Life, Hierarchy, and the Thermodynamic Machinery of Planet Earth

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Stochastic Methods in Climate Modelling
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Gaia vs. Maximum Entropy Production

Lovelock: chemical disequilibrium in the Earth's atmosphere due to widespread life

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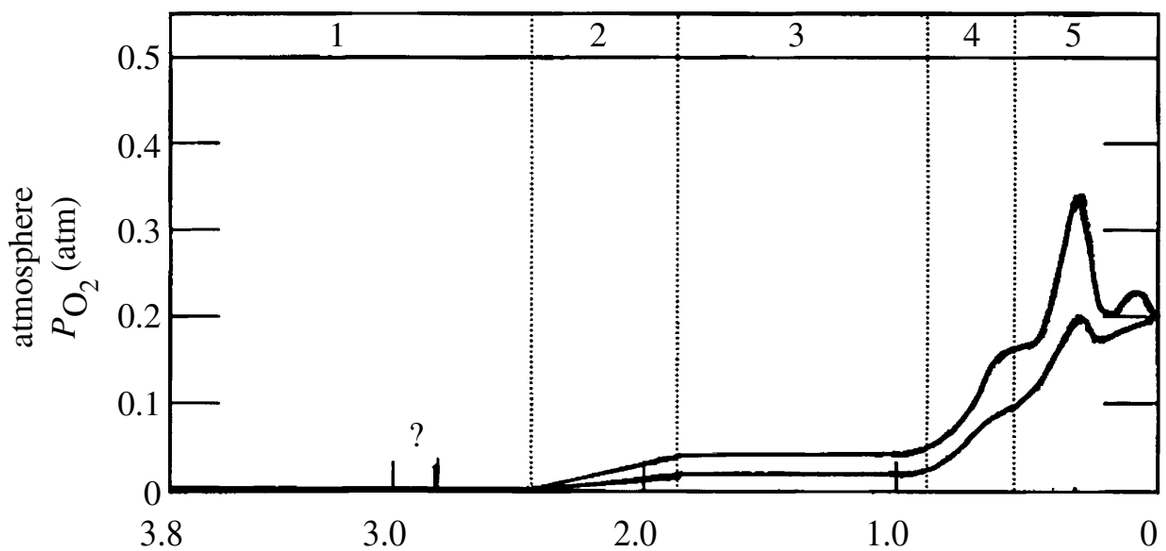
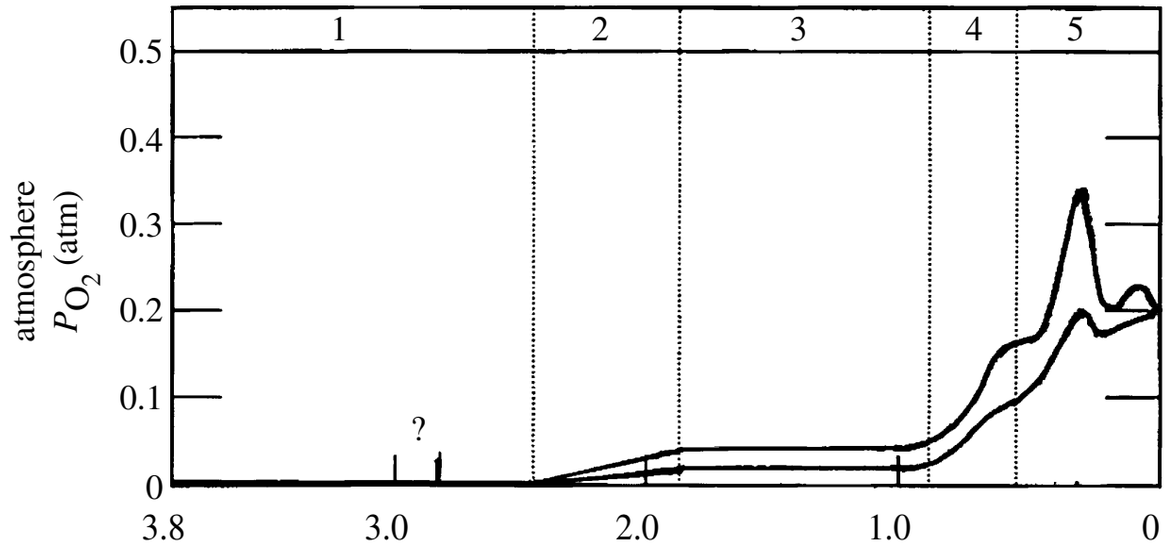


Gaia vs. Maximum Entropy Production

Lovelock: chemical disequilibrium in the Earth's atmosphere due to widespread life

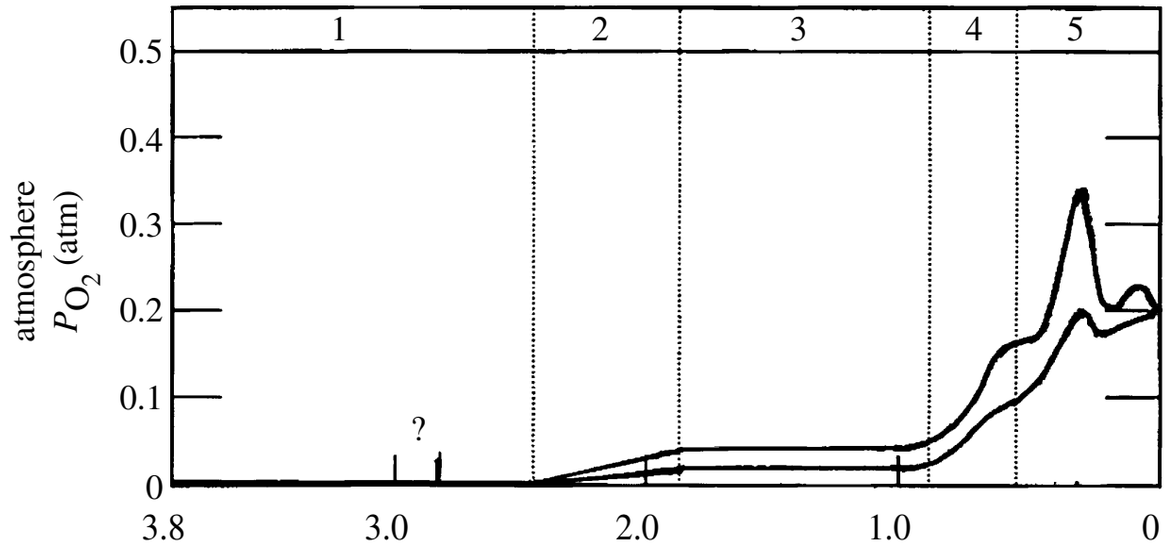


Earth: evolution away from equilibrium

Gaia vs. Maximum Entropy Production

Lovelock: chemical disequilibrium in the Earth's atmosphere due to widespread life

MEP: fastest approach to equilibrium



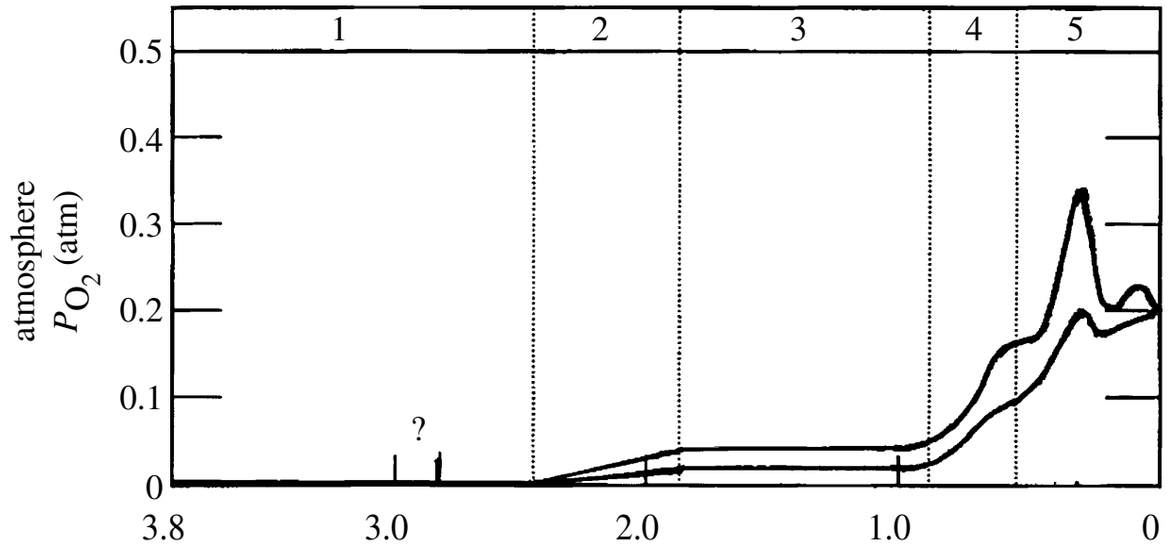
Earth: evolution away from equilibrium

Gaia vs. Maximum Entropy Production

Lovelock: chemical disequilibrium in the Earth's atmosphere due to widespread life

MEP:
fastest approach to equilibrium

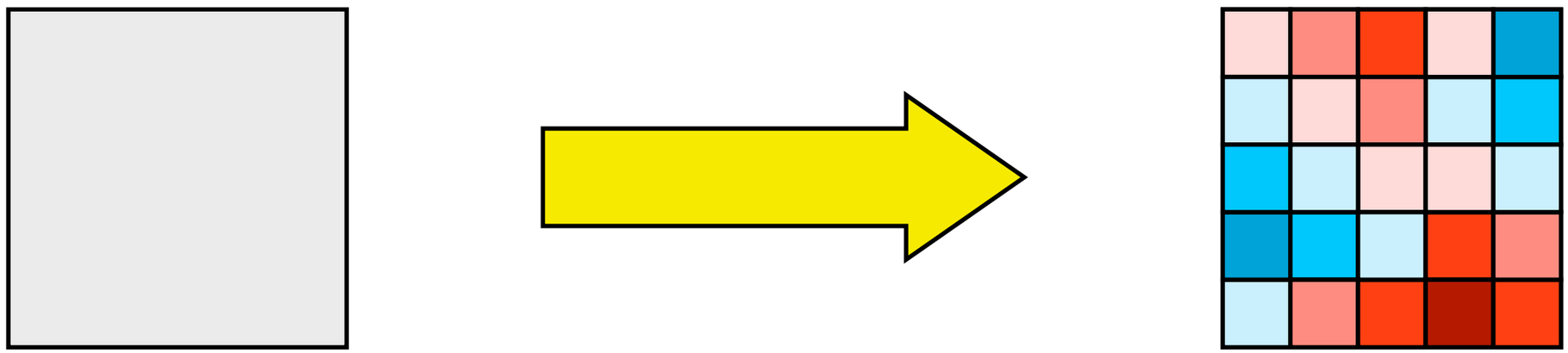
???



Earth:
evolution away from equilibrium

Importance of Maintaining Disequilibrium

<u>thermodynamics and variability</u>

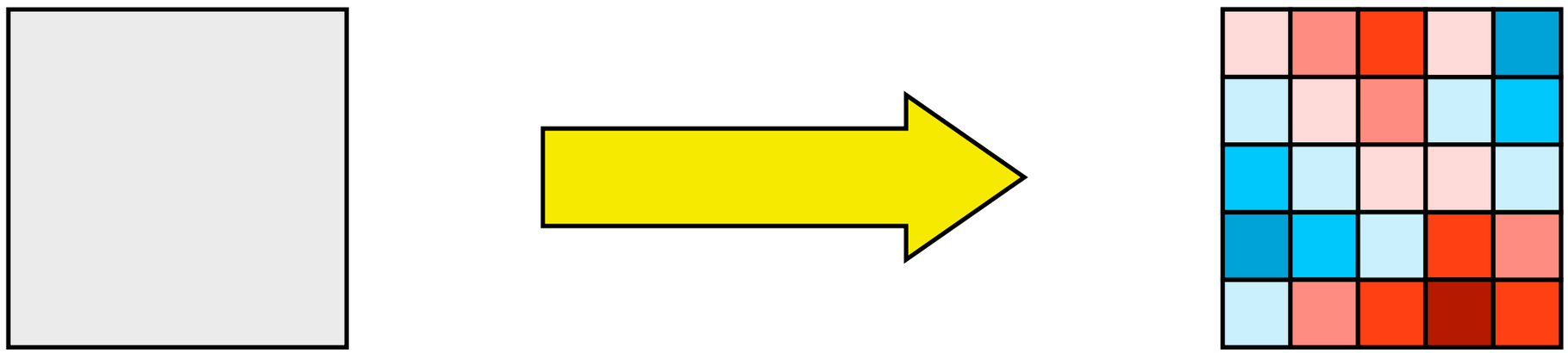


thermodynamic equilibrium

far from equilibrium

Importance of Maintaining Disequilibrium

thermodynamics and variability



thermodynamic equilibrium

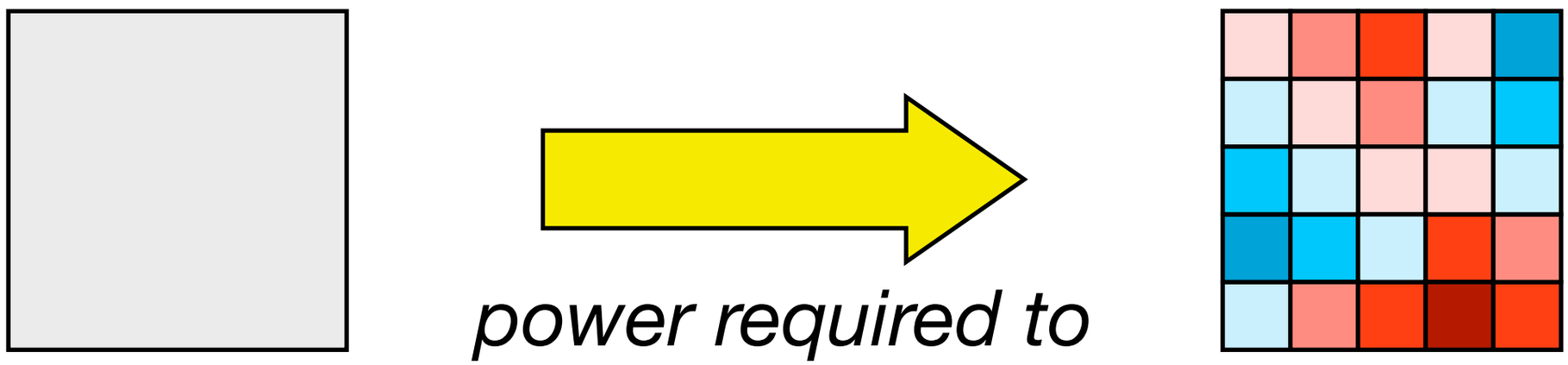
uniform, constant

far from equilibrium

spatial and temporal variability

Importance of Maintaining Disequilibrium

<u>thermodynamics and variability</u>



power required to maintain disequilibrium

thermodynamic equilibrium

far from equilibrium

How does the Earth system generate and maintain thermodynamic disequilibrium?

… and why should we care?

Outline

1. **Background:**
   - How to maintain disequilibrium?
   - How much power can be generated?
2. **Earth system:** Power generation, transfer, hierarchy and maximization
3. **Implications:** So what?

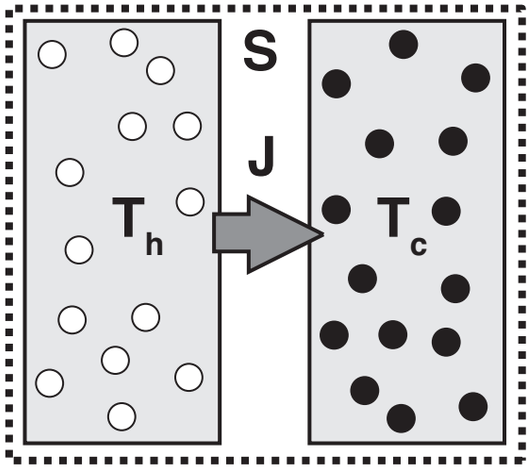
Maintaining Disequilibrium

first law: $$dU = dQ - dW$$

second law: $$dS = dQ/T \geq 0$$

Maintaining Disequilibrium

a. 2-box model



$$dQ = 0$$

$$J = k \cdot (T_h - T_c)$$

first law:

$$c \cdot \frac{dT_h}{dt} = -J$$

$$c \cdot \frac{dT_c}{dt} = J$$

$$c \cdot \left(\frac{dT_h}{dt} + \frac{dT_c}{dt} \right) = 0$$

second law:

$$\frac{dS_h}{dt} = -\frac{J}{T_h}$$

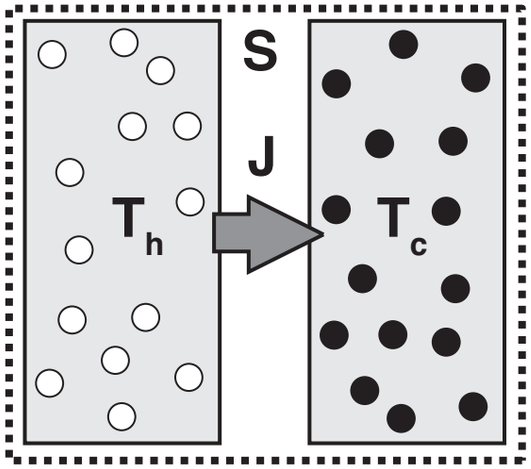
$$\frac{dS_c}{dt} = \frac{J}{T_c}$$

$$\frac{dS_{tot}}{dt} = J \cdot \left(\frac{1}{T_c} - \frac{1}{t_h} \right) = \sigma \geq= 0$$

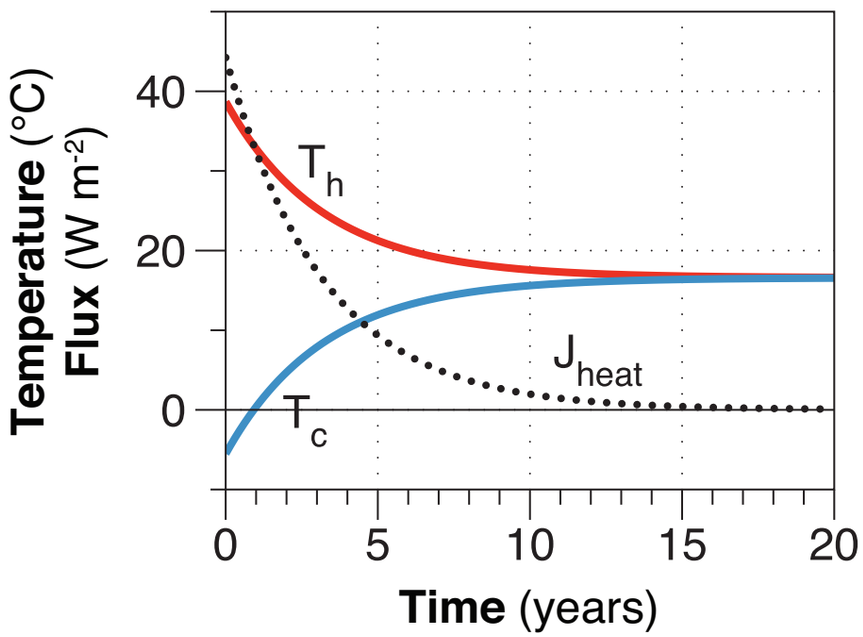
Maintaining Disequilibrium

$$dQ = 0$$

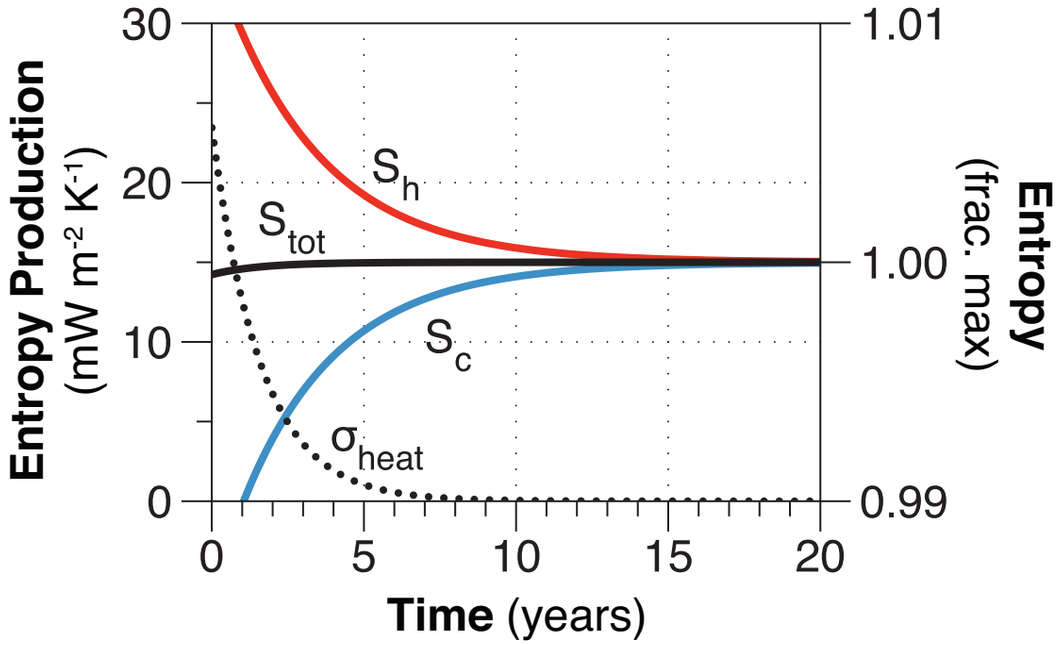
a. 2-box model



b. temperatures



c. entropies



Maintaining Disequilibrium

$$dQ = 0$$

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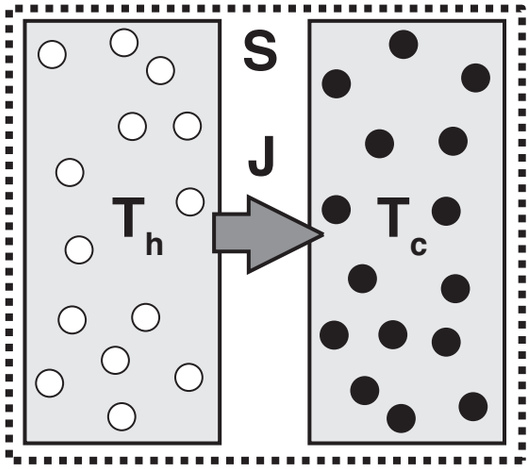
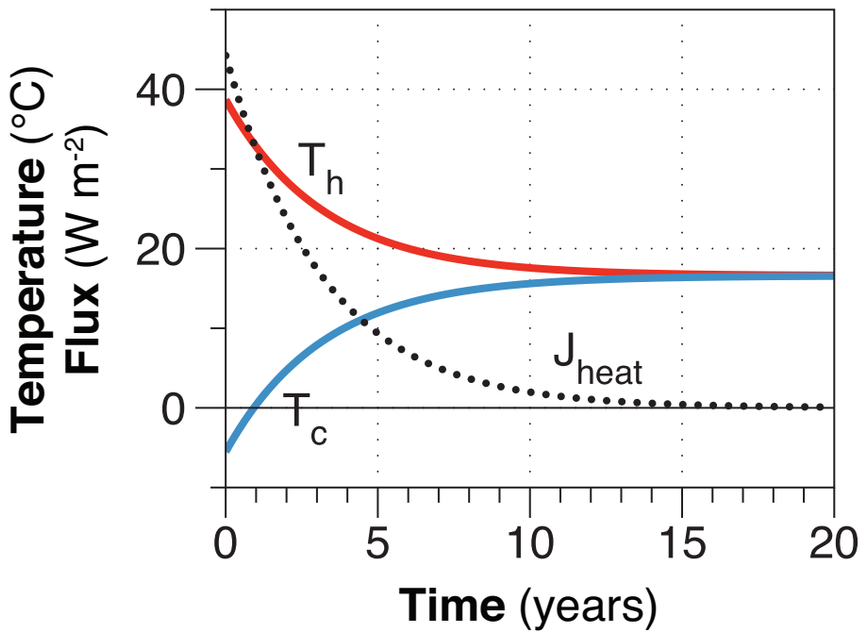


