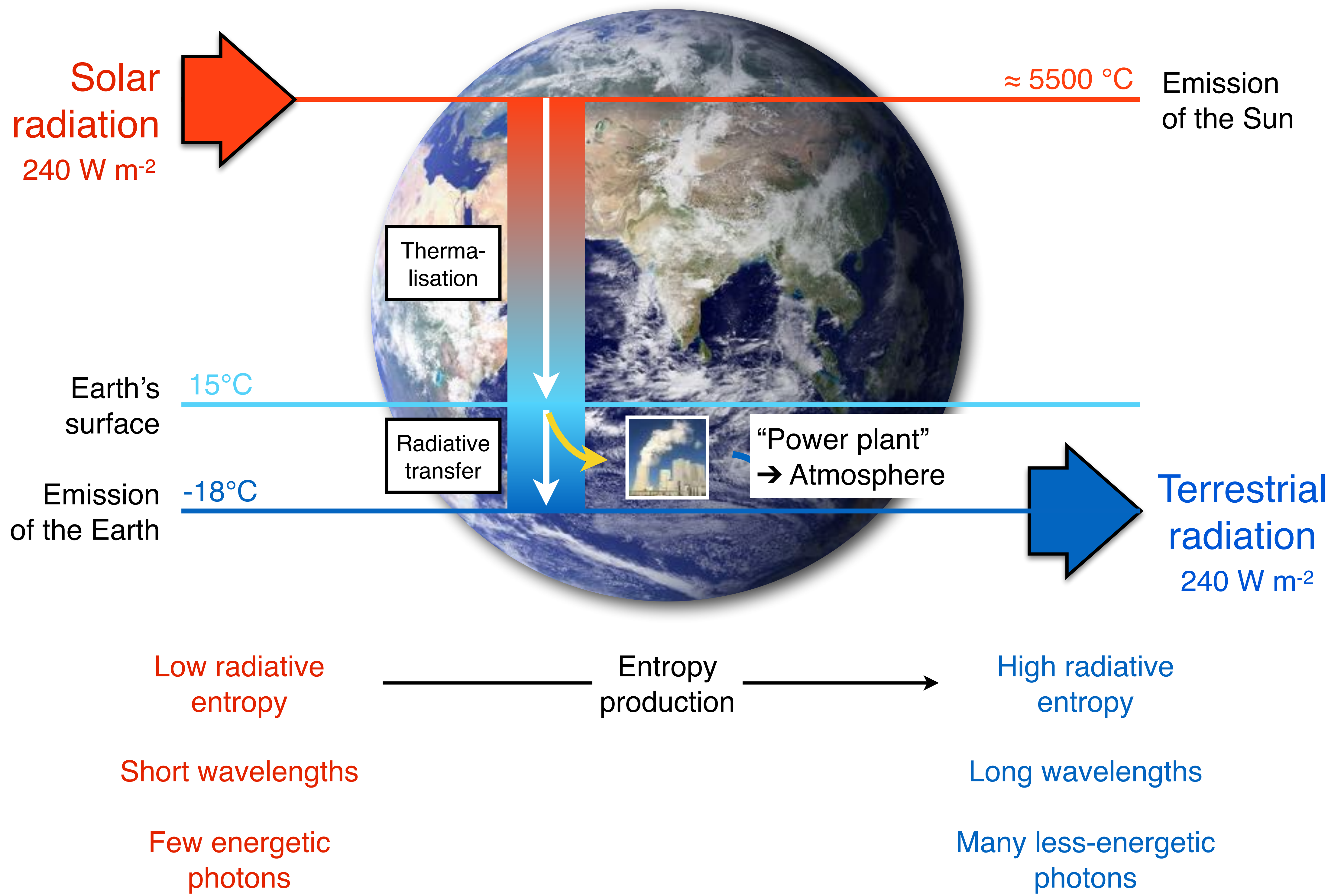
➔ Climate, the hydrological cycle, renewable energy

➔ *Thermodynamics plays central role*

➔ *Relevant to communicate and teach Earth system science*

Image: NASA

Thermodynamics of the Planet



Limits to Free Energy

Heating by combustion
low thermal entropy

J_{in}

$T_{in} \approx 500 - 600°C$

Combustion temperature

Temperature of "waste heat"

$T_{out} \approx 100°C$

J_{out}

Cooling by evaporation
high thermal entropy

G

Useful energy
(no entropy)

First law: Energy conservation

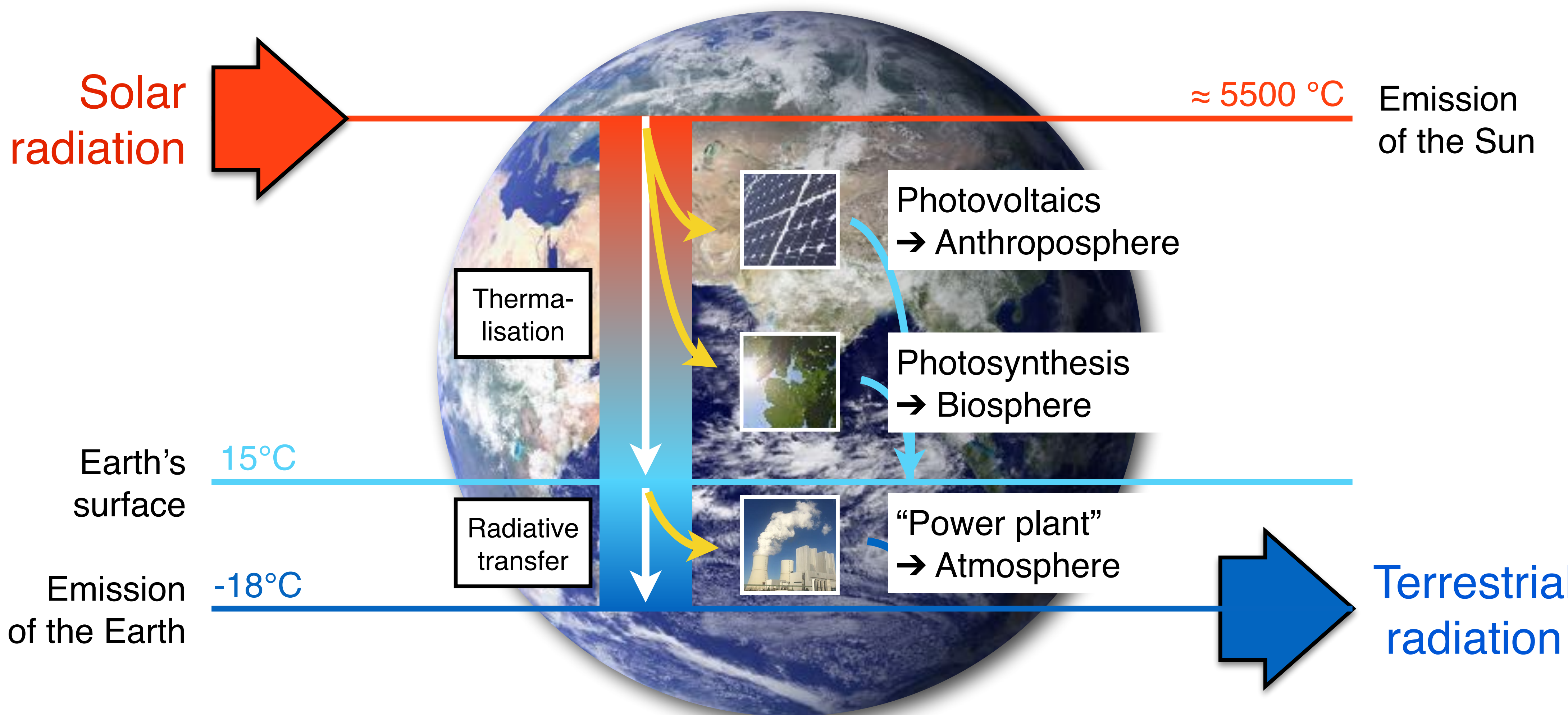
$$J_{in} = J_{out} + G$$

Second law: Entropy increase

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

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

Powering the Planet



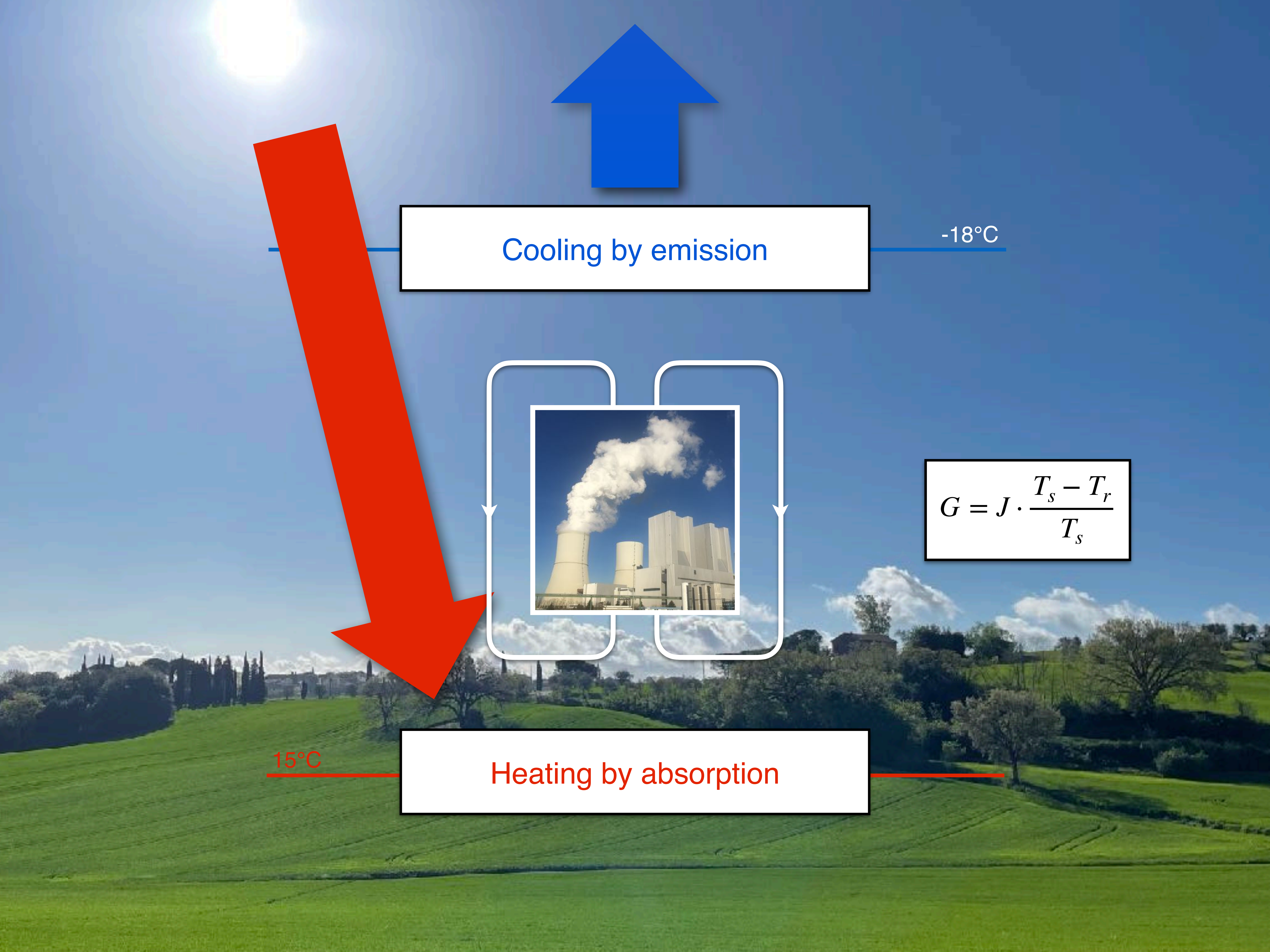
Outline

1. Powering climate
How thermodynamics constrains motion, determines temperatures, and influences global warming

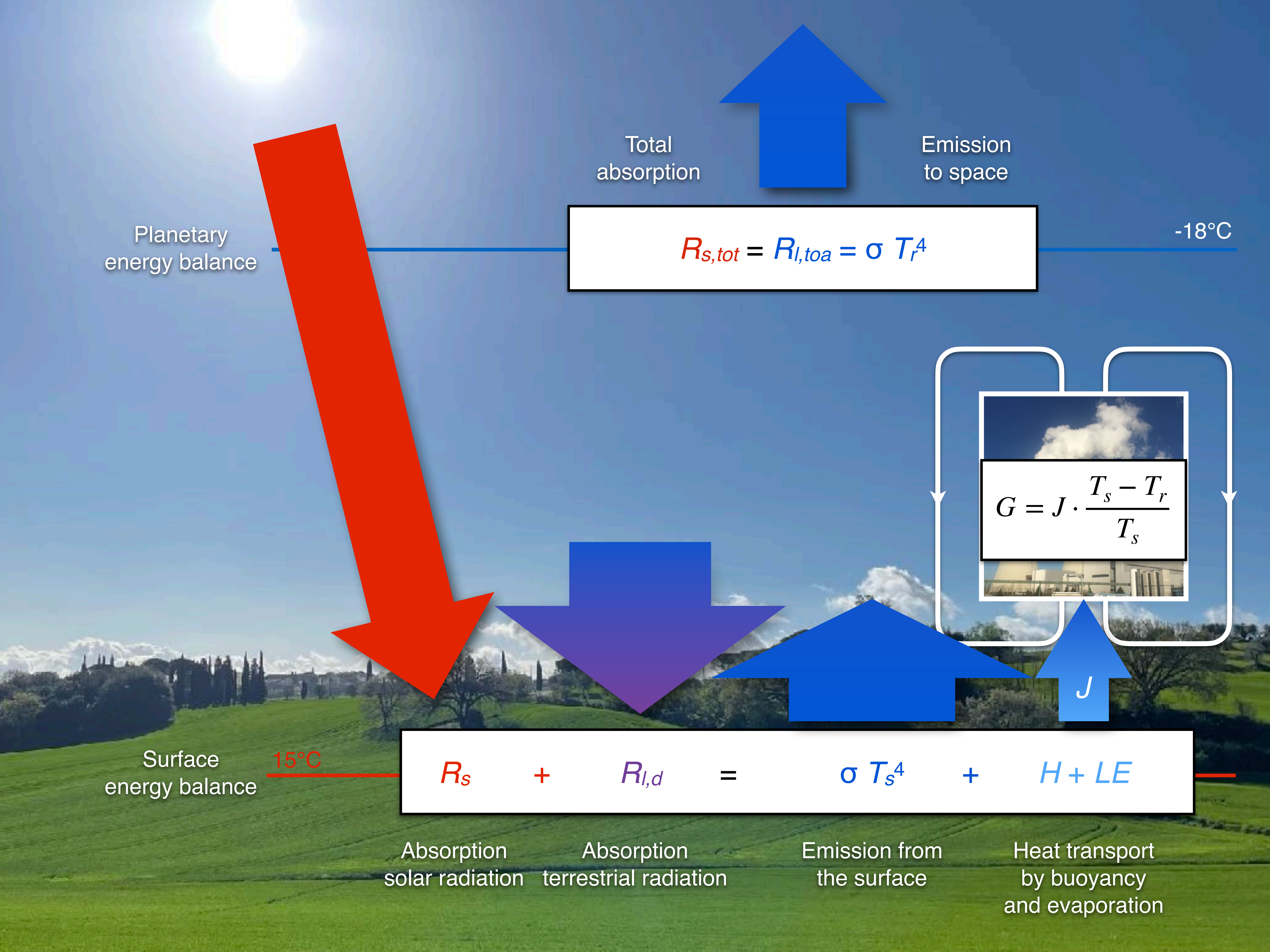
2. Powering the hydrological cycle
How thermodynamics shapes evaporation and precipitation and their responses to global warming

