Understanding the Earth from a thermodynamic systems perspective

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earthsystem.org
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 thermodynamics 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

- A hurricane
- A plant leaf
- A power plant
- Wind turbines

wikipedia.org
NASA
Thermodynamics of the Earth System

Energy conversions are connected and alter the system

Gain of energy (solar radiation)
- Heating
- Buoyancy
- Photosynthesis

Loss of energy (terrestrial radiation)
- Heat transport
- Transformation of radiative properties

Radiative gradients
- Temperature gradients
- Motion
- Hydrologic cycling
- Geochemical cycling
- Biotic activity

Human activity

Associated forms of energy
- Radiative
- Thermal
- Kinetic
- Potential, chemical, kinetic
- Chemical
- Chemical
- Chemical
- Potential, kinetic
- Kinetic
- Thermal

Kleidon (2012), Kleidon (2016)

Thermodynamics sets fundamental laws for all physical processes and is central to driving and maintaining planetary dynamics. But how do Earth system processes perform work, where do they derive energy from, and what are the ultimate limits? This accessible book describes how the laws of thermodynamics apply to Earth system processes, from solar radiation to motion, geochemical cycling and biotic activity. It presents a novel view of the thermodynamic Earth system that explains how it functions and evolves, how different forms of disequilibrium are being maintained, and how evolutionary trends can be interpreted as thermodynamic trends. It also places human activity into a new perspective in which it is treated as a thermodynamic, Earth system process.

This book uses simple conceptual models and basic mathematical treatments to illustrate the application of thermodynamics to Earth system processes, making it ideal for researchers and graduate students across a range of Earth and environmental science disciplines.
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
Thermodynamics of the Earth System

Basics in Thermodynamics

Application to Climate

Application to Geochemistry

Application to Humans

Summary and Outlook

Energy Conversions

Planetary Effects

Solar radiation

Heat

Motion

Chemistry & Life

Humans
Thermodynamics

Thermodynamics happens every day!

**First law:** Energy is conserved

**Second law:** Energy is dispersed (increase of entropy)
Equilibrium Thermodynamics

Gradients are depleted

Non-equilibrium Thermodynamics

Gradients are maintained by energy input

Work is performed
Thermodynamics

Laws of thermodynamics are implemented in budgets

**First law:** Energy conservation $\Rightarrow$ Energy budget

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

**Second law:** Entropy increase $\Rightarrow$ Entropy budget

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

Second law requires $\sigma \geq 0$ $\Rightarrow$ 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
Increase of entropy governs energy conversions from Sun to Earth to Space

Temperature

-18°C

very cold
(high entropy)

15°C

very hot
(low entropy)

≈ 5500 °C

Entropy production

The Sun

$\sigma > 0$

Earth system

$\sigma > 0$

Space

$\sigma = 0$

Solar absorption processes

Climate system processes

Emission from the Earth

Potential for further depletion

Emission from the atmosphere

Cosmic background radiation

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

$\sigma > 0$

$\sigma = 0$

$\sigma > 0$

$\sigma = 0$
Thermodynamic Limits

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

Exhausts remove heat at lower temperature.

Combustion of fuels adds heat.

Power plant performs work through time (“power”).

The Carnot limit:

First law: (energy conservation)

\[ J_{in} = J_{out} + G \]

Second law: (increase in entropy, \( \sigma = dS/dbt \geq 0 \))

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

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

\[ G \leq J_{in} \cdot \frac{T_{in} - T_{out}}{T_{in}} \]
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").

Emission of radiation cools the Earth.

Combustion of fuels adds heat.

Sunlight heats the Earth.