initial temperature gradient is dissipated to a state of thermodynamic equilibrium

b. temperatures



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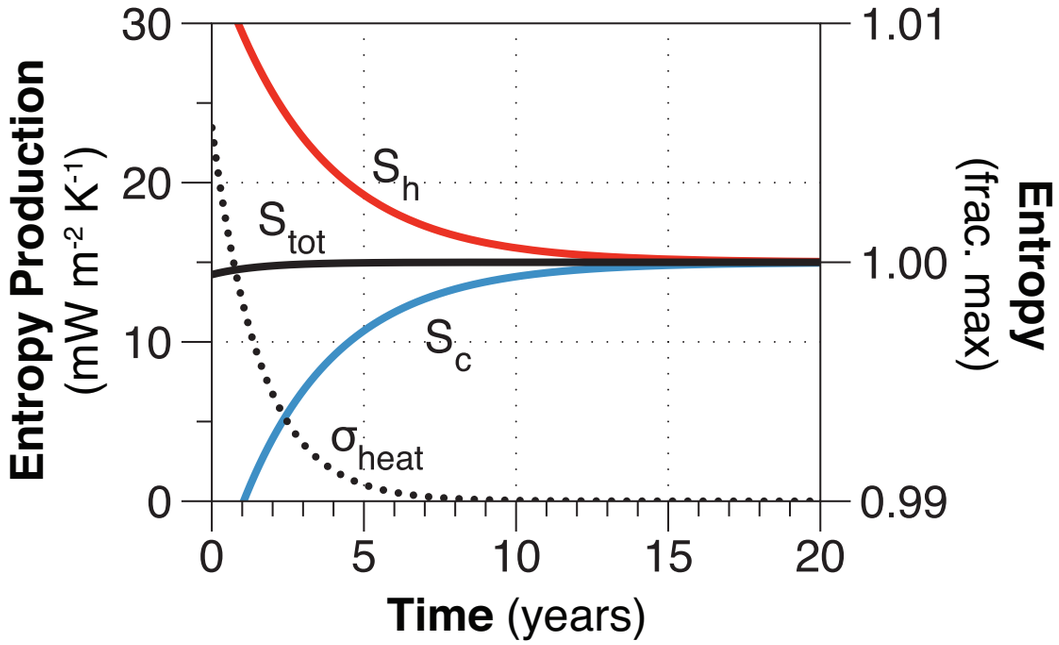

Maintaining Disequilibrium

$$dQ \neq 0$$

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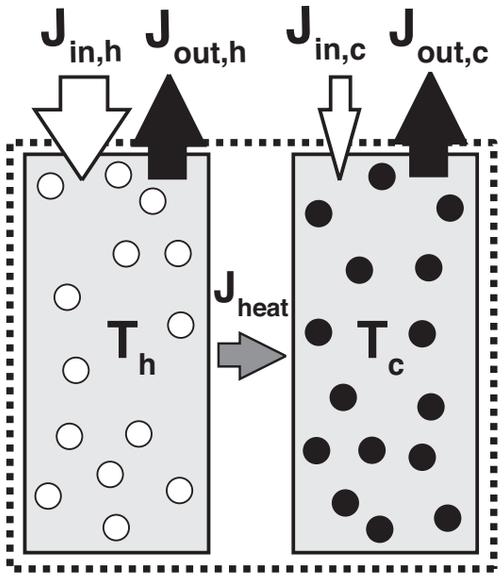
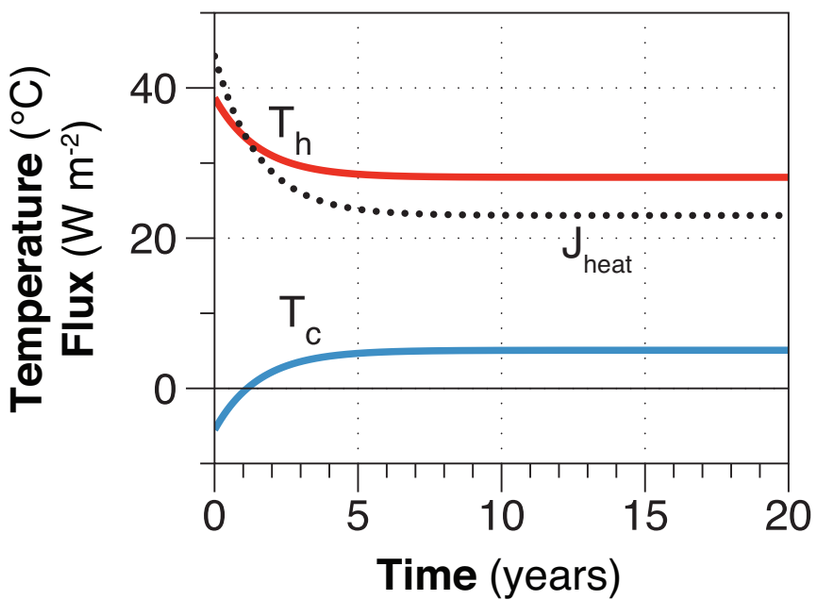
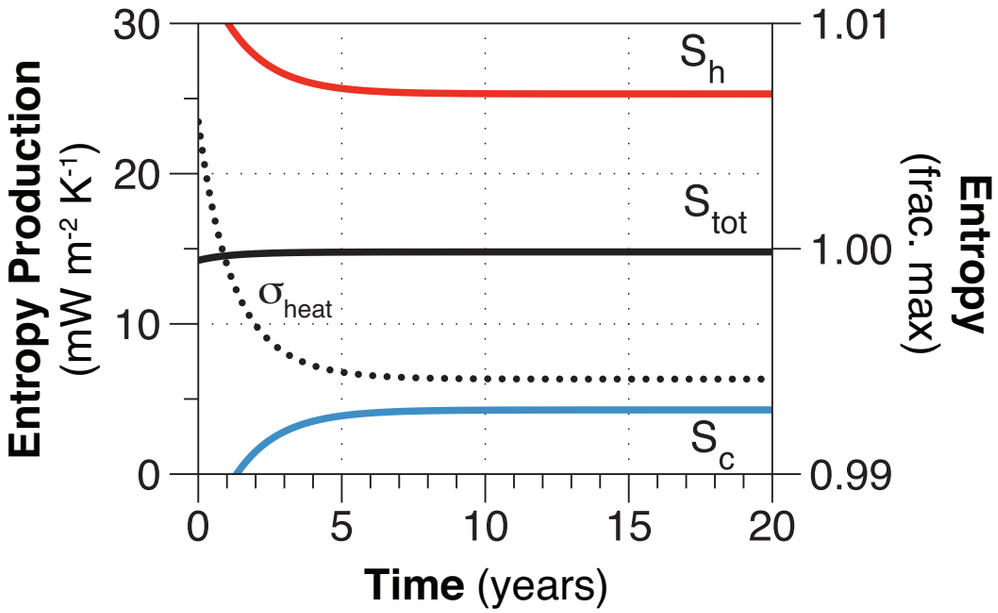


b. temperatures



c. entropies



Maintaining Disequilibrium

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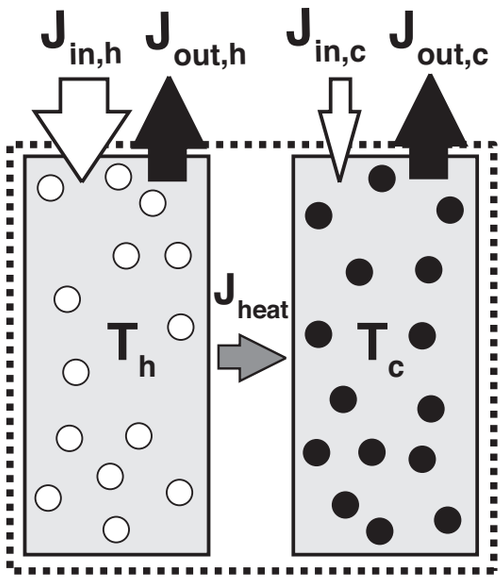
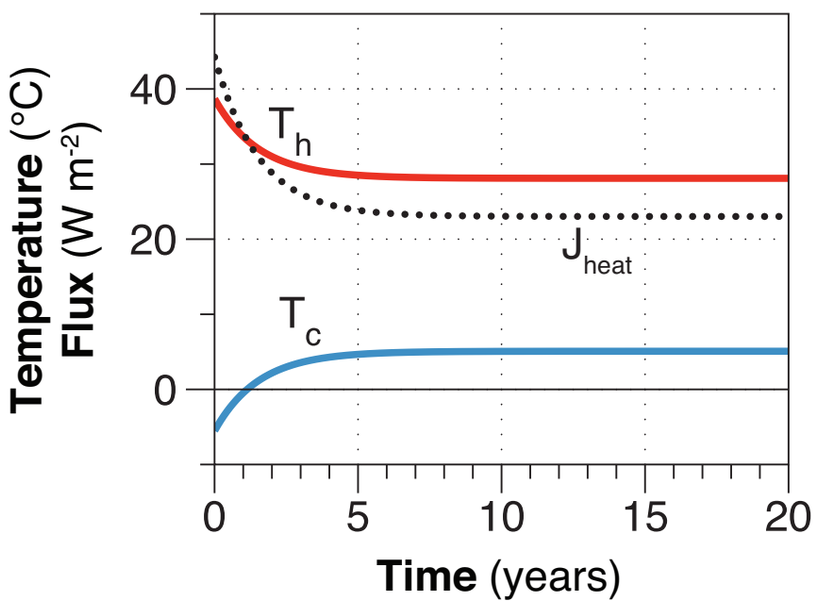


disequilibrium can be maintained by entropy exchange across system's boundary

b. temperatures



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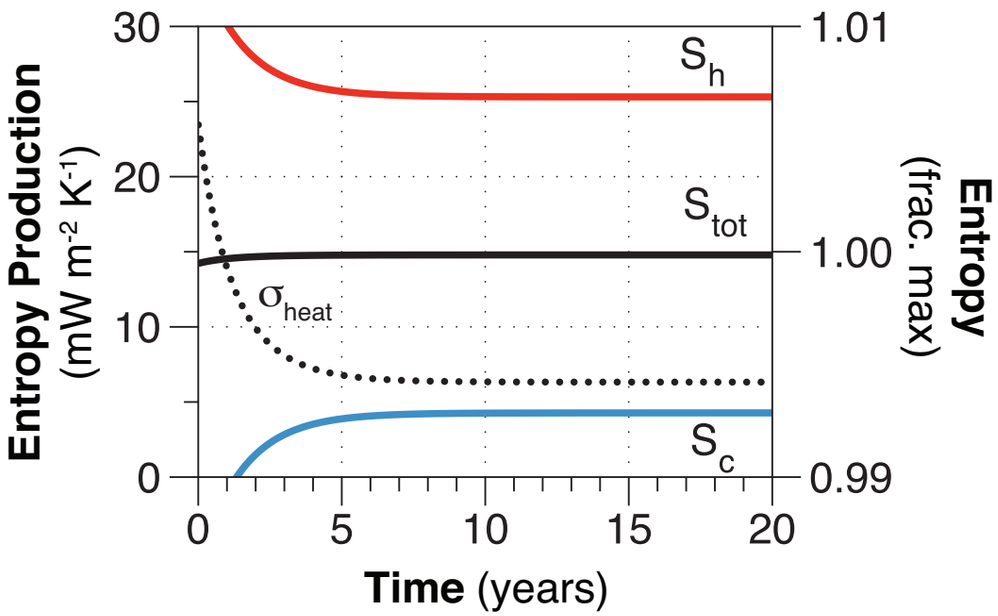

Kleidon (in prep.)

Maintaining Disequilibrium

first law: $$dU = dQ - dW$$

second law: $$dS = dQ/T \geq 0$$

combined:

$$dS_{tot} = \frac{dU + dW}{T}$$

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$$dS_{tot} = \frac{dU + dW}{T} \equiv dS_{heat} + dS_{diseq}$$

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entropy change due to changes in heat content

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entropy change due to changes in heat content

entropy change due to work done on/by the system

Maintaining Disequilibrium

first law: $$dU = dQ - dW$$

second law: $$dS = dQ/T \geq 0$$

or, using Helmholtz free energy A:

$$dA = dU - TdS_{tot} = -dW$$

Maintaining Disequilibrium

first law: $$dU = dQ - dW$$

second law: $$dS = dQ/T \geq 0$$

characterization of disequilibrium:

$$dS_{diseq} = -\frac{dA}{T}$$

Maintaining Disequilibrium

first law: $$\frac{dU}{dt} = J_{net} - (P - D)$$

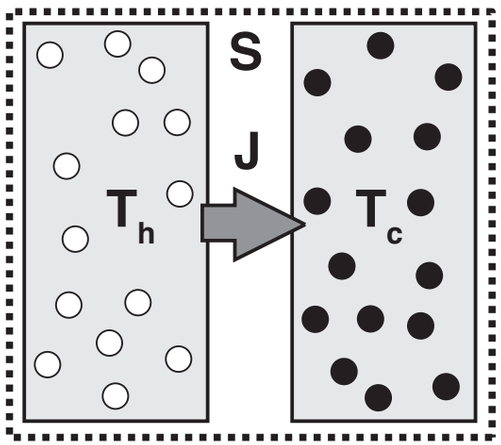
second law: $$\frac{dS}{dt} = \sigma - NEE$$

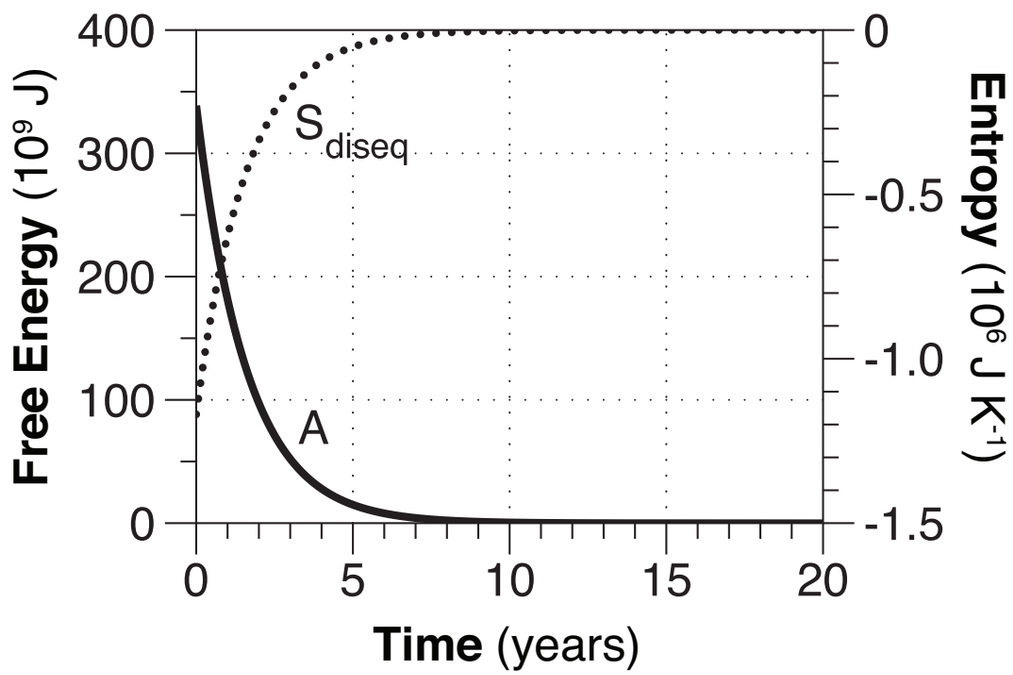
Helmholtz free energy A:

$$\frac{dA}{dt} = P - T \cdot \frac{dS_{diseq}}{dt}$$

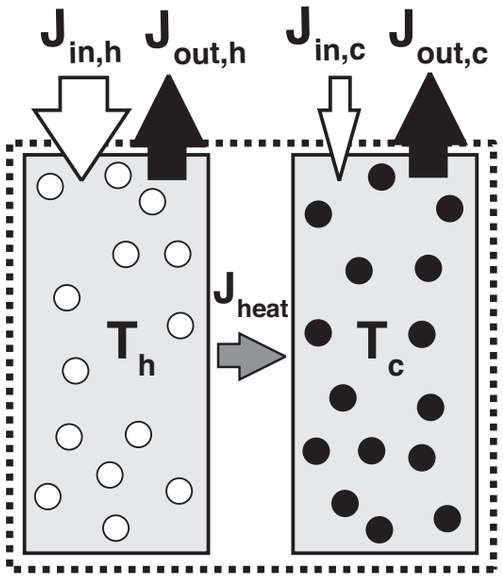
Maintaining Disequilibrium

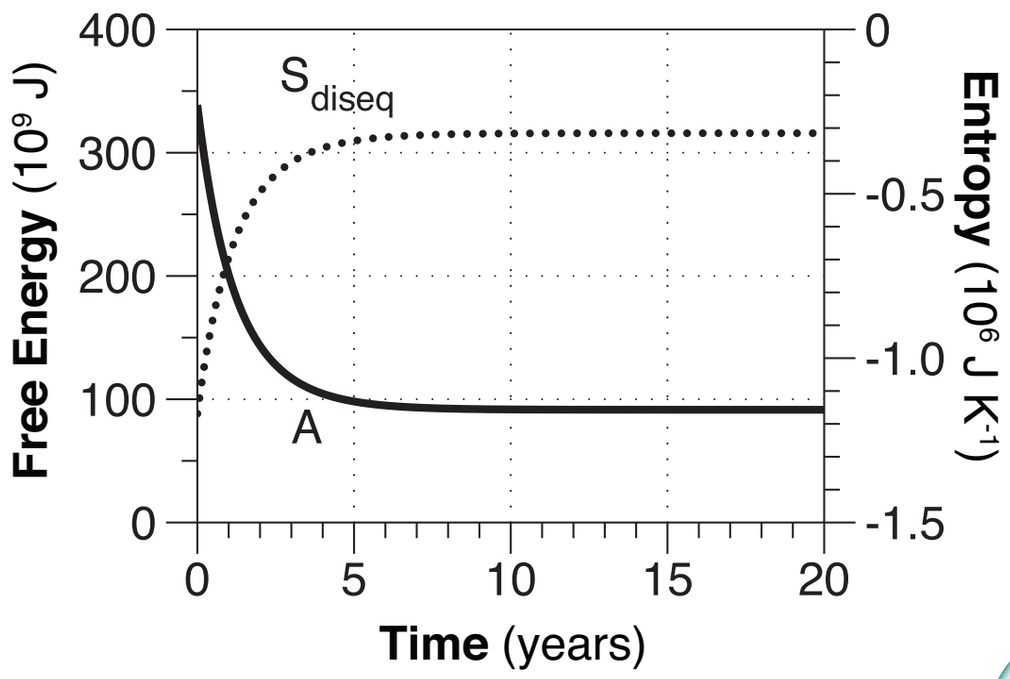
isolated system





non-isolated system





Kleidon (in prep.)

Maintaining Disequilibrium

external fluxes result in heating gradients

first law: $$\frac{dU}{dt} = \boxed{J_{net}} - (P - D)$$

second law: $$\frac{dS}{dt} = \sigma - NEE$$

Helmholtz free energy A:

$$\frac{dA}{dt} = P - T \cdot \frac{dS_{diseq}}{dt}$$

Maintaining Disequilibrium

first law:

$$\frac{dU}{dt} = \boxed{J_{net}} - \boxed{(P} - D)$$

second law:

$$\frac{dS}{dt} = \sigma - NEE$$

extraction of power from a heat gradient ...

Helmholtz free energy A:

$$\frac{dA}{dt} = \boxed{P} - T \cdot \frac{dS_{diseq}}{dt}$$

Maintaining Disequilibrium

first law: $$\frac{dU}{dt} = \boxed{J_{net}} - \boxed{(P} - D)$$

second law: $$\frac{dS}{dt} = \sigma - NEE$$

extraction of power from a heat gradient ...

