



Powering the Planet

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

Aligarh Muslim University

March 2024

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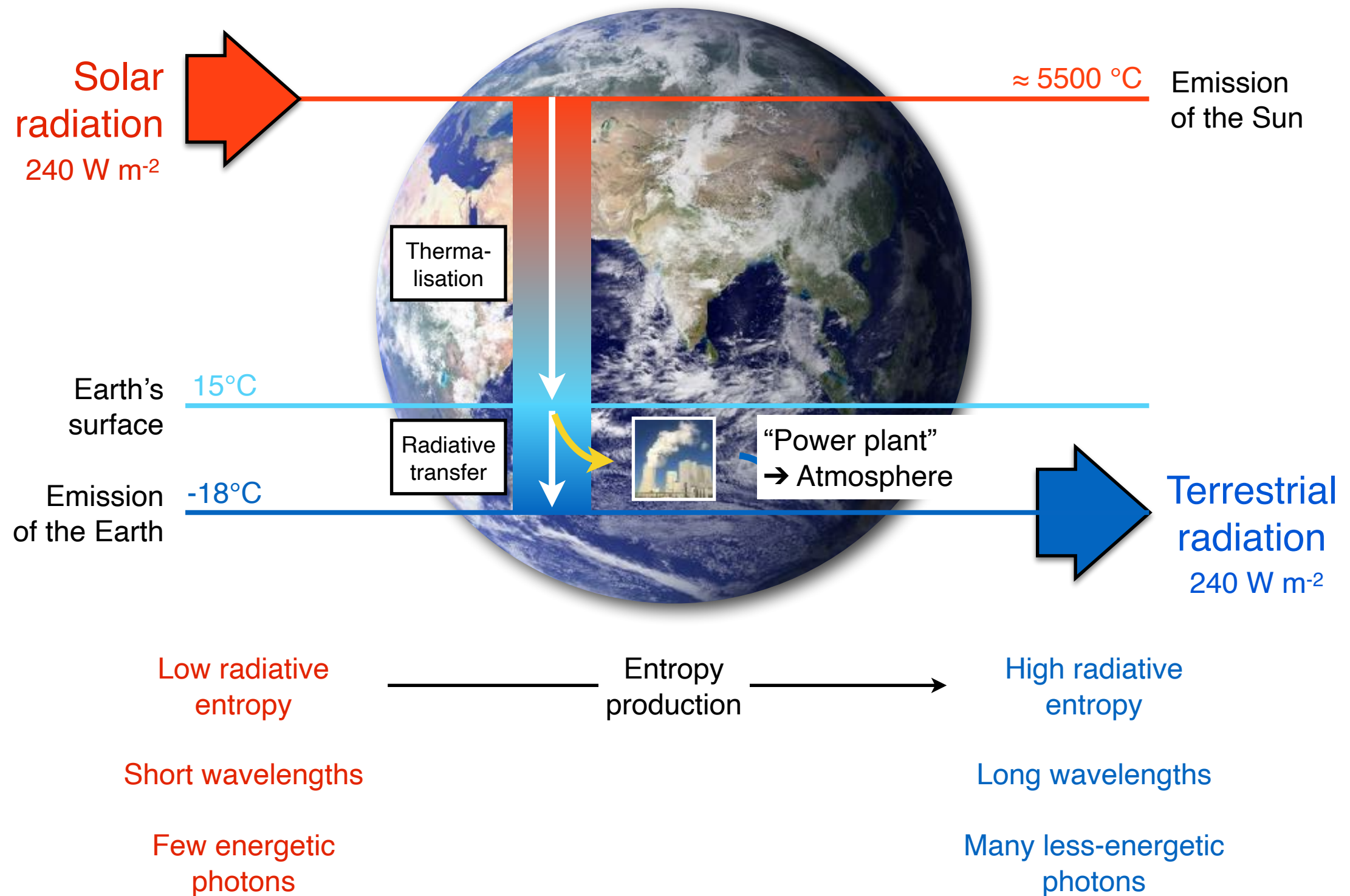
<http://gaia.mpg.de> ❖ earthsytem.org

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*

Thermodynamics of the Planet



Limits to Free Energy



First law: Energy conservation

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

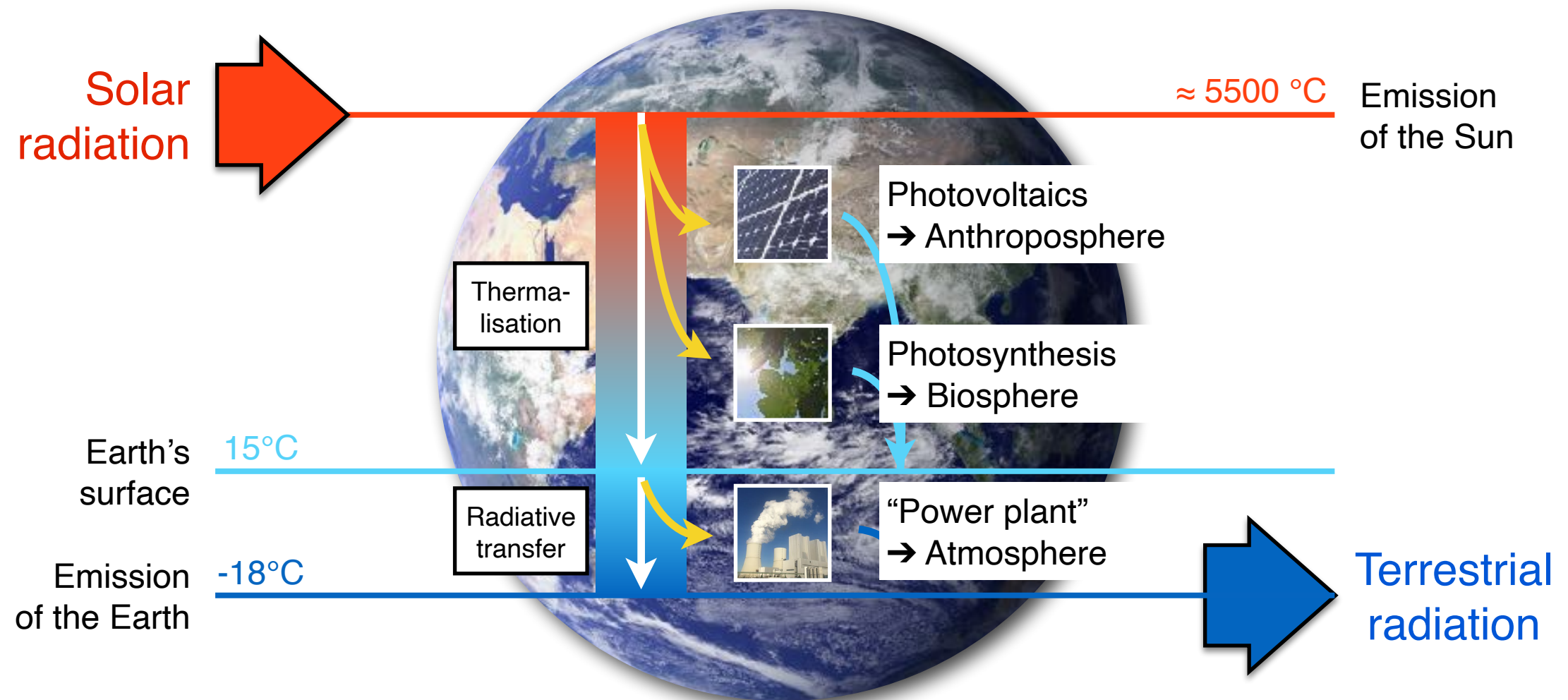
Second law: Entropy increase

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

Useful energy
(no entropy)

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

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

Planetary
energy balance

Total
absorption

Emission
to space

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

-18°C

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

Surface
energy balance

15°C

R_s

+

$R_{l,d}$

=

σT_s^4

+

$H + LE$

Absorption
solar radiation

Absorption
terrestrial radiation

Emission from
the surface

Heat transport
by buoyancy
and evaporation

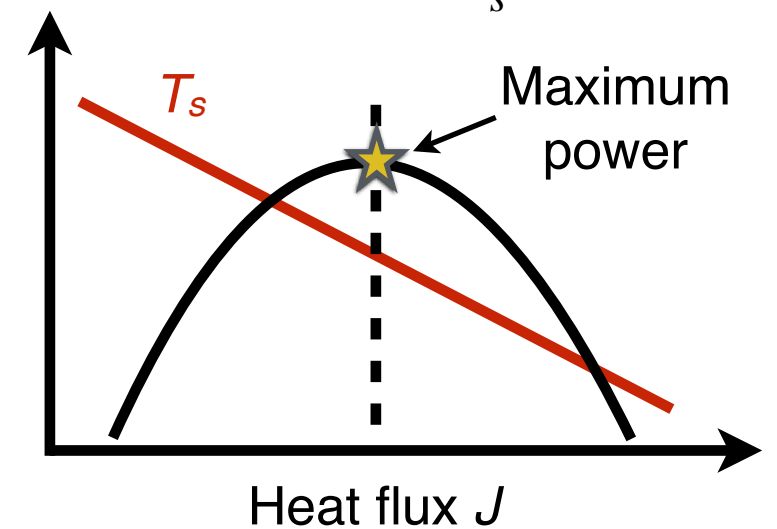
Radiative temperature

-18°C

Surface temperature

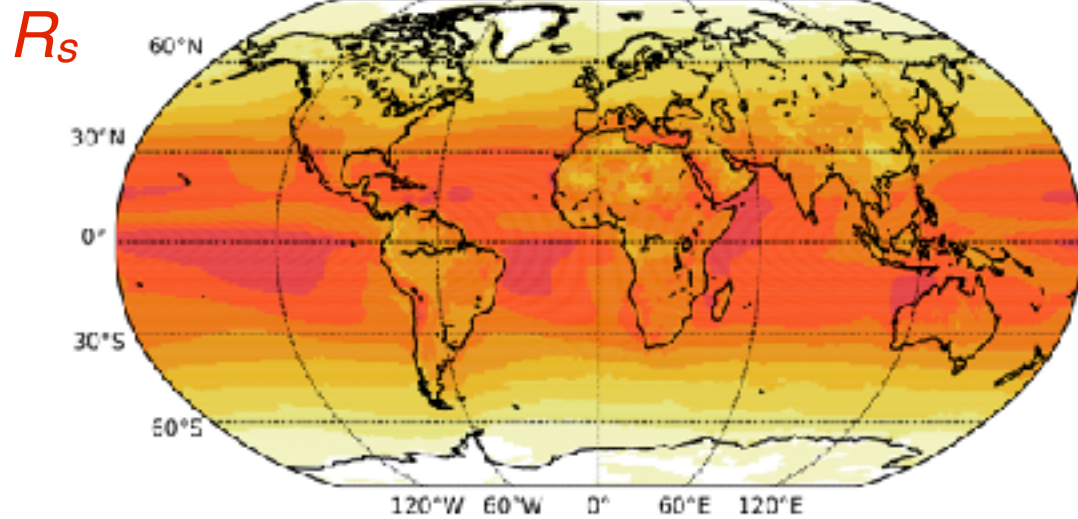
15°C

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

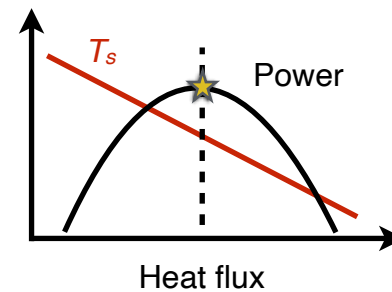
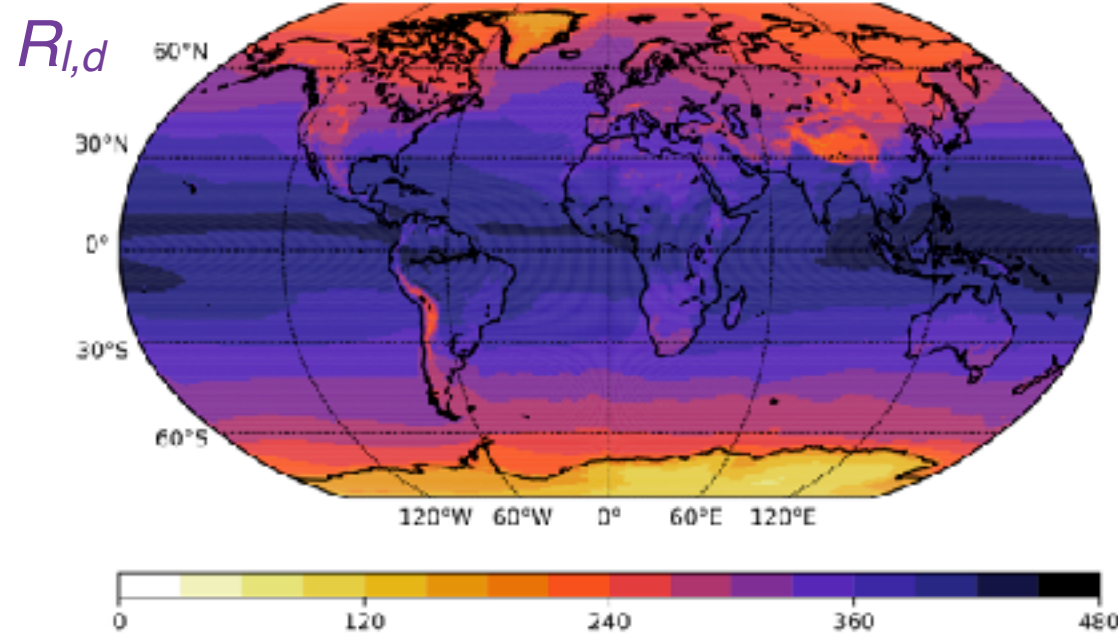


