Life, Hierarchy, and the Thermodynamic Machinery of Planet Earth

Axel Kleidon
akleidon@bgc-jena.mpg.de
Max-Planck-Institute for Biogeochemistry
Jena, Germany

Stochastic Methods in Climate Modelling
26 August 2010

http://gaia.mpg.de
Lovelock: chemical disequilibrium in the Earth’s atmosphere due to widespread life
**Lovelock:** chemical disequilibrium in the Earth’s atmosphere due to widespread life

![Graph showing atmospheric composition over time](http://gaia.mpgh.de)
**Lovelock:** chemical disequilibrium in the Earth’s atmosphere due to widespread life

**Earth:** evolution away from equilibrium
Lovelock: chemical disequilibrium in the Earth’s atmosphere due to widespread life

MEP: fastest approach to equilibrium

Earth: evolution away from equilibrium
**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

thermodynamics and variability

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

thermodynamics and variability

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?
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?
first law: \[ dU = dQ - dW \]

second law: \[ dS = \frac{dQ}{T} \geq 0 \]
Maintaining Disequilibrium

a. 2-box model

\[ dQ = 0 \]

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

a. 2-box model

\[ dQ = 0 \]

b. temperatures

c. entropies
Maintaining Disequilibrium

a. 2-box model

\[ dQ = 0 \]

initial temperature gradient is dissipated to a state of thermodynamic equilibrium

b. temperatures

c. entropies
Maintaining Disequilibrium

a. 2-box model

\[ dQ \neq 0 \]

b. temperatures

c. entropies

\[ dQ \neq 0 \]

\[ J_{in,h} \quad J_{out,h} \quad J_{in,c} \quad J_{out,c} \]

\[ T_h \quad T_c \]

\[ J_{heat} \]

\[ J_{in,h} \quad J_{out,c} \]

\[ \sigma_{heat} \]

\[ S_h \quad S_c \]

\[ S_{tot} \]

Temperature (°C)

Flux (W m\(^{-2}\))

Entropy Production (mW m\(^{-2}\) K\(^{-1}\))

Entropy (frac. max)
Maintaining Disequilibrium

**a. 2-box model**

\[dQ \neq 0\]

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

**b. temperatures**

**c. entropies**

\[\dot{Q} = 0\]

\[\sigma_{\text{heat}}\]
Maintaining Disequilibrium

first law: \[ dU = dQ - dW \]

second law: \[ dS = \frac{dQ}{T} \geq 0 \]

combined:

\[ dS_{tot} = \frac{dU + dW}{T} \]
Maintaining Disequilibrium

first law: \[ dU = dQ - dW \]

second law: \[ dS = \frac{dQ}{T} \geq 0 \]

combined:

\[ dS_{tot} = \frac{dU + dW}{T} \equiv dS_{heat} + dS_{diseq} \]
Maintaining Disequilibrium

first law: \[ dU = dQ - dW \]

second law: \[ dS = dQ/T \geq 0 \]

combined:

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

entropy change due to changes in heat content
Maintaining Disequilibrium

first law: \[ dU = dQ - dW \]

second law: \[ dS = \frac{dQ}{T} \geq 0 \]

combined:

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

- 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: \[ dS = \frac{dQ}{T} \geq 0 \]

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:**

\[ dS_{\text{diseq}} = -\frac{dA}{T} \]
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

Free Energy ($10^9$ J)

Entropy ($10^6$ J K$^{-1}$)

Time (years)

Temperature (°C)

Flux (W m$^{-2}$)

Entropy Production (mW m$^{-2}$ K$^{-1}$)

$T_h$, $S$, $J$, $T_c$

$J_{in,h}$, $J_{out,h}$, $J_{in,c}$, $J_{out,c}$

$S_{diseq}$
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

First law:
\[ \frac{dU}{dt} = J_{\text{net}} - (P - D) \]

Second law:
\[ \frac{dS}{dt} = \sigma - NEE \]

Helmholtz free energy A:
\[ \frac{dA}{dt} = P - T \cdot \frac{dS_{\text{diseq}}}{dt} \]

Extraction of power from a heat gradient...
Maintaining Disequilibrium

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

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

Helmholtz free energy A:
\[
\frac{dA}{dt} = P - T \cdot \frac{dS_{diseq}}{dt}
\]

... 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:
\[ \frac{dU}{dt} = J_{\text{net}} - (P - D) \]

second law:
\[ \frac{dS}{dt} = \sigma + NEE \]