Helmholtz free energy A:

$$\frac{dA}{dt} = \boxed{P} - T \cdot \frac{dS_{diseq}}{dt}$$

... generates free energy and disequilibrium

Maintaining Disequilibrium

first law: $$\frac{dU}{dt} = J_{net} - (P - D)$$

second law: $$\frac{dS}{dt} = \sigma - NEE$$

Helmholtz free energy A:

$$\frac{dA}{dt} = P - T \cdot \frac{dS_{diseq}}{dt}$$

thermodynamic gradients are dissipated…

Maintaining Disequilibrium

first law:

$$\frac{dU}{dt} = J_{net} - (P - D)$$

second law:

$$\frac{dS}{dt} = \sigma - NEE$$

… resulting in entropy production…

Helmholtz free energy A:

$$\frac{dA}{dt} = P - T \cdot \frac{dS_{diseq}}{dt}$$

thermodynamic gradients are dissipated…

Maintaining Disequilibrium

first law:

$$\frac{dU}{dt} = J_{net} - (P - D)$$

… and dissipative heating

second law:

$$\frac{dS}{dt} = \sigma - NEE$$

… resulting in entropy production…

Helmholtz free energy A:

$$\frac{dA}{dt} = P - T \cdot \frac{dS_{diseq}}{dt}$$

thermodynamic gradients are dissipated…

Maintaining Disequilibrium

first law: $$\frac{dU}{dt} = J_{net} - (P - D)$$

second law: $$\frac{dS}{dt} = \sigma - NEE$$

entropy production …

Helmholtz free energy A:

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Maintaining Disequilibrium

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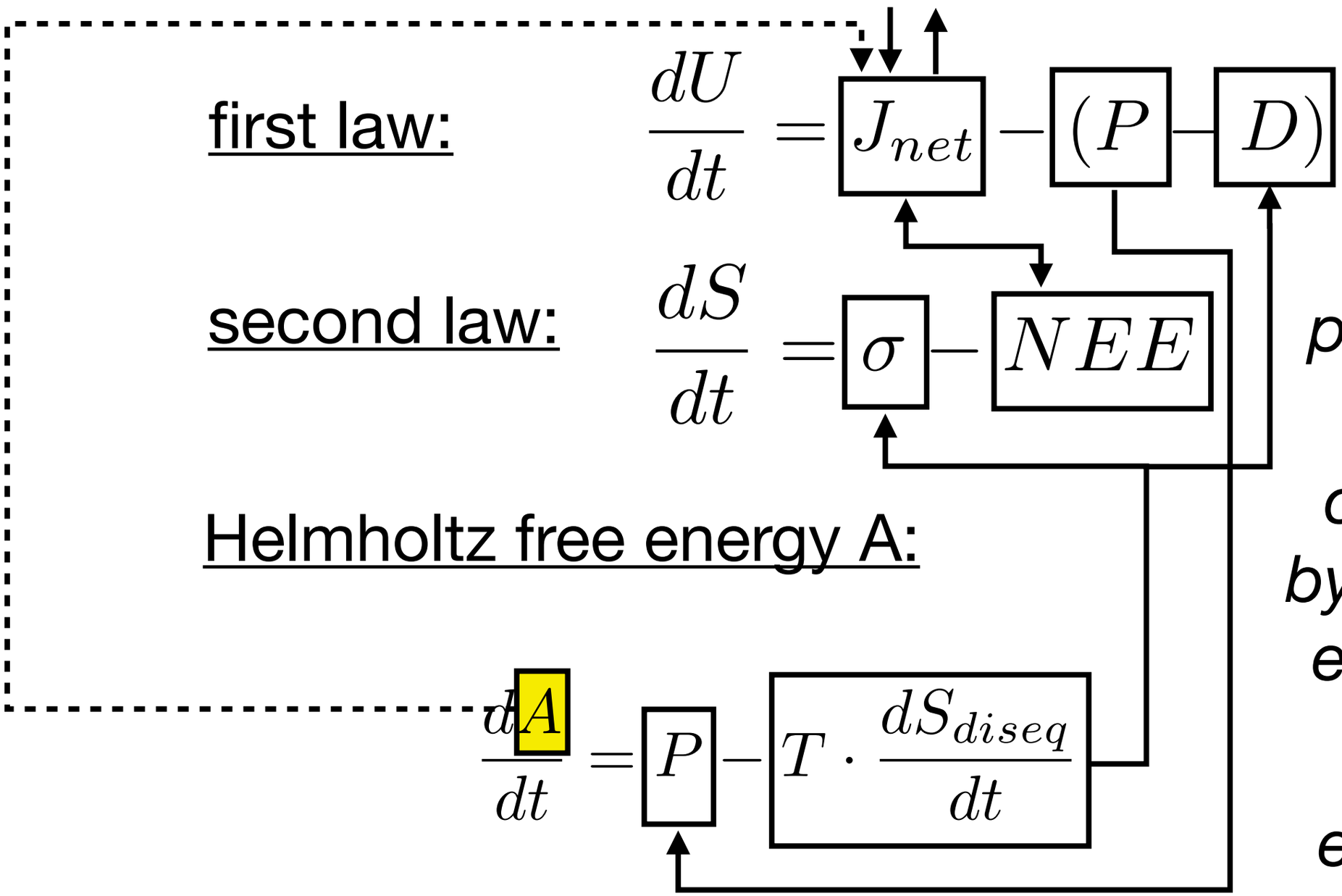
entropy production …

… is constrained by net entropy exchange …

Maintaining Disequilibrium



entropy production …

… is constrained by net entropy exchange …

… but free energy alters heat fluxes and NEE

Maintaining Disequilibrium

first law: $$\frac{dU}{dt} = J_{net} - (P - D)$$

second law: $$\frac{dS}{dt} = \sigma - NEE$$

Helmholtz free energy A:

$$\frac{dA}{dt} = P - T \cdot \frac{dS_{diseq}}{dt}$$

power

entropy production

disequilibrium

Limits to Power Generation and Transfer

first law: $$dU = dQ - dW$$

second law: $$dS = dQ/T \geq 0$$

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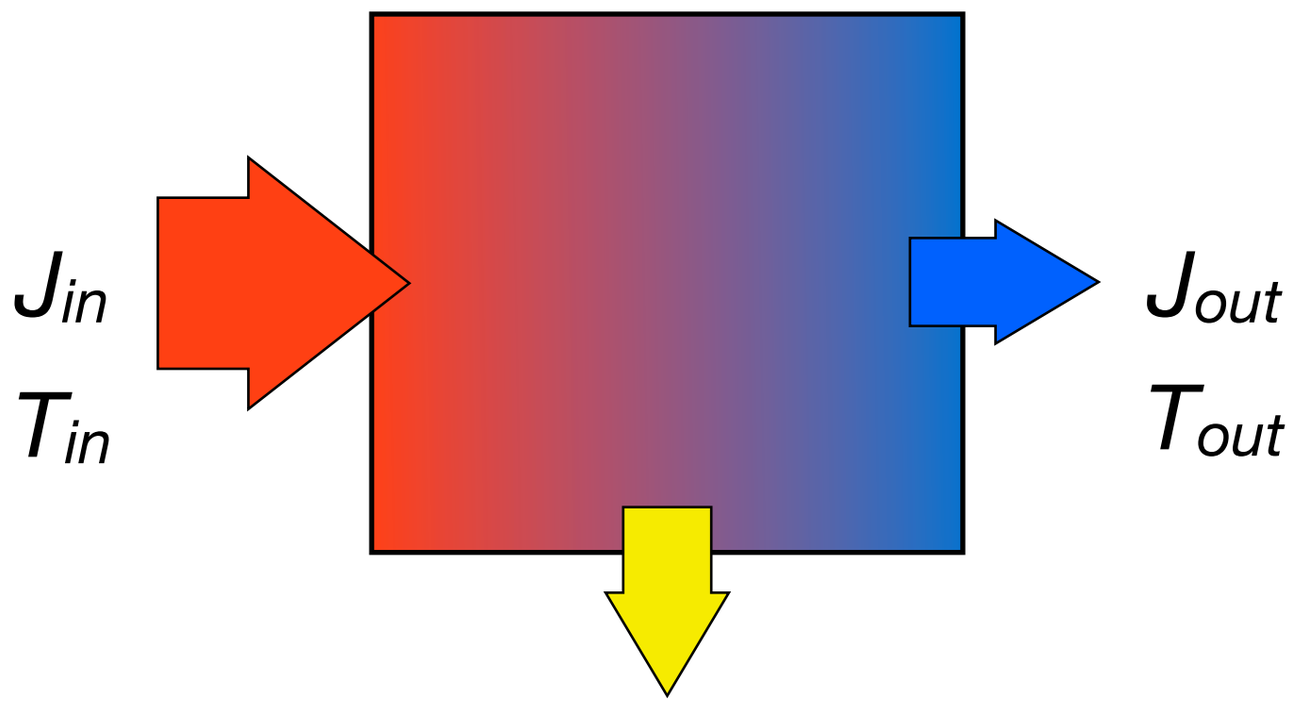
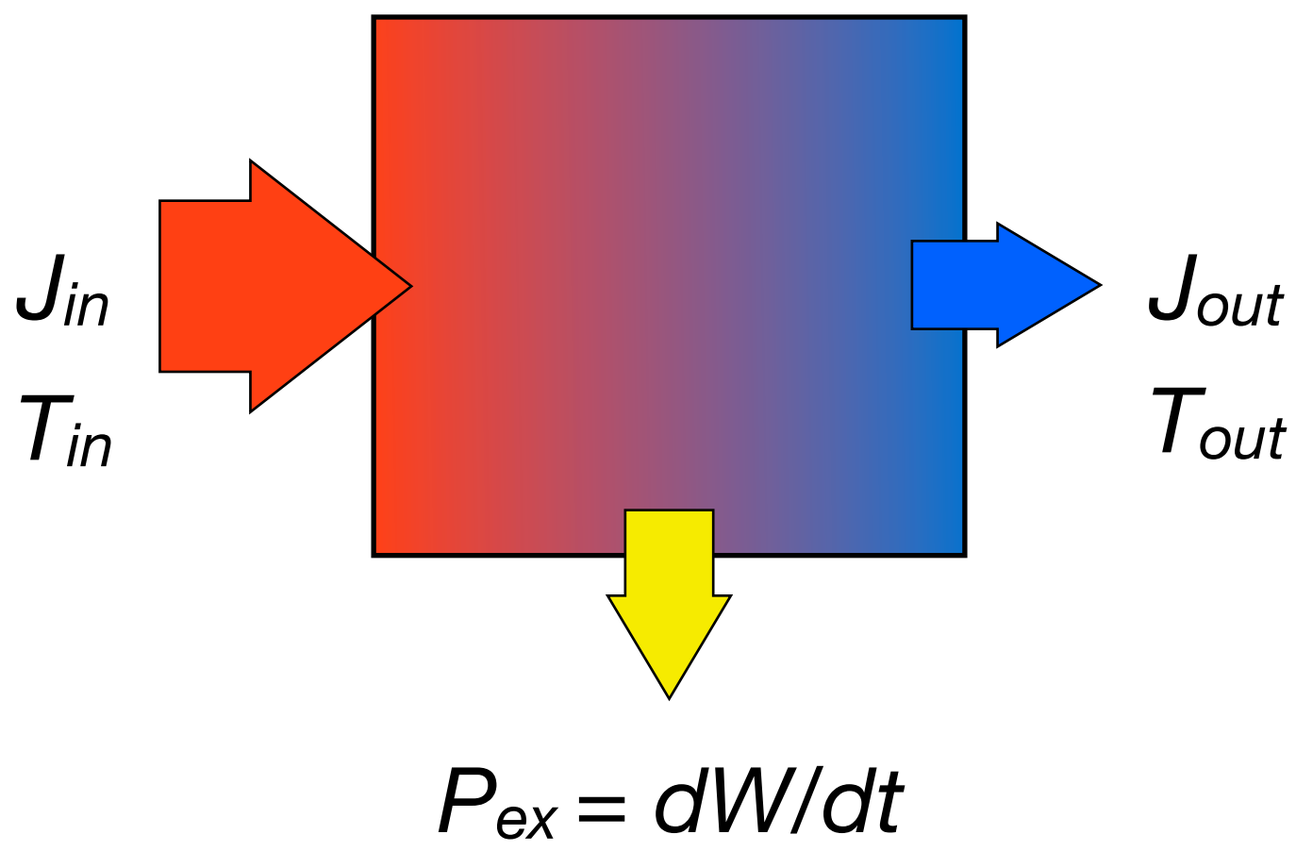


$$P_{ex} = dW/dt$$

Limits to Power Generation and Transfer

first law: $$J_{in} = J_{out} + P_{ex}$$

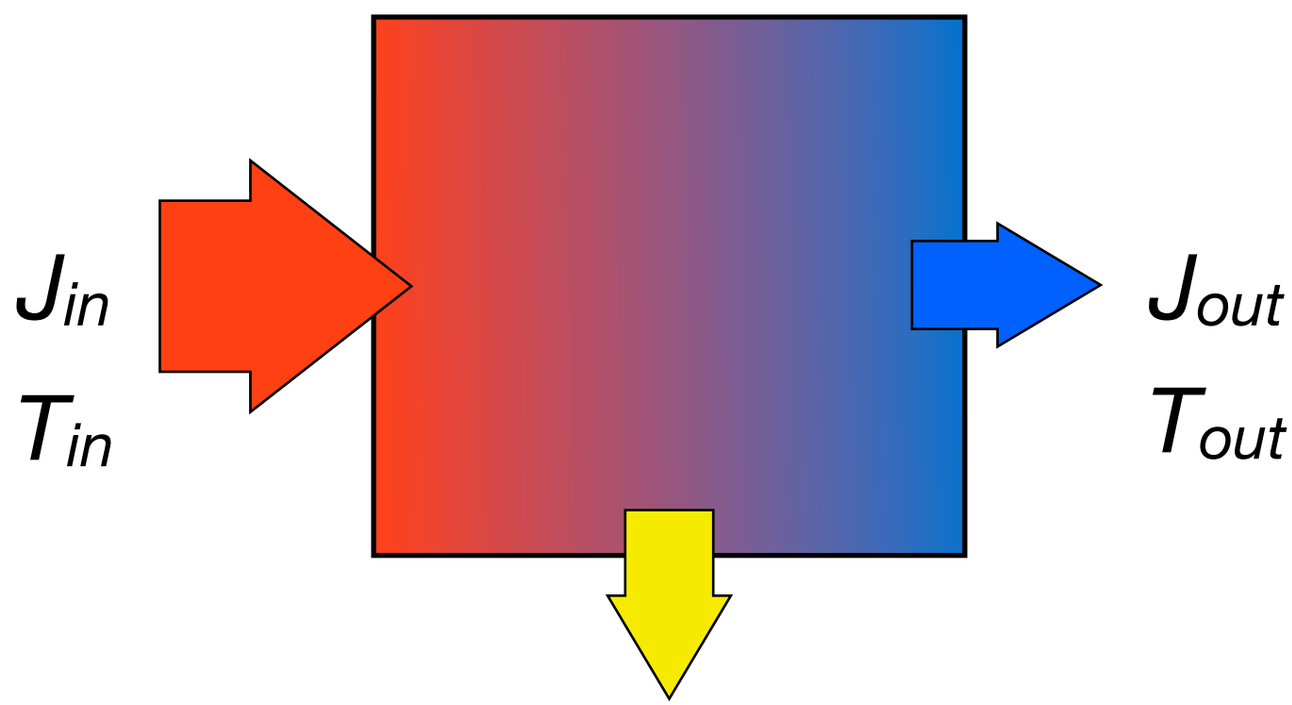
second law: $$dS = dQ/T \geq 0$$



Limits to Power Generation and Transfer

first law: $$J_{in} = J_{out} + P_{ex}$$

second law: $$\frac{J_{in} - P_{ex}}{T_{out}} - \frac{J_{in}}{T_{in}} \geq 0$$



$P_{ex} = dW/dt$

Limits to Power Generation and Transfer

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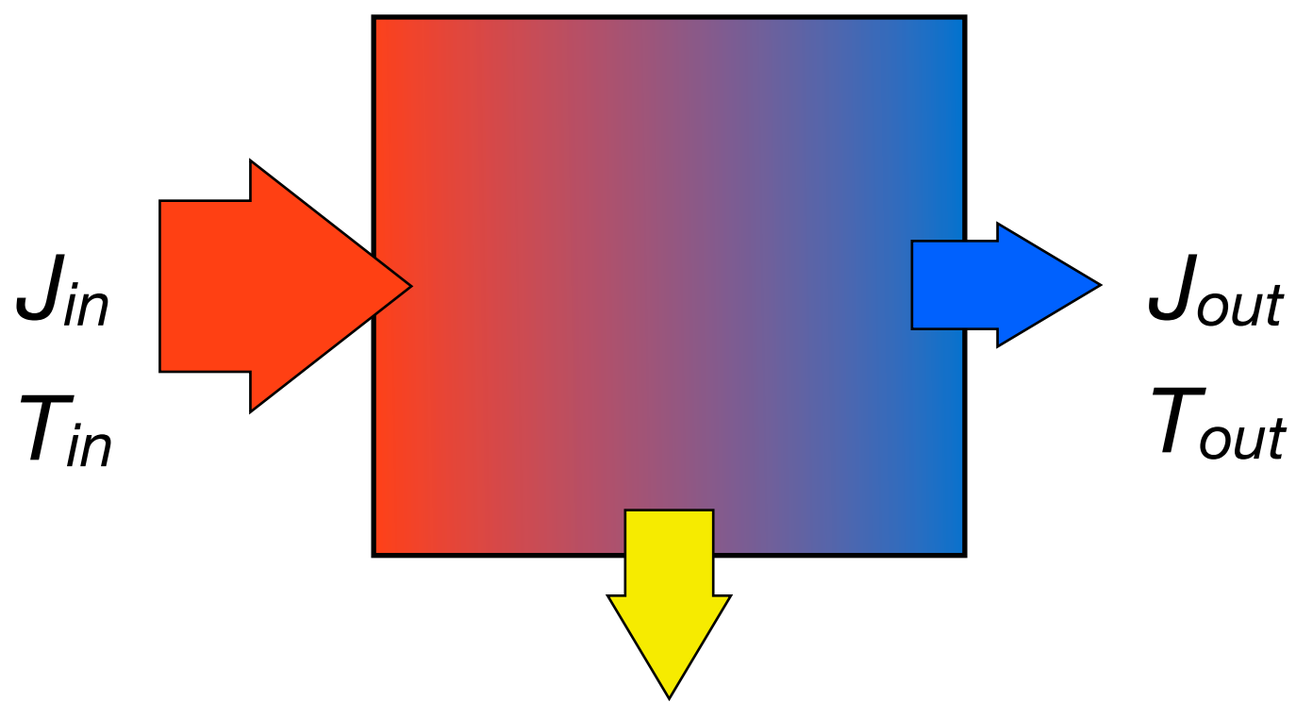
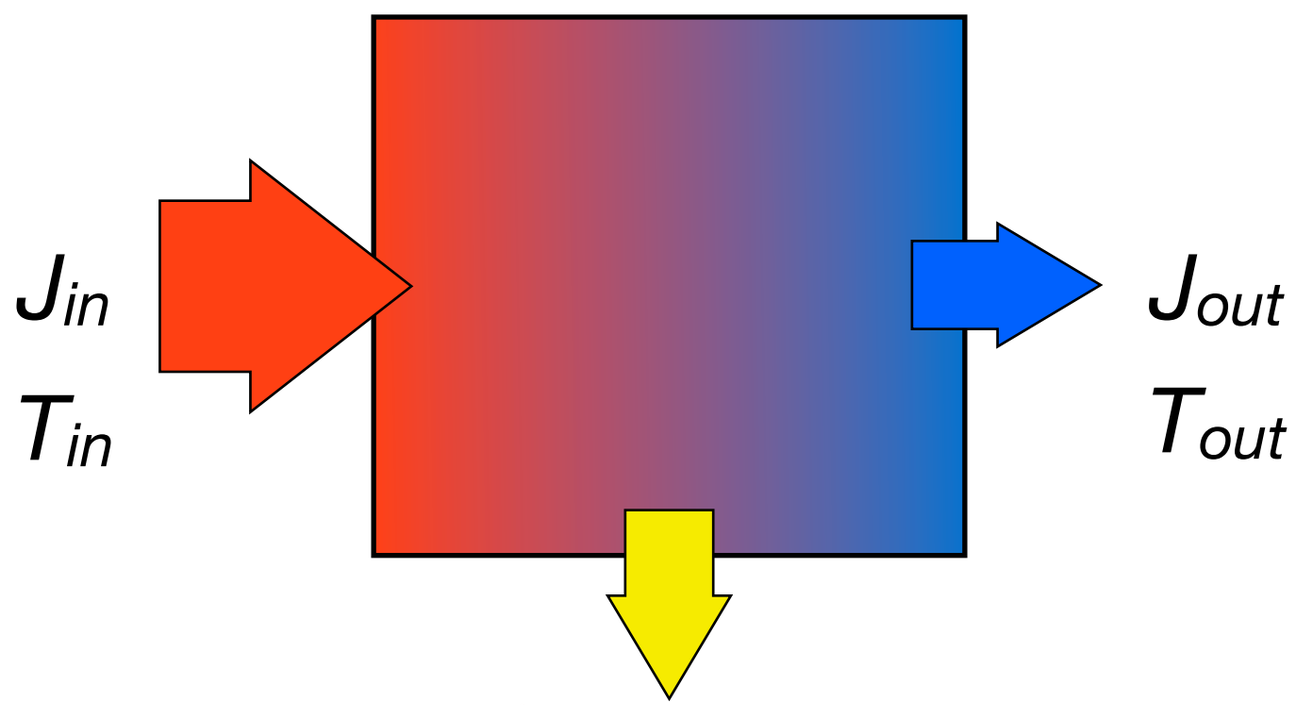


$$P_{ex} \leq J_{in} \cdot \frac{T_{in} - T_{out}}{T_{in}}$$ "Carnot limit"

Limits to Power Generation and Transfer

but in the Earth system…

1. temperature gradient responds to flux;
2. power extraction competes with other irreversible processes (radiative, diffusion)
3. free energy is dissipated in steady state



$$P_{ex} \leq J_{in} \cdot \cancel{\frac{T_{in} - T_{out}}{T_{in}}}$$

"Carnot limit"

Limits to Power Generation and Transfer

first law:

$$c \cdot \frac{dT_h}{dt} = J_{in,h} - J_{out,h} - J_{heat}$$

$$c \cdot \frac{dT_c}{dt} = J_{in,c} - J_{out,c} + J_{heat}$$

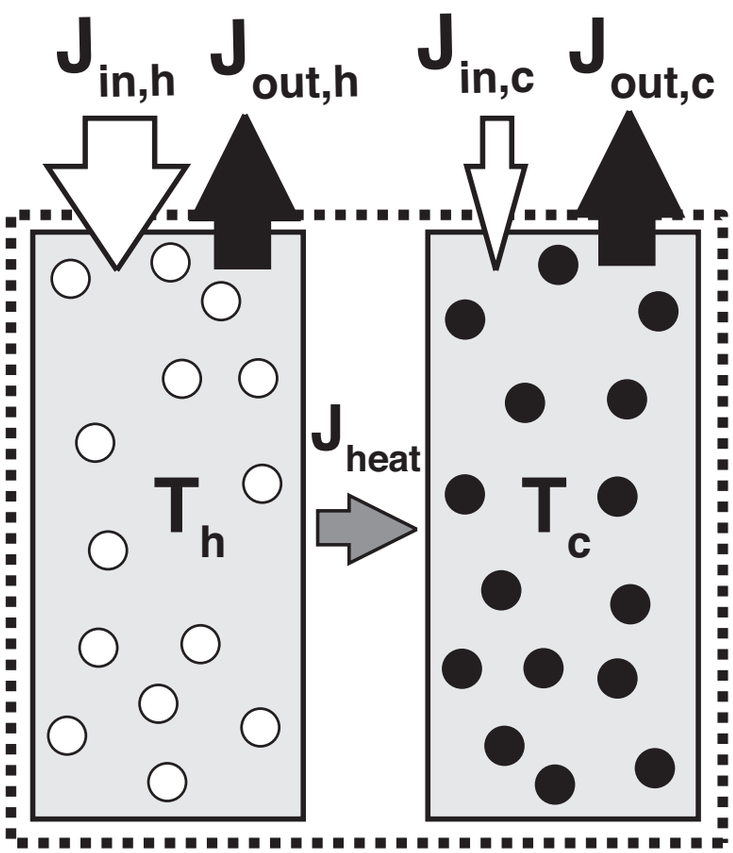
second law:

$$\frac{dS_{tot}}{dt} = \frac{dS_h}{dt} + \frac{dS_c}{dt} = \sigma_{mix,h} + \sigma_{mix,c} + \sigma_{heat} - NEE$$

$$\sigma_{heat} = J_{heat} \cdot \left(\frac{1}{T_c} - \frac{1}{T_h} \right)$$

$$\sigma_{heat} = J_{heat} \cdot \frac{T_h - T_c}{T_h T_c}$$

"2-box climate model"