Surface heating by absorption of radiation

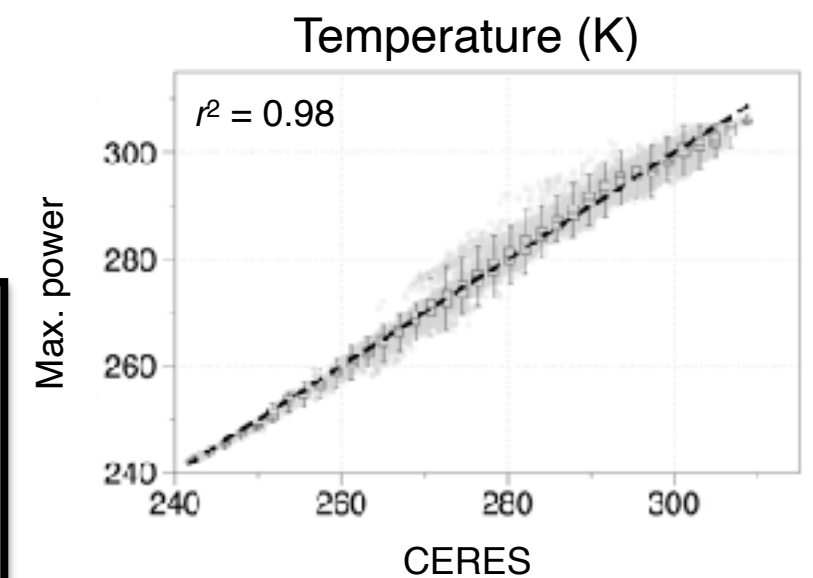
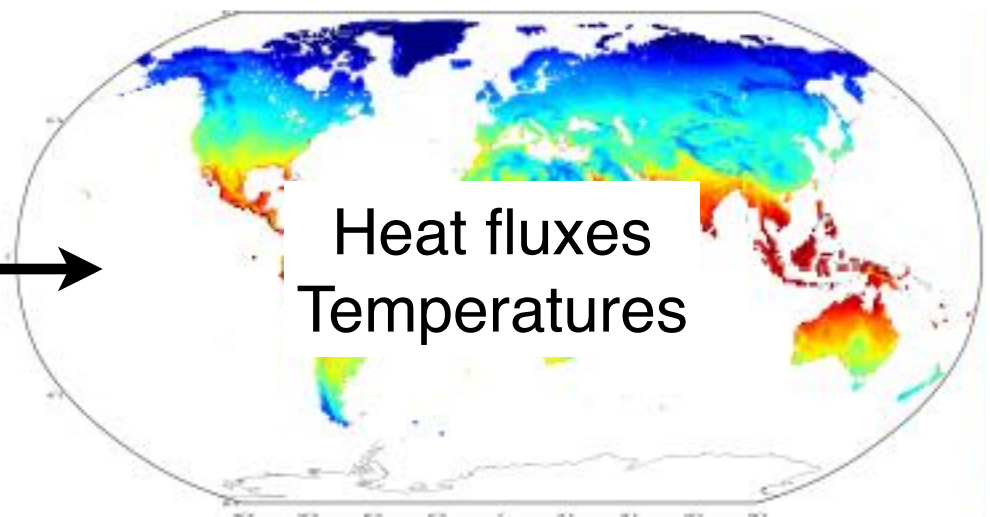
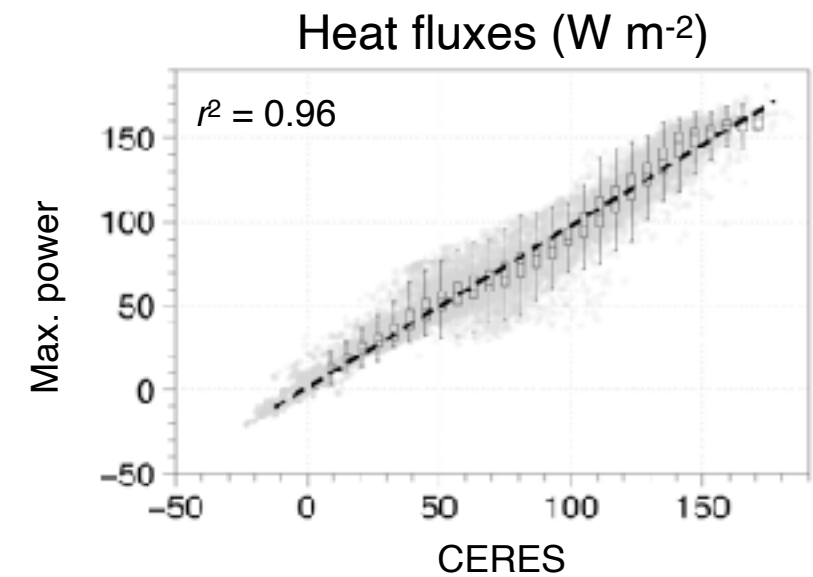
Solar (W m^{-2})



Terrestrial (W m^{-2})

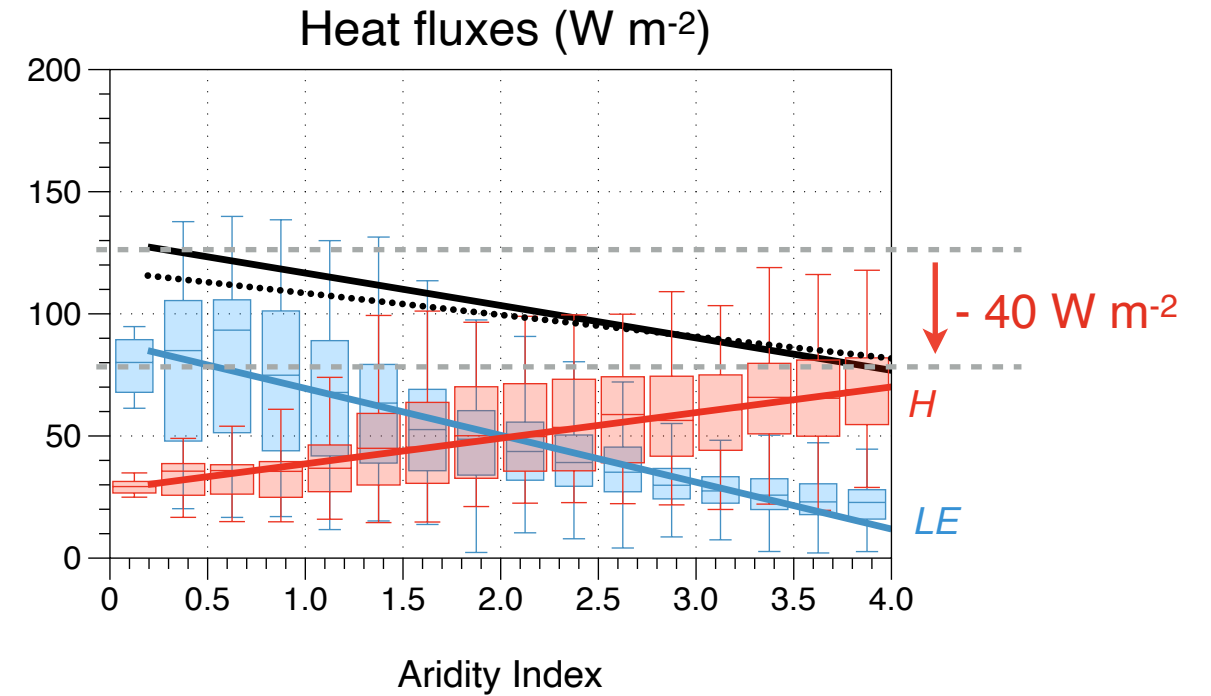
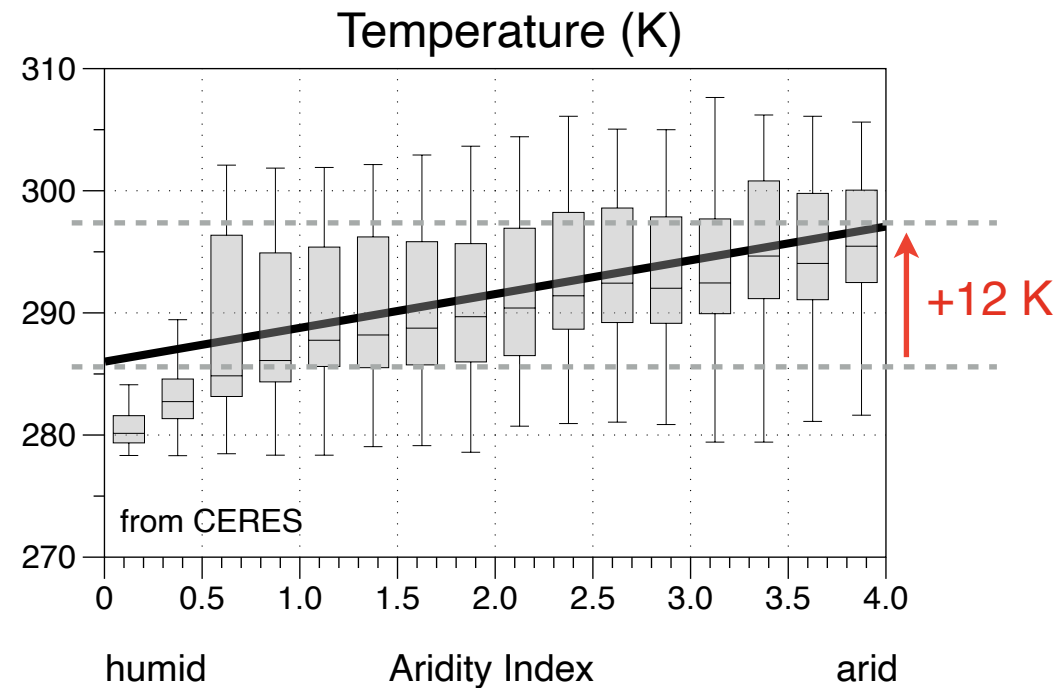


Maximum
power



Atmosphere
works as hard
as it can!