Helmholtz free energy A:
\[ \frac{dA}{dt} = P - T \cdot \frac{dS_{\text{diseq}}}{dt} \]

thermodynamic gradients are dissipated…

… resulting in entropy production…
Maintaining Disequilibrium

first law:
\[
\frac{dU}{dt} = J_{net} - (P - T \cdot dS_{diseq})
\]

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

Helmholtz free energy A:
\[
\frac{dA}{dt} = P - T \cdot \frac{dS_{diseq}}{dt}
\]

... and dissipative heating

... resulting in entropy production...

thermodynamic gradients are dissipated...
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

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

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

Helmholtz free energy A:
\[
\frac{dA}{dt} = P - T \cdot \frac{dS_{diseq}}{dt}
\]

entropy production ...
... is constrained by net entropy exchange ...
Maintaining Disequilibrium

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

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

Helmholtz free energy A: \[
\frac{dA}{dt} = P - T \cdot \frac{dS_{\text{diseq}}}{dt}
\]

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:

\[
\frac{dA}{dt} = P - T \cdot \frac{dS_{diseq}}{dt}
\]
Limits to Power Generation and Transfer

first law: \[ dU = dQ - dW \]

second law: \[ dS = \frac{dQ}{T} \geq 0 \]
Limits to Power Generation and Transfer

first law: \[ dU = dQ - dW \]

second law: \[ dS = \frac{dQ}{T} \geq 0 \]

\[ P_{ex} = \frac{dW}{dt} \]
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

first law:  \[ J_{in} = J_{out} + P_{ex} \]

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

\[ P_{ex} \leq J_{in} \cdot \frac{T_{in} - T_{out}}{T_{in}} \quad \text{“Carnot limit”} \]
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

\[ P_{ex} \leq J_in \cdot \frac{T_{in} - T_{out}}{T_{in}} \]

“Carnot limit”
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"
first law:

\[
\frac{dT_h}{dt} = c \left( J_{in,h} - J_{out,h} - J_{heat} \right) \\
\frac{dT_c}{dt} = c \left( J_{in,c} - J_{out,c} + J_{heat} \right) \\
T_h - T_c = \frac{(\Delta J_{in} - 2J_{heat})}{k_b}
\]

second law:

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

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

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

“2-box climate model”
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:**

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

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

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

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

\[
P_{ex} \leq \frac{\Delta J_{in}}{8} \cdot \frac{T_{h,0} - T_{c,0}}{T_{h,0}}
\]
Limits to Power Generation and Transfer

**sensitivity to \( J_{\text{heat}} \)**

- **a. temperatures**
  - Graph showing temperature vs. heat flux \( J_{\text{heat}} \) with \( T_h \) and \( T_c \) axes.

- **b. entropies**
  - Graph showing entropy vs. heat flux \( J_{\text{heat}} \) with \( S_h \), \( S_{\text{tot}} \), and \( S_c \) axes.

- **c. entropy production and power**
  - Graph showing entropy production vs. heat flux \( J_{\text{heat}} \) with \( P_{\text{ex}} \) and \( \sigma_{\text{ex}} \) axes.

- **d. free energy and disequilibrium**
  - Graph showing free energy vs. heat flux \( J_{\text{heat}} \) and entropy vs. heat flux \( J_{\text{heat}} \) with \( A \) and \( S_{\text{diseq}} \) axes.
Limits to Power Generation and Transfer

sensitivity to $J_{\text{heat}}$

a. temperatures

![Graph showing temperatures vs. heat flux $J_{\text{heat}}$]

b. entropies

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

c. entropy production and power

![Graph showing entropy production vs. heat flux $J_{\text{heat}}$]

d. free energy and disequilibrium

![Graph showing free energy vs. heat flux $J_{\text{heat}}$]

Kleidon (in prep.)
Limits to Power Generation and Transfer

entropy production and power

![Graph showing entropy production, power, and entropy flux as functions of heat flux.](http://gaia.mpg.de)

Heat Flux $J_{heat}$ (W m$^{-2}$)

Entropy Production (mW m$^{-2}$ K$^{-1}$)

Power (W m$^{-2}$)

Free Energy (MJ m$^{-2}$)

Disequilibrium (MJ m$^{-2}$ K$^{-1}$)