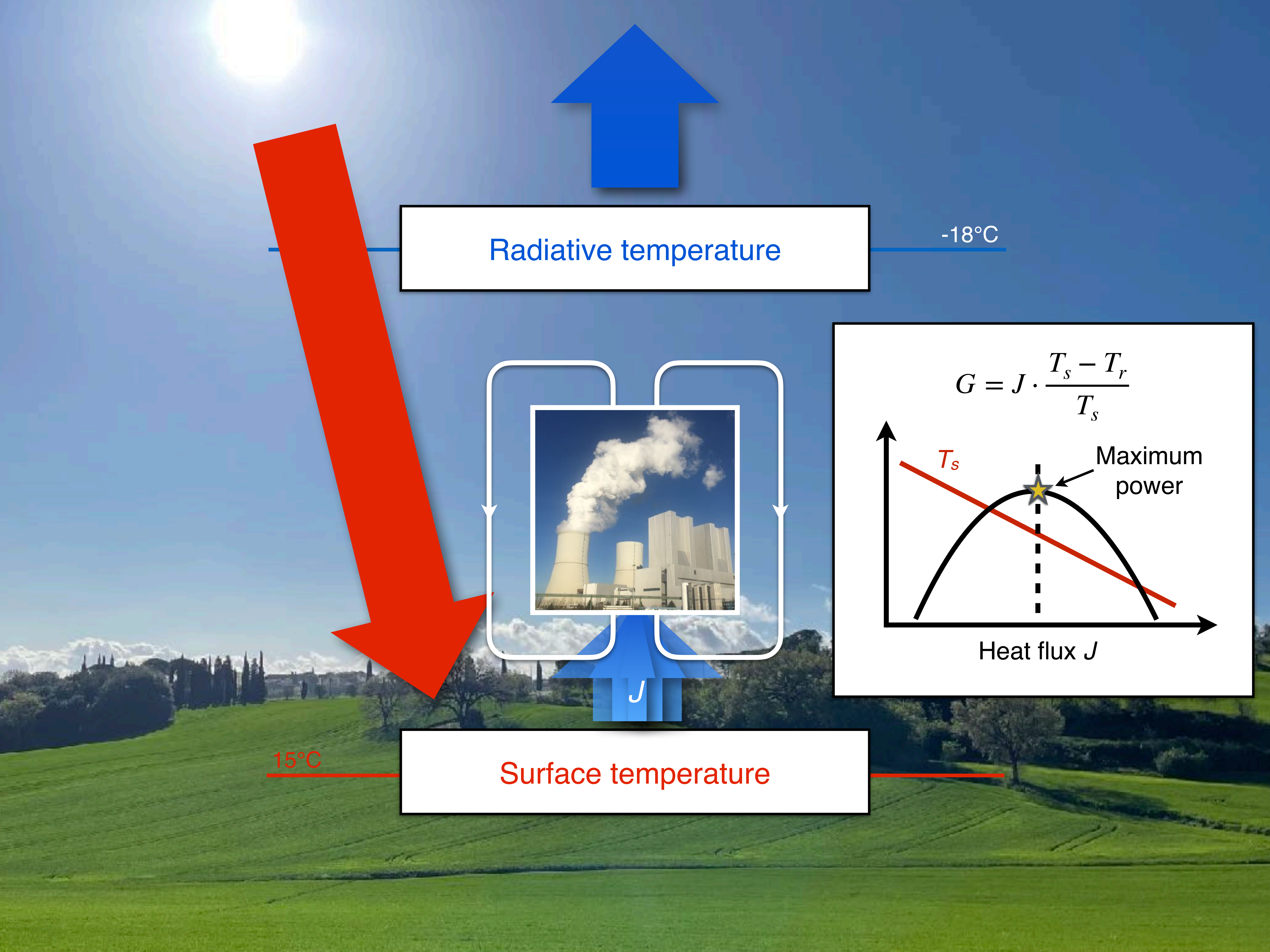
3. Powering human societies
How thermodynamics generates energy that can be used as renewable energy

Summary



Cooling by emission
-18°C
$$G = J \cdot \frac{T_s - T_r}{T_s}$$
15°C
Heating by absorption

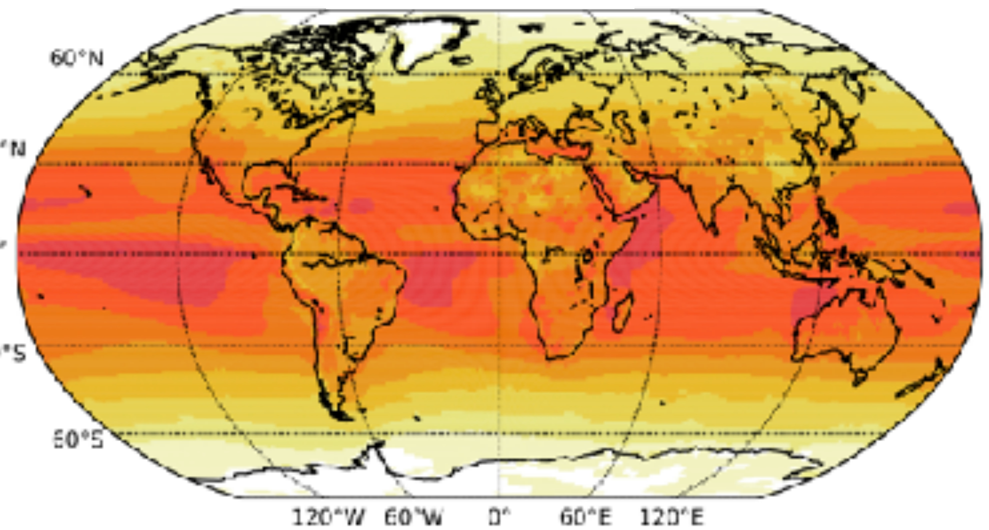

Total absorption
Emission to space
Planetary energy balance
$R_{s,tot} = R_{l,toa} = \sigma T_r^4$
-18°C
$G = J \cdot \frac{T_s - T_r}{T_s}$
J
Surface energy balance
15°C
$R_s + R_{l,d} = \sigma T_s^4 + H + LE$
Absorption solar radiation
Absorption terrestrial radiation
Emission from the surface
Heat transport by buoyancy and evaporation


Radiative temperature
-18°C
Surface temperature
15°C
J
$G = J \cdot \frac{T_s - T_r}{T_s}$
T_s
Maximum power
Heat flux J

Surface heating by absorption of radiation

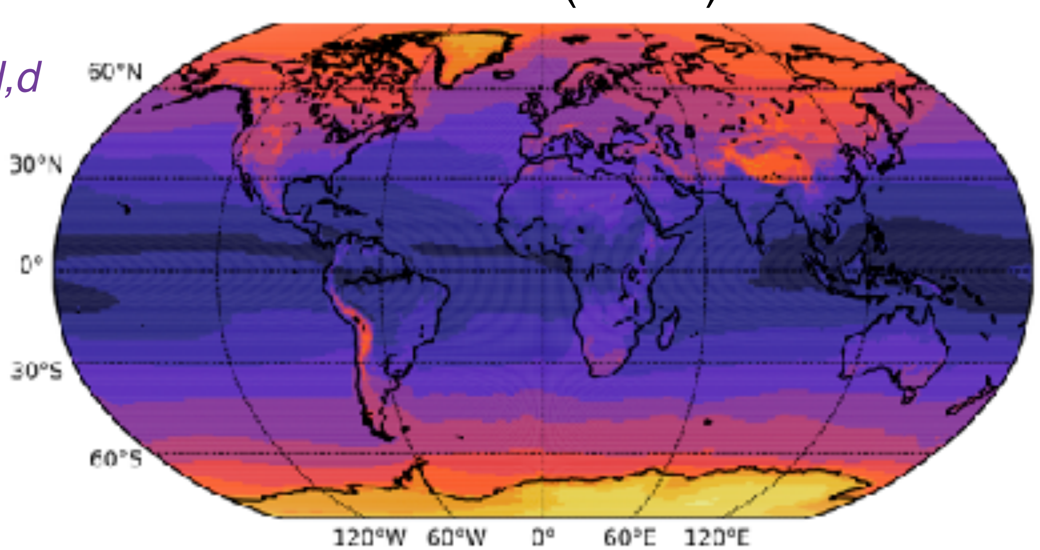
Solar ($W\ m^{-2}$)

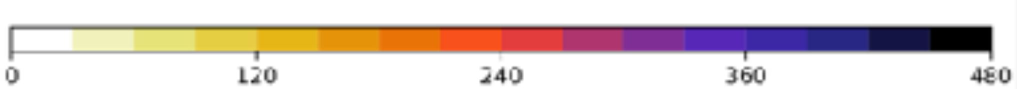
R_s

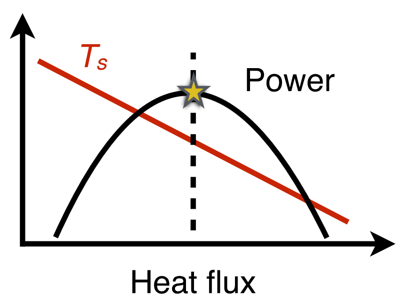


Terrestrial ($W\ m^{-2}$)

$R_{l,d}$

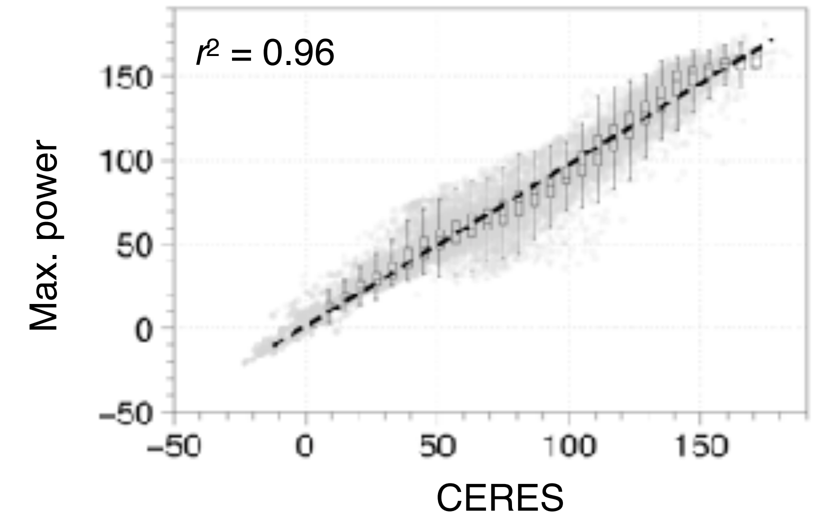


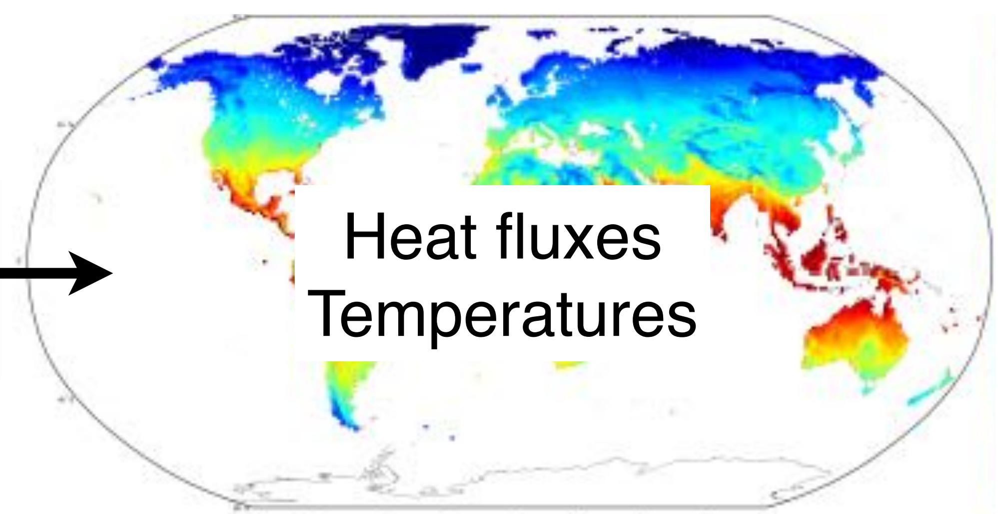




Maximum power

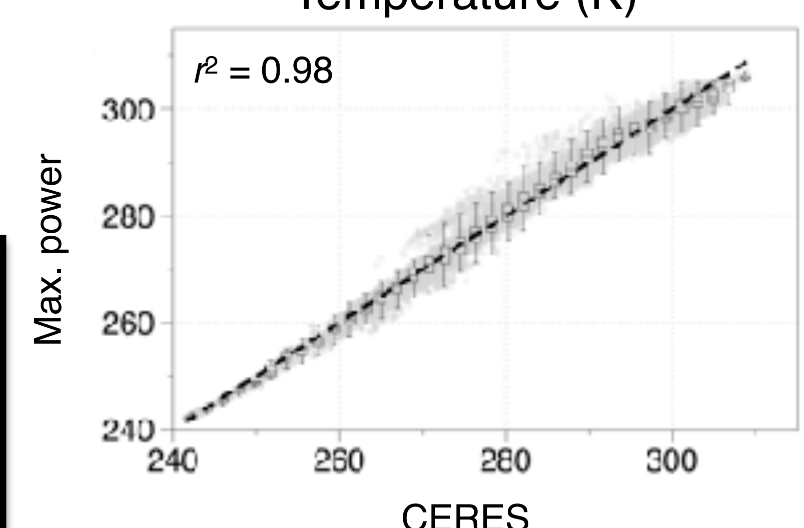
Heat fluxes ($W\ m^{-2}$)





Heat fluxes
Temperatures

Temperature (K)