Limits to Power Generation and Transfer

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$$c \cdot \frac{dT_c}{dt} = J_{in,c} - J_{out,c} + J_{heat}$$

$$T_h - T_c = (\Delta J_{in} - 2J_{heat})/k_b$$

second law:

$$\frac{dS_{tot}}{dt} = \frac{dS_h}{dt} + \frac{dS_c}{dt} = \sigma_{mix,h} + \sigma_{mix,c} + \sigma_{heat} - NEE$$

$$\sigma_{heat} = J_{heat} \cdot \left(\frac{1}{T_c} - \frac{1}{T_h}\right)$$

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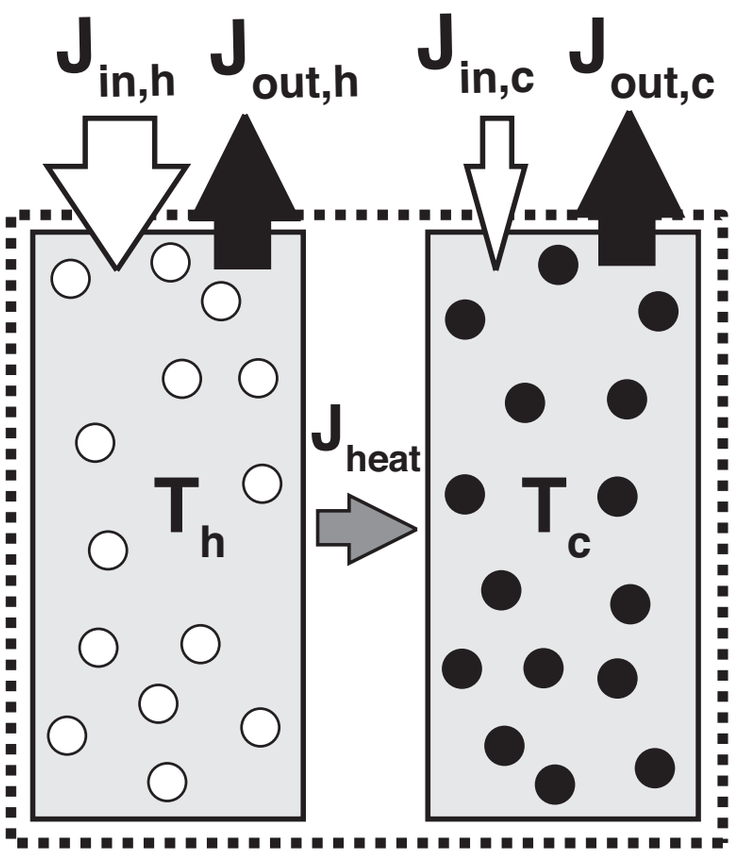
"2-box climate model"



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second law:

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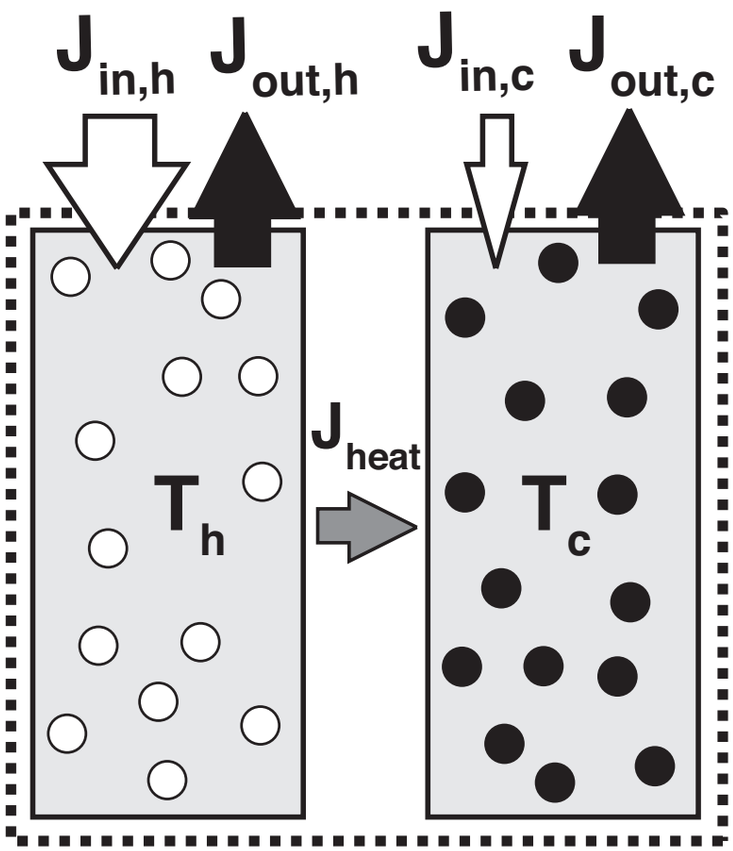
"2-box climate model"



$$\sigma_{heat} = J_{heat} \cdot \left(\frac{1}{T_c} - \frac{1}{T_h}\right)$$

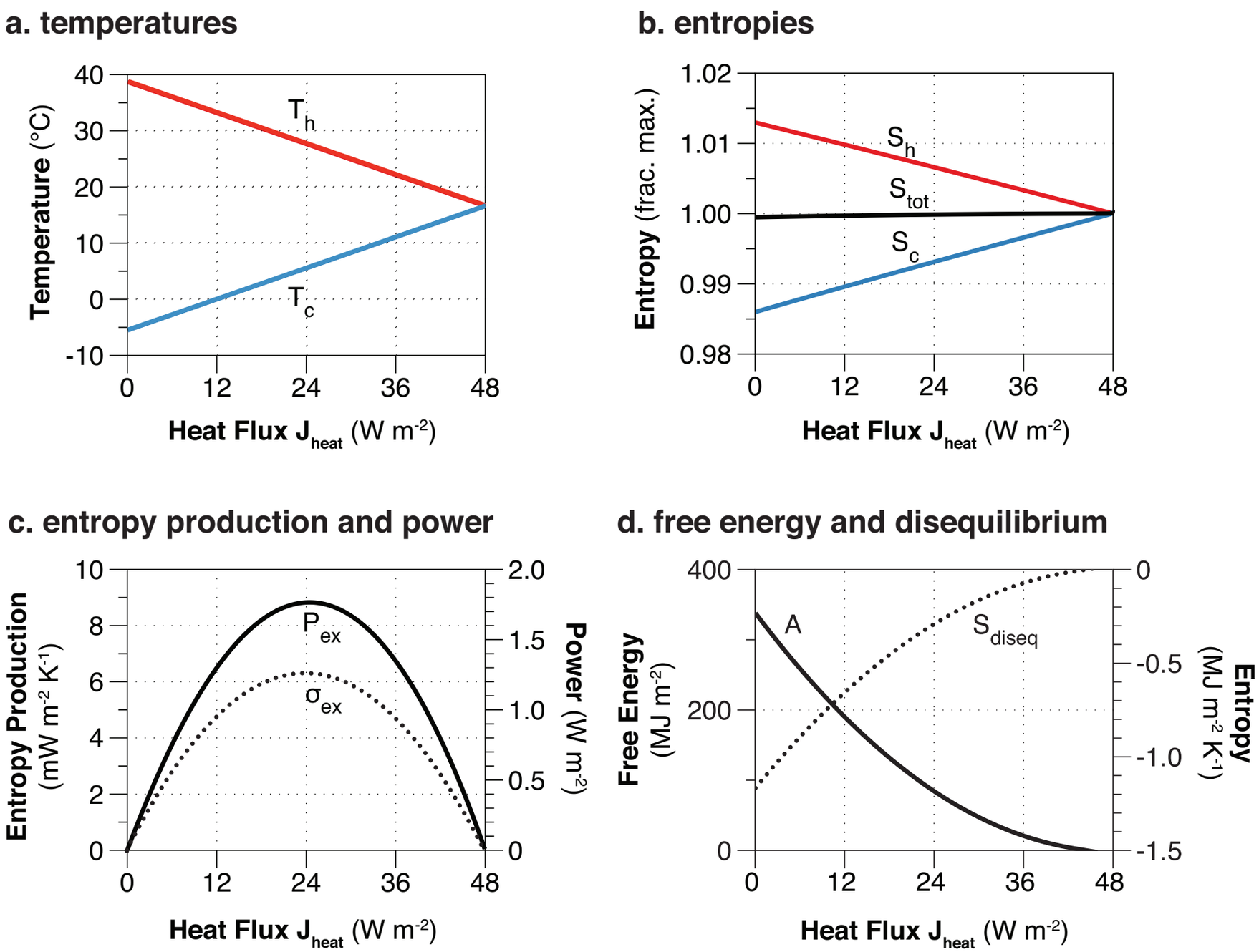
$$\sigma_{heat} = J_{heat} \cdot \frac{T_h - T_c}{T_h T_c}$$

$$P_{ex} = J_{heat} \cdot \frac{\Delta J_{in} - 2J_{heat}}{k_b \cdot T_h}$$

$$P_{ex} \leq \frac{\Delta J_{in}}{8} \cdot \frac{T_{h,0} - T_{c,0}}{T_{h,0}}$$

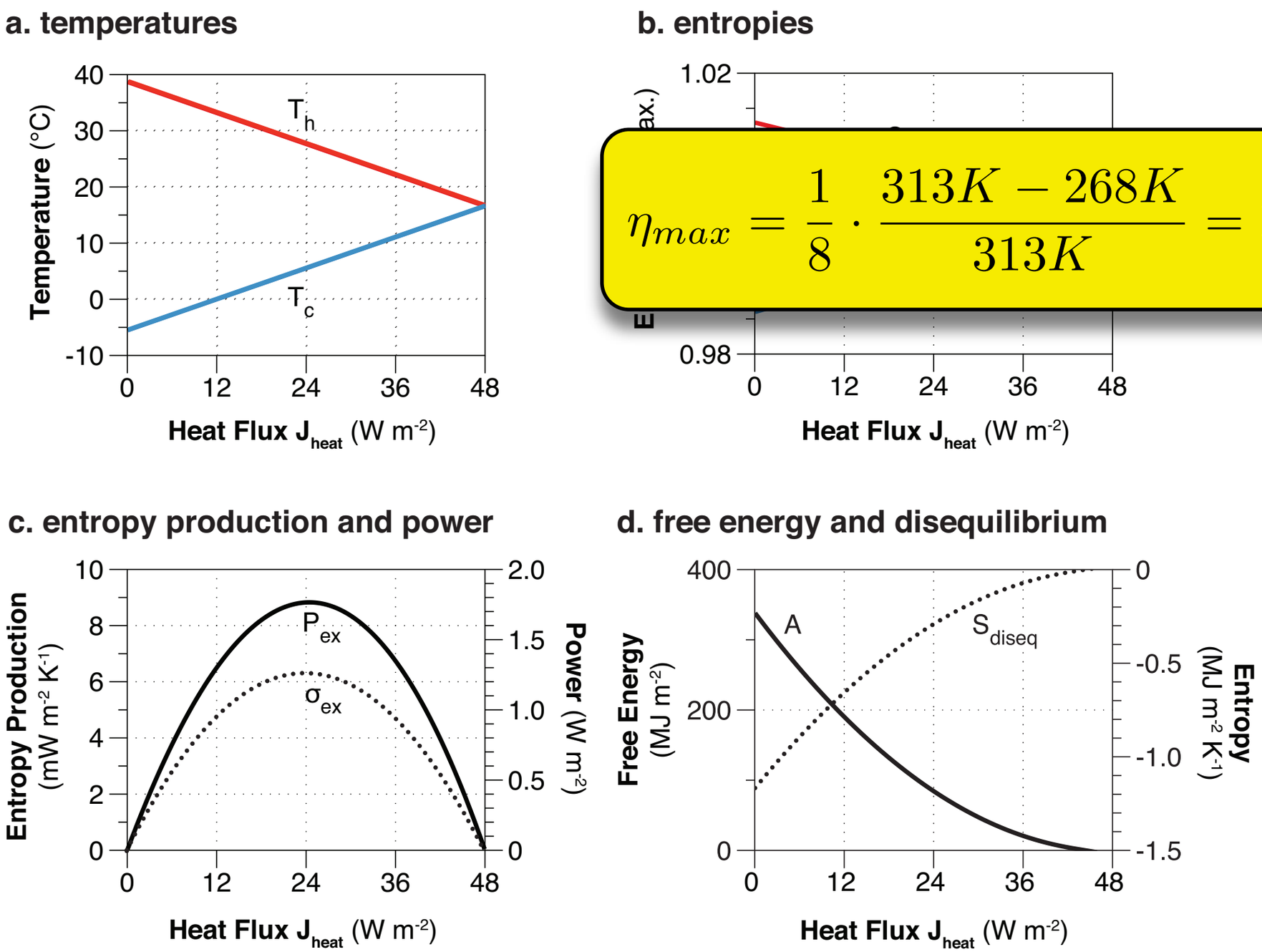
Limits to Power Generation and Transfer

sensitivity to J_{heat}



Limits to Power Generation and Transfer

sensitivity to J_{heat}

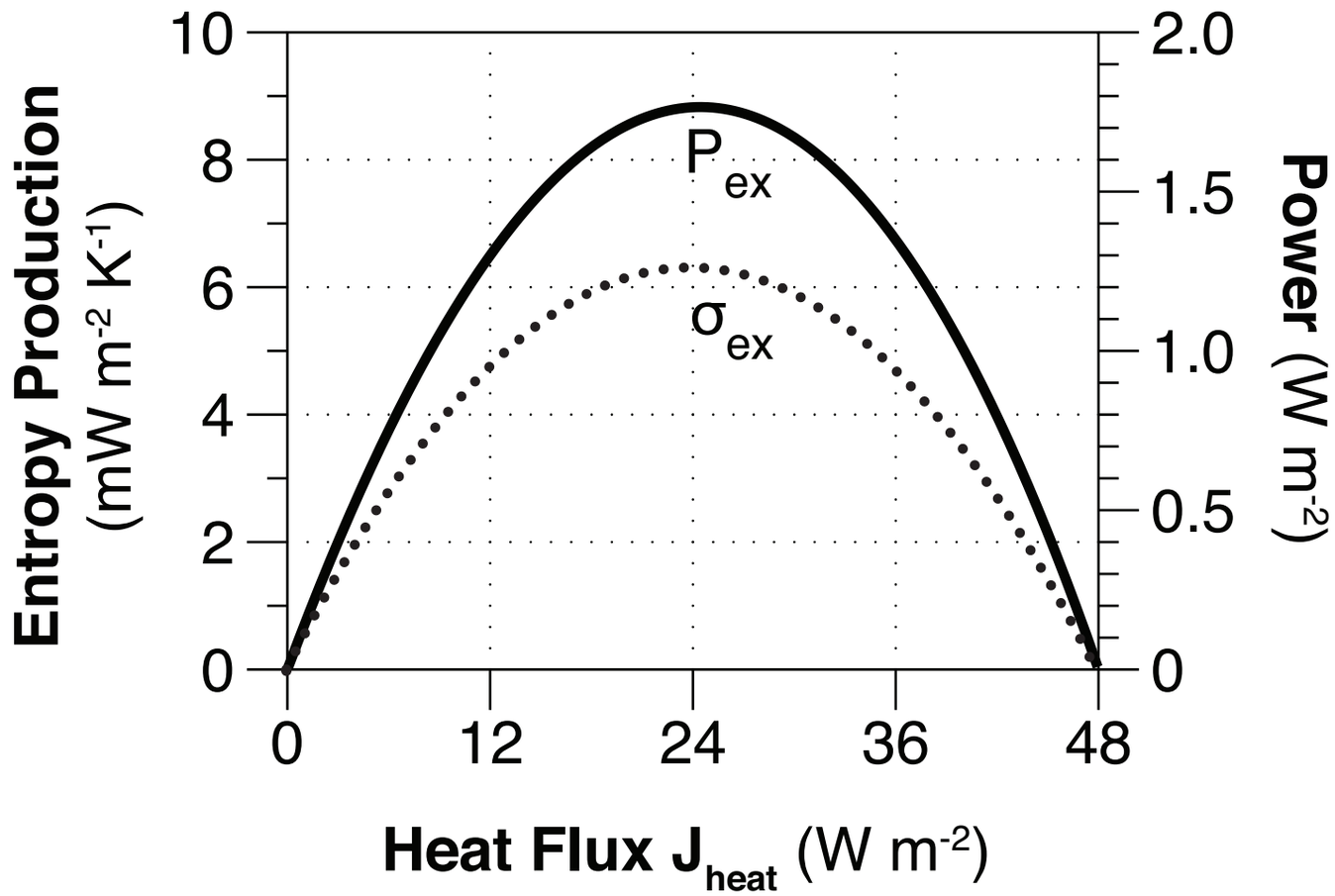


$$\eta_{max} = \frac{1}{8} \cdot \frac{313K - 268K}{313K} = 1.8\%$$

Kleidon (in prep.)

Limits to Power Generation and Transfer

entropy production and power



Limits to Power Generation and Transfer

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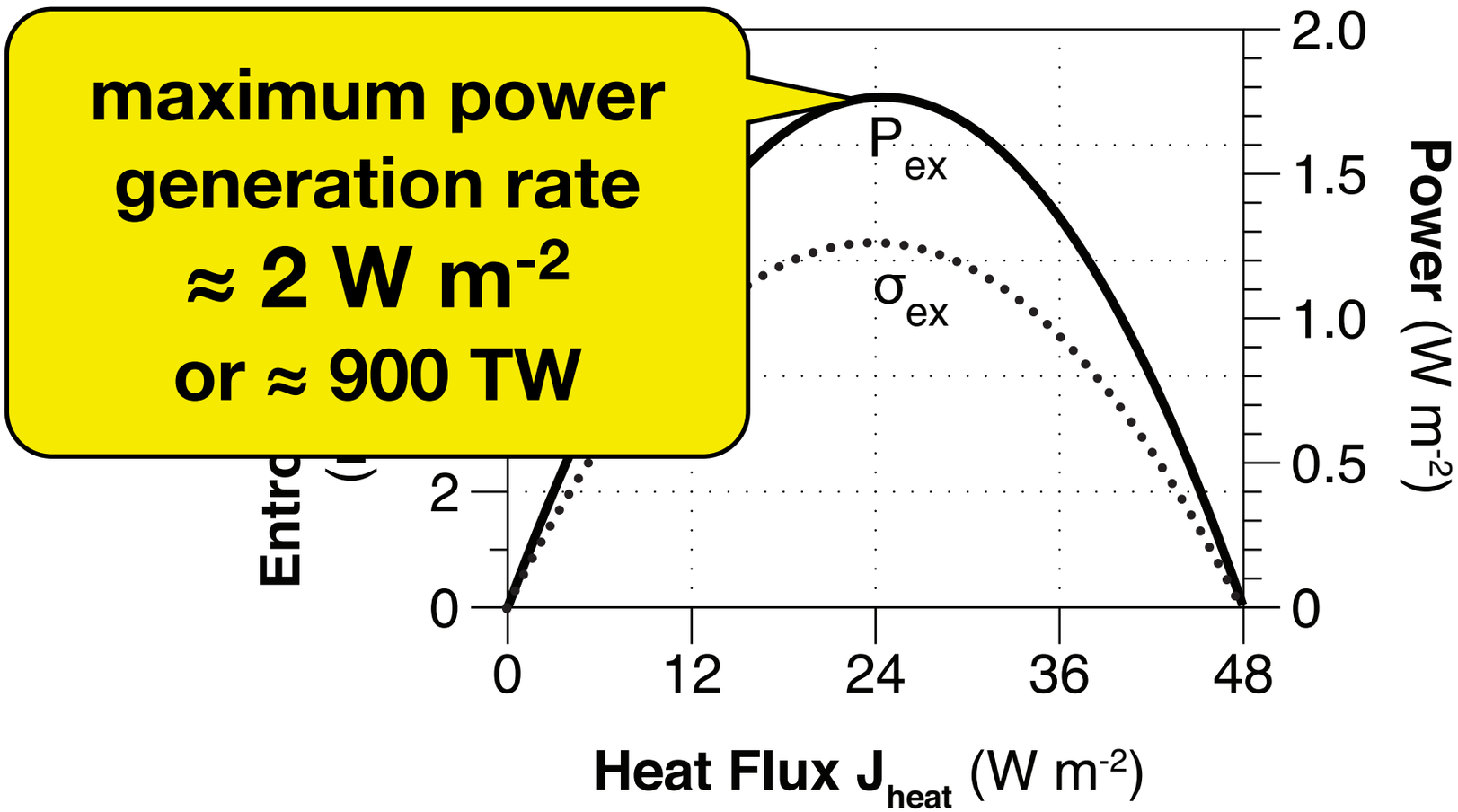