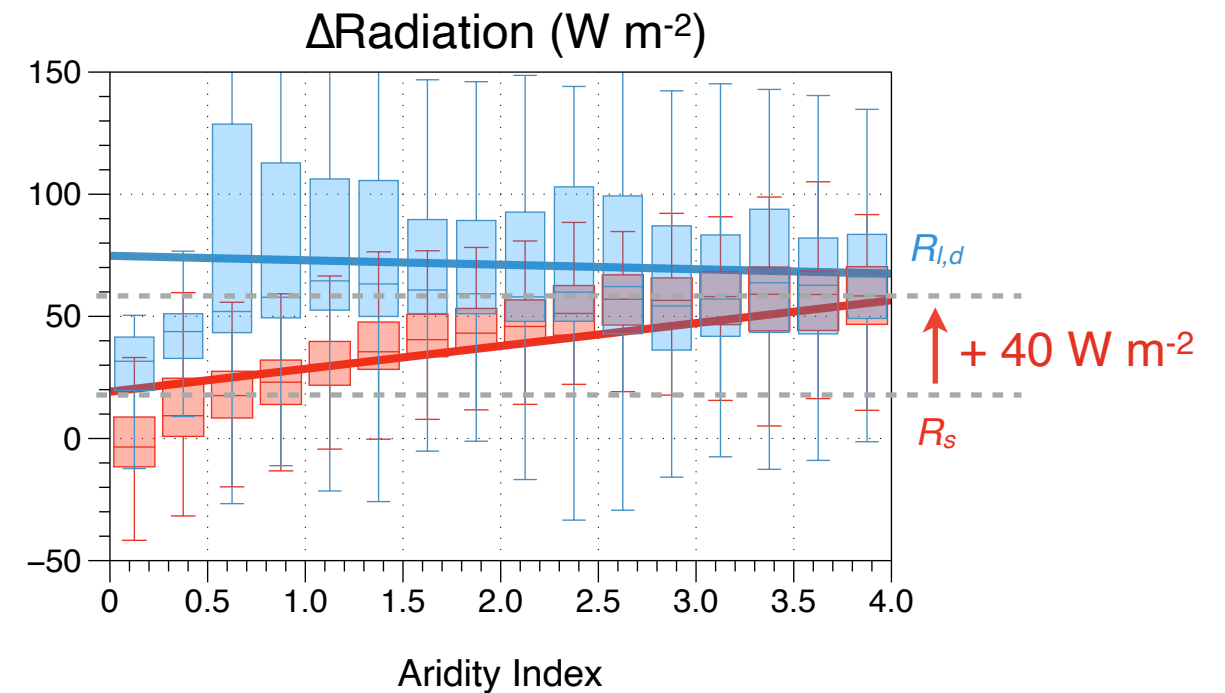
Why are deserts warmer?



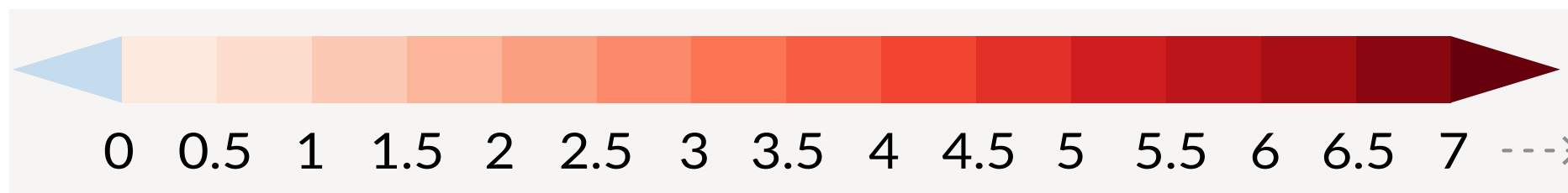
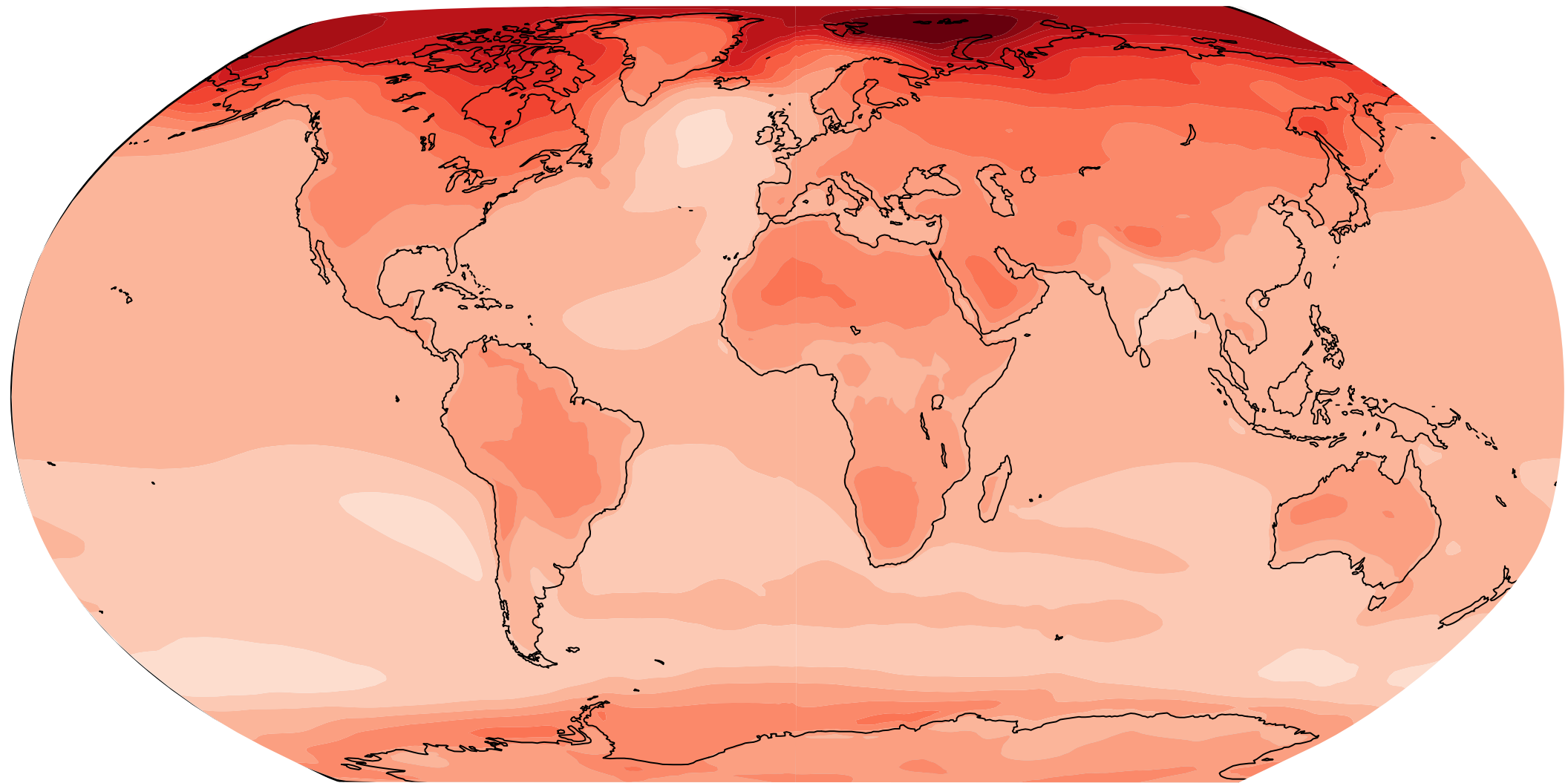
$$\Delta T_s = \frac{\Delta R_s + \Delta R_{l,d} - \Delta LE - \Delta H}{4\sigma T_{s,0}^3}$$