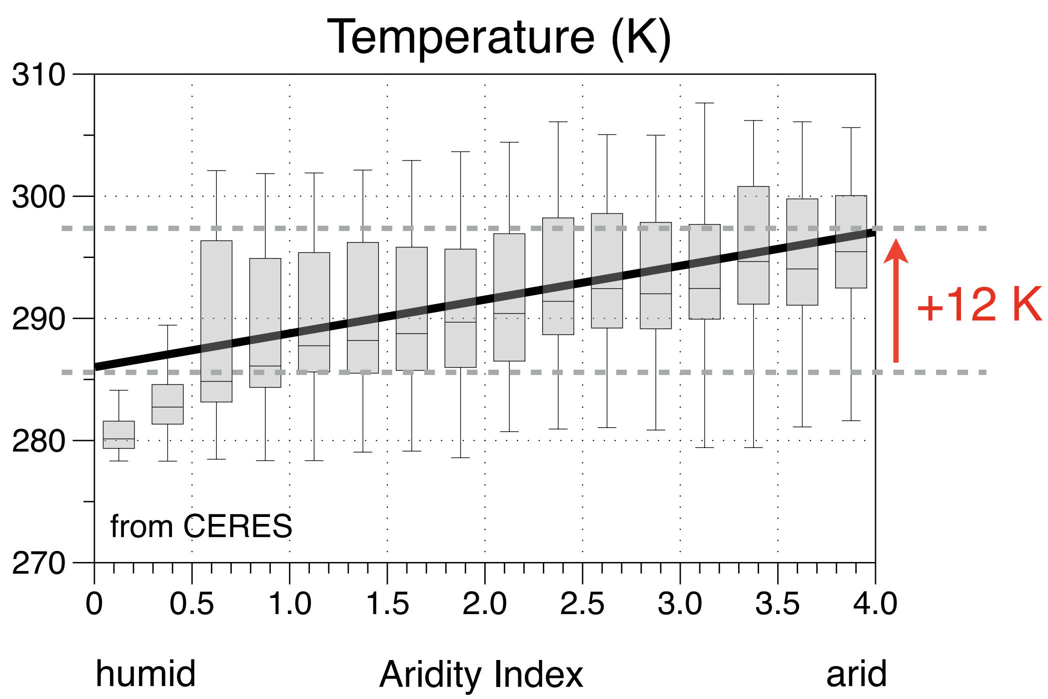


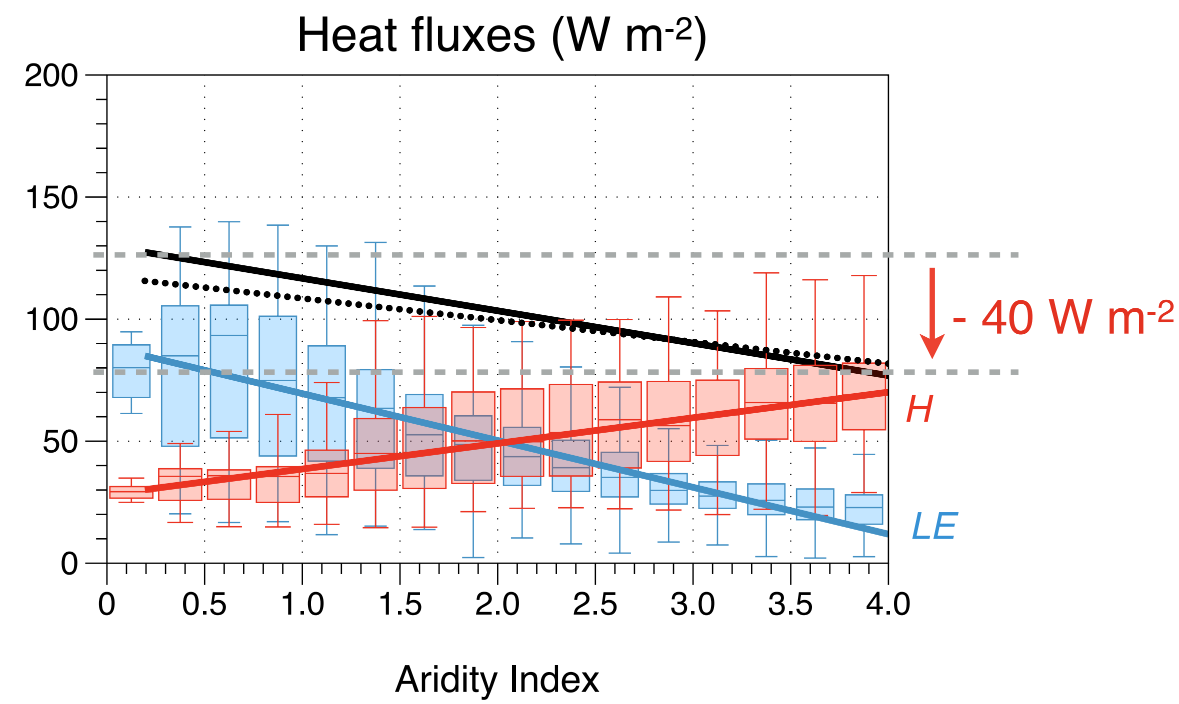
Atmosphere works as hard as it can!

Data: NASA-CERES

Ghausi et al. (2023)

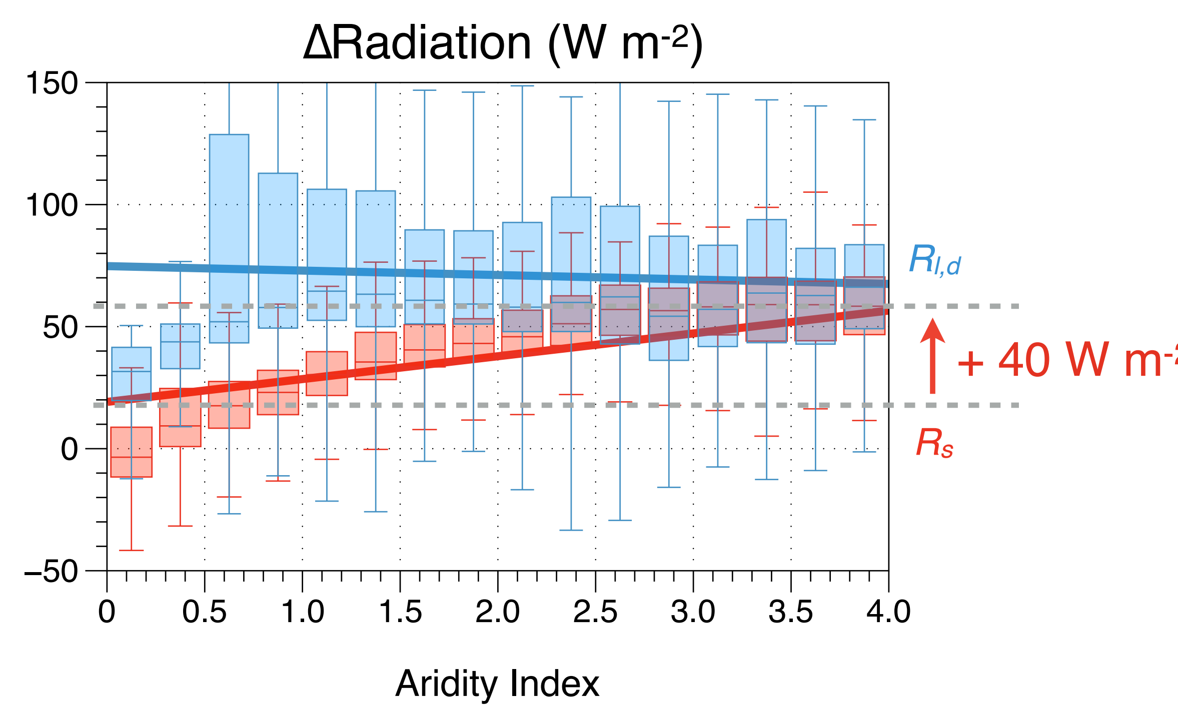
Why are deserts warmer?





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

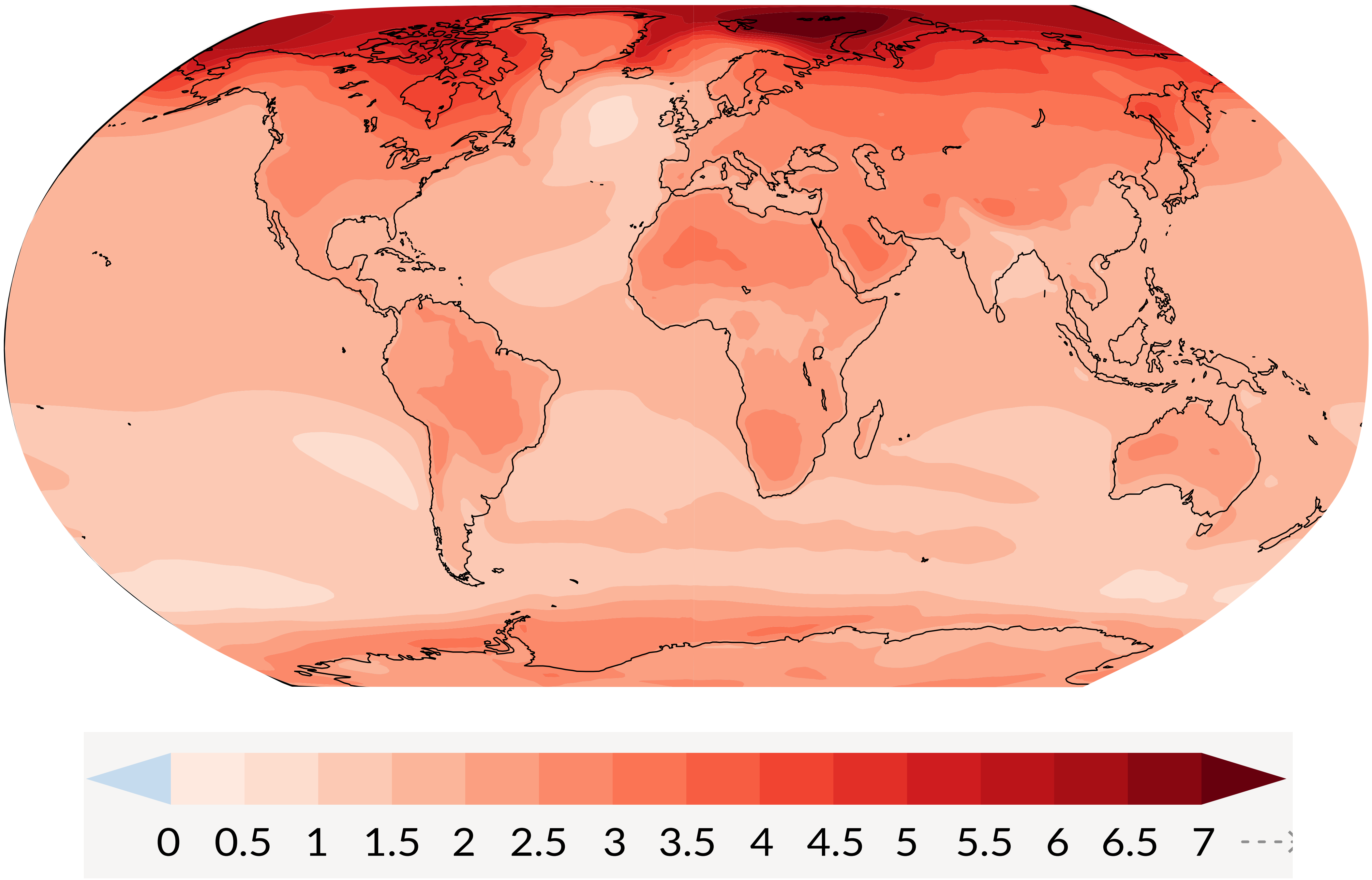
$$\Delta T_s \approx +14 \text{ K}$$



Deserts are warmer because
(a) more solar radiation
(b) weaker power plant!

Ghausi et al. (2023)