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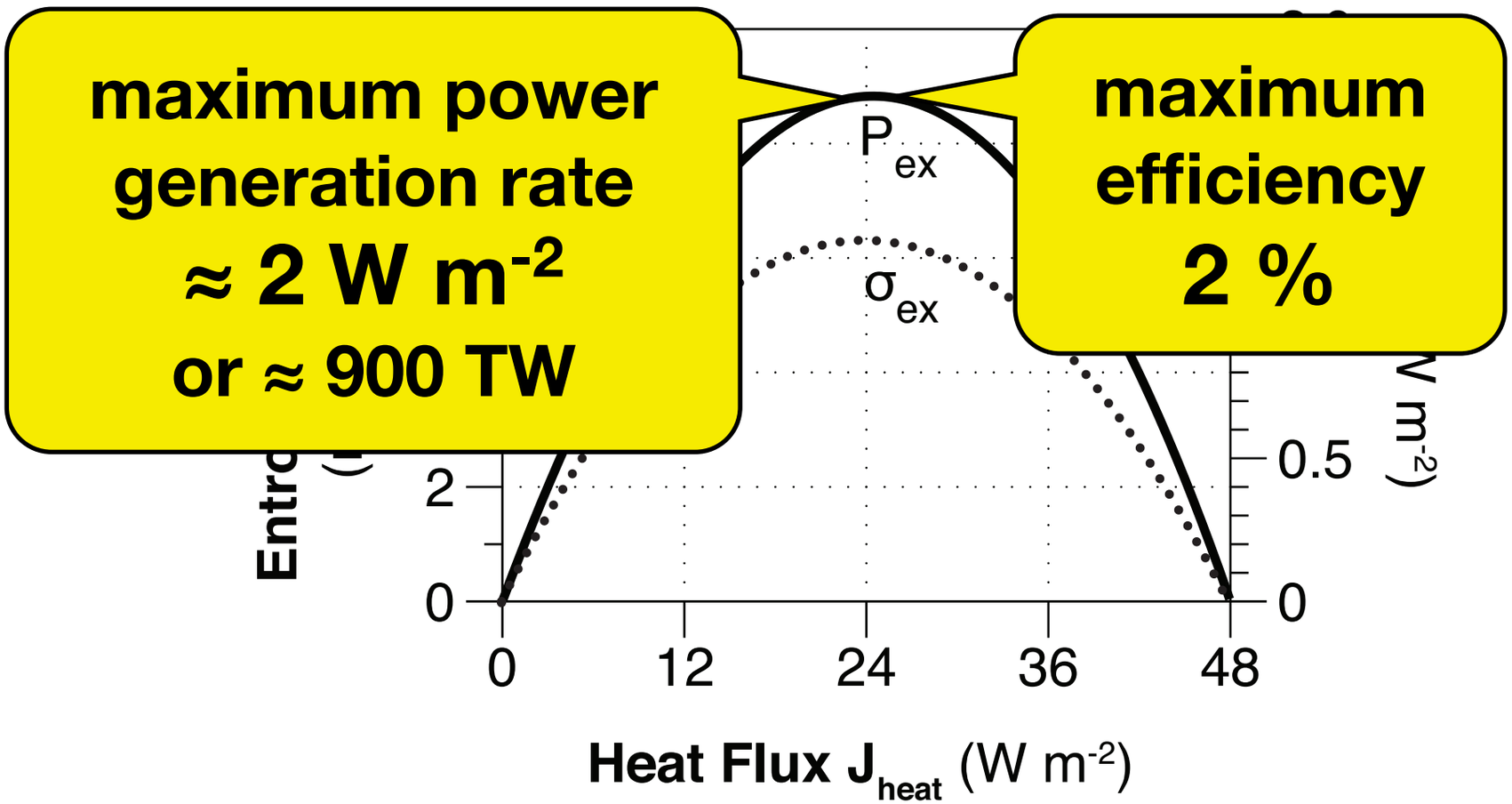

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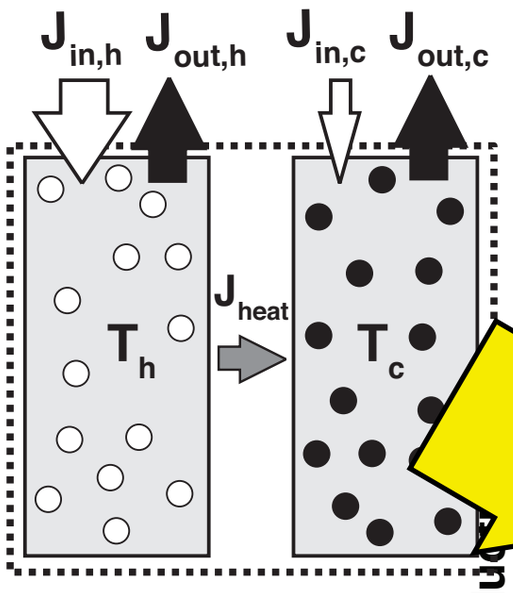
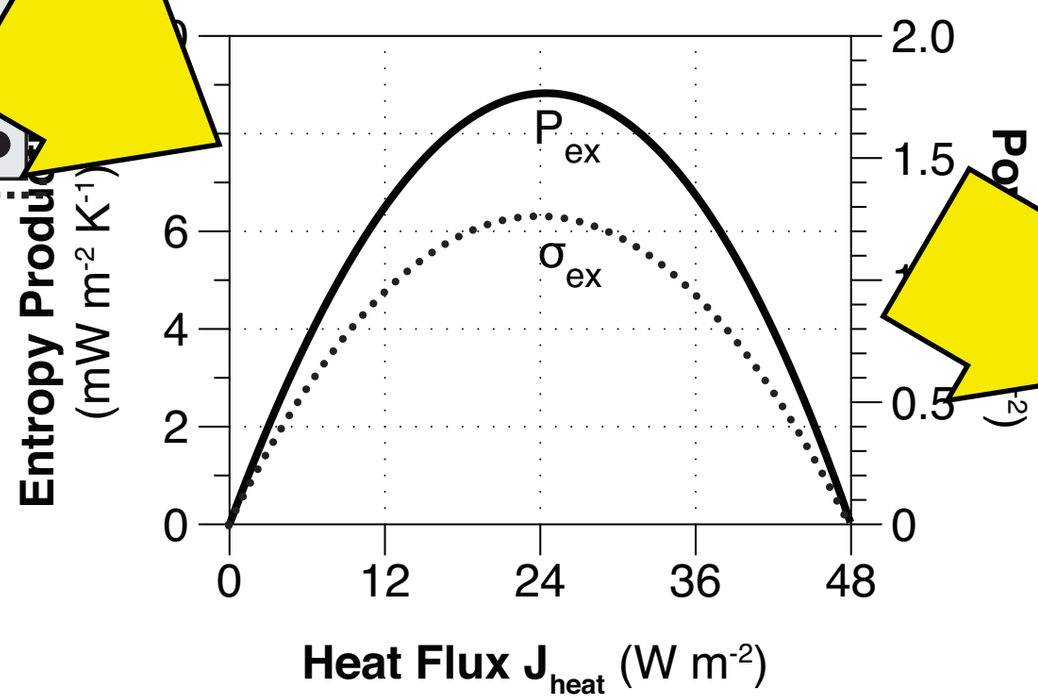


radiative forcing creates heating gradient



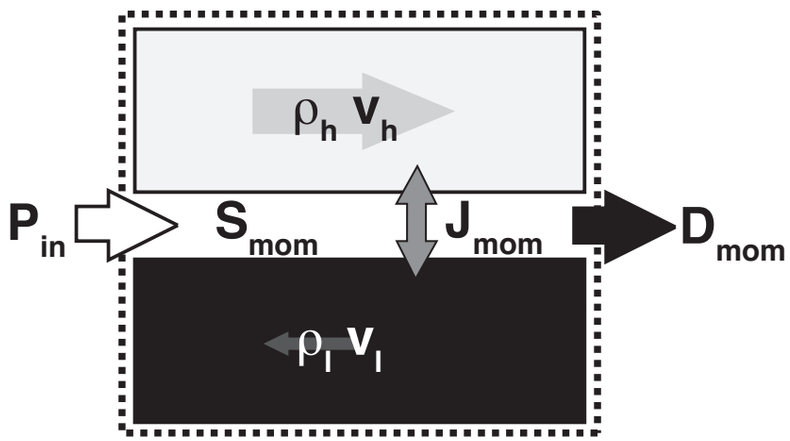
extracted power generate motion

motion transports heat

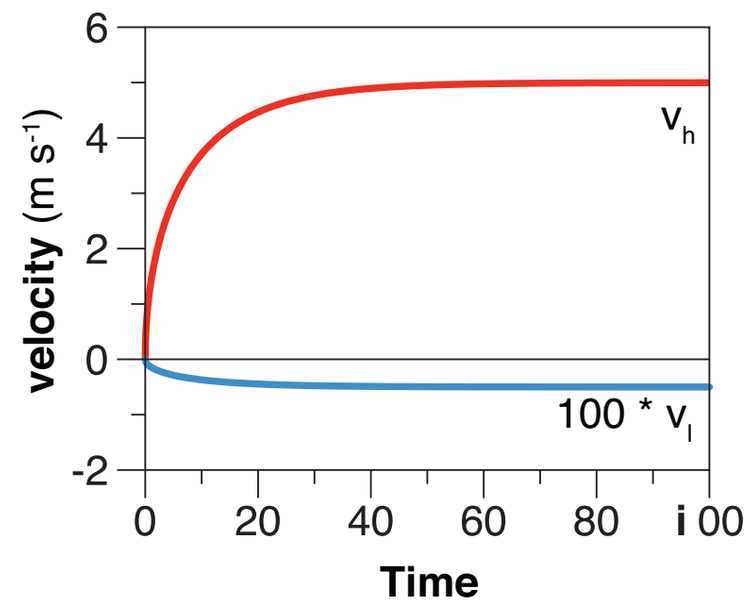
Limits to Power Generation and Transfer

momentum balance model

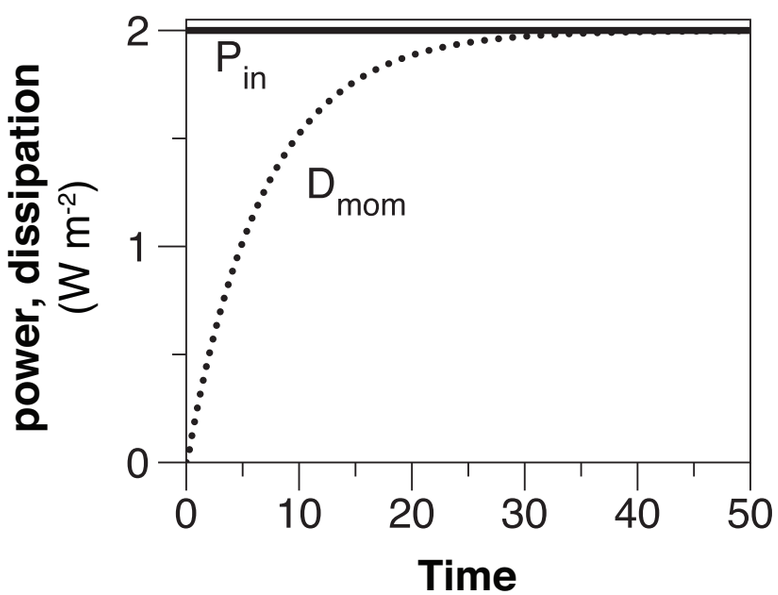
a. 2-box model



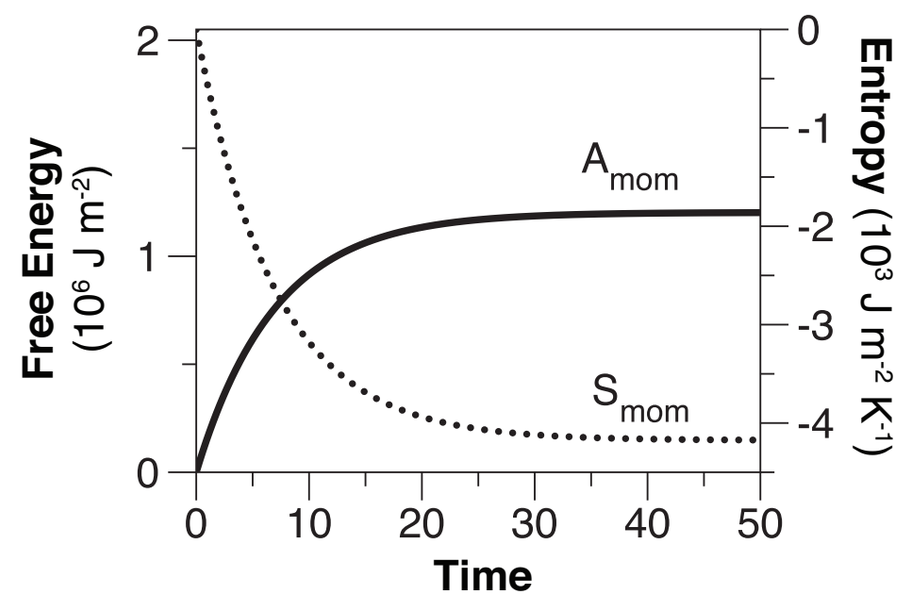
b. velocities



c. power, dissipation



d. free energy, disequilibrium

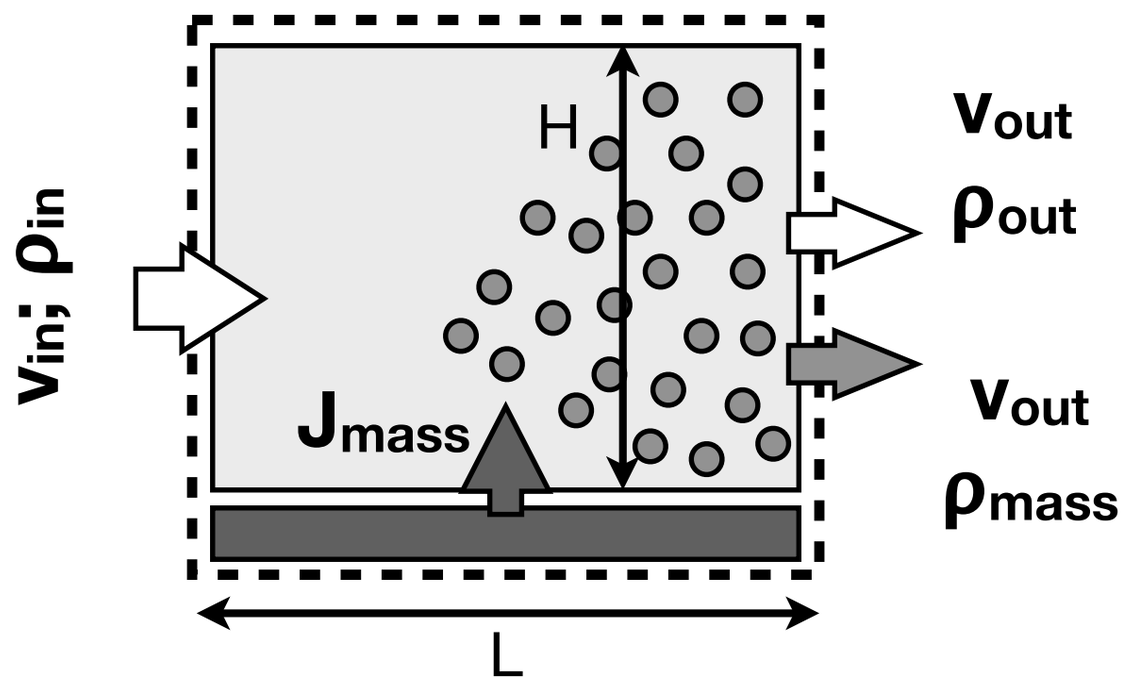


Kleidon (in prep.)

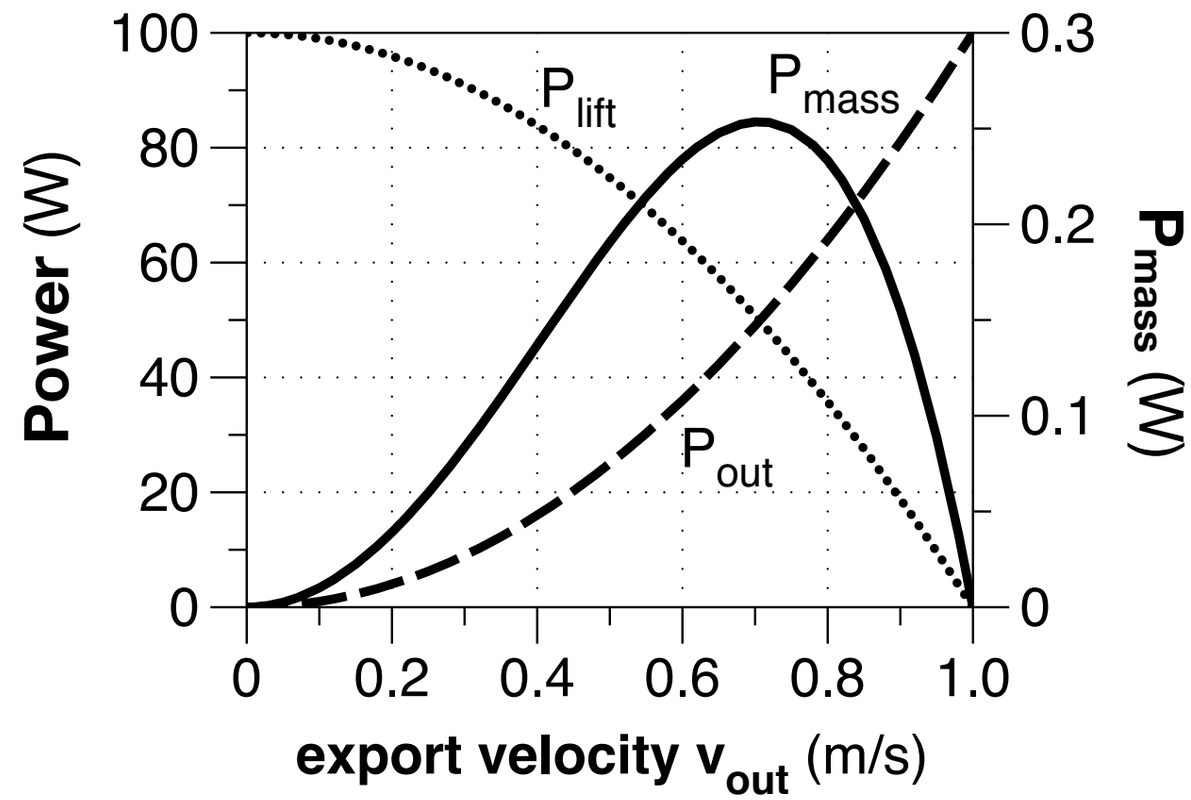
Limits to Power Generation and Transfer

motion can be used to power transport of suspended solids

a. box-model

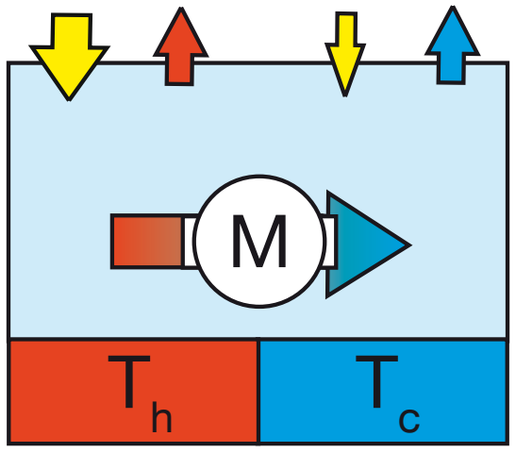


b. power

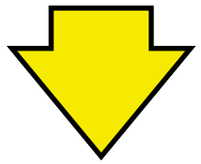


Limits to Power Generation and Transfer

heat engine:
large scale circulation driven by differential radiative heating between tropics and poles



radiative gradient



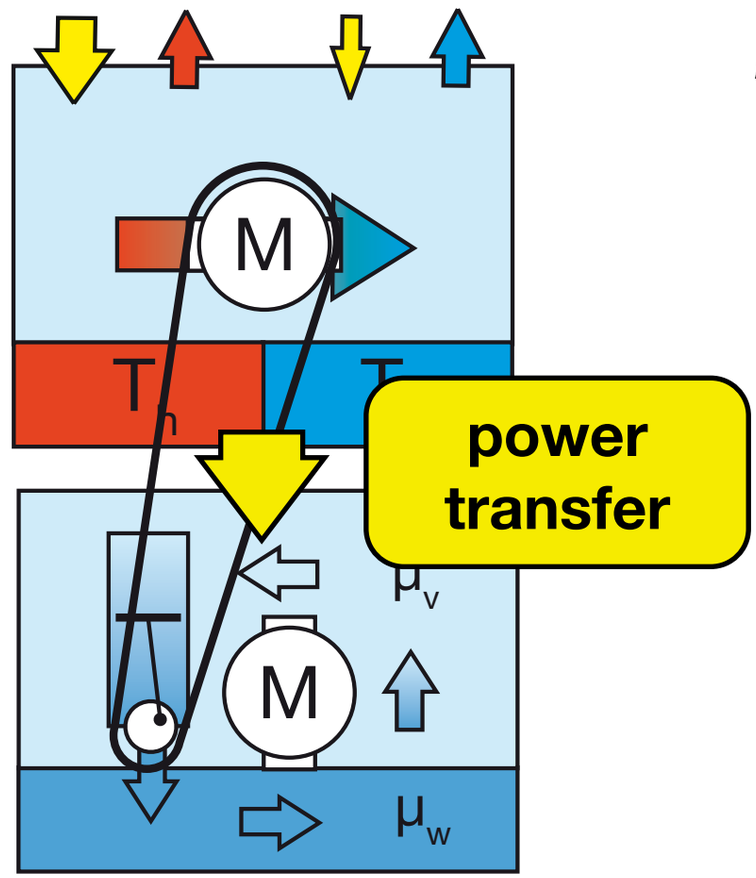
maximum power

motion

Limits to Power Generation and Transfer

heat engine:
large scale circulation driven by differential radiative heating between tropics and poles

dehumidifier:
circulation acts to dehumidify the atmosphere and runs the water cycle



radiative gradient

motion

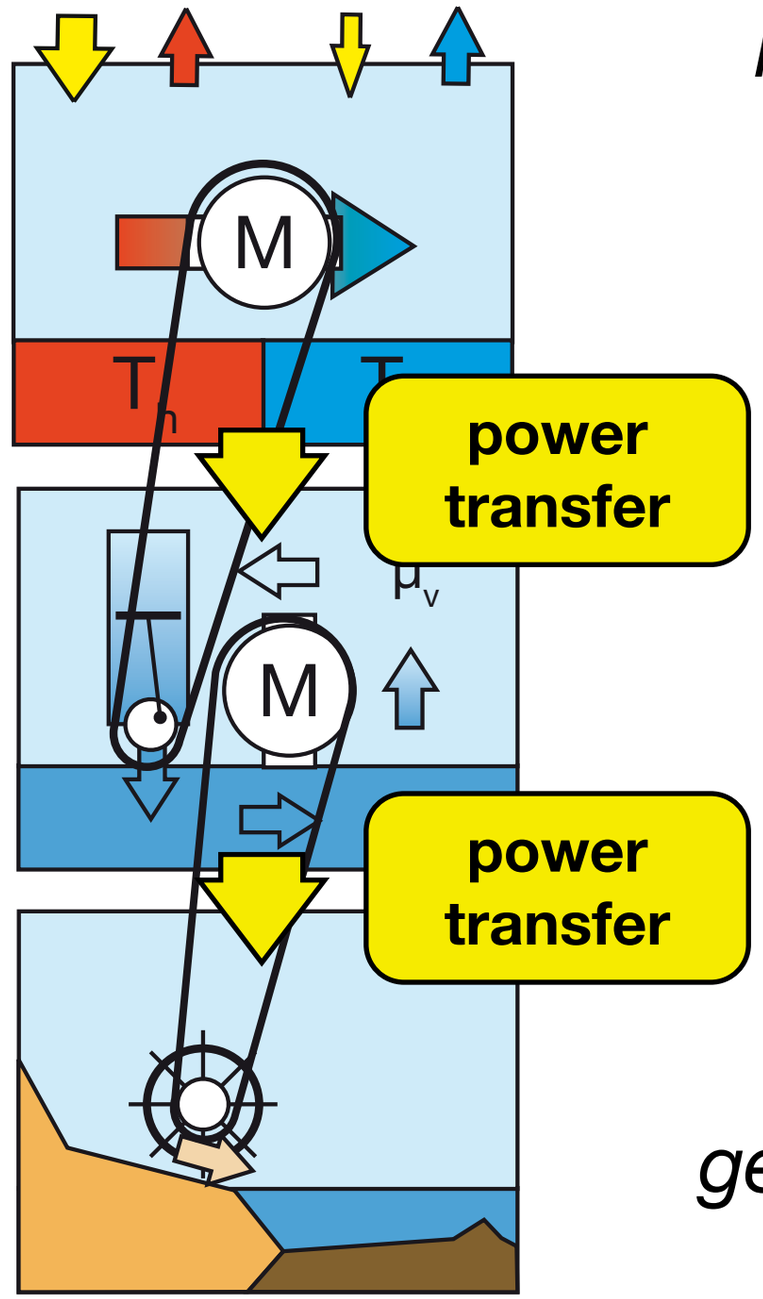
water cycling

Limits to Power Generation and Transfer

heat engine:
large scale circulation driven by differential radiative heating between tropics and poles

dehumidifier:
circulation acts to dehumidify the atmosphere and runs the water cycle

transporter:
water cycle runs the cycling of rocks (dissolution, suspension)