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

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



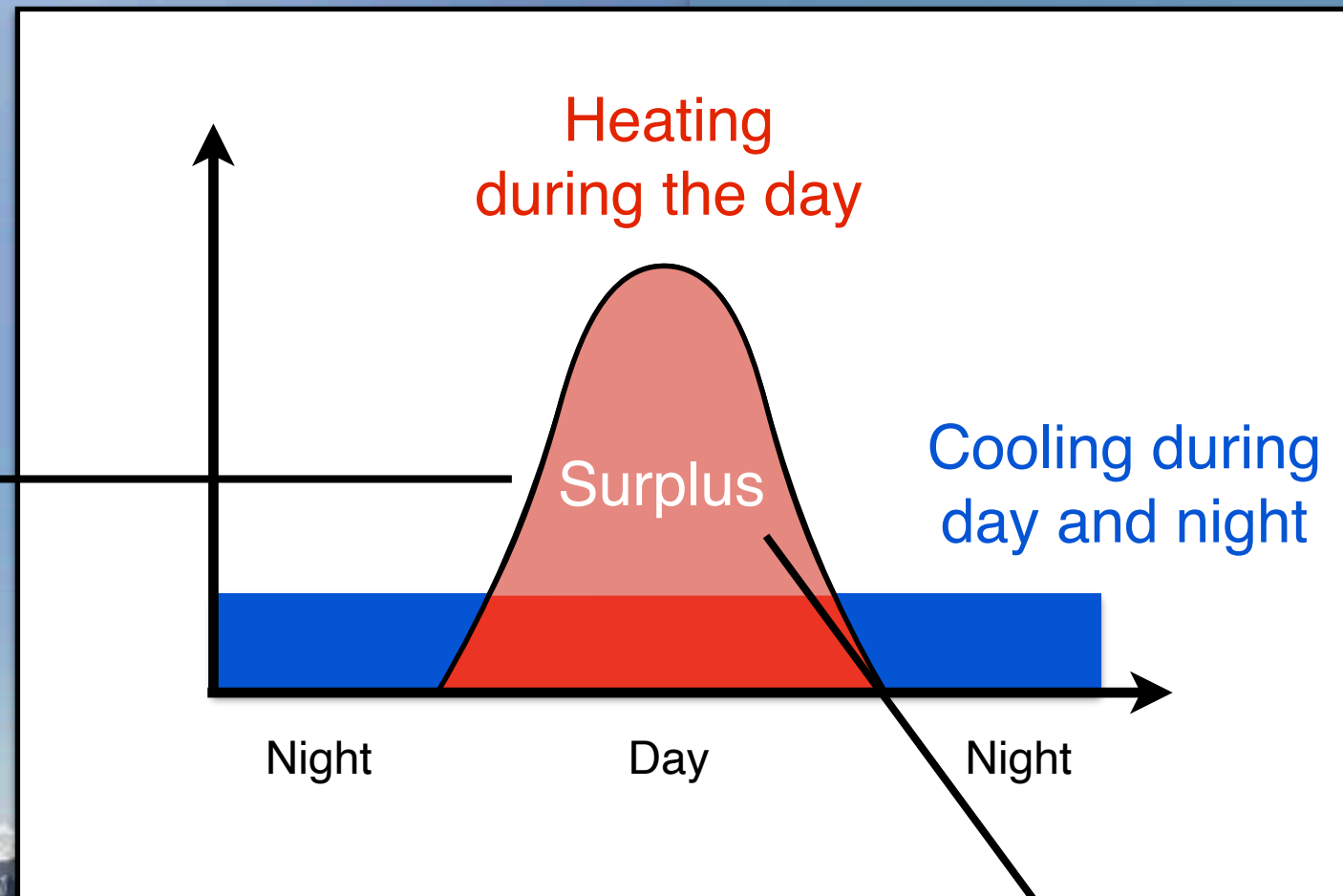
Global Warming at +2 K



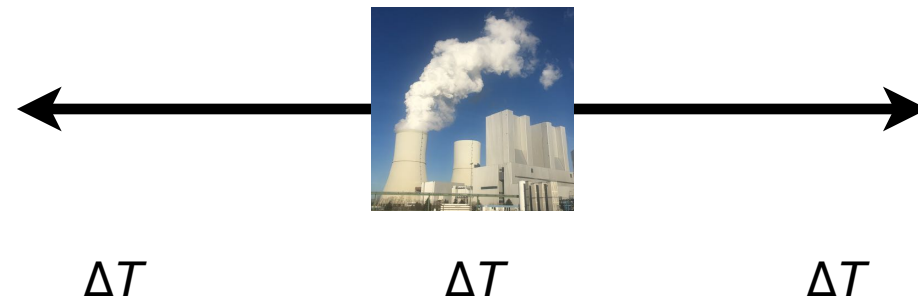
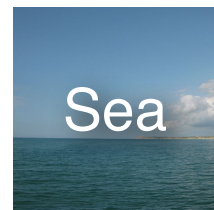
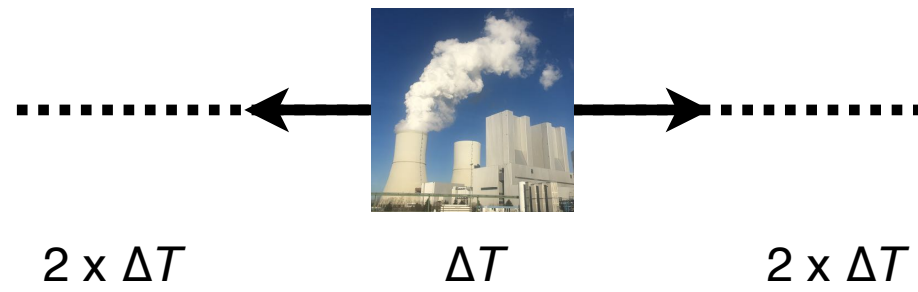
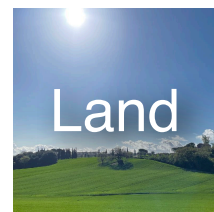
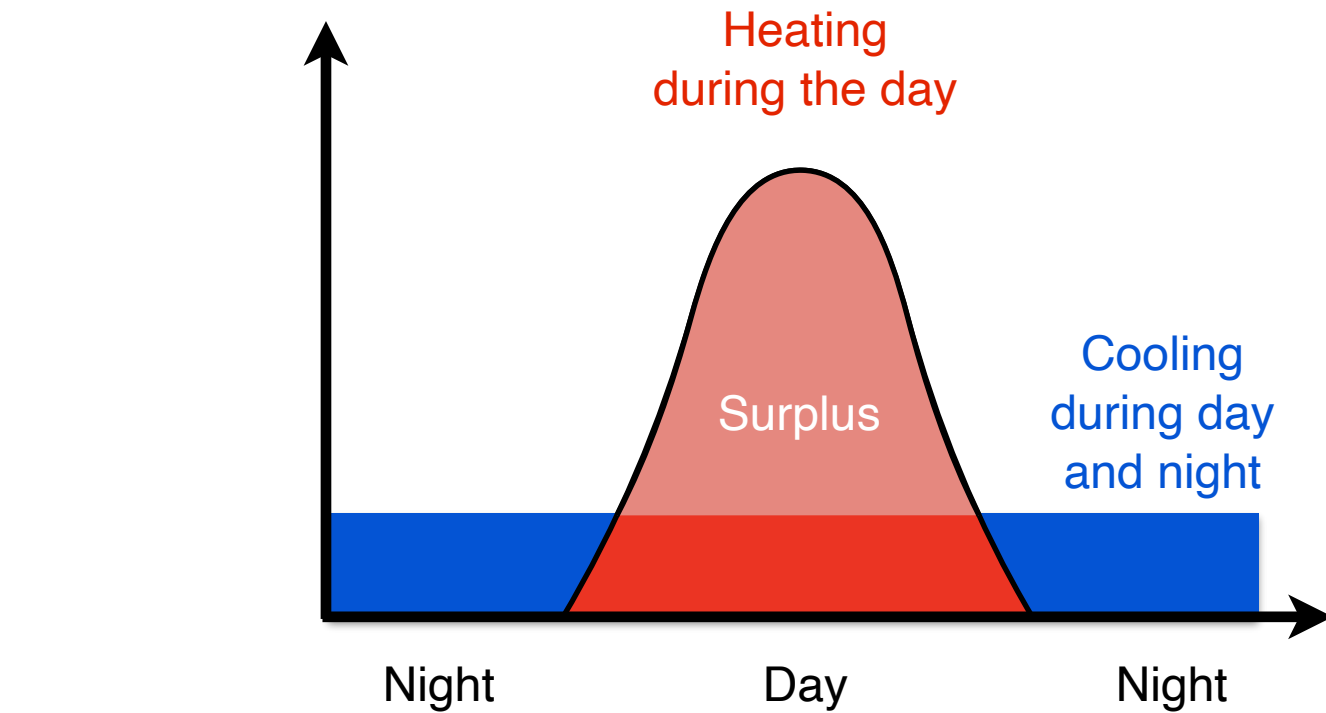
Temperature Difference (K)

Why does land heat up more strongly than the sea?

Changes in heat storage above the surface

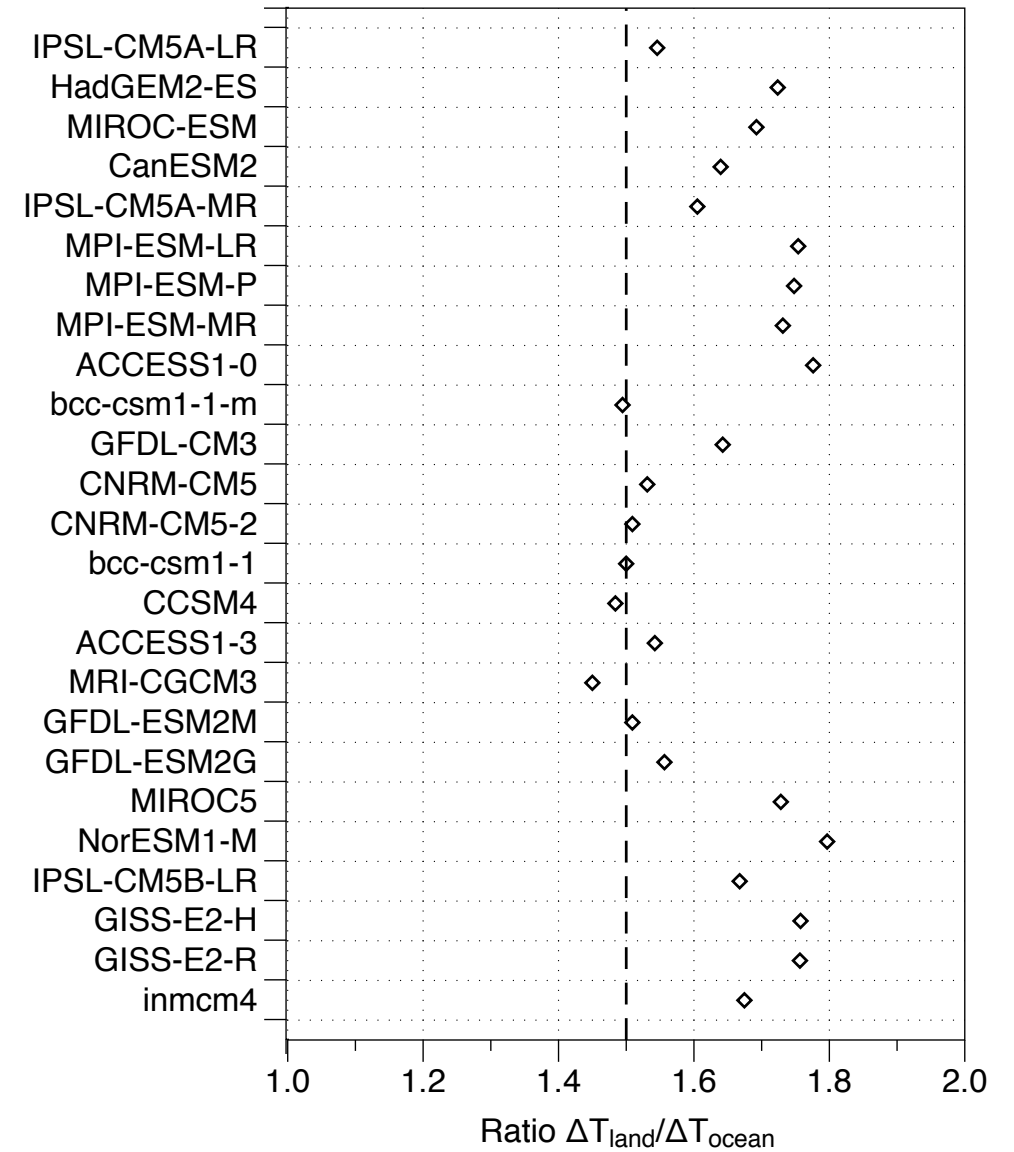


Changes in heat storage below the surface



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

Climate model scenarios



Data: CMIP5

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

Powering the Climate System

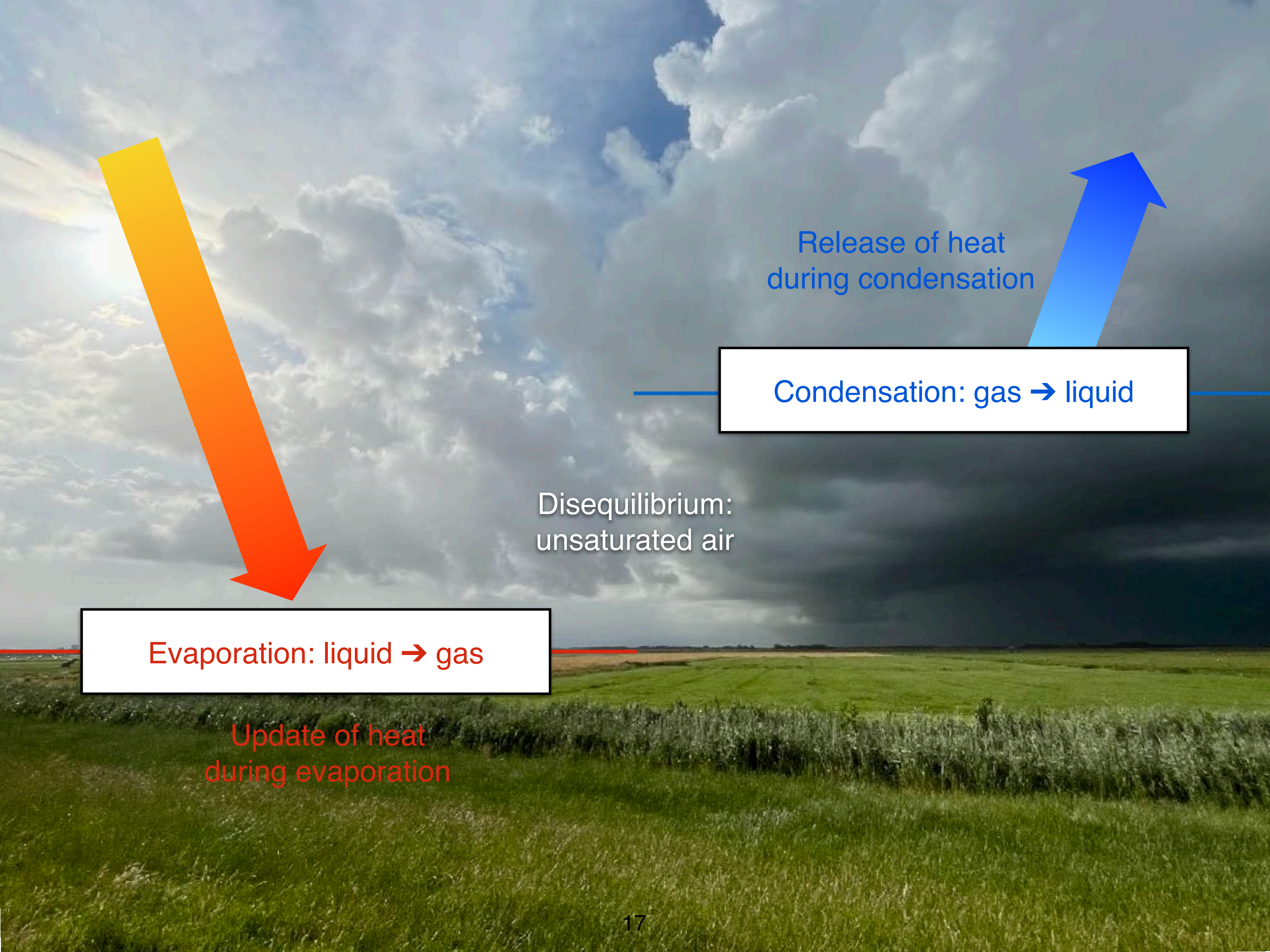
- Atmosphere appears to work as hard as it can
- Predicts temperatures and energy balance partitioning across continents
- Deserts are warmer because
 - (a) more solar radiation
 - (b) weaker power plant!
- Land heats more strongly with global warming than the sea because power is only generated during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

Saturation

Evaporation: liquid → gas

=

Condensation: gas → liquid



Release of heat
during condensation

Condensation: gas → liquid

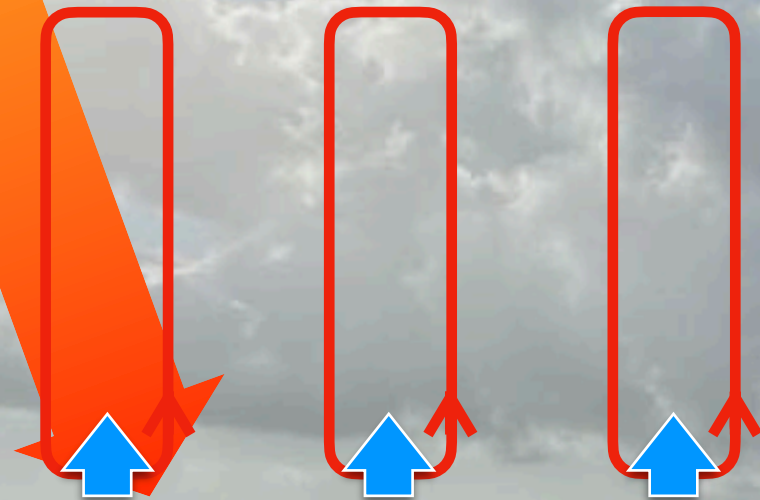
Disequilibrium:
unsaturated air

Evaporation: liquid → gas

Update of heat
during evaporation

Evaporation phase

Precipitation phase



Evaporation: liquid \rightarrow gas

Work done by solar heating:
generates buoyancy, transports water vapor,
humidifies atmosphere, depletes disequilibrium