Kleidon (in prep.)
Limits to Power Generation and Transfer

**entropy production and power**

maximum power generation rate

\[ \approx 2 \text{ W m}^{-2} \]

or

\[ \approx 900 \text{ TW} \]
Limits to Power Generation and Transfer

entropy production and power

maximum power generation rate
≈ 2 W m\(^{-2}\)
or ≈ 900 TW

maximum efficiency
2 %
Limits to Power Generation and Transfer

**momentum balance model**

a. 2-box model

\[ \rho_h v_h \]

\[ P_{in} \quad S_{mom} \quad J_{mom} \quad D_{mom} \]

b. velocities

\[ v_h \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 70 \quad 80 \quad 90 \quad 100 \]

\[ \text{velocity (m s}^{-1} \text{)} \]

\[ 0 \quad 2 \quad 4 \quad 6 \]

\[ \text{Time} \]

\[ 100 \times v_i \]

c. power, dissipation

\[ P_{in} \quad D_{mom} \]

\[ 0 \quad 1 \quad 2 \]

\[ \text{power, dissipation (W m}^{-2} \text{)} \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \]

\[ \text{Time} \]

d. free energy, disequilibrium

\[ A_{mom} \quad S_{mom} \]

\[ 0 \quad -1 \quad -2 \quad -3 \quad -4 \]

\[ \text{Free Energy (10}^6 \text{J m}^{-2} \text{)} \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \]

\[ \text{Entropy (10}^3 \text{J m}^{-2} K^{-1}) \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \]

\[ \text{Time} \]

Kleidon (in prep.)

http://gaia.mpg.de
motion can be used to power transport of suspended solids

**a. box-model**

- \( V_{in}, \rho_{in} \)
- \( J_{mass} \)
- \( V_{out}, \rho_{out} \)
- \( V_{in} \) and \( \rho_{in} \) are the input volume and density, respectively.
- \( J_{mass} \) represents the mass flux.
- \( V_{out} \) and \( \rho_{out} \) are the output volume and density, respectively.

**b. power**

- The diagram shows the relationship between export velocity \( v_{out} \) and power output \( P_{out} \).
- The power output is plotted against the export velocity, with separate curves for lift power \( P_{lift} \) and mass power \( P_{mass} \).
- The graph indicates that as the export velocity increases, the power output initially increases but then decreases, reaching a peak at a certain velocity.

Kleidon (in prep.)
**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**

---

Kleidon (in prep.)

http://gaia.mpg.de
**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**

Kleidon (in prep.)
**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

cascade of power transfer causes disequilibrium

gain of energy (sunlight)
- heating
- buoyancy
- dehumidification, desalination
- dissolution, transport

radiative gradients
- temperature gradients
- motion

hydrologic cycling
geochemical cycling

transformation of crust
heat transport

continental crust cycling
oceanic crust cycling
mantle convection
temperature gradients
buoyancy

heat generation (radiogenic, crystallization)

subduction

loss of energy (infrared radiation)
- transformation of atmosphere
- heat transport
Power Generation within the Earth System

- Gain of energy (solar radiation)
- Temperature gradients
- Radiative gradients
- Loss of energy (infrared radiation)
- Hydrologic cycling
- Geochemical cycling
- Continental crust cycling
- Oceanic crust cycling
- Mantle convection
- Rock formation
- Heat generation (radiogenic, crystallization)
- Heat transport
- Subduction
- Dehumidification, desalination
- Dissolution, transport
- Buoyancy
- Transformation of atmosphere
- Transformation of crust

Cascade of power transfer causes disequilibrium

Cascade of effects cause interactions and feedbacks

Kleidon (in prep.)

http://gaia.mpg.de
Power Generation within the Earth System

1 W/m²
≈ 510 TW

climate system:
- atm. circulation 900 TW (KE)
- water cycling 558 TW (PE)
- desalination 39 TW (CE)
- cont. runoff 13 TW (KE)
- dissolution <1 TW (CE)

KE: Kinetic Energy
PE: Potential Energy
CE: Chemical Energy

gain of energy (sunlight)
radiative gradients
temperature gradients
motion
buoyancy
dehumidification, desalination
dissolution, transport
rock formation
subduction
buoyancy
oceanic crust cycling
continental crust cycling
heat transport
transformation of crust
mantle convection
temperature gradients
radiogenic, crystallization
heat generation

http://gaia.mpg.de
**energy balance:**

\[
\Phi_h = -\frac{2k_mN}{r} \frac{\partial T_m}{\partial r} - k_mN \frac{\partial^2 T_m}{\partial r^2}
\]

**analytical solution:**

\[
T_m(r) = T_{core} - \frac{\Phi_h}{6k_mN} r^2
\]

**entropy production:**

\[
\sigma_m = \frac{J_s A_s}{T_s} - \int_V \frac{\Phi_h}{T} dV
\]

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

after Lorenz (2002)
Power Generation within the Earth System

entropy production:

Figure 3.

temperature profile:

Figure 5.