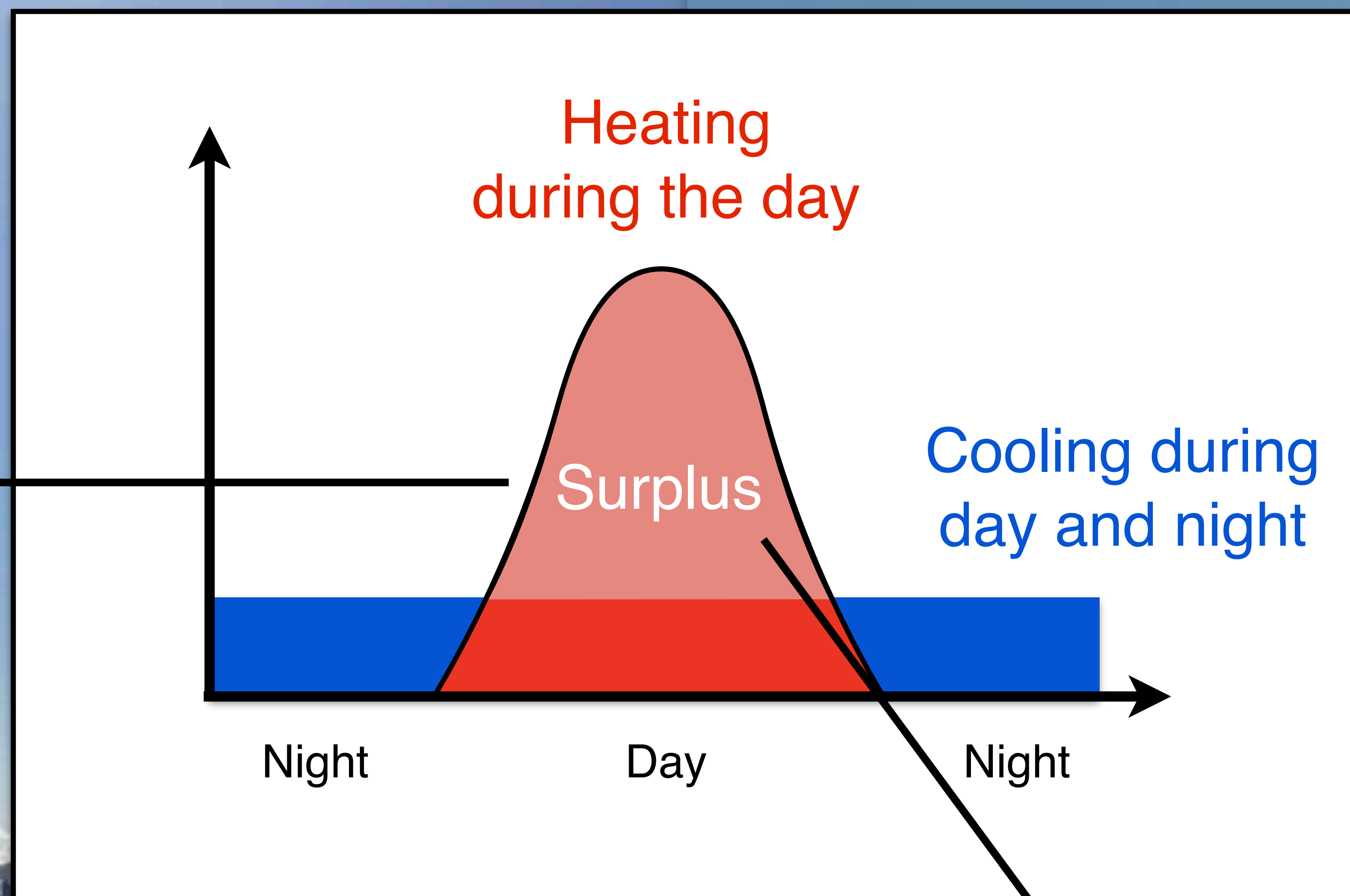
Global Warming at +2 K



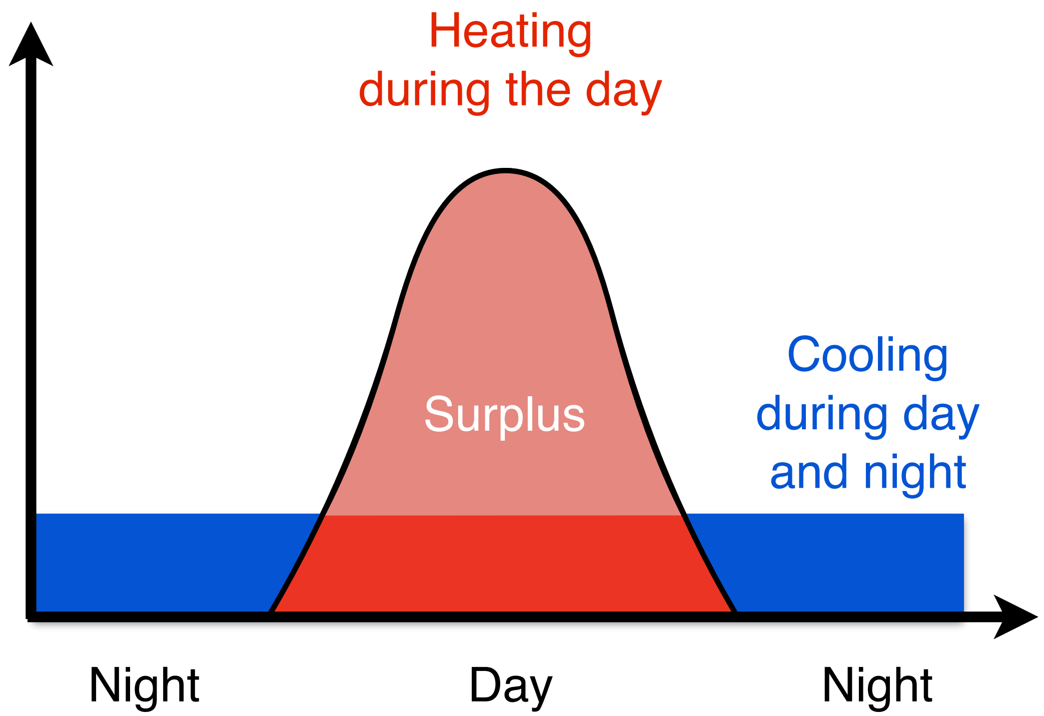
IPCC AR6 Figure SPM.5

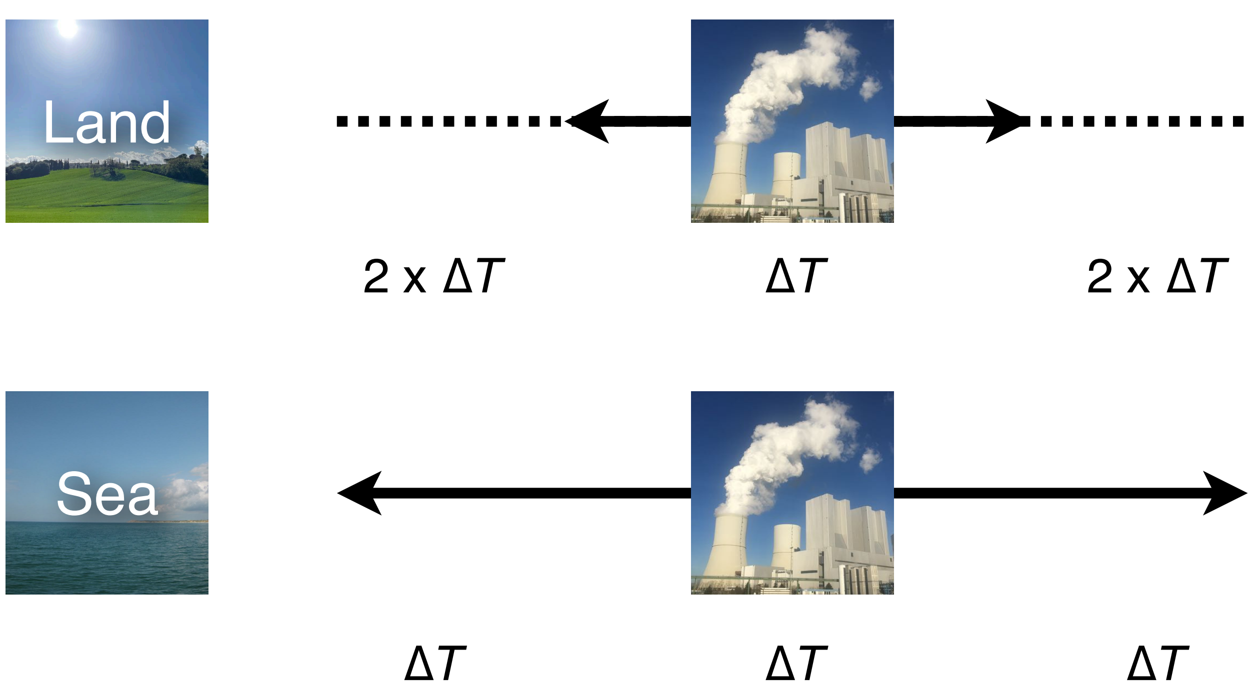
Why does land heat up more strongly than the sea?

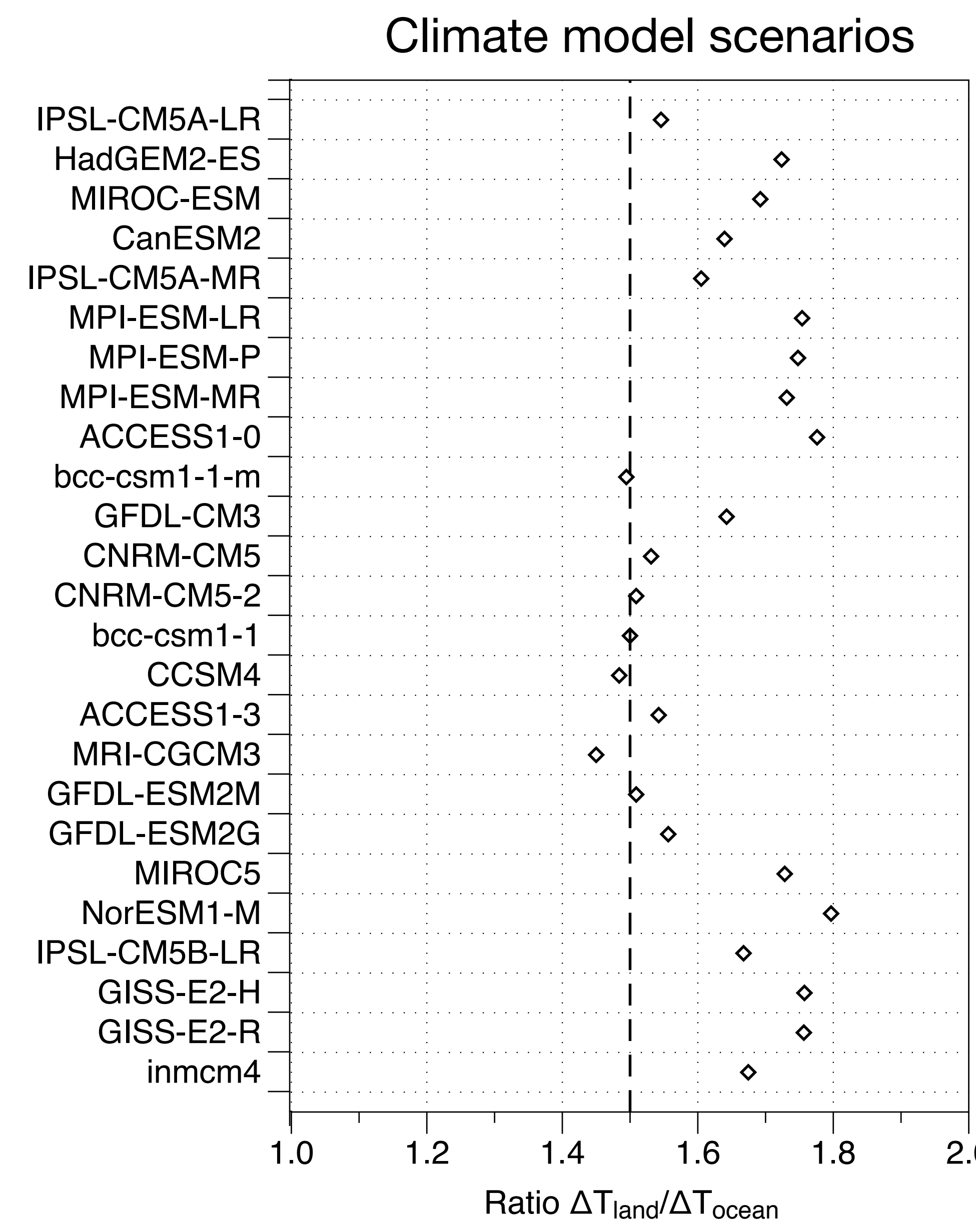
Changes in heat storage above the surface



Changes in heat storage *below* the surface







Data: CMIP5

$$\Delta\overline{T_{Land}} \approx 1.5 \cdot \Delta\overline{T_{Sea}}$$

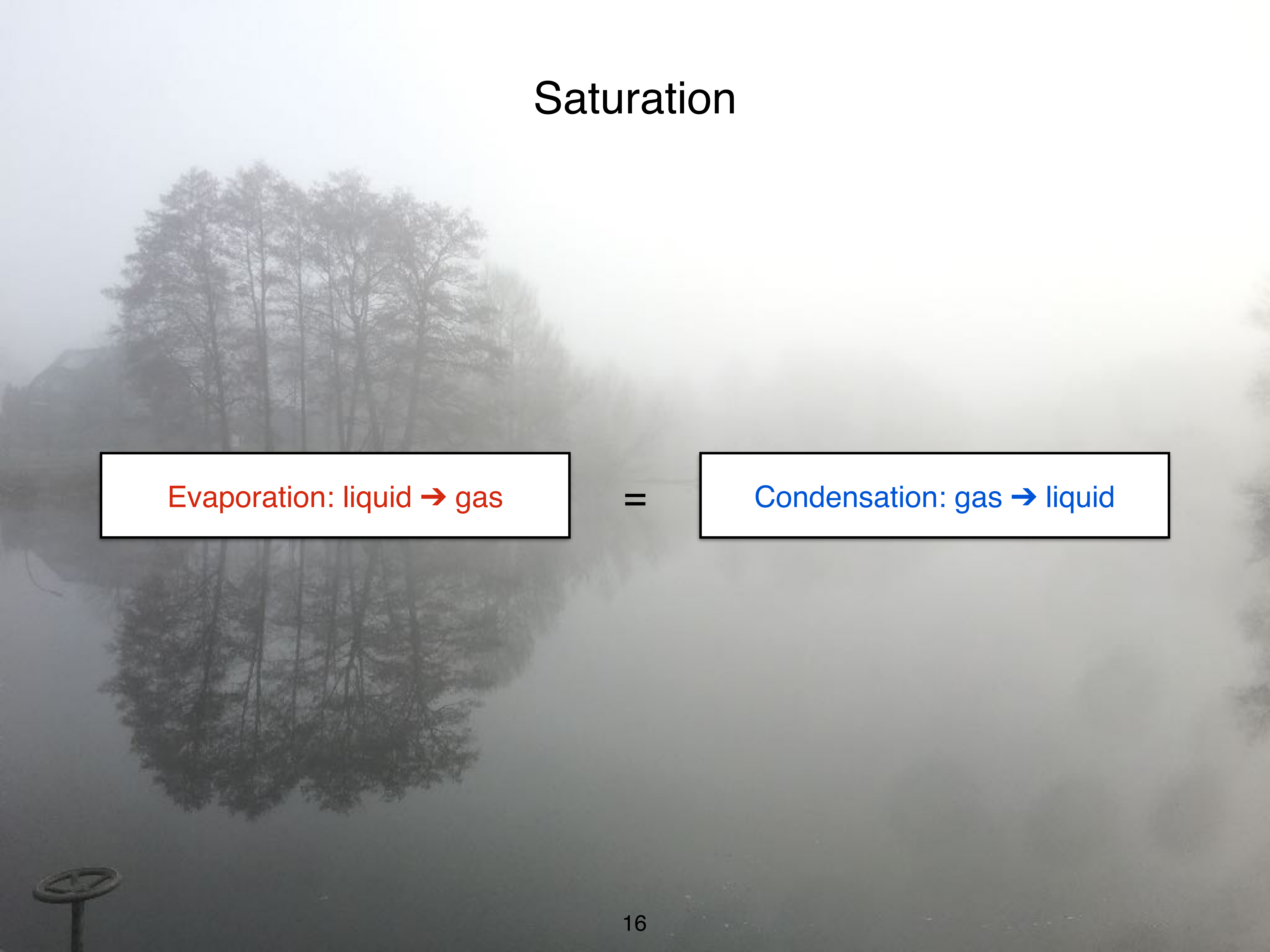
Land heats more strongly than the sea because power is only generated during the day!

Kleidon and Renner (2017) Earth Syst. Dynam.