Condensation: gas \rightarrow liquid

Work done by condensational heating:
generates buoyancy, transports water vapour,
dehumidifies atmosphere, generates disequilibrium

Absorbed
solar radiation

Max.
power



Turbulent
heat fluxes

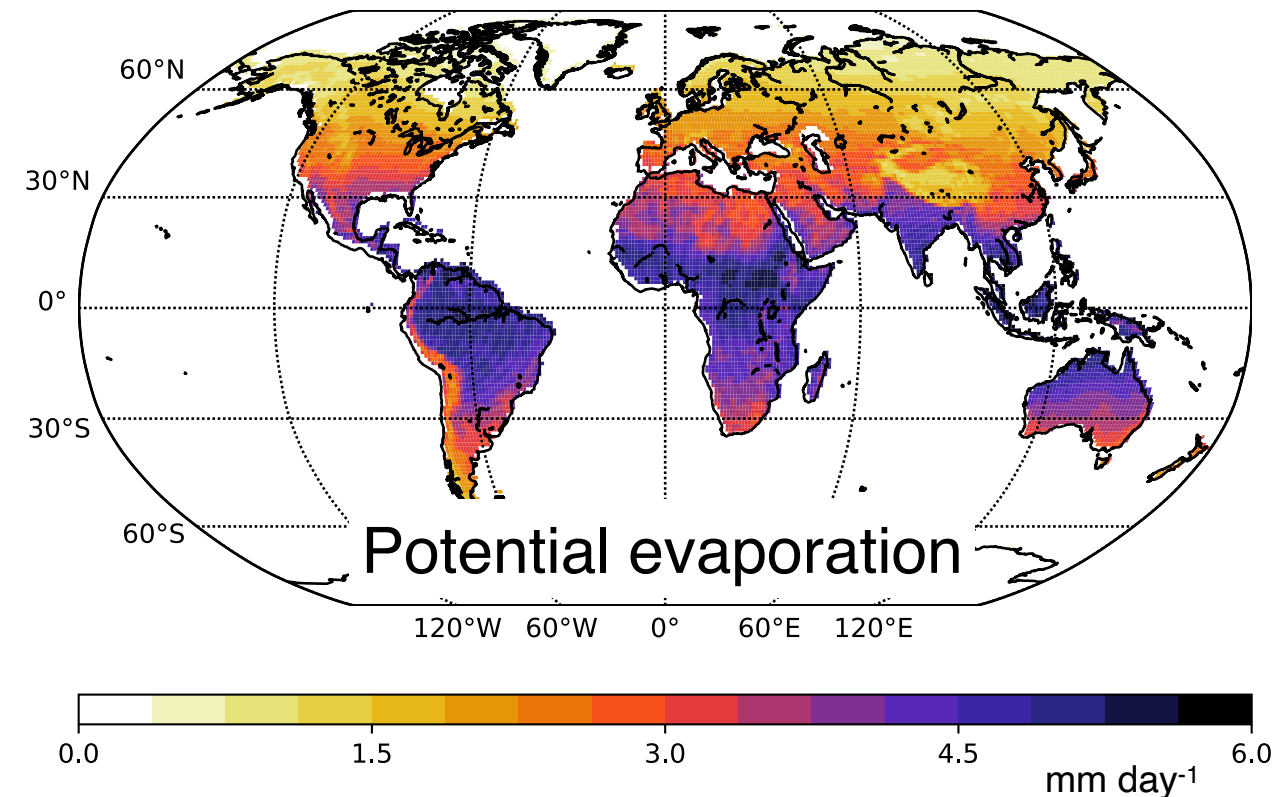
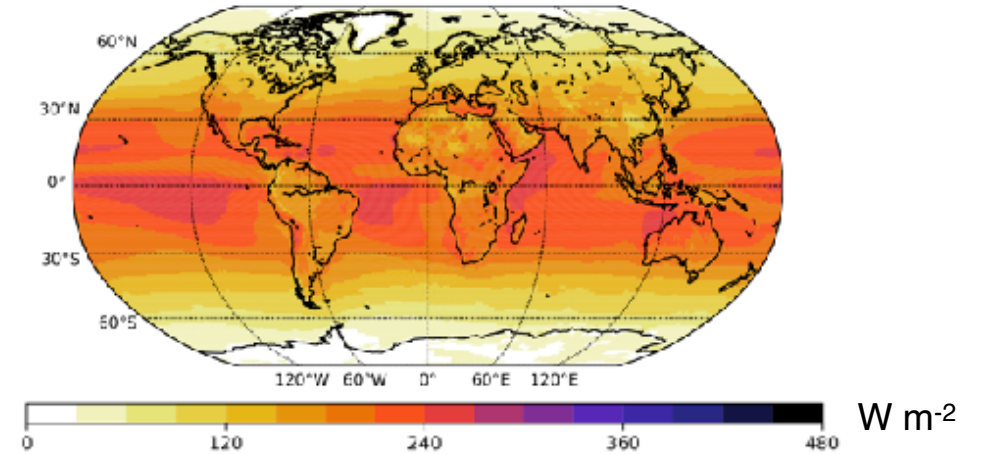
$\gamma/(s+\gamma)$

$s/(s+\gamma)$

Sensible
heat flux
(buoyancy)

Latent
heat flux
(evaporation)

Thermodynamic
equilibrium
partitioning



Absorbed
solar radiation

Max.
power



Turbulent
heat fluxes

$\gamma/(s+\gamma)$

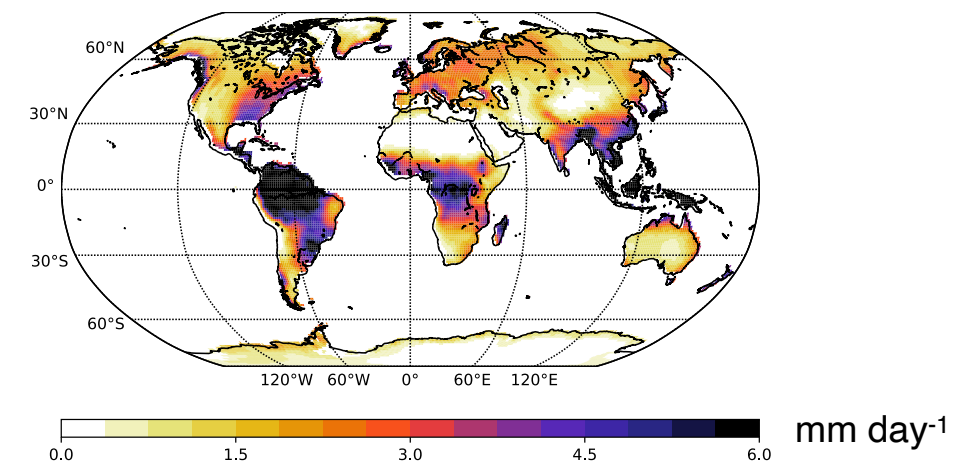
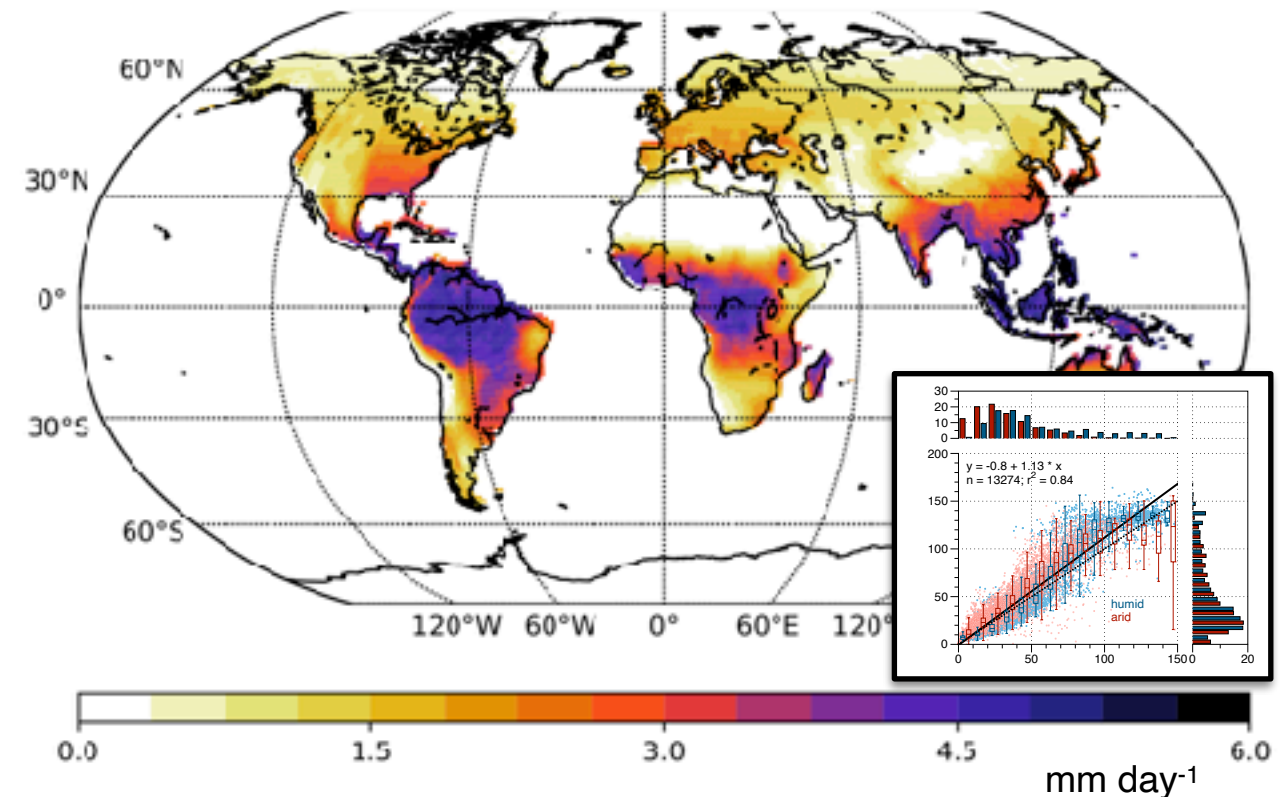
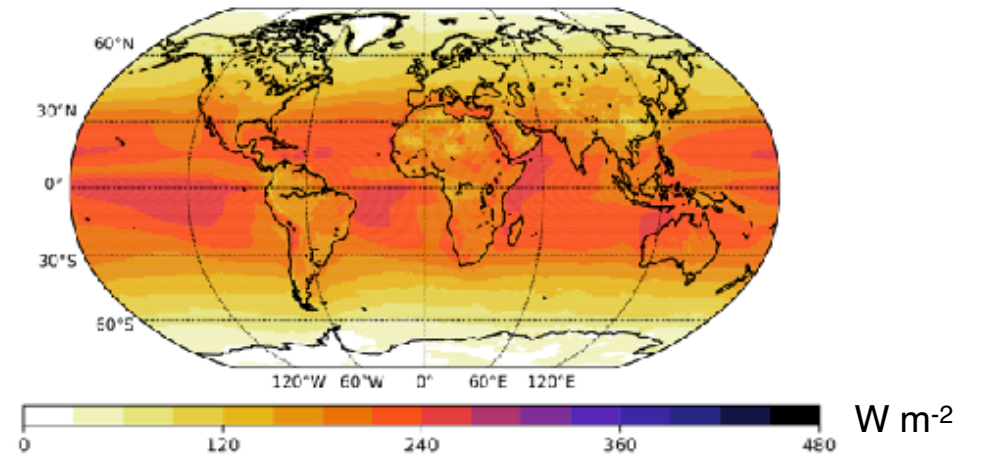
$s/(s+\gamma)$