Table 3

Abstract

Conclusions
 entropy production by oceanic crust cycling:

entropy production by continental crust cycling:

Dyke et al., Earth System Dynamics Discussion, in press.
Power Generation within the Earth System

1 W/m² ≈ 510 TW

climate system:
- atm. circulation 900 TW (KE)
- water cycling 558 TW (PE)
- desalination 39 TW (CE)
- cont. runoff 13 TW (KE)
- dissolution <1 TW (CE)

Earth’s interior:
- mantle convect. 12 TW (KE)
- oceanic crust 28 TW (KE)
- continental crust <1 TW (PE)

KE: Kinetic Energy
PE: Potential Energy
CE: Chemical Energy
Power Generation within the Earth System

1 W/m²
≈ 510 TW

**climate system:**
- atm. circulation: 900 TW (KE)
- water cycling: 558 TW (PE)
- desalination: 39 TW (CE)
- cont. runoff: 13 TW (KE)
- dissolution: <1 TW (CE)

**biosphere:**
- biotic activity: 215 TW (CE)

**Earth’s interior:**
- mantle convect.: 12 TW (KE)
- oceanic crust: 28 TW (KE)
- continental crust: <1 TW (PE)

KE: Kinetic Energy
PE: Potential Energy
CE: Chemical Energy
Power Generation within the Earth System

1 W/m²
≈ 510 TW

human system:
from biotic activity 25 TW
from fossil fuels 17 TW

climate system:
atm. circulation 900 TW (KE)
water cycling 558 TW (PE)
desalination 39 TW (CE)
cont. runoff 13 TW (KE)
dissolution <1 TW (CE)

biosphere:
biotic activity 215 TW (CE)

Earth’s interior:
mantle convect. 12 TW (KE)
oceanic crust 28 TW (KE)
continental crust <1 TW (PE)

KE: Kinetic Energy
PE: Potential Energy
CE: Chemical Energy

http://gaia.mpg.de
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

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

**Earth:**
power generation and transfer evolves variables away from equilibrium
Thermodynamics and Gaia

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

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

**Earth:**
power generation and transfer evolves variables away from equilibrium

http://gaia.mpg.de
**Lovelock:** chemical disequilibrium in the Earth’s atmosphere due to widespread life

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

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

**Earth:**
power generation and transfer evolves variables away from equilibrium
**Thermodynamics and Gaia**

**Lovelock:** chemical disequilibrium in the Earth’s atmosphere due to life

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

*evolution towards greater disequilibrium in Earth’s history*  
*=> more power generation?*
Human Imprint and Global Change

1 W/m²
≈ 510 TW

human system:
from biotic activity 25 TW
from fossil fuels 17 TW

biosphere:
biotic activity 215 TW (CE)

Earth’s interior:
mantle convect. 12 TW (KE)
oceanic crust 28 TW (KE)
continental crust <1 TW (PE)

climate system:
atm. circulation 900 TW (KE)
water cycling 558 TW (PE)
desalination 39 TW (CE)
cont. runoff 13 TW (KE)
dissolution <1 TW (CE)

KE: Kinetic Energy
PE: Potential Energy
CE: Chemical Energy

http://gaia.mpg.de
Human Imprint and Global Change

- Global warming
- Geo-engineering
- Tropical deforestation
- Renewable energy
- Water crisis
- Biodiversity loss
- Food supply
- Population explosion
how to characterize a car:

*temperature of the engine*

*or*

*the power of the engine?*
Human Imprint and Global Change

Earth → temperature → power

image: NASA
Human Imprint and Global Change

- geo-engineering
- global warming
- tropical deforestation
- biodiversity loss
- population explosion
- food supply
- water crisis
- renewable energy
- power?
- global warming
- geo-engineering
- tropical deforestation
- biodiversity loss
- population explosion
- food supply
- water crisis
- renewable energy
- power?
Human Imprint and Renewable Energies

- solar power
- wind power (wave power, ocean power)
- power transfer
- hydropower, osmotic power
=> impacts are unavoidable!
Human Imprint and Renewable Energies

natural dissipation (= generation)

extracted wind power

intensity of wind removal

Miller, Gans, Kleidon (submitted)

http://gaia.mpg.de
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 $\approx$ MEP
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 \( \approx \) MEP

2. **Earth system:**
   - hierarchy of power generation and transfer
   - global work budget: the missing budget
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

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