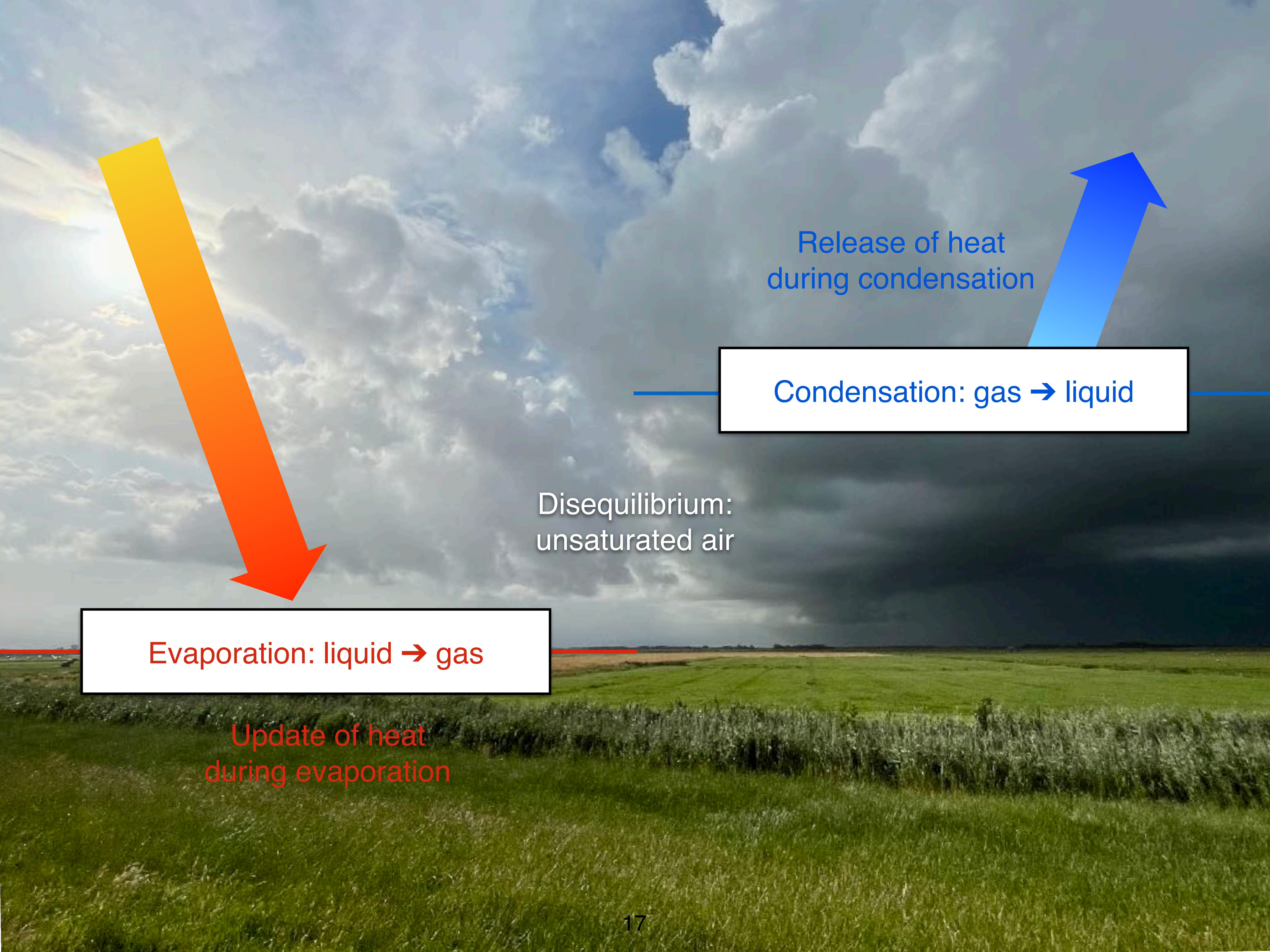
Powering the Climate System

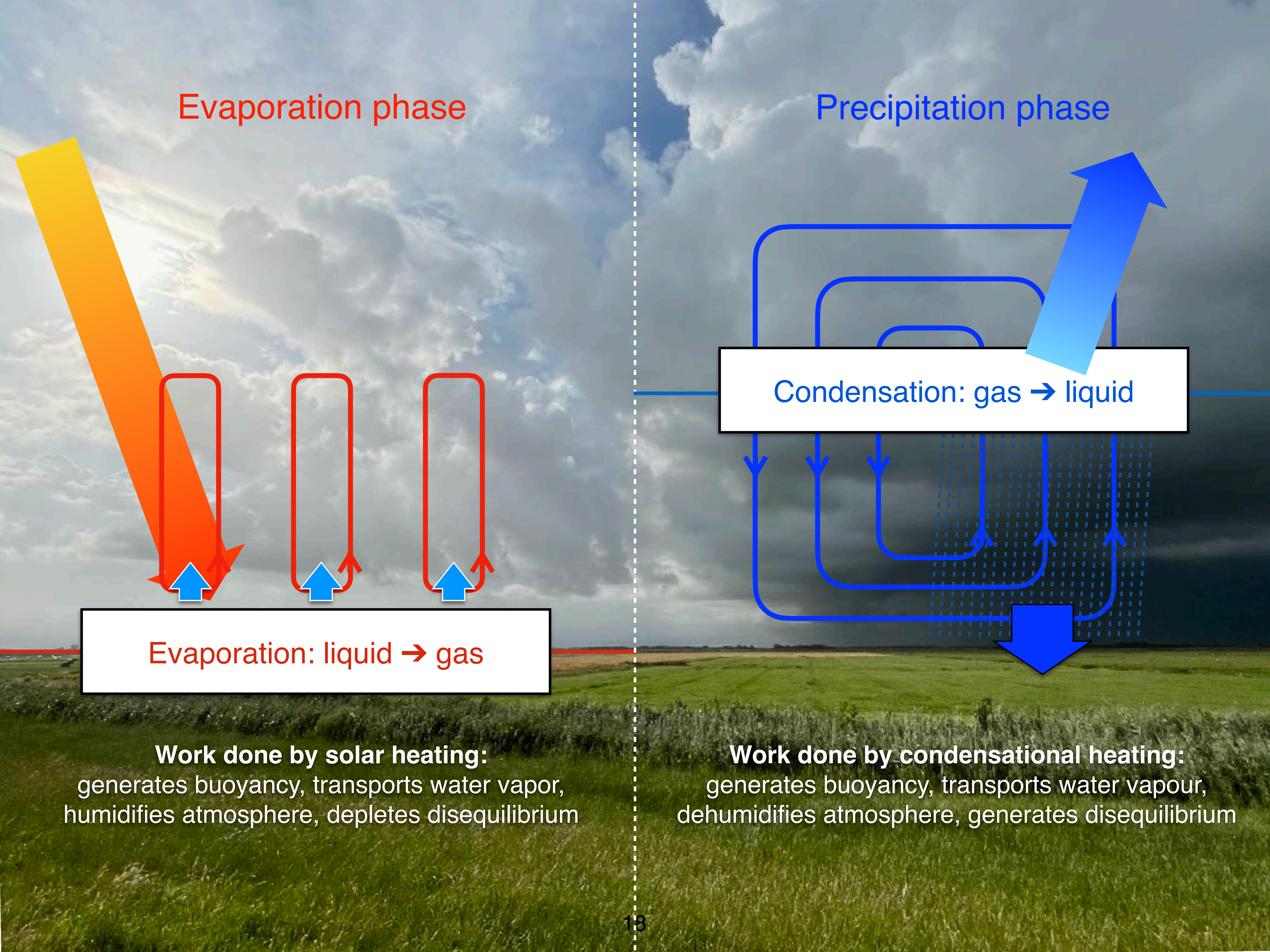
- Atmosphere appears to work as hard as it can
- Predicts temperatures and energy balance partitioning across continents
- Deserts are warmer because
  (a) more solar radiation
  (b) weaker power plant!
- Land heats more strongly with global warming than the sea because power is only generated during the day!

Saturation



Evaporation: liquid ➔ gas = Condensation: gas ➔ liquid


Release of heat
during condensation
Condensation: gas ➔ liquid
Disequilibrium:
unsaturated air
Evaporation: liquid ➔ gas
Update of heat
during evaporation


Evaporation phase
Evaporation: liquid ➔ gas
Work done by solar heating:
generates buoyancy, transports water vapor,
humidifies atmosphere, depletes disequilibrium
Precipitation phase
Condensation: gas ➔ liquid
Work done by condensational heating:
generates buoyancy, transports water vapour,
dehumidifies atmosphere, generates disequilibrium

Absorbed
solar radiation

Max.
power

Turbulent
heat fluxes

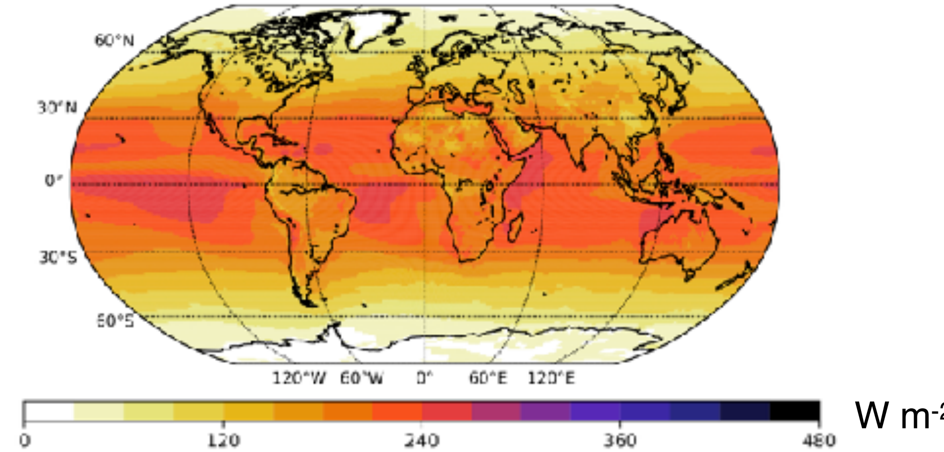
Thermodynamic
equilibrium
partitioning

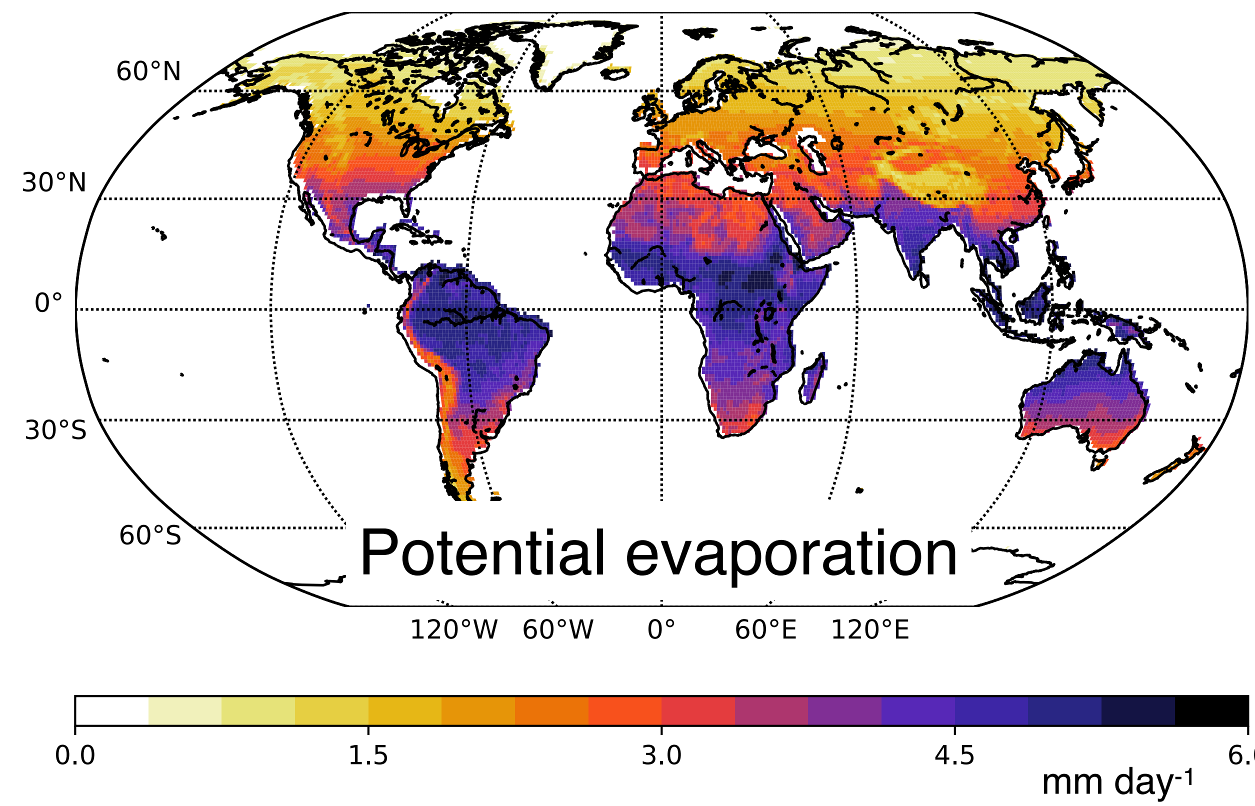
$\gamma/(s+\gamma)$

$s/(s+\gamma)$

Sensible
heat flux
(buoyancy)

Latent
heat flux
(evaporation)





Absorbed
solar radiation

Max.
power

Turbulent
heat fluxes

Thermodynamic
equilibrium
partitioning

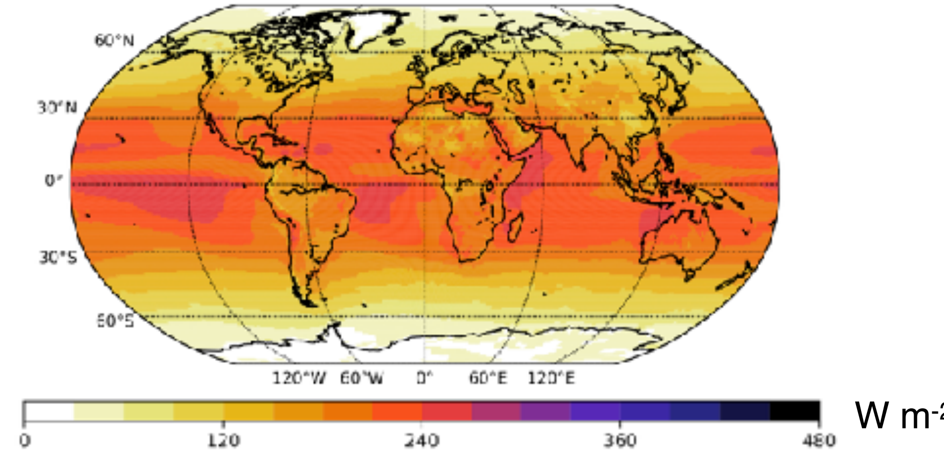
γ/(s+γ)

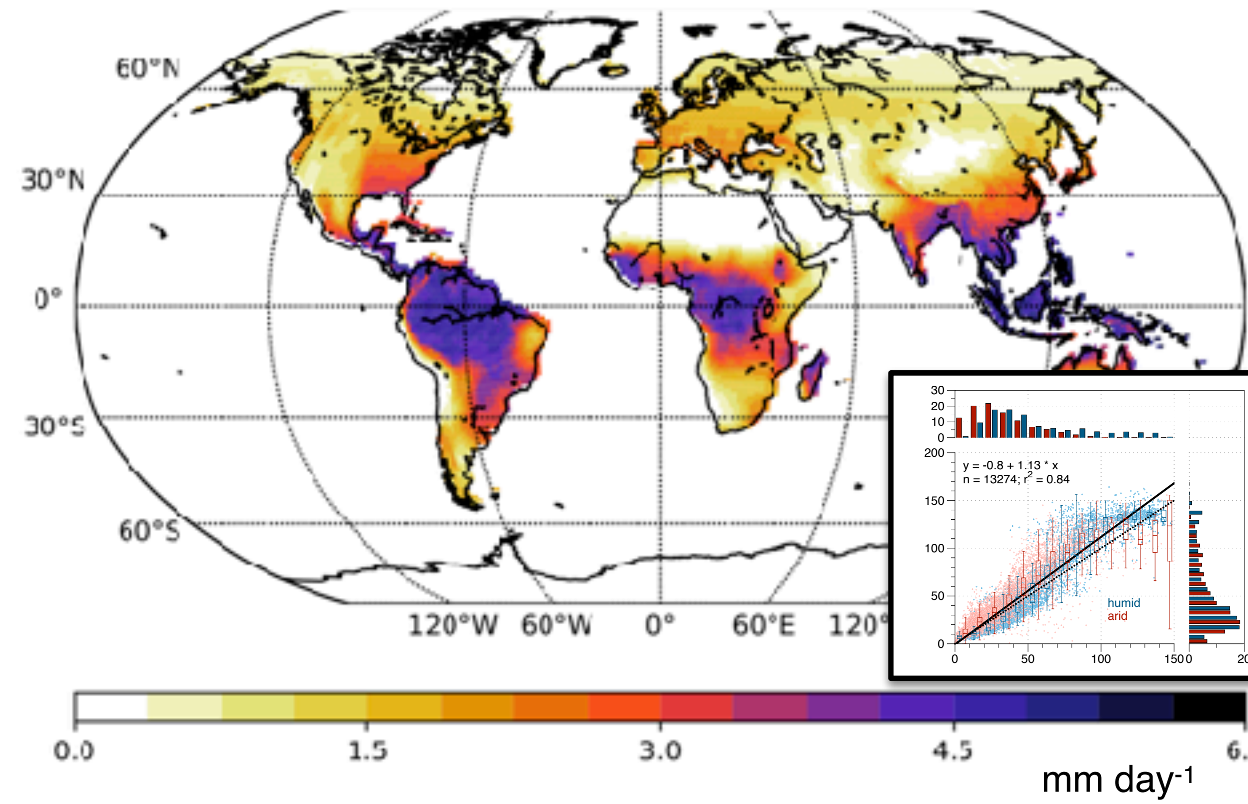
s/(s+γ)

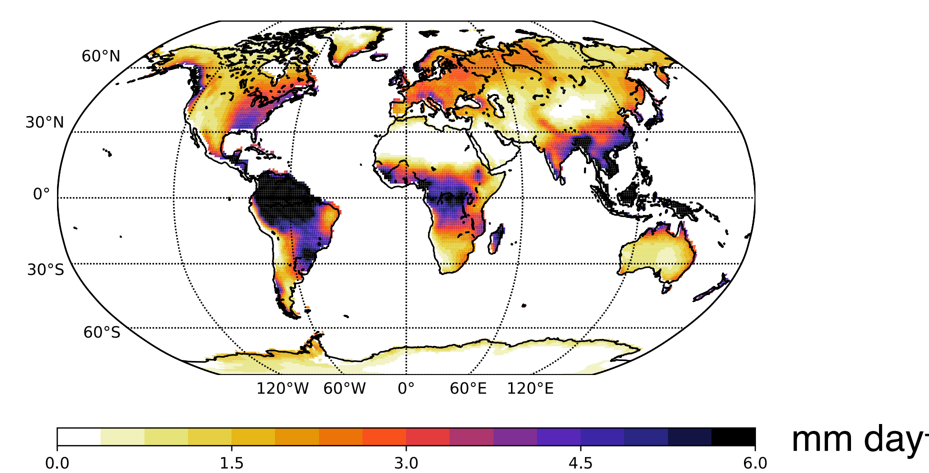
Sensible
heat flux
(buoyancy)