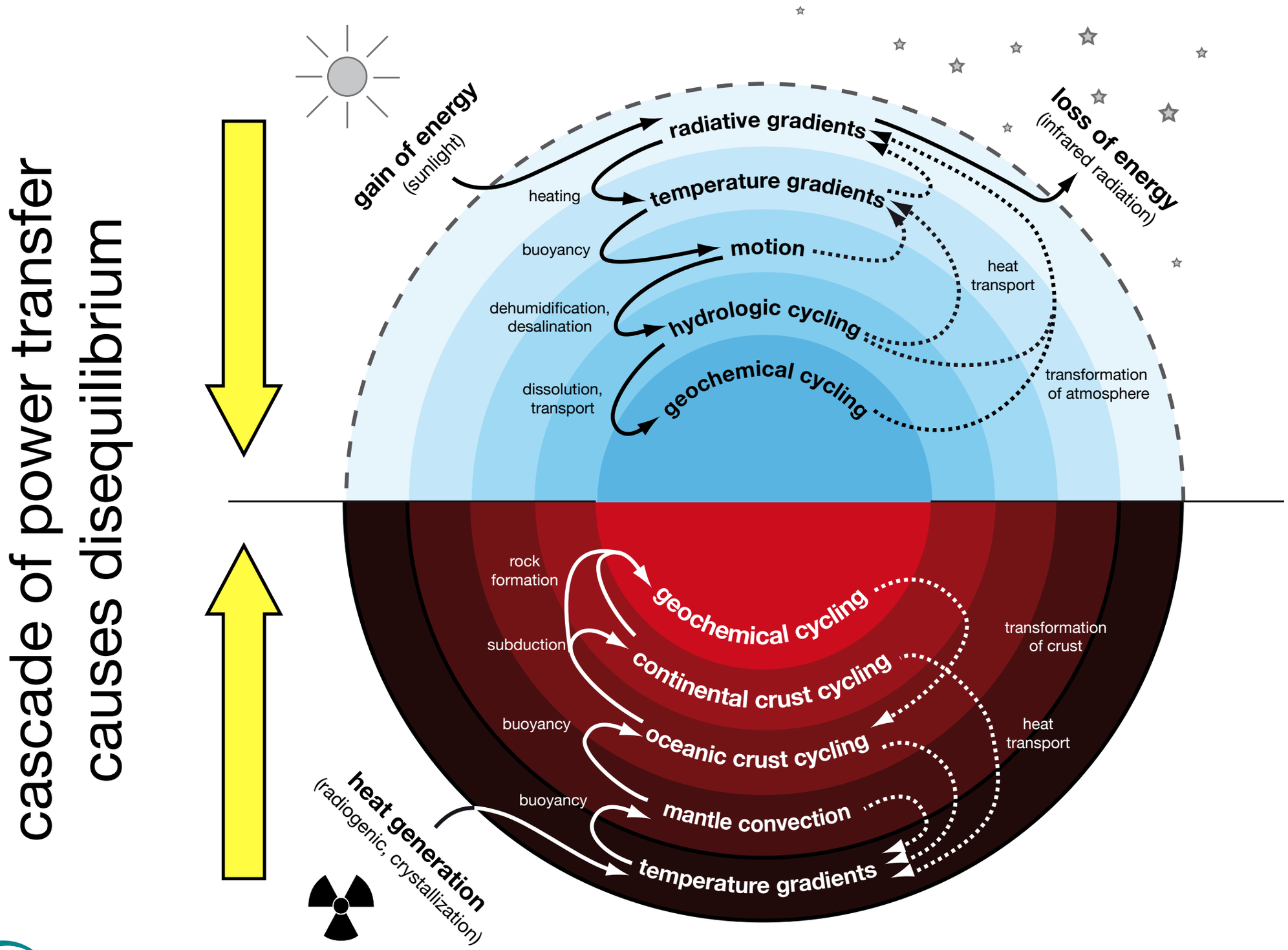
radiative gradient

motion

water cycling

geochemical cycling

Power Generation within the Earth System



MPI-BGC Jena

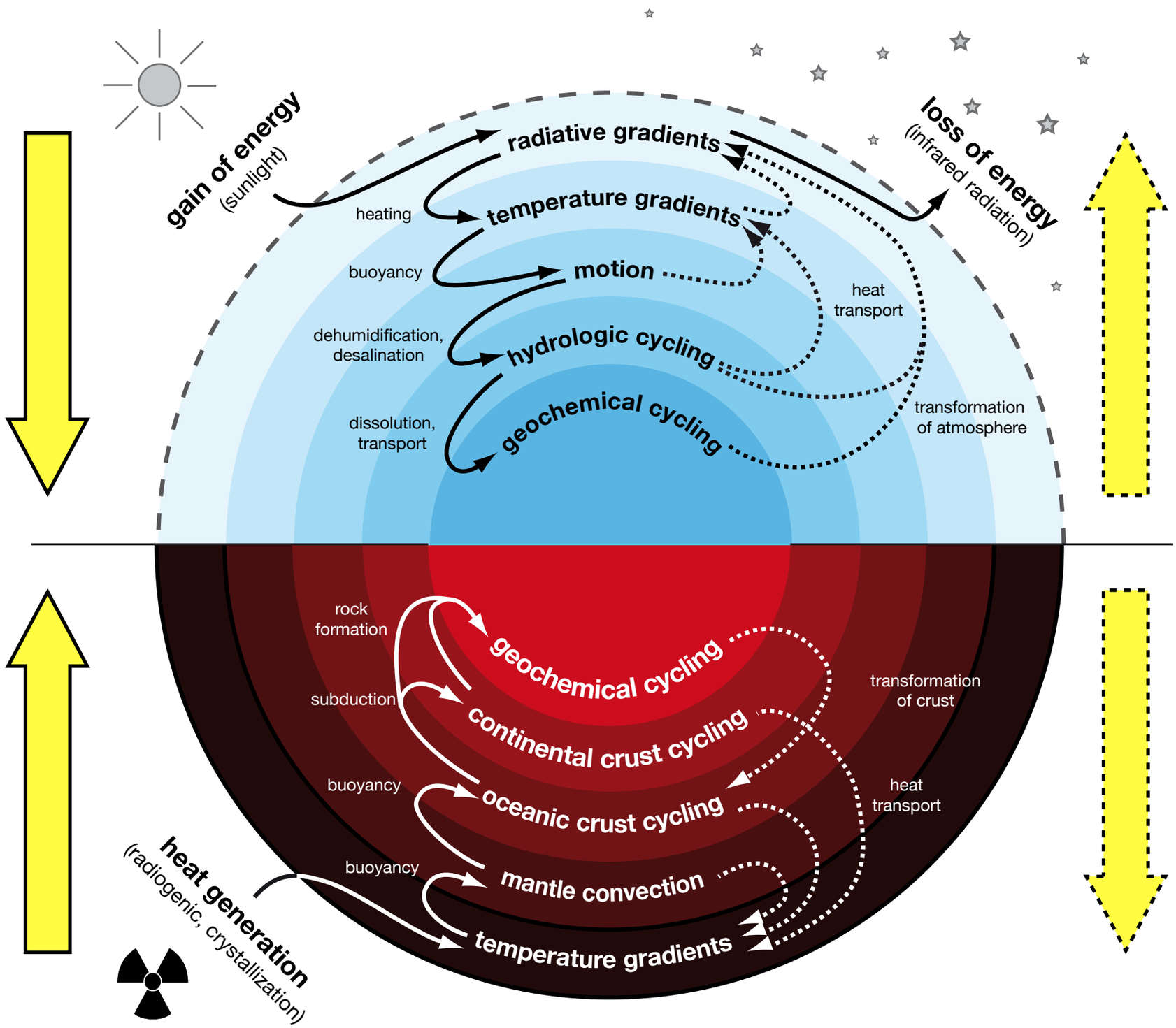
Kleidon (in prep.)

http://gaia.mpg.de

BIOSPHERIC THEORY AND MODELLING

Power Generation within the Earth System

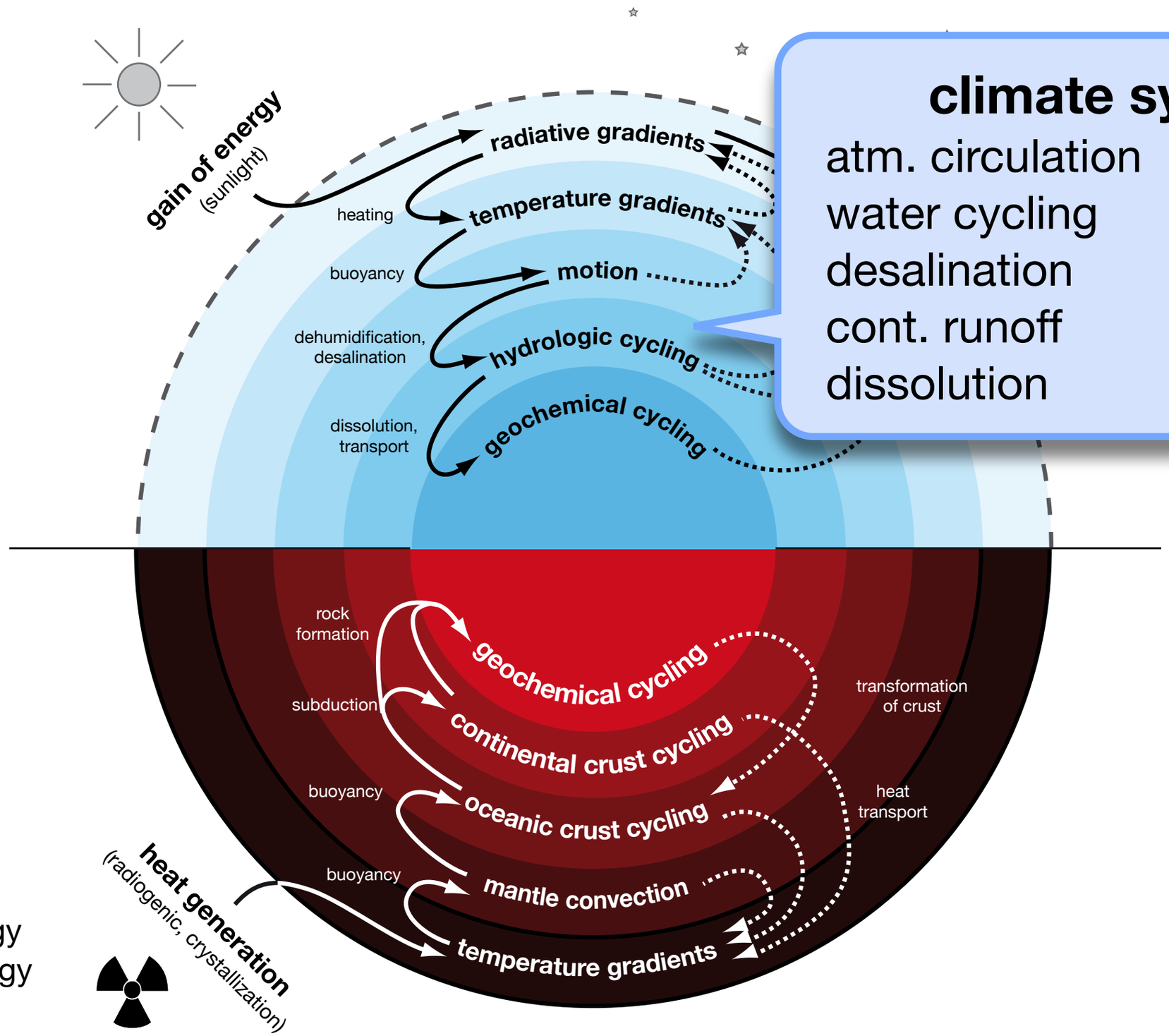
cascade of power transfer
causes disequilibrium



cascade of effects cause
interactions and feedbacks

Power Generation within the Earth System

1 W/m^2
≈ 510 TW



climate system:

atm. circulation	900 TW	(KE)
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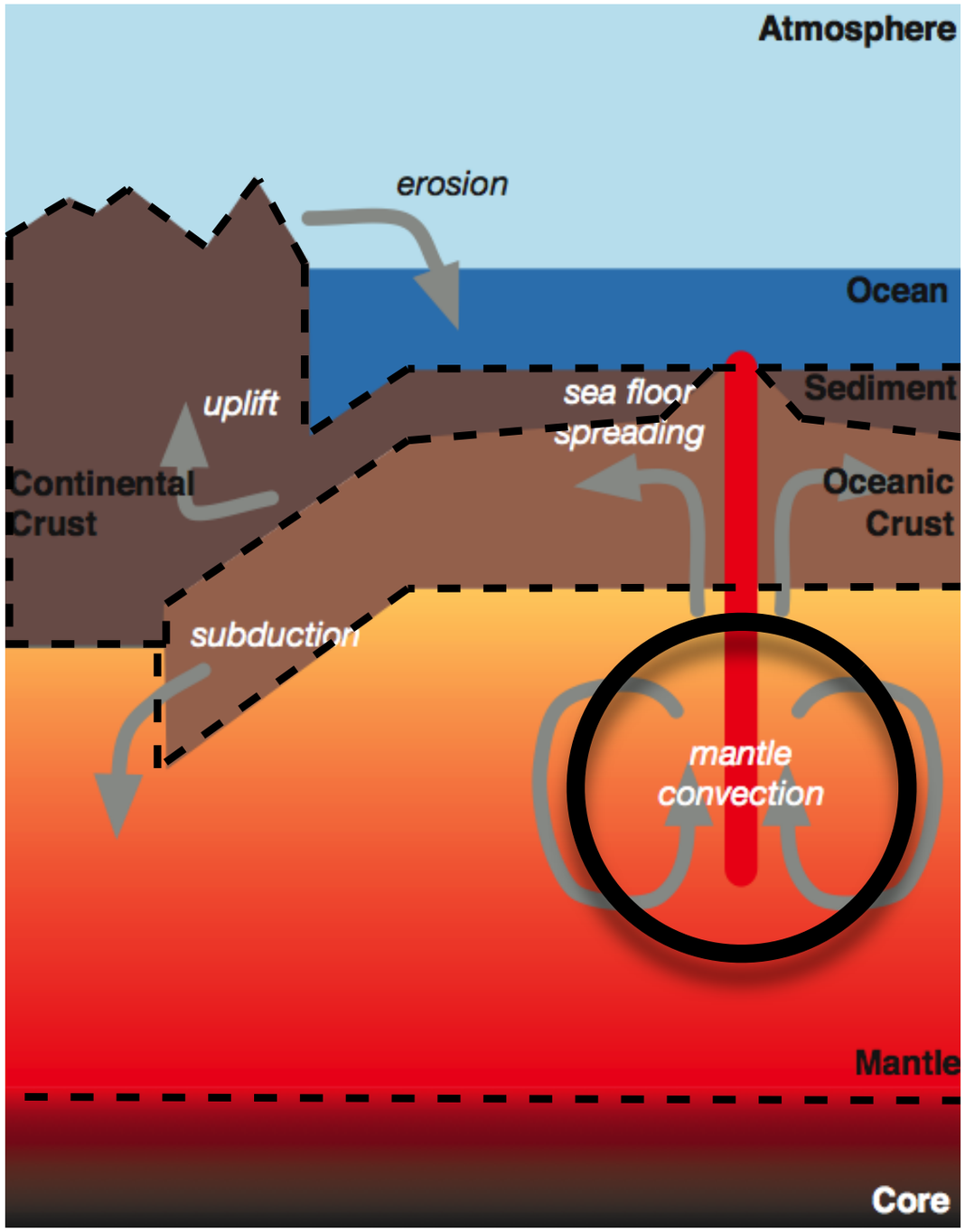
Power Generation within the Earth System



energy balance:

$$\Phi_{\mathrm{h}} = -\frac{2k_m N}{r}\frac{\partial T_{\mathrm{m}}}{\partial r} - k_m N \frac{\partial^2 T_{\mathrm{m}}}{\partial r^2}$$

analytical solution:

$$T_{\mathrm{m}}(r) = T_{\mathrm{core}} - \frac{\Phi_{\mathrm{h}}}{6k_m N} r^2$$

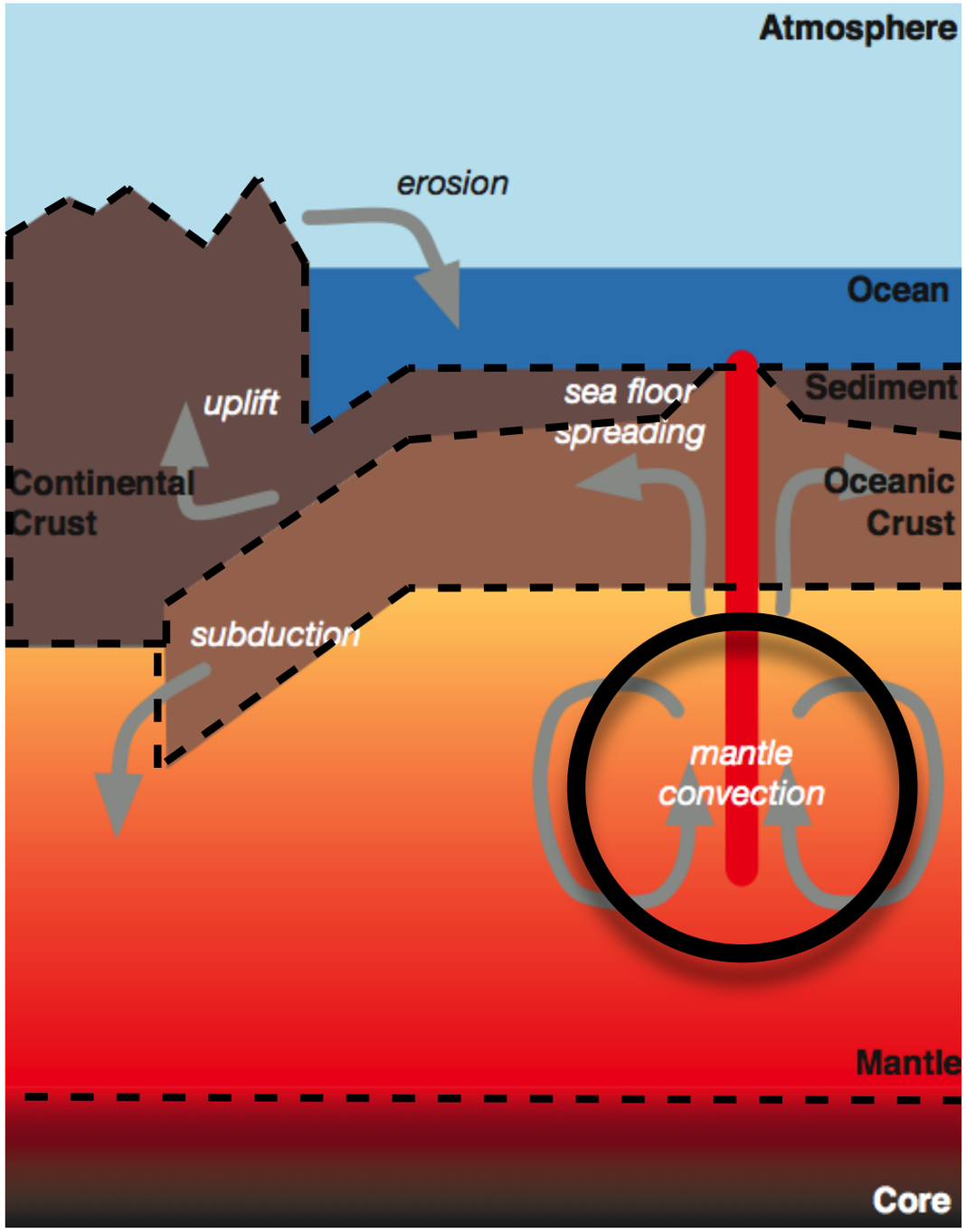
entropy production:

$$\sigma_{\mathrm{m}} = \frac{J_{\mathrm{s}} A_{\mathrm{s}}}{T_{\mathrm{s}}} - \int_V \frac{\Phi_{\mathrm{h}}}{T} dV$$

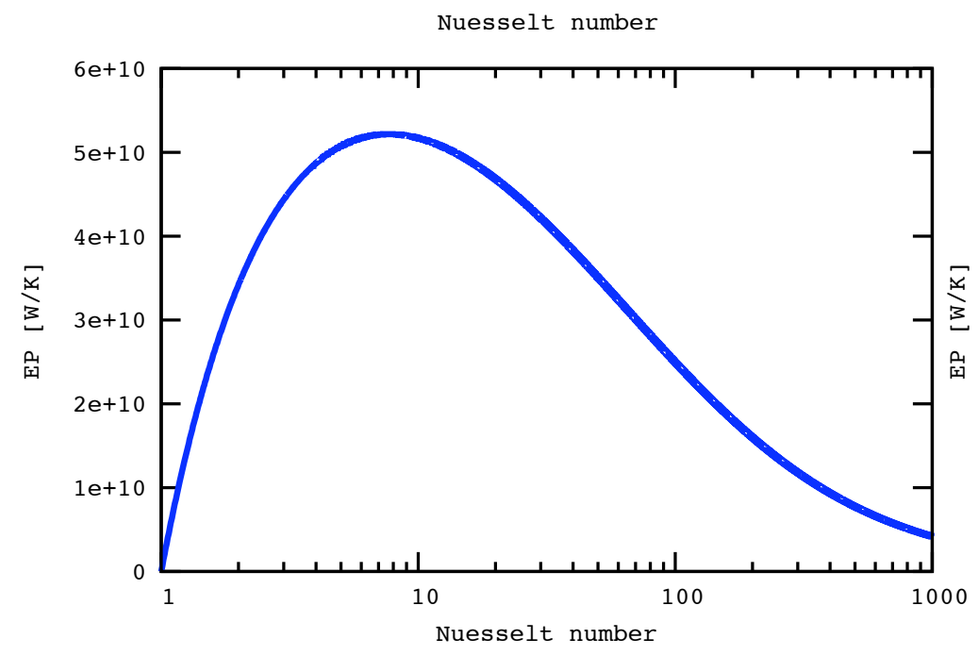
=> max. entropy production with respect to Nusselt number N

after Lorenz (2002)