Earth system processes perform work.
Thermodynamics of the Earth System

Generating free energy for the dynamics of the Earth system

- Sun’s emission temperature
- Solar radiation (low entropy)
- Terrestrial radiation (high entropy)
- Surface temperature
- Radiative temperature
- Energy conversions
  - Generation
  - Free energy
  - Dissipation
  - Heat engines
  - Photochemistry, Photovoltaics
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:

Thermodynamics and Climate

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

Climatological mean

\[ J_{\text{opt}} = \frac{R_s}{2} \]

Diurnal variation

\[ J_{\text{opt}} = R_s - \frac{R_{\text{s,avg}}}{2} \]

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

Kleidon and Renner (2018)
*Earth Syst. Dynam.*
Example: Precipitation sensitivity to global warming (4xCO2) and solar geoengineering (G)

\[ P = E = \frac{s}{s + \gamma} \cdot \frac{R_s}{2} \]
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

Chemical disequilibrium and free energy

Solar radiation

Photodissociation and ionisation

Disequilibria: O₂ vs. O₃
H₂O vs. OH

O₃ 20 TW
OH 0.2 TW

Hydrologic cycling

Disequilibria: N₂ + O₂ vs. NO

Lightning

H₂O 28 TW
NOₓ 10⁻³ TW
CH₄ 0.7 TW

O₂ + CH₂O 220 TW

Photo-synthesis

Disequilibria: CO₂ + H₂O vs. CH₂O + O₂
CH₄ + CO₂ vs. CH₂O
N₂ + H₂O vs. NH₃ + O₂

NH₃ 0.1 TW

Human activity

NH₃, NOₓ 0.1 TW

Interior heat loss

< 47 TW

O₂ + CH₂O 18 TW

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Absorption of solar radiation can chemically alter molecules

**Ultraviolet Radiation**
(More energetic radiation
(wavelengths shorter than visible light)

Example:
\[
\text{O}_2 + 5.2 \text{ eV} \rightarrow \text{O} + \text{O}
\]

**Visible Light**
(Less energetic radiation
(Visible light and near infrared)

Example:
\[
\frac{1}{2} \text{H}_2\text{O} + 8 \times 1.8 \text{ eV} \rightarrow \frac{1}{2} \text{O} + \text{H}^+ + \text{e}^-
\]

(Photosynthesis)

**Photoionization**
removes electrons
from nucleus

Example:
\[
\text{H} + 13.6 \text{ eV} \rightarrow \text{H}^+ + \text{e}^-
\]

**Photodissociation**
breaks molecular
bonds

Example:
\[
\frac{1}{2} \text{H}_2\text{O} + 8 \times 1.8 \text{ eV} \rightarrow \frac{1}{2} \text{O} + \text{H}^+ + \text{e}^-
\]

**Photoexcitation**
brings electrons into
a more energetic state
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.*
Productivity of the biosphere is limited by physical mixing and exchange, which in turn is thermodynamically limited. Yields about 220 TW for photosynthesis, based on NASA MODIS data of the years 2002-2005.
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

Data source: data.oecd.org
Thermodynamics and Human Activity

Human energy consumption:

- Food (agriculture, uses photosynthesis)
  \( \approx 8 \) TW

- Socioeconomic activity (fossil fuels, “buried sunshine”)
  \( \approx 18 \) TW

Similar magnitude as Earth system processes

Effects to the Earth system:

- Reduction of natural ecosystems
- Increase of atmospheric CO\(_2\)
Earth system process

Incoming solar radiation

Generation of heating differences by absorption

Generation of atmospheric motion

Generation of ocean waves

Generation of ocean currents

Renewable energy

≈ 175000 TW → Solar power

Absorption 70%
Differential heating 40%

≈ 49000 TW

Conversion (max.) 2%

≈ 1000 TW → Wind power

Conversion (obs.) 6%

≈ 60 TW → Wave power

Conversion (obs.) 8%

≈ 5 TW → Power from ocean currents
Efficiency of Photosynthesis: <3% 

Efficiency of Photovoltaics: ≈ 20%
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
Mercury

Type II
Venus, Mars

Type III
early Earth, Mars?

Type IV
Earth

Type V
Earth 2200?

Free energy generated by:

- Abiotic (Motion, Photochemistry)
- Life (Photosynthesis)
- Technology (Photovoltaics)

Increased generation
Understanding Earth with Thermodynamics

**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)