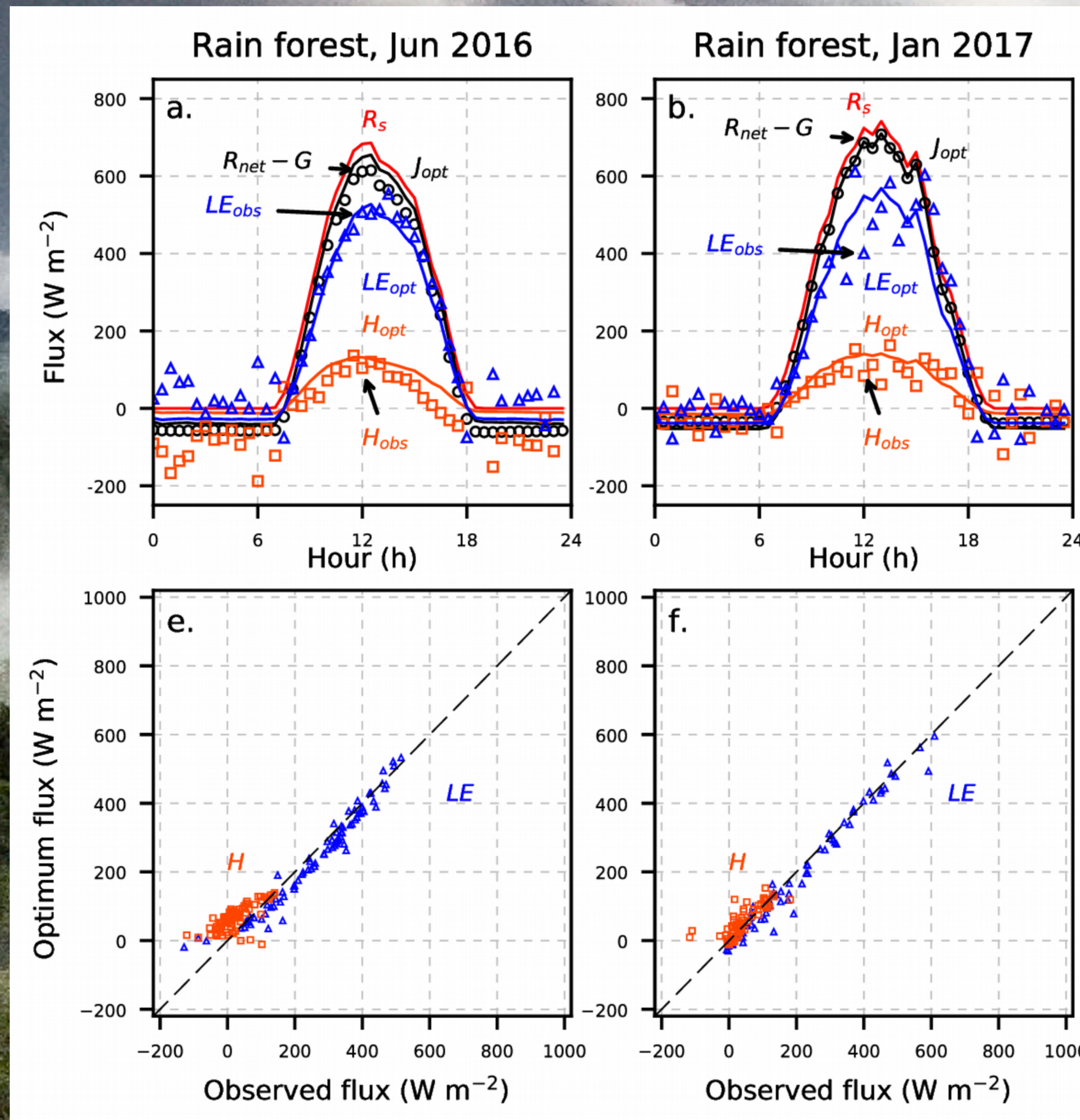
Latent
heat flux
(evaporation)

Precipitation



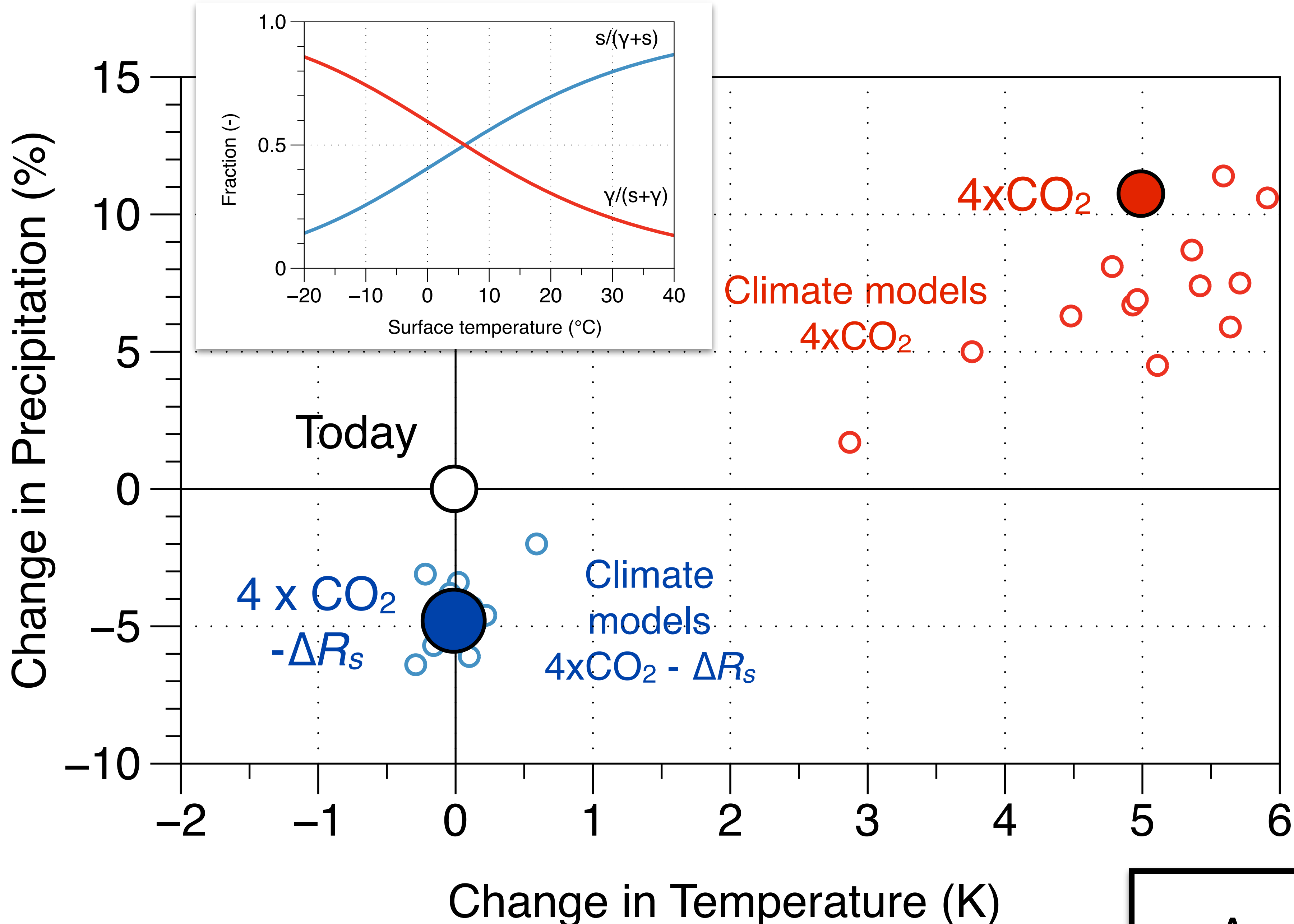






Conte et al. (2019) GRL

Global Warming



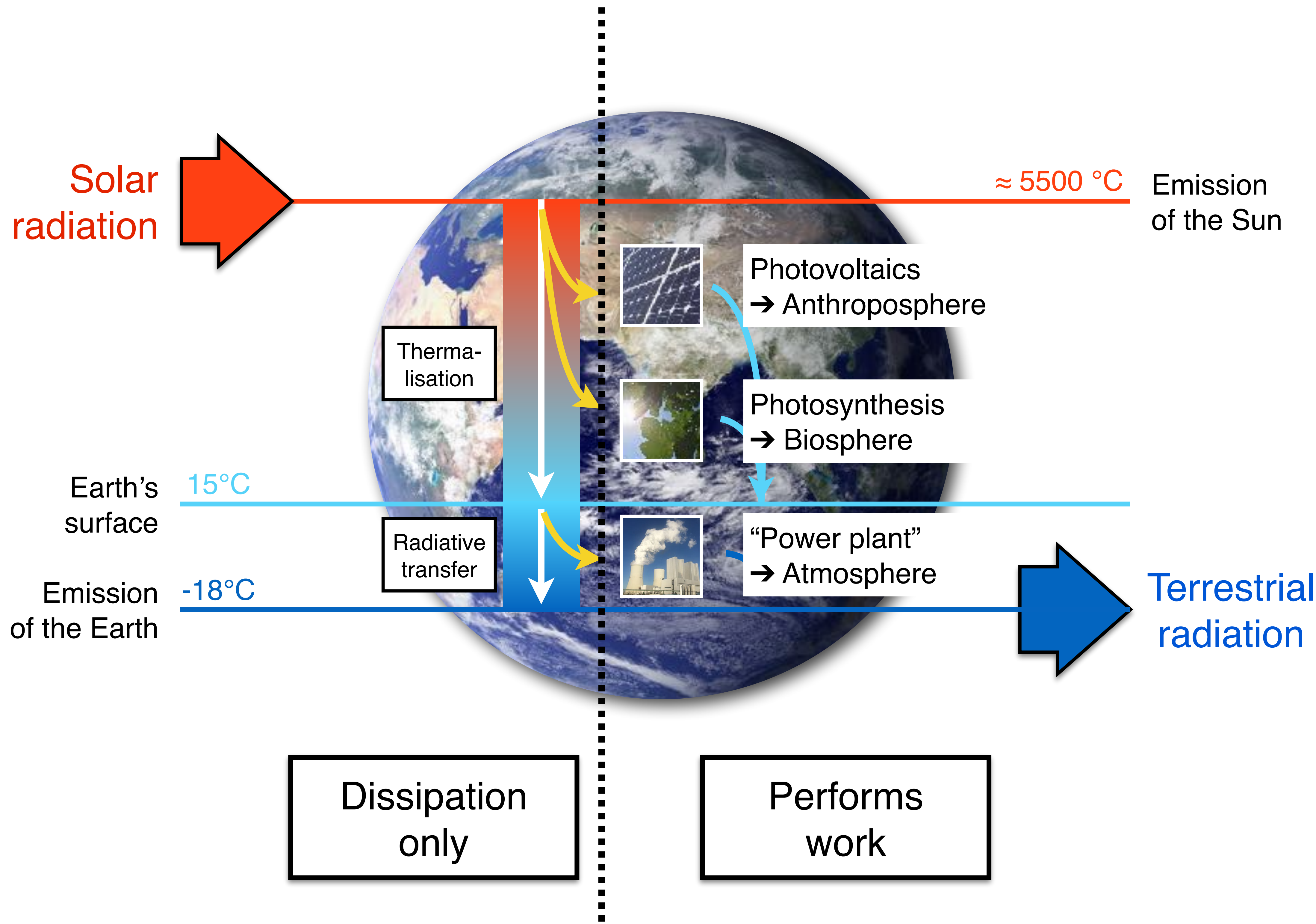
Acceleration of the hydrological cycle mostly explained by thermodynamics

Climate models: GeoMIP
Kleidon and Renner (2013)
Kleidon, Kravitz, Renner (2015)
Kleidon und Renner (2015)

Powering the Hydrological Cycle

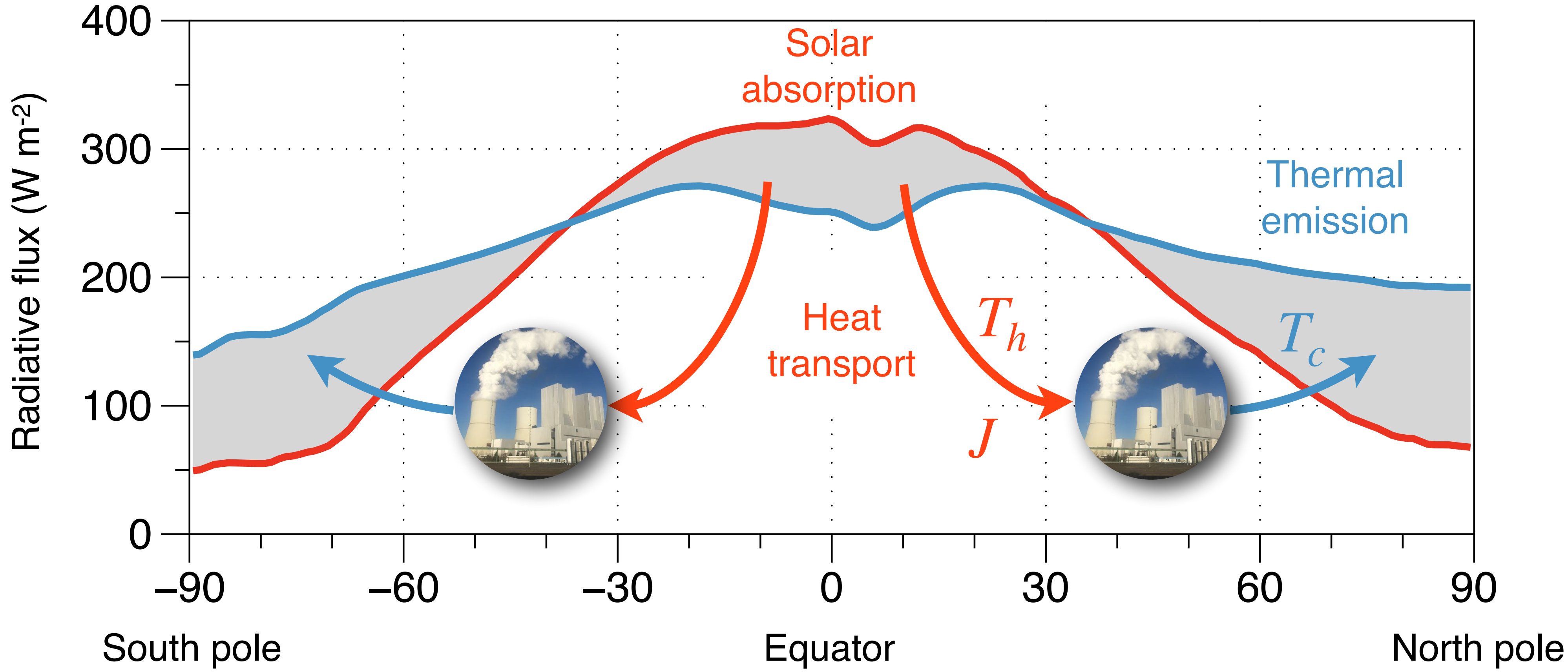
- Hydrologic cycle represents thermodynamic disequilibrium
- (Potential) evaporation is set by thermodynamic constraints: ability to add and transport vapor
- Rainforest appears to operate at this thermodynamic limit
- Acceleration of the hydrological cycle mostly explained by thermodynamics

Renewable Energy



Solar radiation
≈ 5500 °C
Emission of the Sun
Photovoltaics
➔ Anthroposphere
Therma-lisation
Photosynthesis
➔ Biosphere
Earth's surface
15°C
Radiative transfer
"Power plant"
➔ Atmosphere
Emission of the Earth
-18°C
Terrestrial radiation
Dissipation only
Performs work

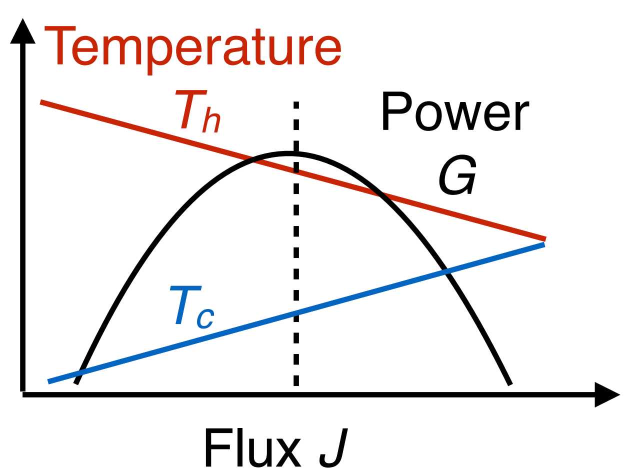
Generation of Large-scale Wind Energy



Thermodynamic limit:

$$G = J \cdot \frac{T_h - T_c}{T_h}$$

More transport ➔ less efficiency:



Maximum power:

Heat flux: 50 W m^{-2}

T_h - T_c: ≈ 30 K

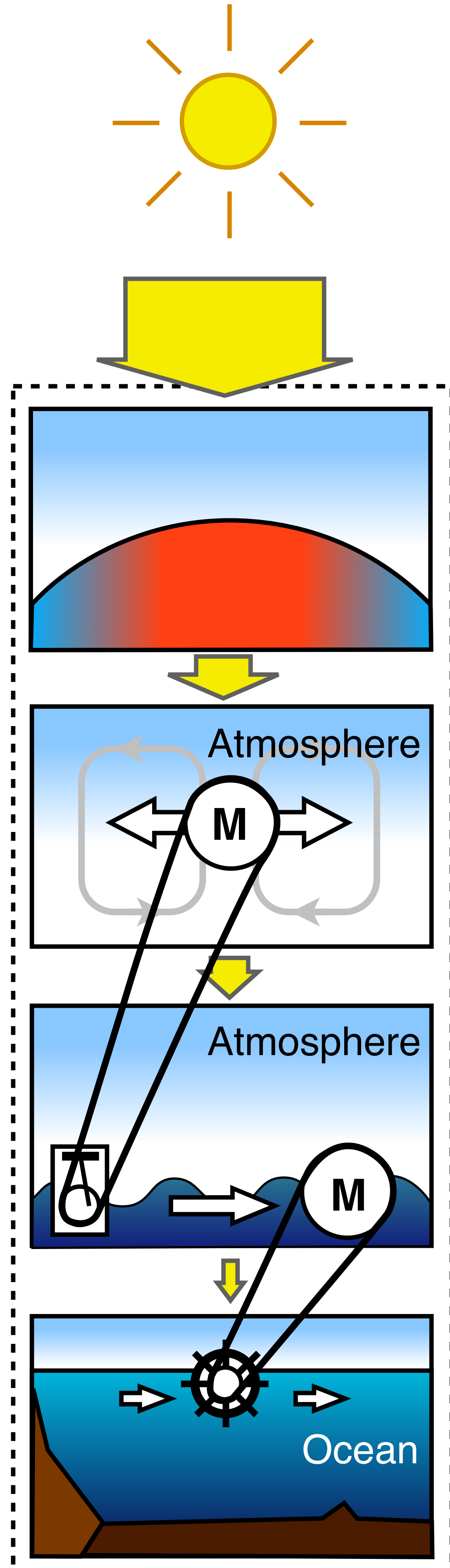
Power: 0.5 x 50 x 10% ≈ 2.5 W m^{-2}

Global: ≈ 1000 TW

Efficiency: ≈ 1%

Kleidon (2021) Met. Z.; Data: NASA-CERES

Earth system process		Renewable energy
Solar irradiation	≈ 175000 TW →	Solar power
	Absorption 70% *Differential heating* 40%	
Absorption generates heating	≈ 49000 TW	
	Conversion (maximal) 2%	
Heating differences cause motion	≈ 1000 TW →	Wind energy
	Conversion (observed) 6%	
Motion generates waves	≈ 60 TW →	Wave energy
	Conversion (observed) 8%	
Waves generate ocean currents	≈ 5 TW →	Energy from ocean currents
	≈ 20 TW	Human societies



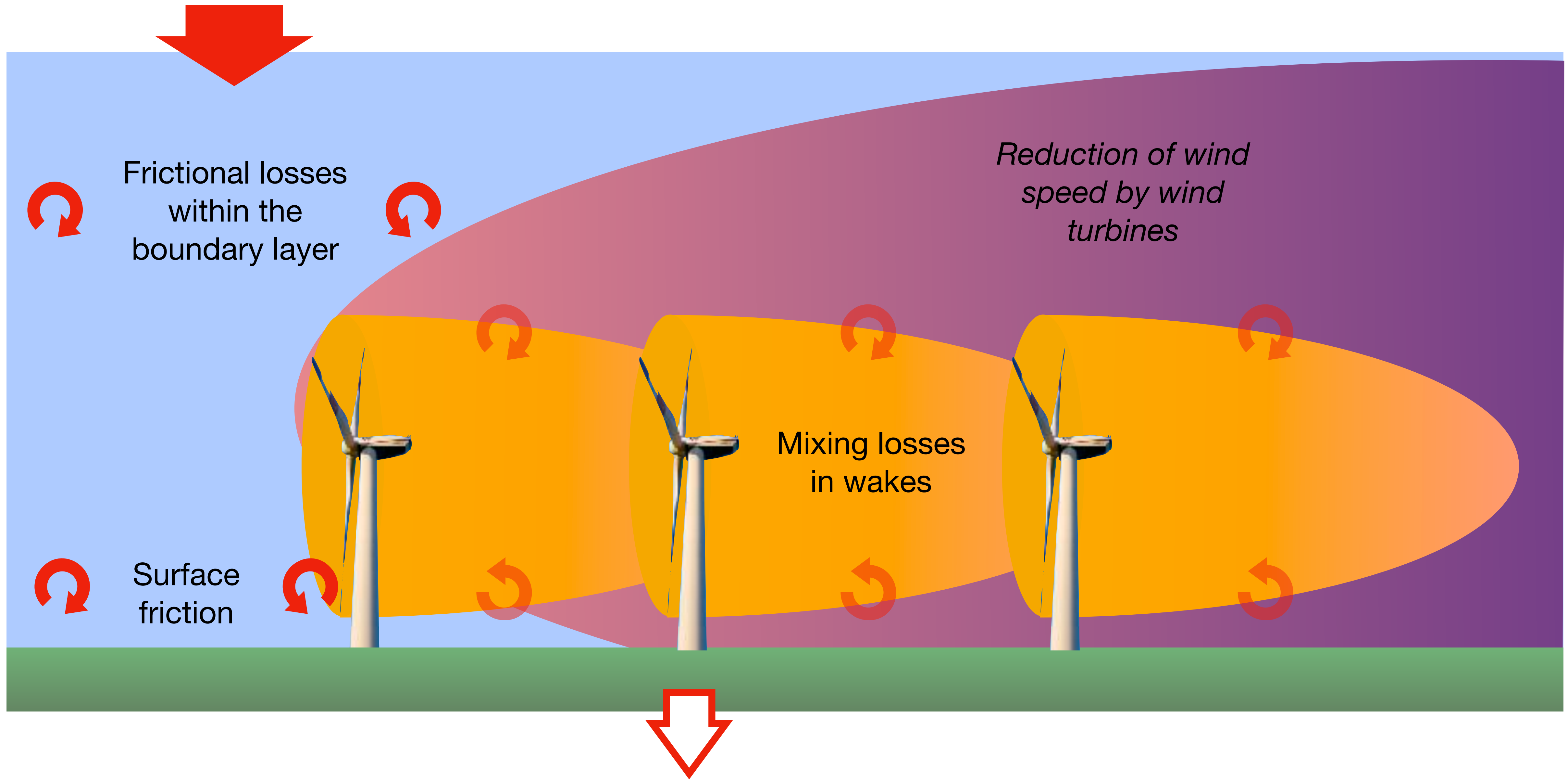
Kleidon (2019) PhysIUZ

1000 TW

Input of kinetic energy
from the free atmosphere

1-2 km

≈ 50%
500 TW



< 38% Electrical energy

≈ 50%
500 TW

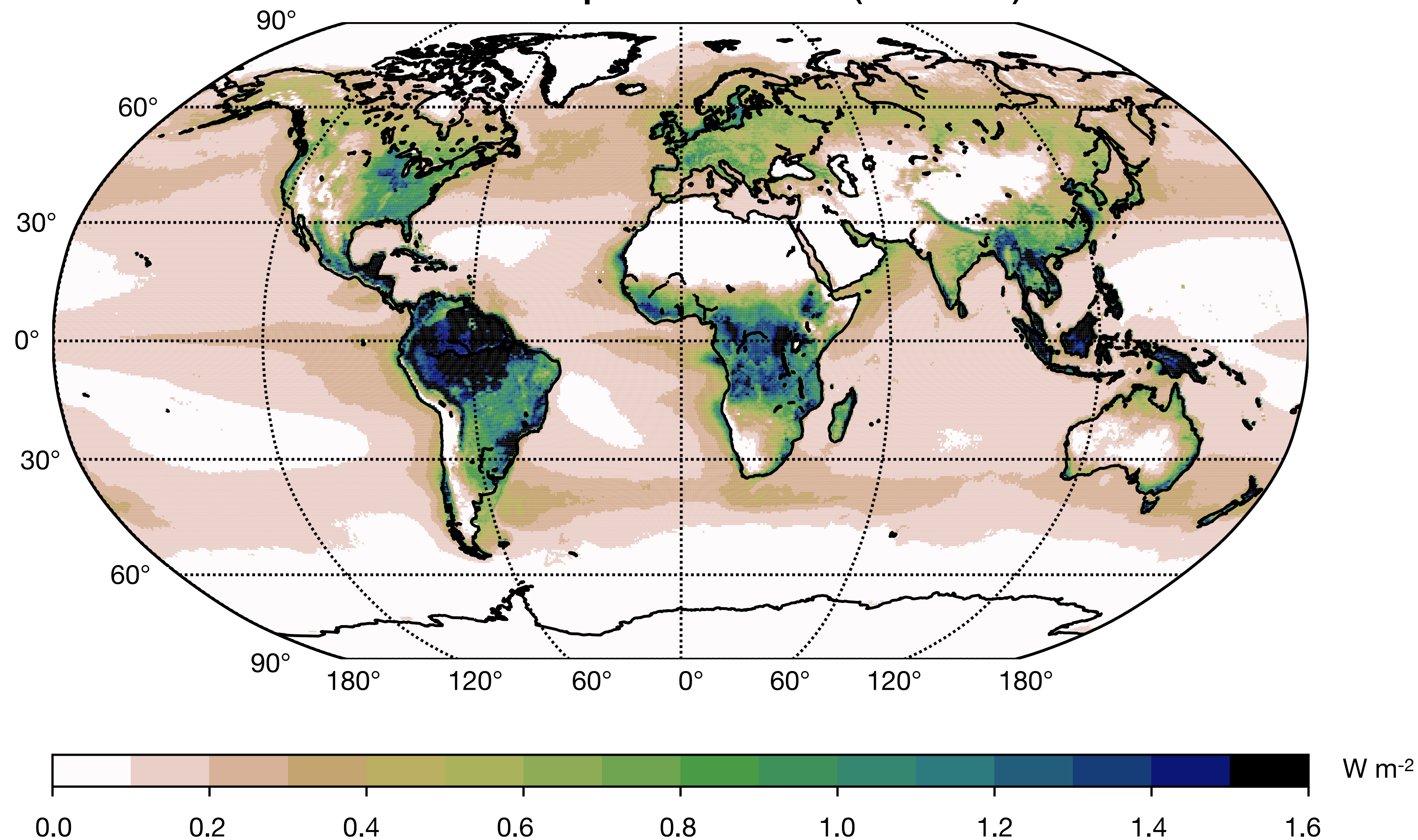
≥ 310 TW

≤ 190 TW

Kleidon (2023)

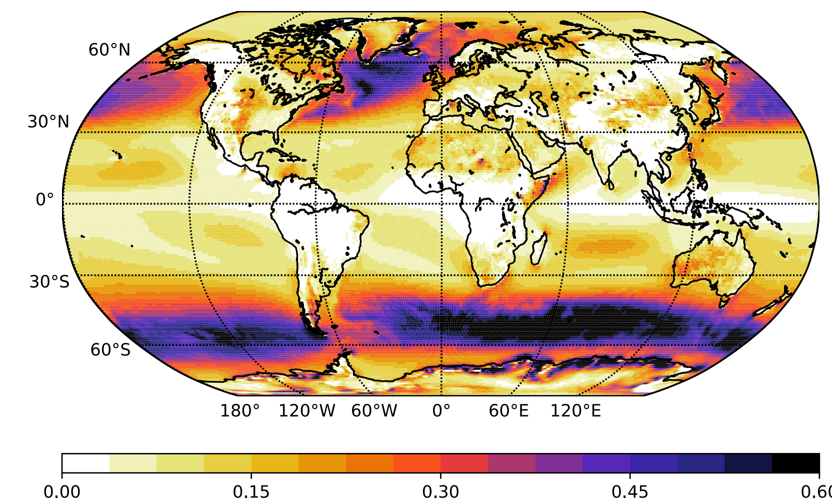
Power from Photosynthesis

Biomass production (“NPP")

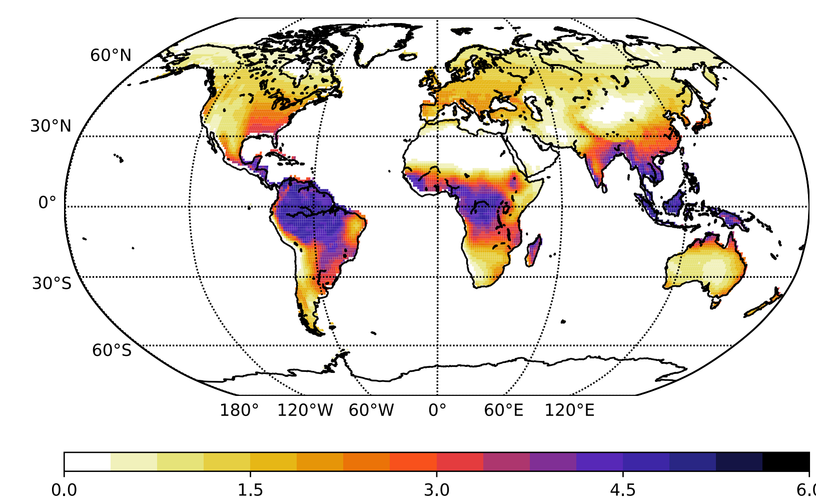


Land: 152 TW (≈ 1%)