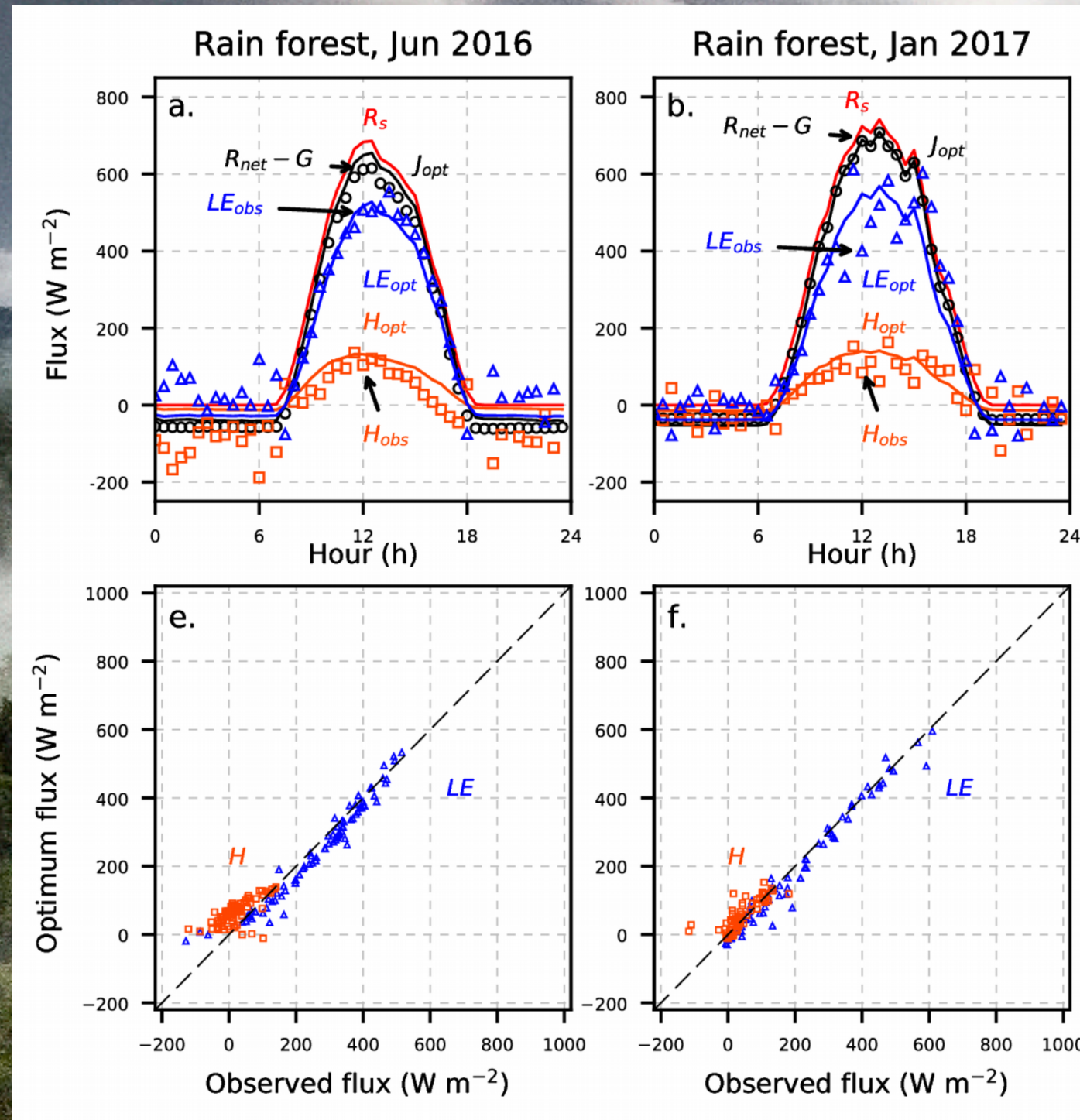
Sensible
heat flux
(buoyancy)

Latent
heat flux
(evaporation)

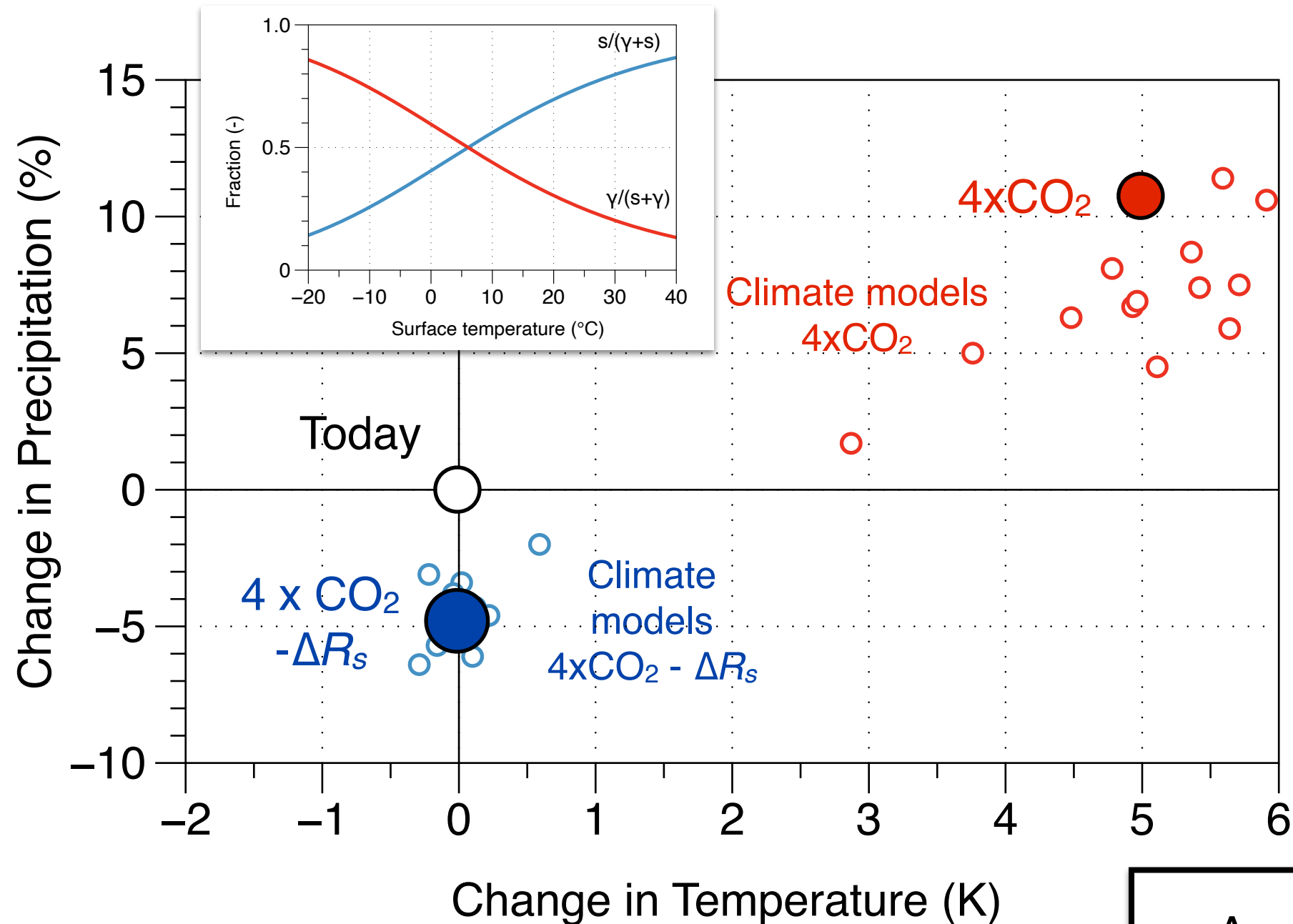
Precipitation

Thermodynamic
equilibrium
partitioning





Global Warming



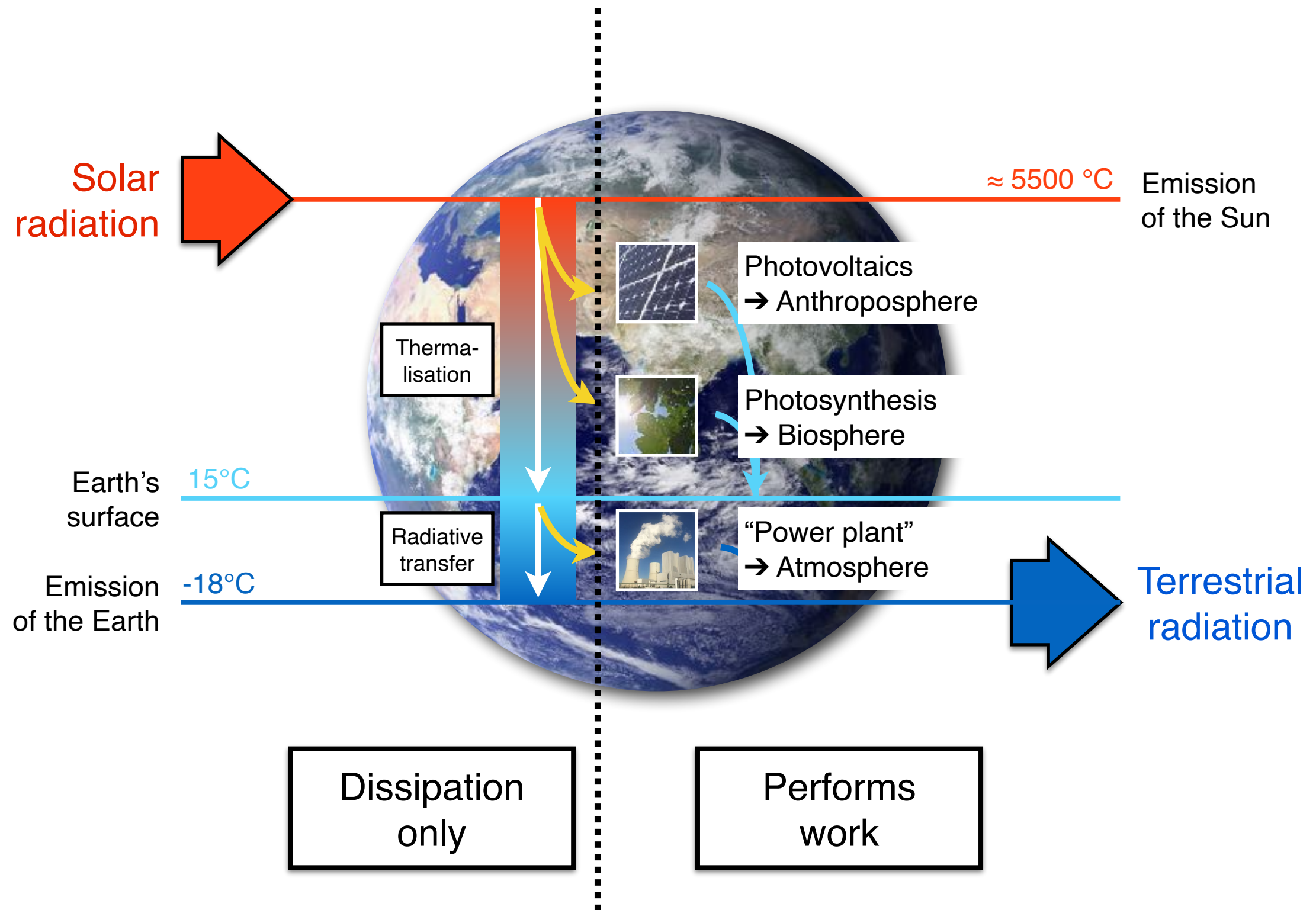
Acceleration of the hydrological cycle mostly explained by thermodynamics