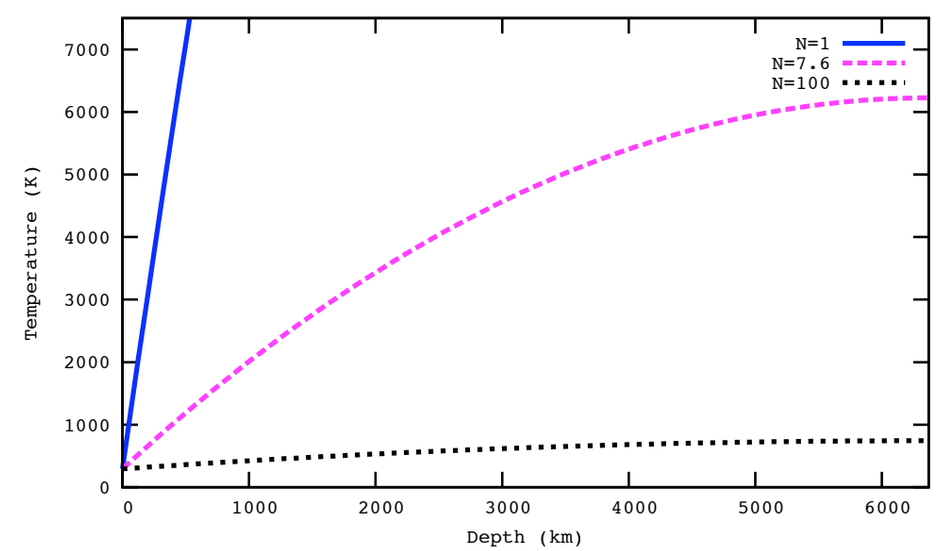
Power Generation within the Earth System



entropy production:



temperature profile:



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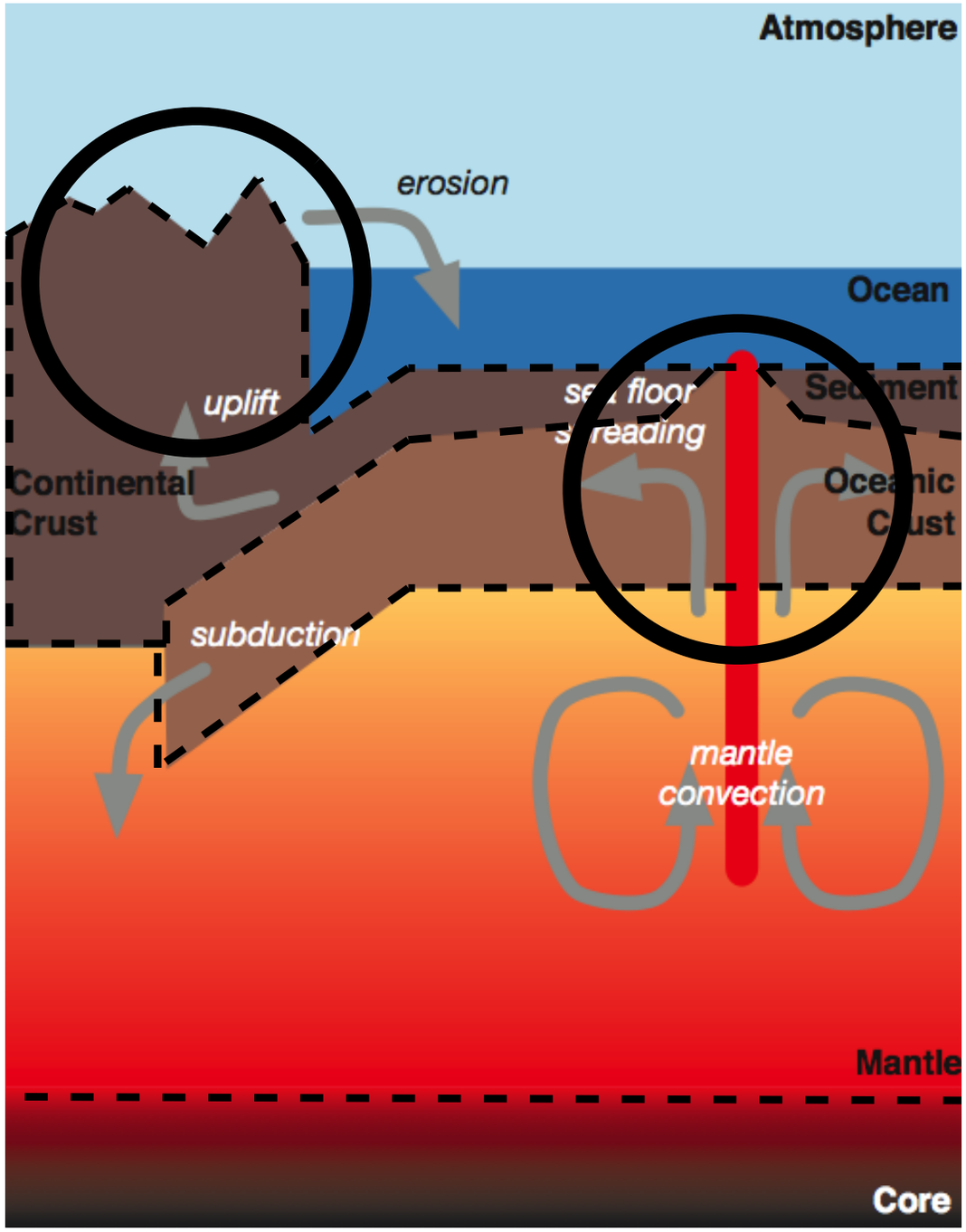
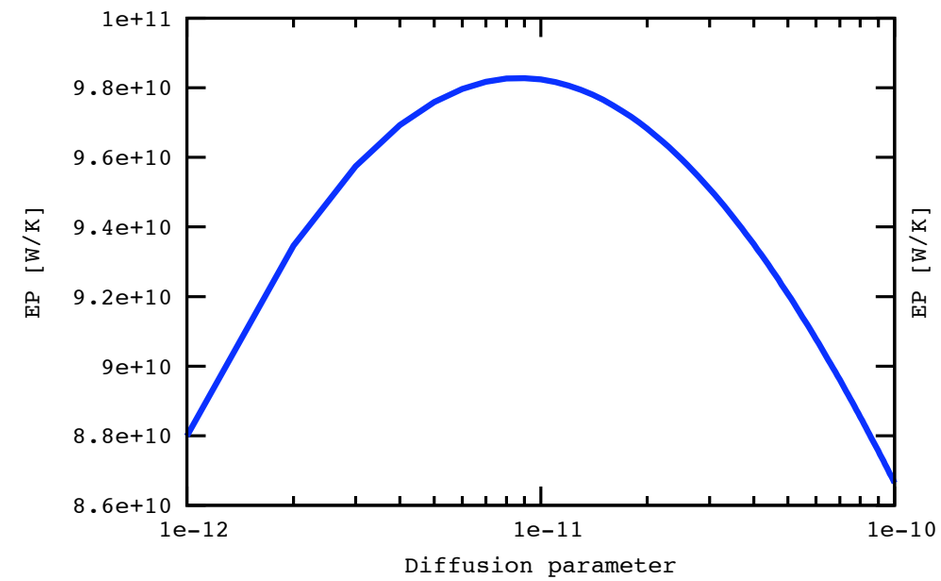
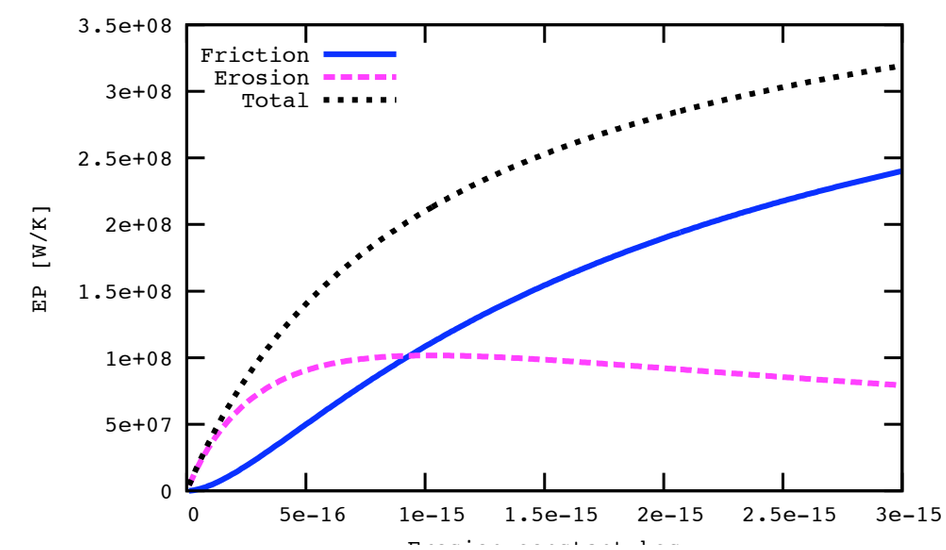


entropy production by oceanic crust cycling:



entropy production by continental crust cycling:



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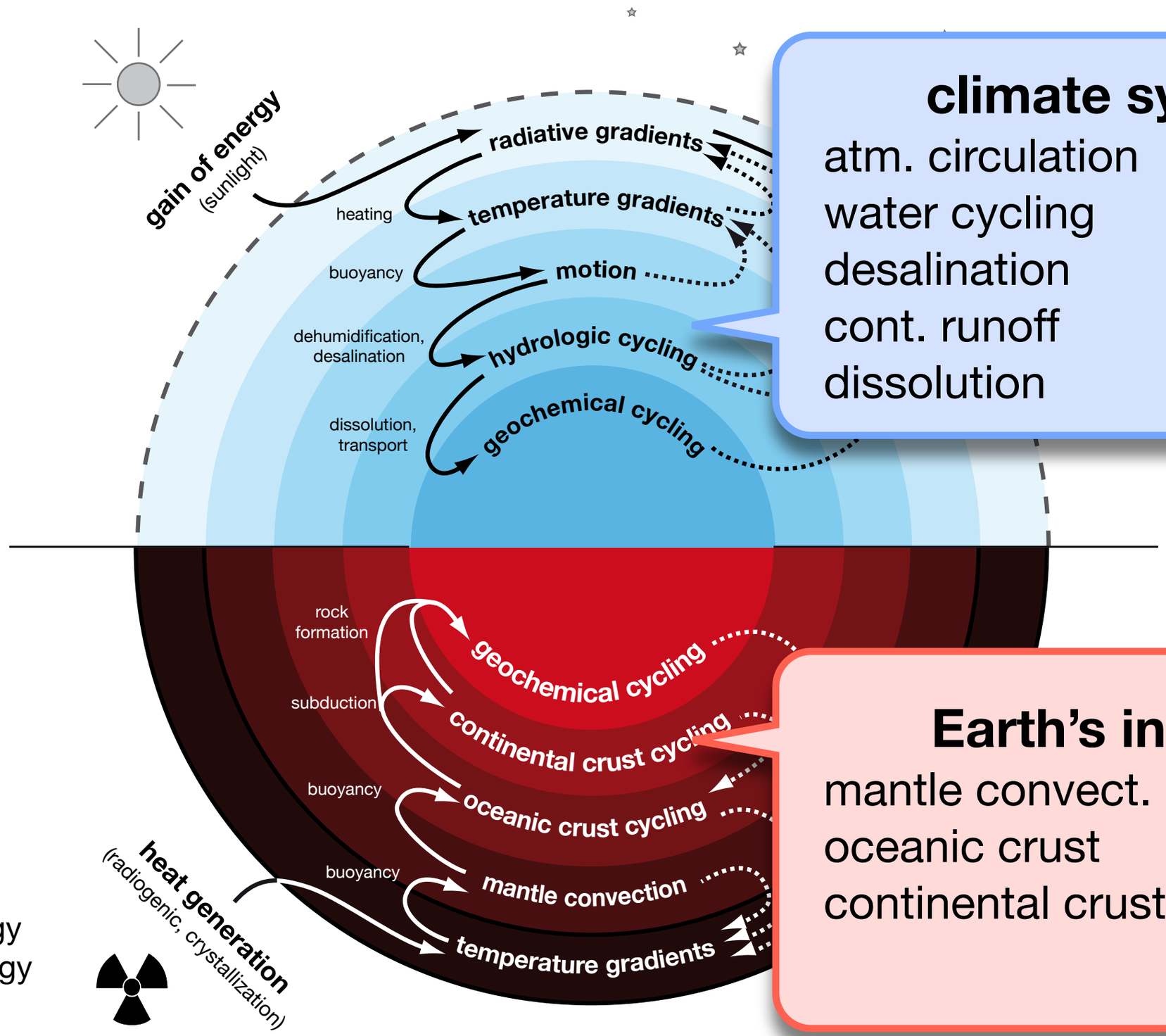

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Earth's interior:

mantle convect.	12 TW	(KE)
oceanic crust	28 TW	(KE)
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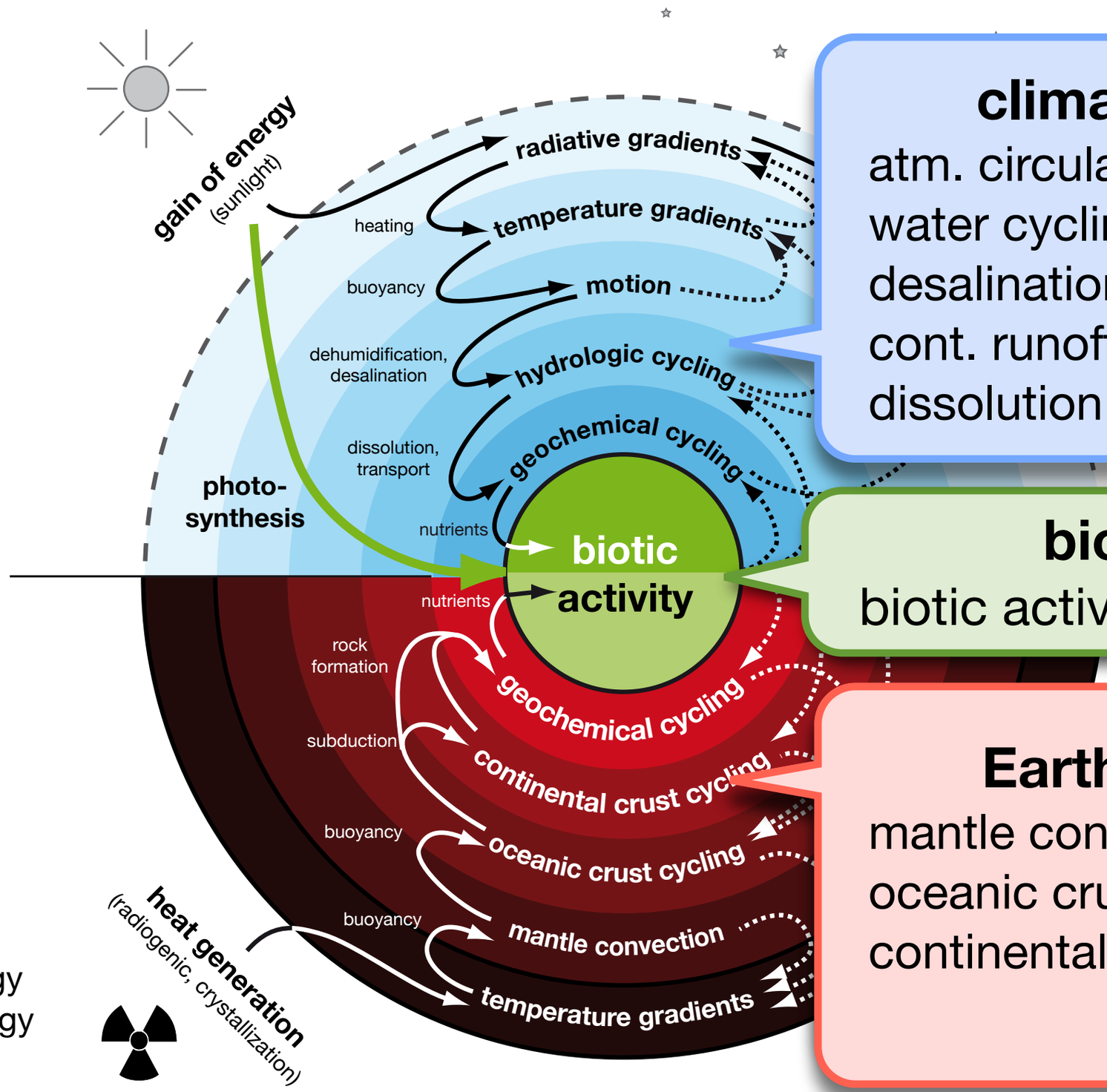

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biotic activity	215 TW	(CE)

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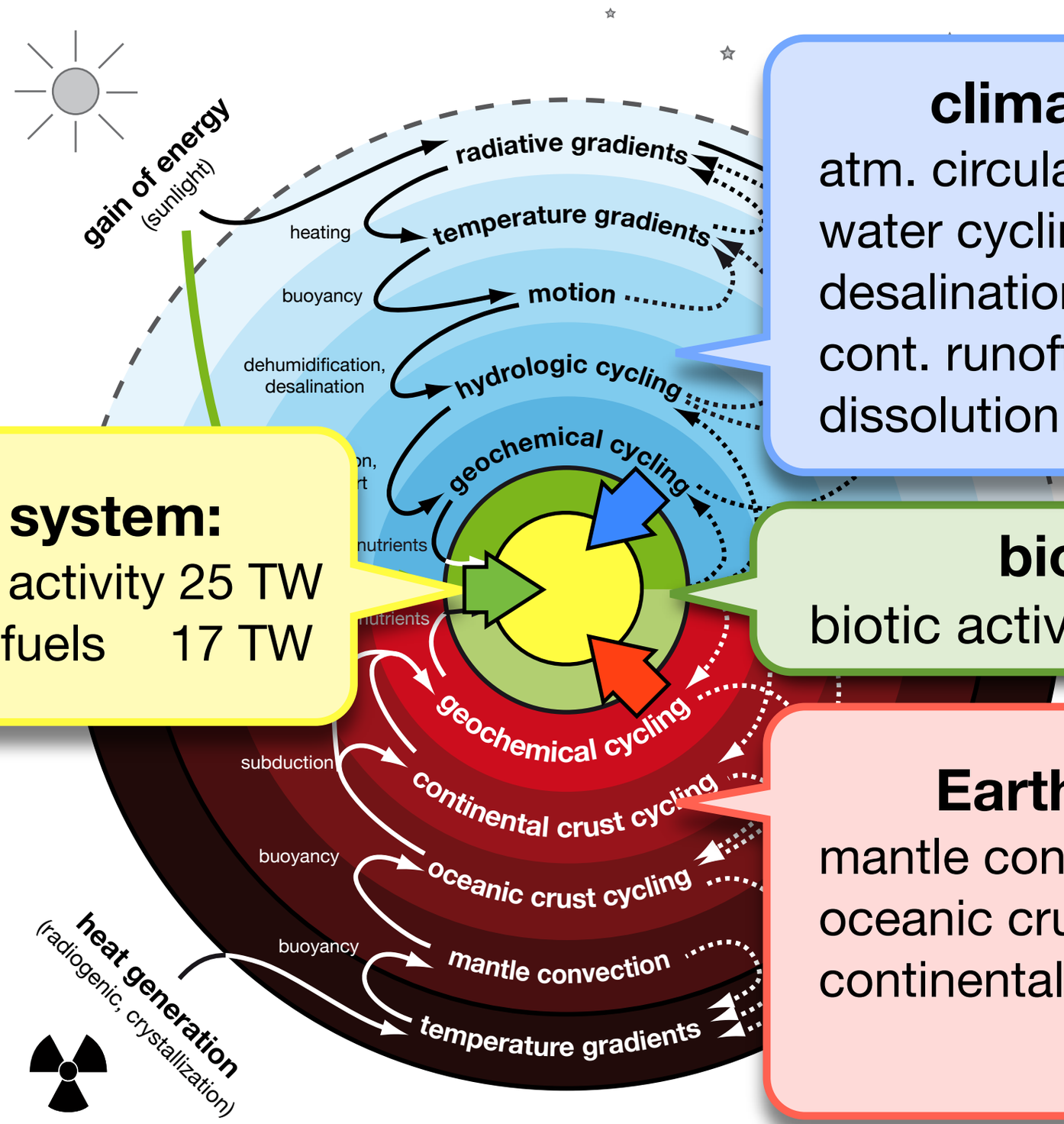

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human system:

from biotic activity	25 TW
from fossil fuels	17 TW

biosphere:

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Implications of a “Powerful” Perspective

- **a. Earth system modeling:** Do models transfer power adequately? Most probably not…
- **b. Gaia:** How does this hierarchy of power generation and transfer relate to the Gaia hypothesis?
- **c. Human imprint:** Humans as a planetary force

Thermodynamics and Gaia

MEP:
maximum power transfer enables higher rates of entropy production in a hierarchy

Thermodynamics and Gaia

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Earth:
power generation and transfer evolves variables away from equilibrium

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Life:
adds substantial amount of free energy to geochemical cycling (215 TW >> 1 TW)

Thermodynamics and Gaia

Lovelock: chemical disequilibrium in the Earth's atmosphere due to widespread life