Ocean: mixing



Land: gas exchange



based on Field et al. (1998) Science, 281: 237-240
updated using MODIS Daten

Wind energy

Efficiency: < 1%
Power: 1 000 TW

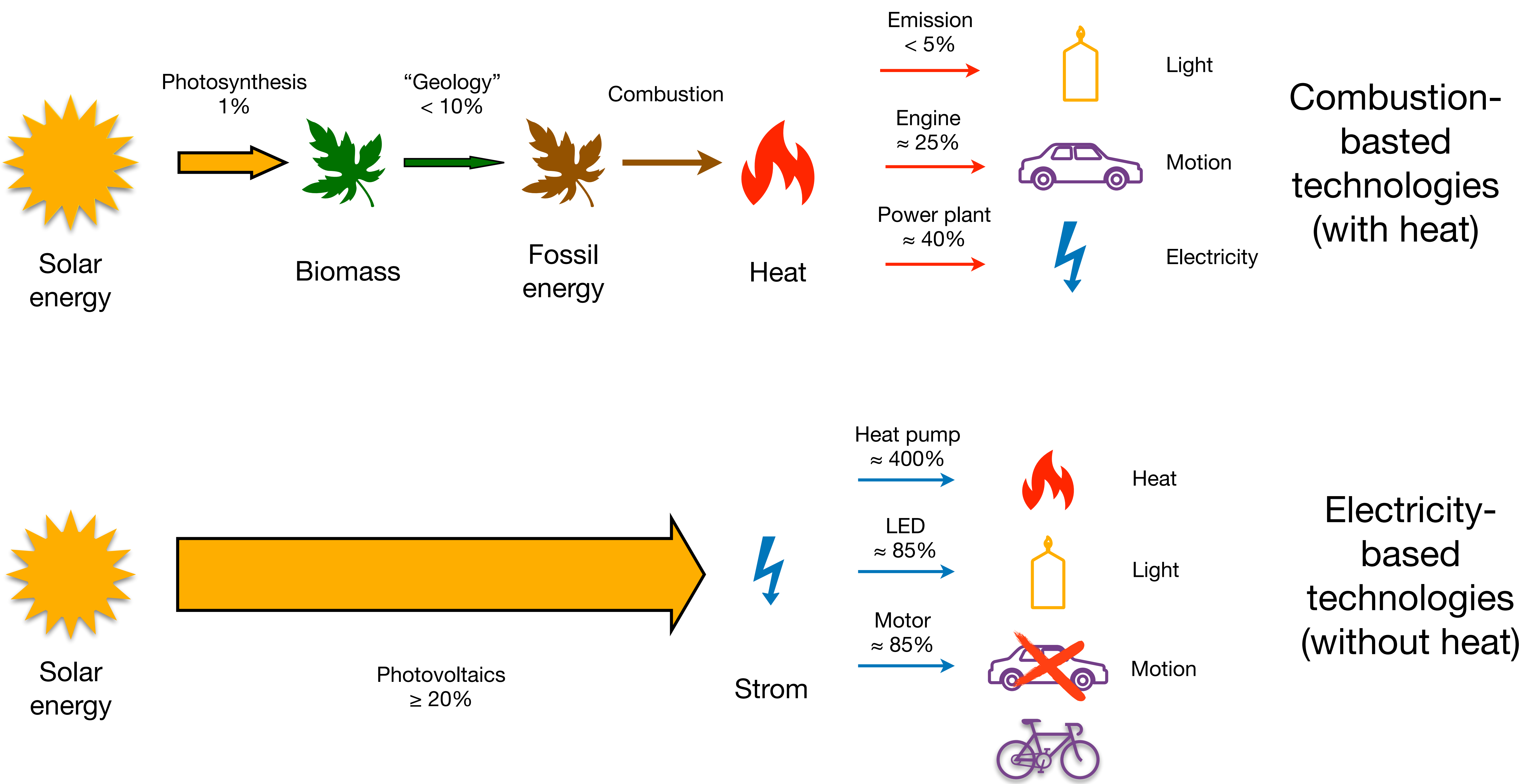
Photosynthesis

Efficiency: < 1%
Power: 152 TW

Photovoltaics

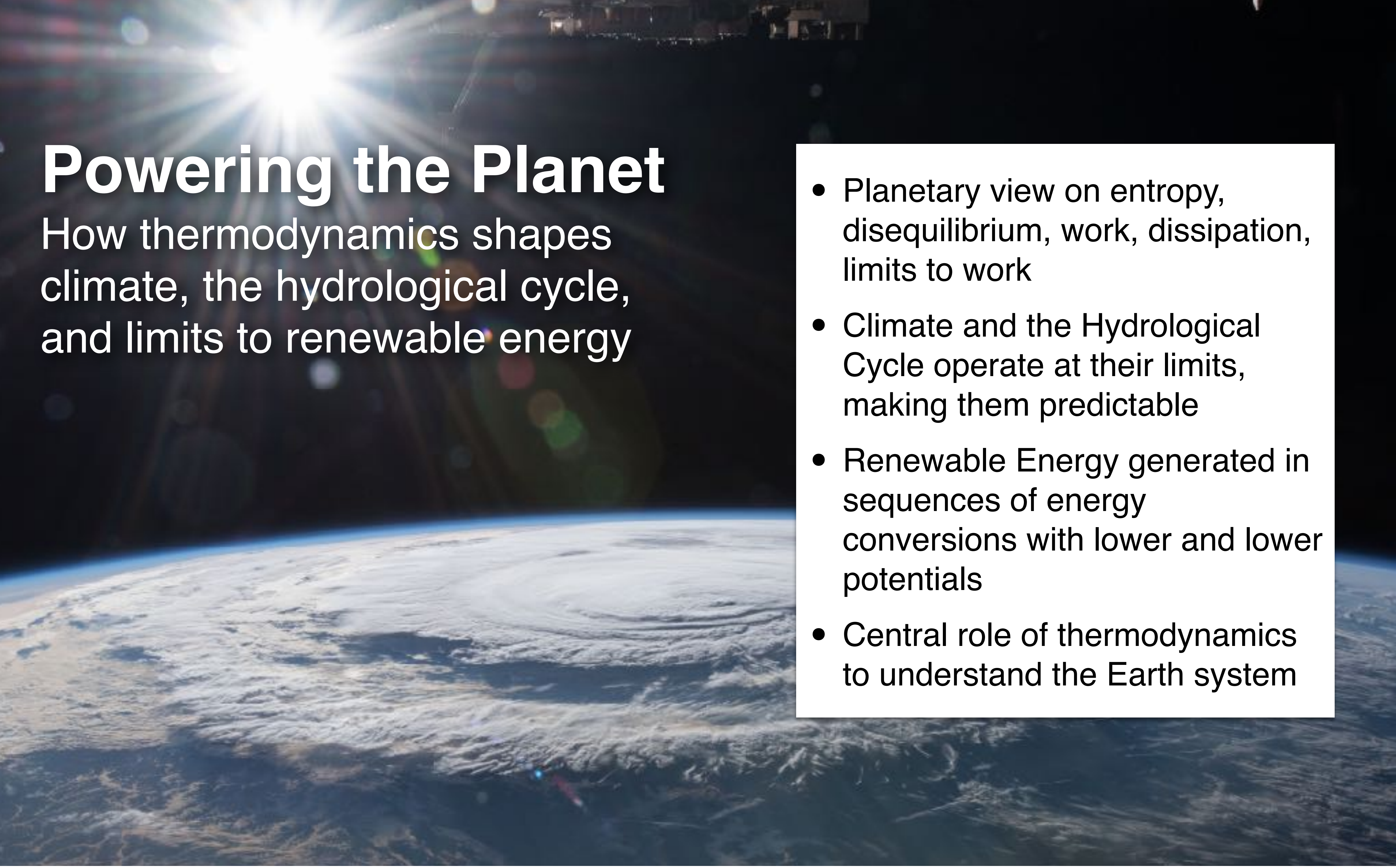
Efficiency: ≈ 20%
Power: 35 000 TW

Energy Transition = Huge Increase in Efficiency



Powering Human Societies

- Photovoltaics has greatest potential to generate electricity from Sunlight
- Potential of wind energy is much reduced
- Photosynthesis is quite inefficient, hence low potential
- Substantial potential to reduce primary energy demand by electrification



Powering the Planet

How thermodynamics shapes climate, the hydrological cycle, and limits to renewable energy

- Planetary view on entropy, disequilibrium, work, dissipation, limits to work
- Climate and the Hydrological Cycle operate at their limits, making them predictable
- Renewable Energy generated in sequences of energy conversions with lower and lower potentials
- Central role of thermodynamics to understand the Earth system

Aligarh Muslim University
March 2024

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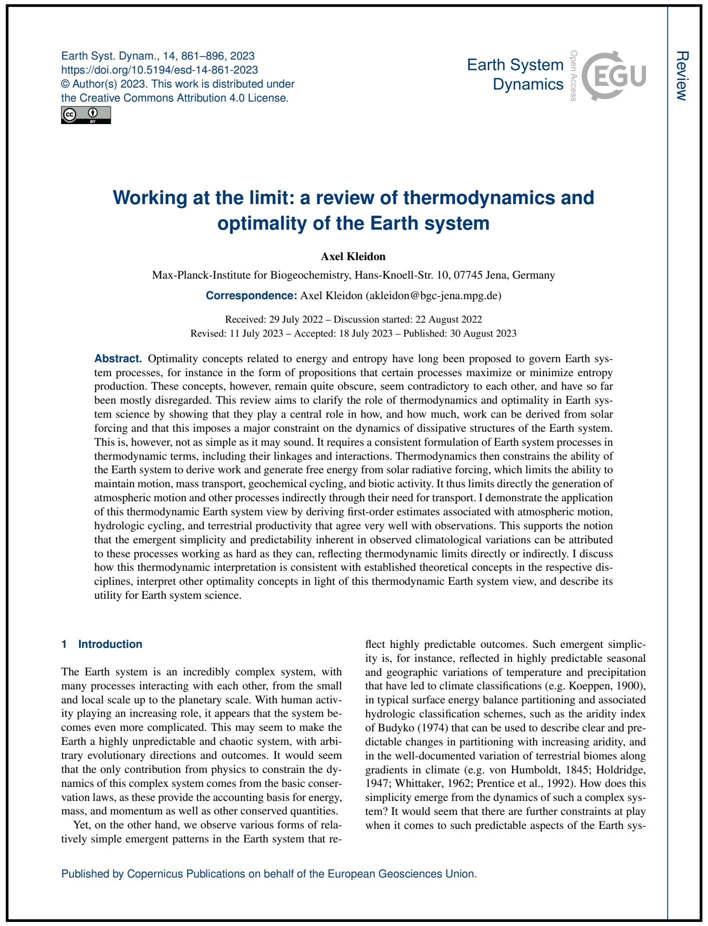
http://gaia.mpg.de ❖ earthsystem.org

Literature


Earth Syst. Dynam., 14, 861–896, 2023
https://doi.org/10.5194/esd-14-861-2023
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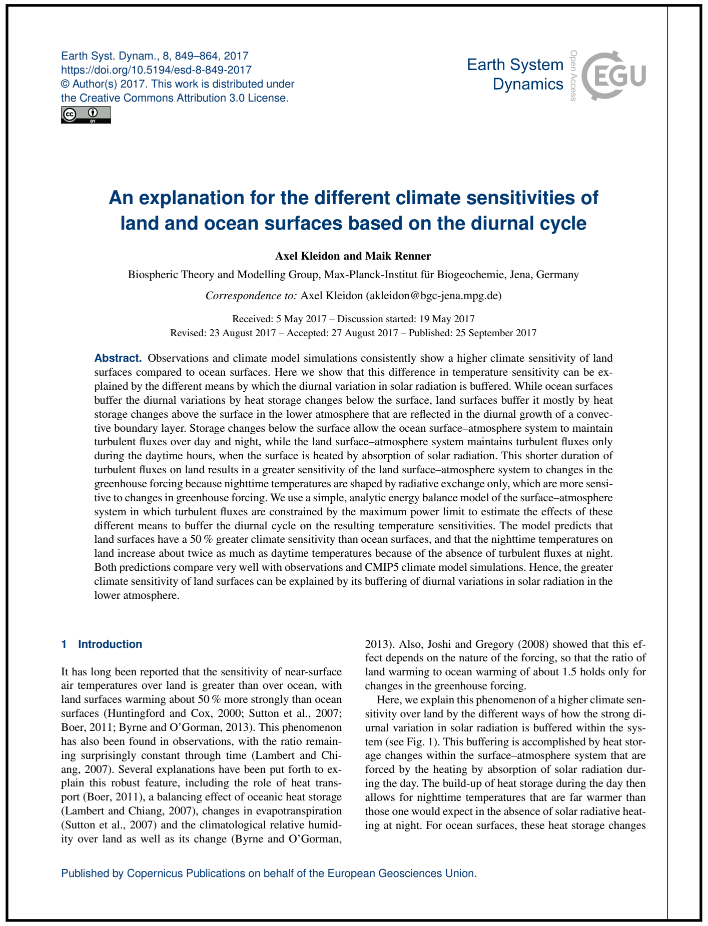
Working at the limit: a review of thermodynamics and optimality of the Earth system

Axel Kleidon


PNAS

Radiative controls by clouds and thermodynamics shape surface temperatures and turbulent fluxes over land

Sarosh Alam Ghausi, Yinglin Tian, Erwin Zehe, and Axel Kleidon


Earth Syst. Dynam., 8, 849–864, 2017
https://doi.org/10.5194/esd-8-849-2017

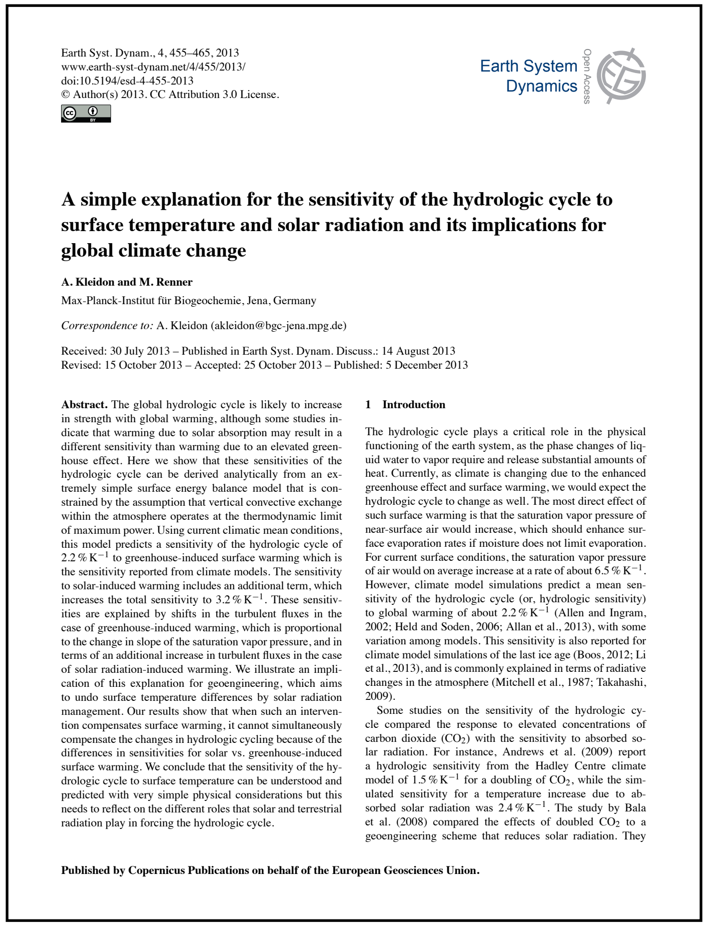
An explanation for the different climate sensitivities of land and ocean surfaces based on the diurnal cycle

Axel Kleidon and Maik Renner


BBA - Bioenergetics 1862 (2021) 148303

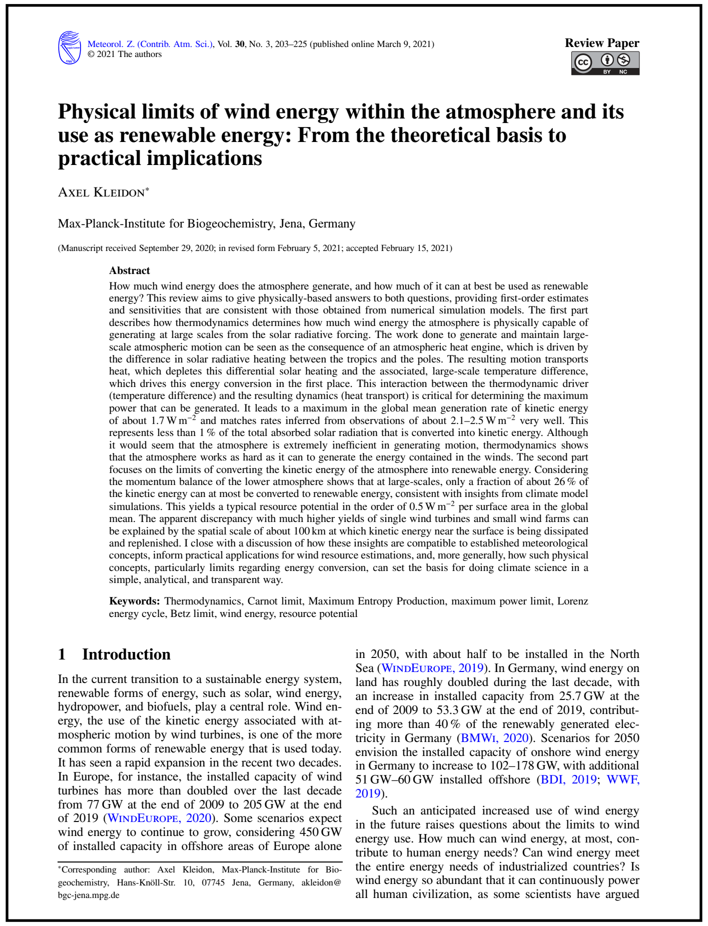
What limits photosynthesis? Identifying the thermodynamic constraints of the terrestrial biosphere within the Earth system

Axel Kleidon


Earth Syst. Dynam., 4, 455–465, 2013
www.earth-syst-dynam.net/4/455/2013/
doi:10.5194/esd-4-455-2013

A simple explanation for the sensitivity of the hydrologic cycle to surface temperature and solar radiation and its implications for global climate change

A. Kleidon and M. Renner


Meteorol. Z. (Contrib. Atm. Sci.), Vol. 30, No. 3, 203–225 (published online March 9, 2021)

Physical limits of wind energy within the atmosphere and its use as renewable energy: From the theoretical basis to practical implications

Axel Kleidon

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