Powering the Hydrological Cycle

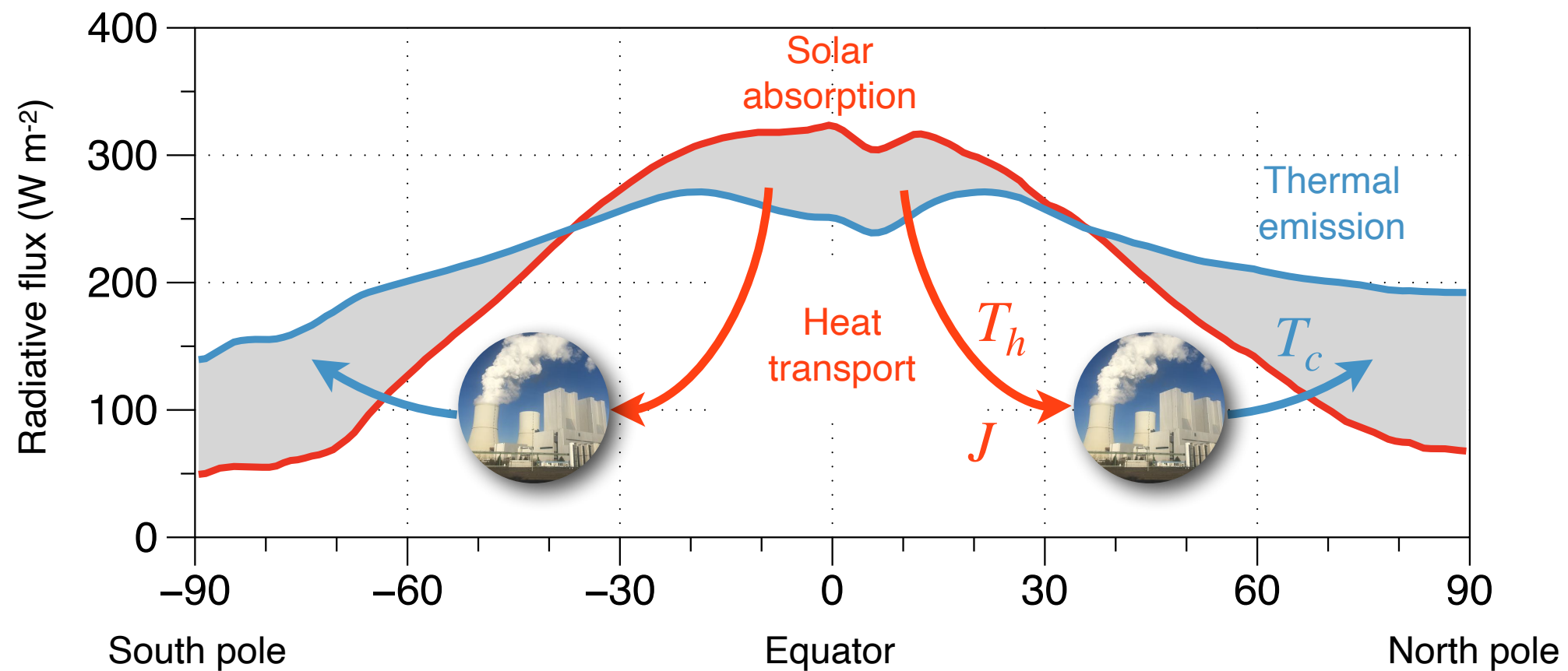
- Hydrologic cycle represents thermodynamic disequilibrium
- (Potential) evaporation is set by thermodynamic constraints: ability to add and transport vapor
- Rainforest appears to operate at this thermodynamic limit
- Acceleration of the hydrological cycle mostly explained by thermodynamics

Renewable Energy





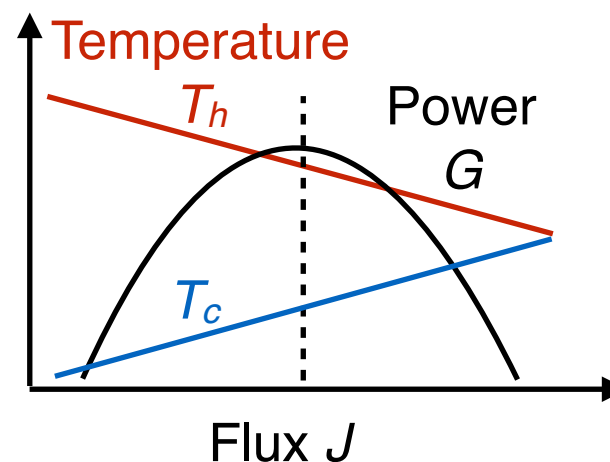
Generation of Large-scale Wind Energy



Thermodynamic limit:

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

More transport
→ less efficiency:



Maximum power:

Heat flux:	50 W m^{-2}
$T_h - T_c$:	$\approx 30 \text{ K}$
Power:	$0.5 \times 50 \times 10\%$
	$\approx 2.5 \text{ W m}^{-2}$
Global:	$\approx 1000 \text{ TW}$
Efficiency:	$\approx 1\%$

Earth system process

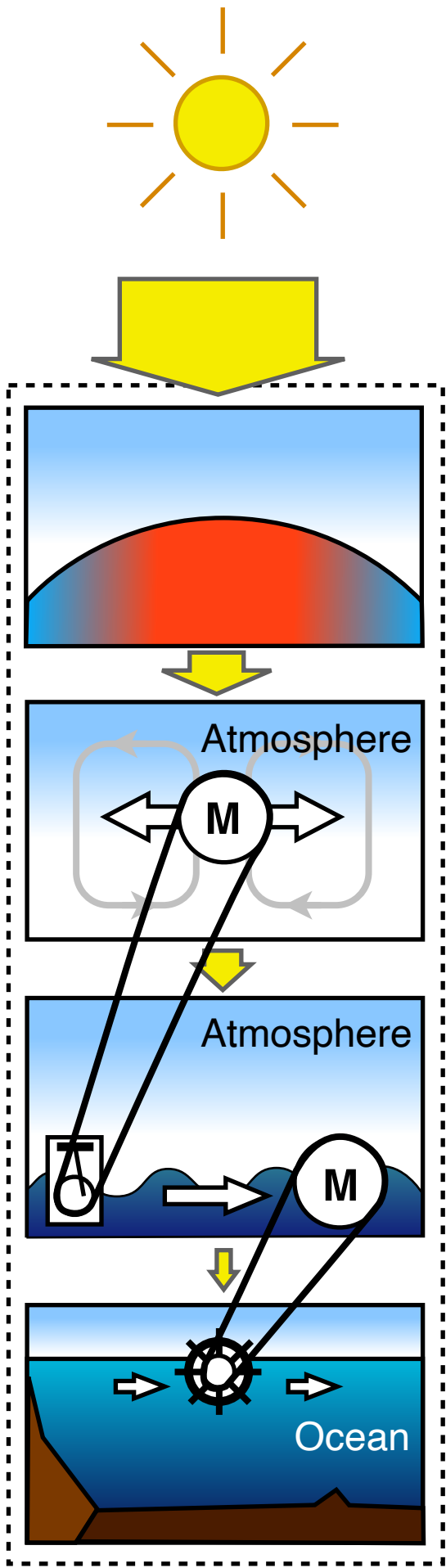
Solar irradiation

Absorption generates heating

Heating differences cause motion

Motion generates waves

Waves generate ocean currents



≈ 175000 TW

Absorption 70%
Differential heating 40%

≈ 49000 TW

Conversion (maximal)
2%

≈ 1000 TW

Conversion (observed)
6%

≈ 60 TW

Conversion (observed)
8%

≈ 5 TW

≈ 20 TW

Renewable energy

Solar power

Wind energy

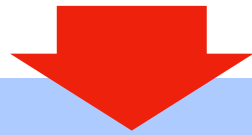
Wave energy

Energy from ocean currents

Human societies

1000 TW

Input of kinetic energy
from the free atmosphere



1-2 km

≈ 50%
500 TW



Frictional losses
within the
boundary layer



*Reduction of wind
speed by wind
turbines*



Mixing losses
in wakes



Surface
friction



< 38% Electrical
energy

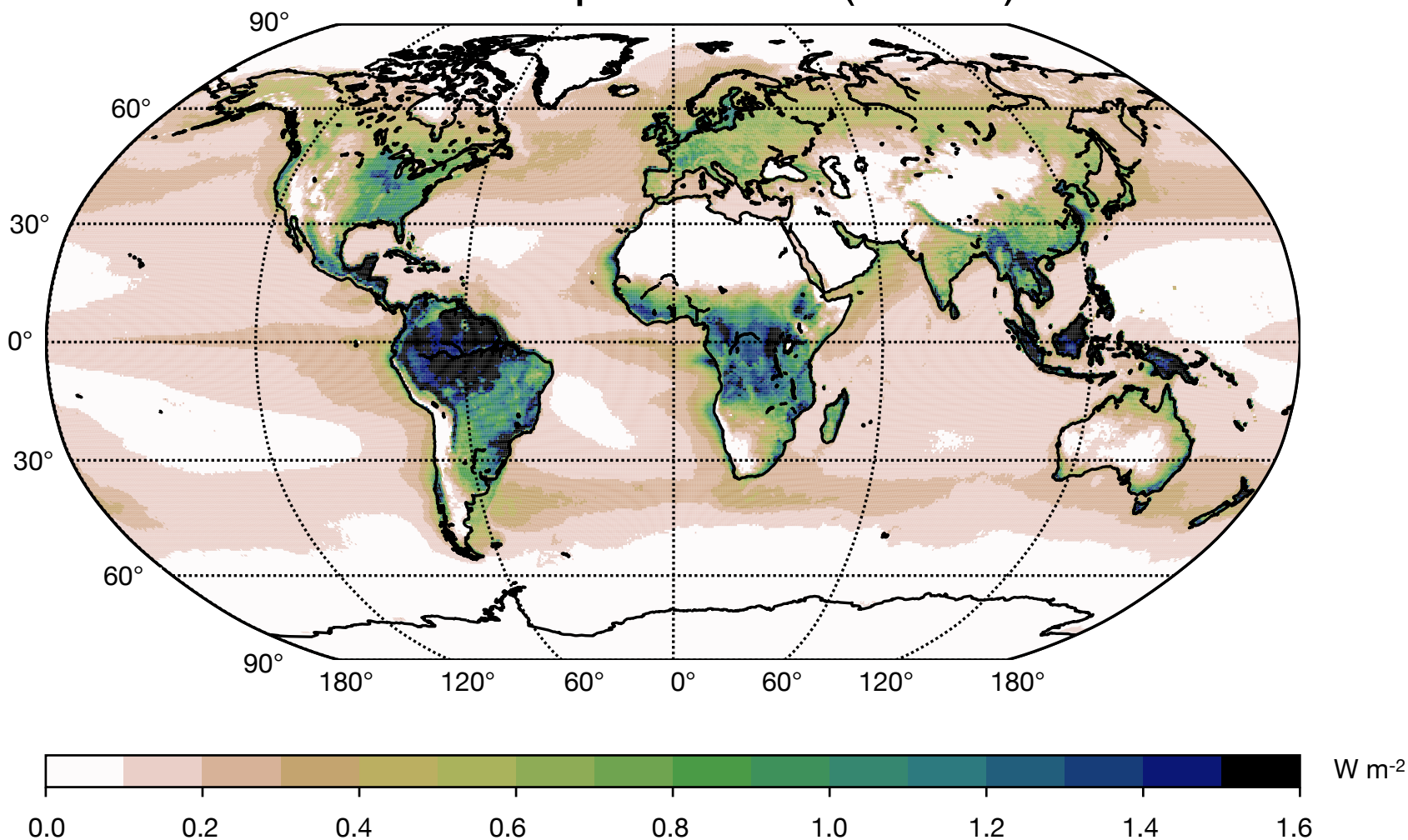
≈ 50%
500 TW

≥ 310 TW

≤ 190 TW

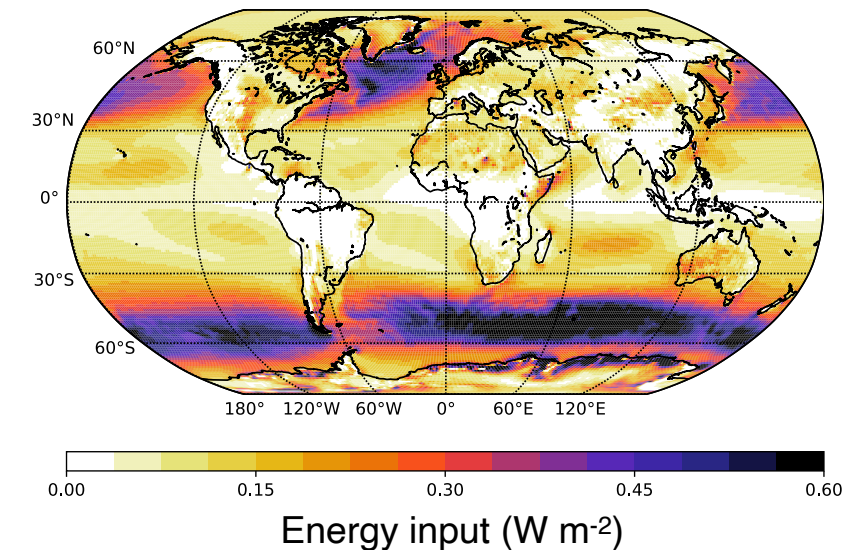
Power from Photosynthesis

Biomass production ("NPP")