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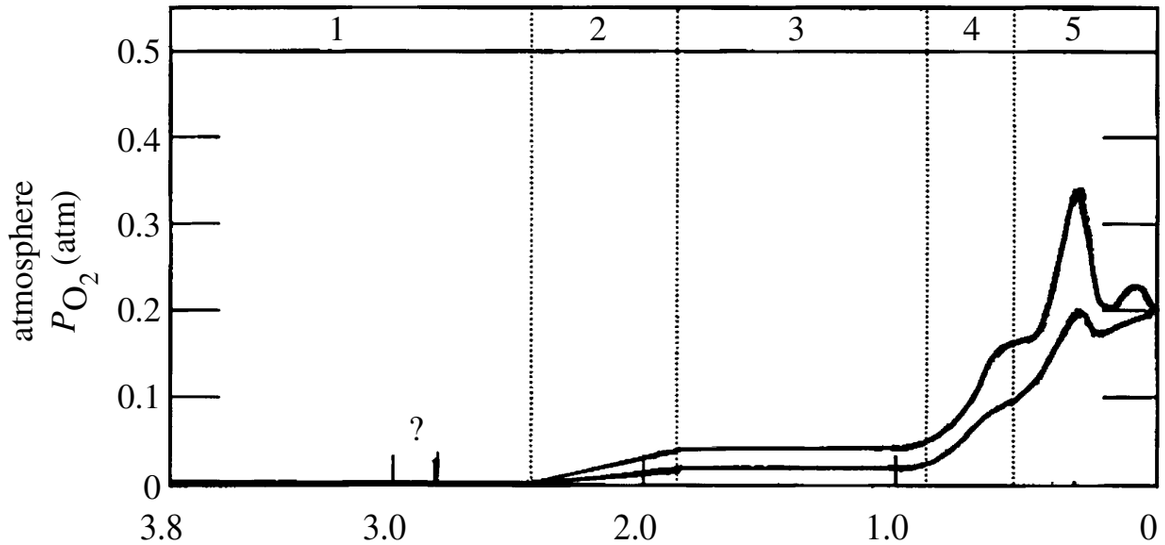
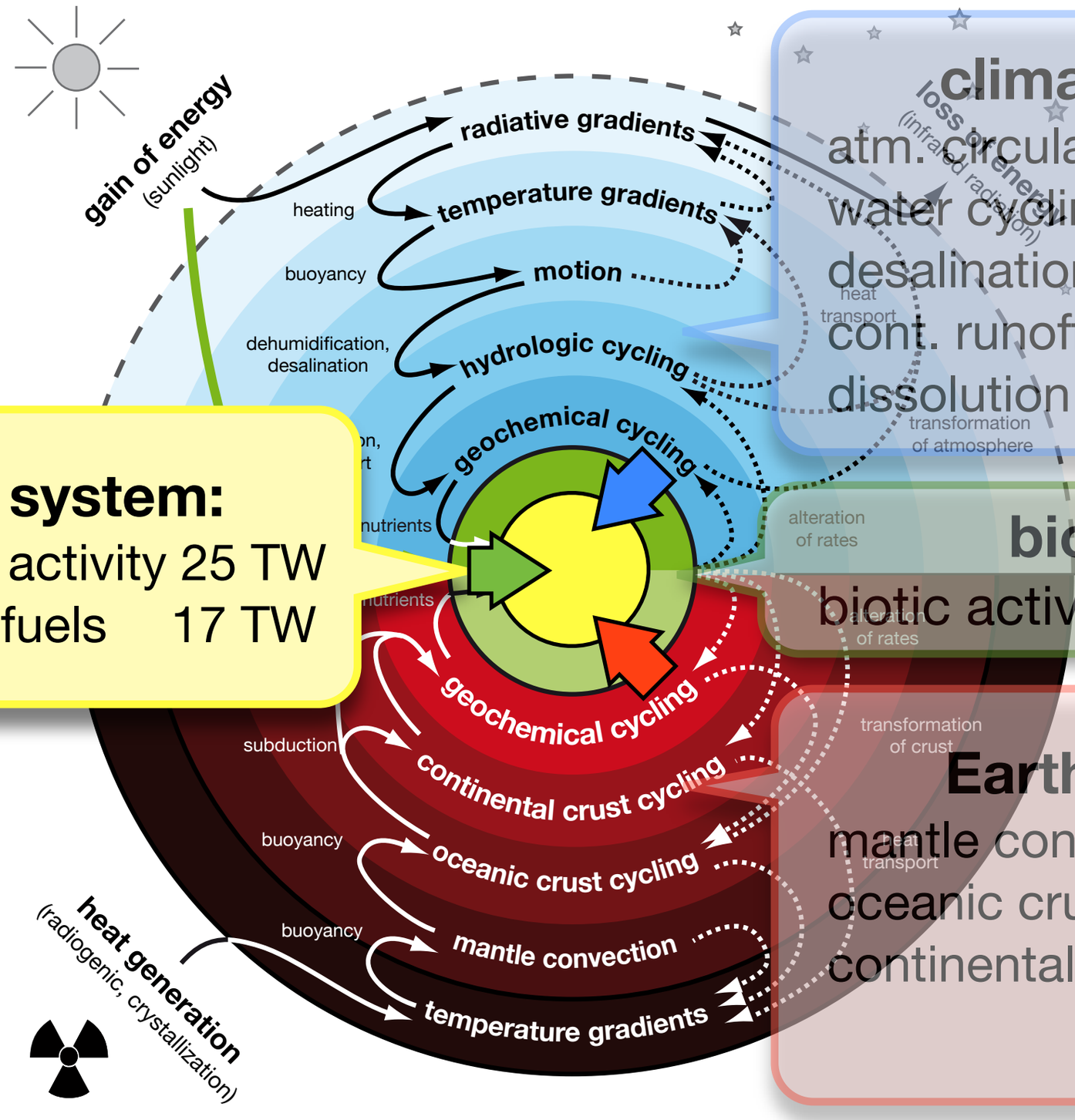


evolution towards greater disequilibrium in Earth's history
=> more power generation?

Human Imprint and Global Change

1 W/m^2
≈ 510 TW



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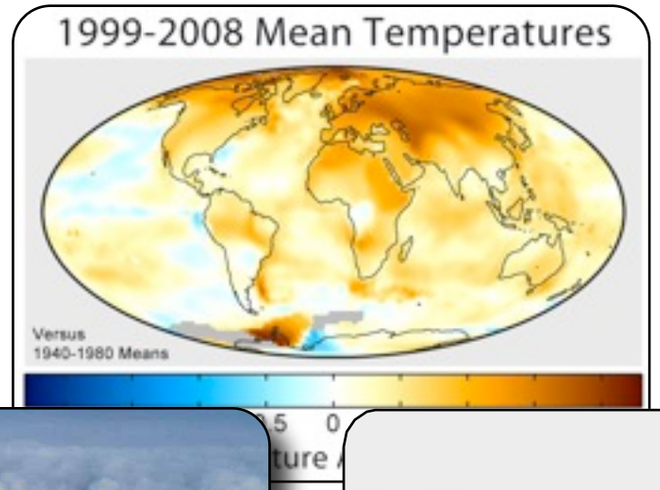
Human Imprint and Global Change

global warming

geo-engineering

tropical deforestation



renewable energy

biodiversity loss

water crisis

population explosion

food supply

Human Imprint and Global Change

<u>how to characterize a car:</u>

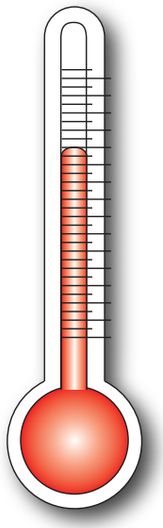
temperature of the engine

or

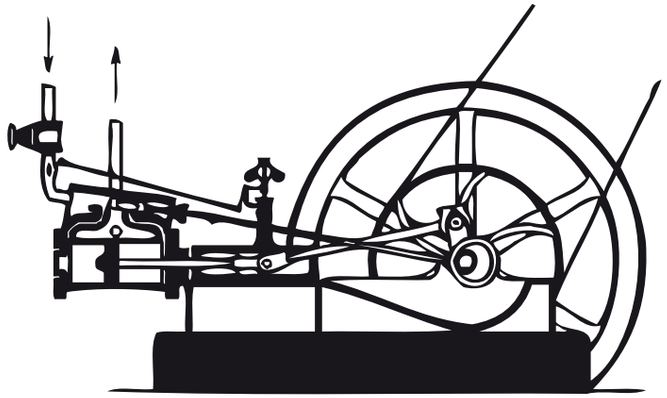
the power of the engine?

image: wikimedia.org; porsche.de

Human Imprint and Global Change



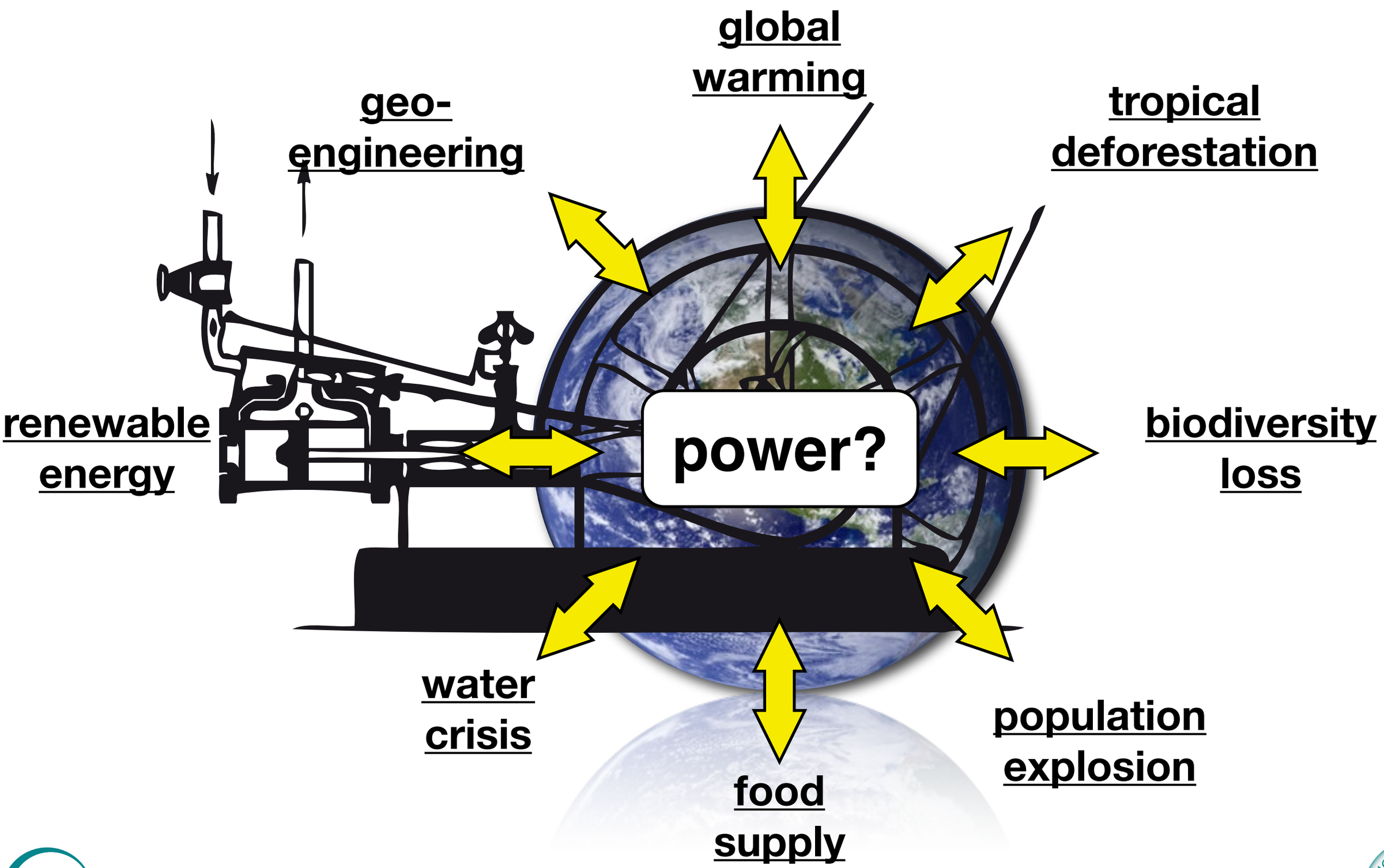
temperature



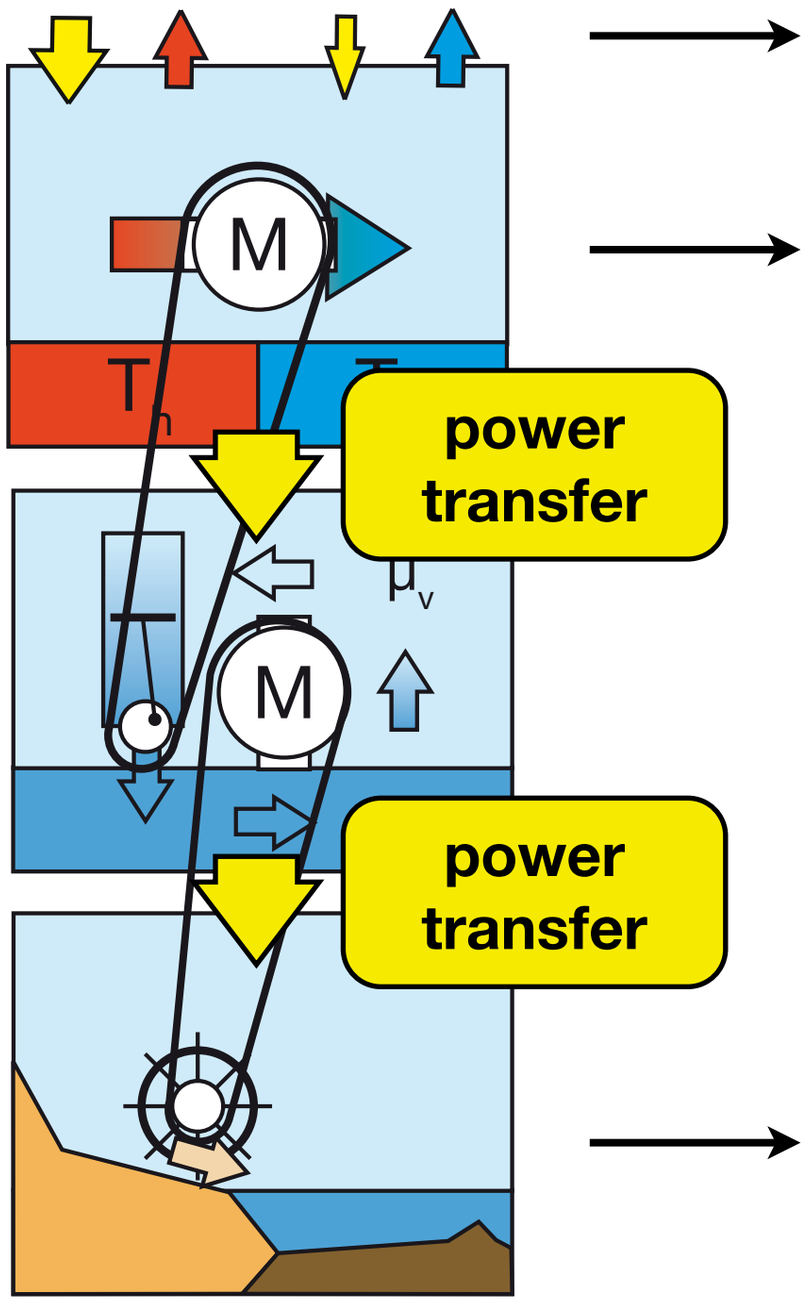
power

image: NASA

Human Imprint and Global Change



Human Imprint and Renewable Energies

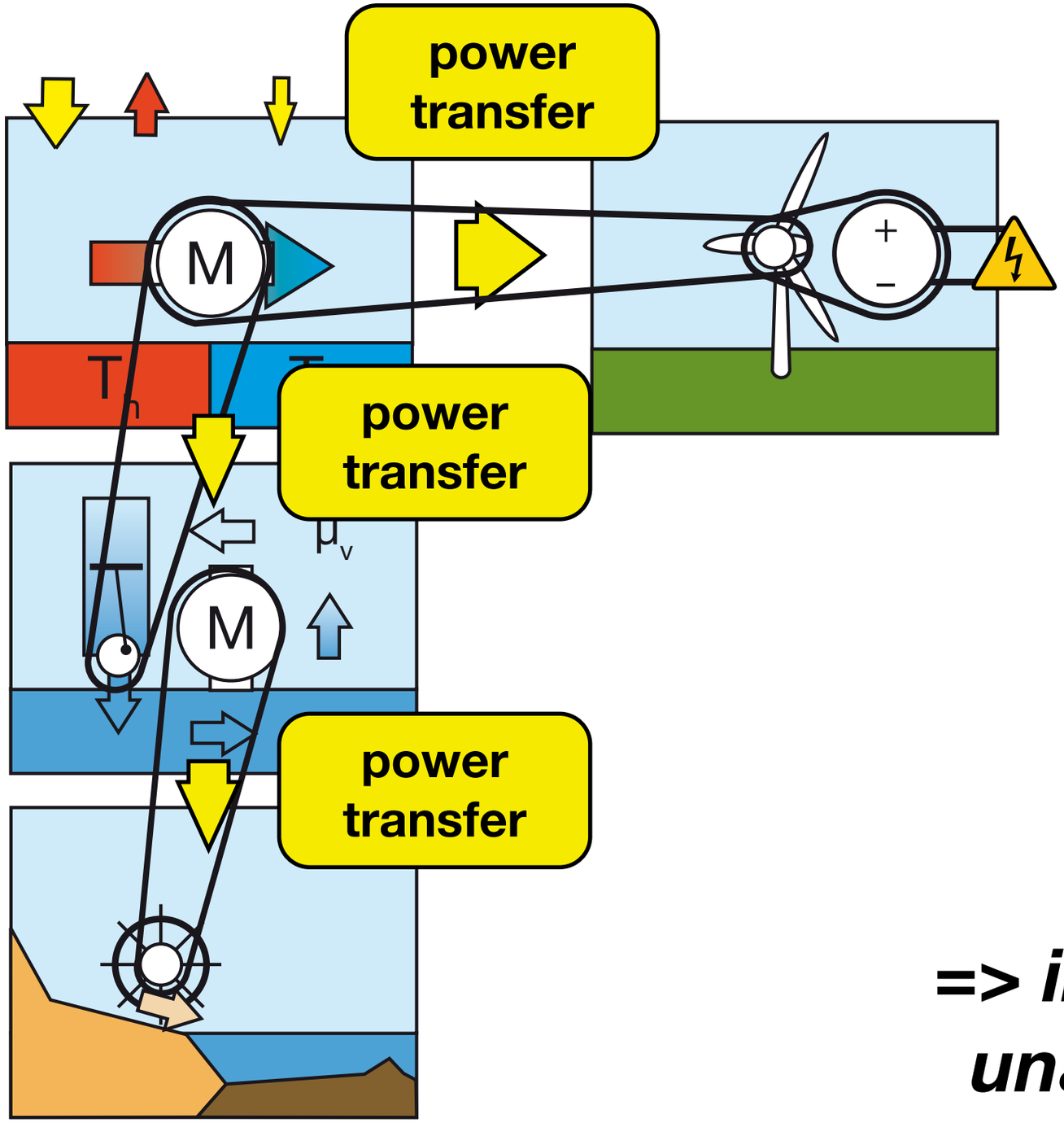


solar power

wind power
(wave power, ocean power)

hydropower,
osmotic power

Human Imprint and Renewable Energies

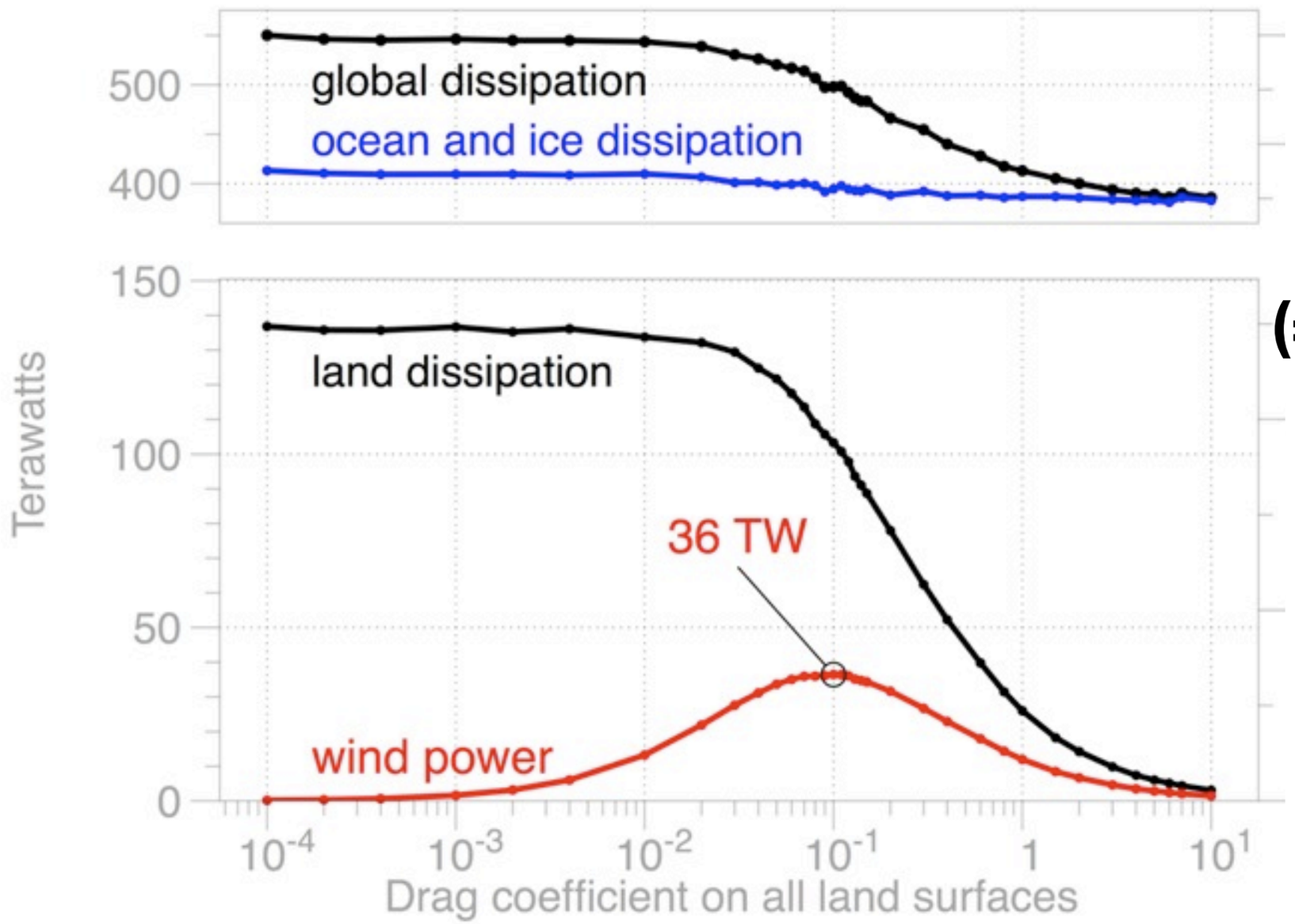


impacts

impacts

=> impacts are unavoidable!

Human Imprint and Renewable Energies



natural dissipation (= generation)

extracted wind power

intensity of wind removal

Miller, Gans, Kleidon (submitted)

Human Imprint and Renewable Energies

wind power extraction reduces power availability and generation within the Earth system

solar power enhances absorption of sunlight and thereby can **increase** power generation within the Earth system

Outline

1. **Background:**
   - link between disequilibrium, spatiotemporal variability and power generation => limits to stochastic forcing?
   - thermodynamic limits to power generation << Carnot
   - max. power generation = max. dissipation ≈ MEP

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   - max. power generation = max. dissipation ≈ MEP
2. **Earth system:**
   - hierarchy of power generation and transfer
   - global work budget: the missing budget
3. **Implications:**
   - do models adequately capture power transfer?
   - life as a substantial power generator
   - humans as planetary dissipator
   - limits and impacts of renewable energy