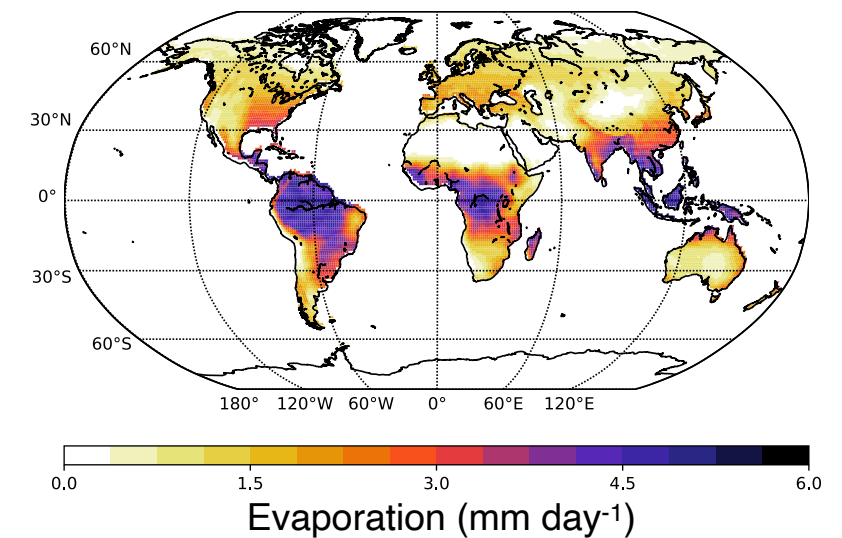


Land: 152 TW ($\approx 1\%$)

Ocean: mixing



Land: gas exchange



Wind energy



Efficiency: $< 1\%$
Power: 1 000 TW

Photosynthesis



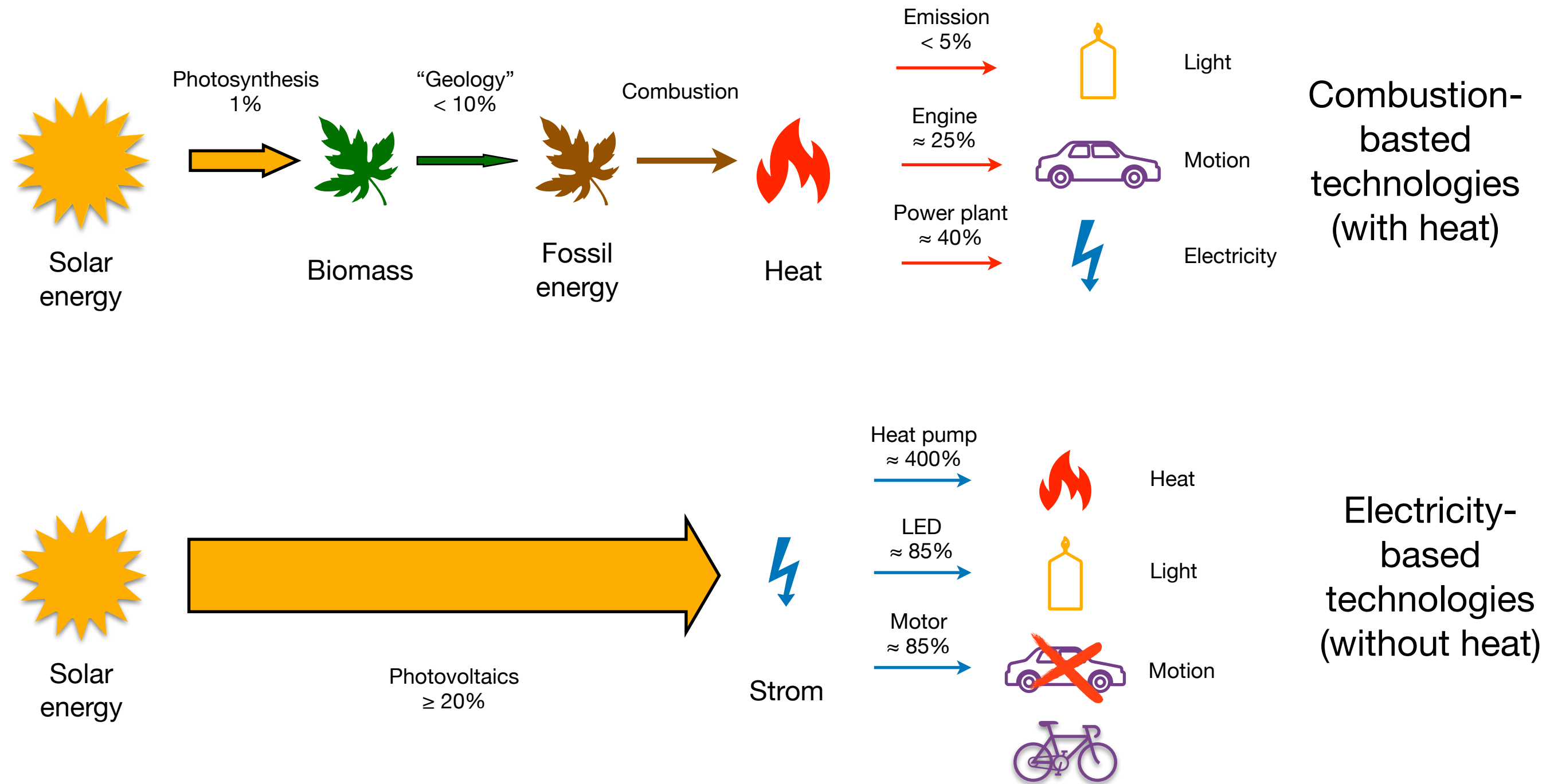
Efficiency: $< 1\%$
Power: 152 TW

Photovoltaics



Efficiency: $\approx 20\%$
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

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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

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Received: 29 July 2022 – Discussion started: 22 August 2022
Revised: 11 July 2023 – Accepted: 18 July 2023 – Published: 30 August 2023

Abstract. Optimality concepts related to energy and entropy have long been proposed to govern Earth system processes, for instance in the form of propositions that certain processes maximize or minimize entropy production. These concepts, however, remain quite obscure, seem contradictory to each other, and have so far been mostly disregarded. This review aims to clarify the role of thermodynamics and optimality in Earth system science by showing that they play a central role in how, and how much, work can be derived from solar forcing and that this imposes a major constraint on the dynamics of dissipative structures of the Earth system. This is, however, not as simple as it may sound. It requires a consistent formulation of Earth system processes in thermodynamic terms, including their linkages and interactions. Thermodynamics then constrains the ability of the Earth system to derive work and generate free energy from solar radiative forcing, which limits the ability to maintain motion, mass transport, geochemical cycling, and biotic activity. It thus limits directly the generation of atmospheric motion and other processes indirectly through their need for transport. I demonstrate the application of this thermodynamic Earth system view by deriving first-order estimates associated with atmospheric motion, hydrologic cycling, and terrestrial productivity that agree very well with observations. This supports the notion that the emergent simplicity and predictability inherent in observed climatological variations can be attributed to these processes working as hard as they can, reflecting thermodynamic limits directly or indirectly. I discuss how this thermodynamic interpretation is consistent with established theoretical concepts in the respective disciplines, interpret other optimality concepts in light of this thermodynamic Earth system view, and describe its utility for Earth system science.

1 Introduction

The Earth system is an incredibly complex system, with many processes interacting with each other, from the small and local scale up to the planetary scale. With human activity playing an increasing role, it appears that the system becomes even more complicated. This may seem to make the Earth a highly unpredictable and chaotic system, with arbitrary evolutionary directions and outcomes. It would seem that the only contribution from physics to constrain the dynamics of this complex system comes from the basic conservation laws, as these provide the accounting basis for energy, mass, and momentum as well as other conserved quantities.

Yet, on the other hand, we observe various forms of relatively simple emergent patterns in the Earth system that re-

fect highly predictable outcomes. Such emergent simplicity is, for instance, reflected in highly predictable seasonal and geographic variations of temperature and precipitation that have led to climate classifications (e.g. Köppen, 1900), in typical surface energy balance partitioning and associated hydrologic classification schemes, such as the aridity index of Budyko (1974) that can be used to describe clear and predictable changes in partitioning with increasing aridity, and in the well-documented variation of terrestrial biomes along gradients in climate (e.g. von Humboldt, 1845; Holdridge, 1947; Whittaker, 1962; Prentice et al., 1992). How does this simplicity emerge from the dynamics of such a complex system? It would seem that there are further constraints at play when it comes to such predictable aspects of the Earth sys-

Published by Copernicus Publications on behalf of the European Geosciences Union.

BBA - Bioenergetics 1862 (2021) 148303



Contents lists available at ScienceDirect

BBA - Bioenergetics

journal homepage: www.elsevier.com/locate/bbaio



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

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ARTICLE INFO

Keywords:
Photosynthesis
Thermodynamics
Stability
Evaporation
Ecosystems
Maximum power

ABSTRACT

Photosynthesis converts sunlight into the chemical free energy that feeds the Earth's biosphere, yet at levels much lower than what thermodynamics would allow for. I propose here that photosynthesis is nevertheless thermodynamically limited, but this limit acts indirectly on the material exchange. I substantiate this proposition for the photosynthetic activity of terrestrial ecosystems, which are notably more productive than the marine biosphere. The material exchange for terrestrial photosynthesis involves water and carbon dioxide, which I evaluate using global observation-based datasets of radiation, photosynthesis, precipitation and evaporation. I first calculate the conversion efficiency of photosynthesis in terrestrial ecosystems and its climatological variation, with a median efficiency of 0.77% ($n = 13,276$). The rates tightly correlate with evaporation on land ($r^2 = 0.87$), which demonstrates the importance of the coupling of photosynthesis to material exchange. I then infer evaporation from the maximum material exchange between the surface and the atmosphere that is thermodynamically possible using datasets of solar radiation and precipitation. This inferred rate closely correlates with the observation-based land evaporation dataset ($r^2 = 0.84$). When this rate is converted back into photosynthetic activity, the resulting patterns correlate highly with the observation-based dataset ($r^2 = 0.66$). This supports the interpretation that it is not energy directly that limits terrestrial photosynthesis, but rather the material exchange that is driven by sunlight. This interpretation can explain the very low, observed conversion efficiency of photosynthesis in terrestrial ecosystems as well as its spatial variations. More generally, this implies that one needs to take the necessary material flows and exchanges associated with life into account to understand the thermodynamics of life. This, ultimately, requires a perspective that links the activity of the biosphere to the thermodynamic constraints of transport processes in the Earth system.

1. Introduction

Photosynthesis is the most dominant process by which chemical free energy is generated in the Earth's system [1] and which sustains the Earth's biosphere. This chemical free energy, and the associated chemical disequilibrium, is reflected in the high concentration of oxygen in the Earth's atmosphere and the large amounts of reduced, organic carbon compounds elsewhere, such as the biomass associated with the biosphere, organic carbon stored in soils, and hydrocarbons contained in geologic reservoirs. This energy has substantially transformed the physical and chemical environment of the Earth, from covering tropical regions with lush rainforests to transforming an atmosphere to low greenhouse gas concentrations, particularly of carbon dioxide, and high levels of reactive oxygen. We may ask which factors ultimately constrain the level of photosynthetic activity? Are the constraints the kinetic reaction constants at the molecular scale, constraints to biological evolution, environmental factors, or the fundamental laws of

thermodynamics?

What I want to propose here is that the answer likely lies in the combination of the latter two factors, that is, that the laws of thermodynamics limit photosynthetic activity, but that this limit acts through environmental factors rather than directly on the energy conversion process from solar radiation into the chemical free energy stored in carbohydrates. To illustrate this proposition, I focus on the photosynthetic activity on land, as terrestrial ecosystems at large scales are substantially more productive than the marine counterparts. This is reflected at the planetary scale in estimates of how much carbon is taken up in form of CO_2 by photosynthesis. While the marine biosphere takes up around $50 \times 10^{15} \text{ g}$ of carbon per year [2] over about three quarters of the planetary surface that are covered by oceans, the terrestrial biosphere takes up more than twice as much ($123 \times 10^{15} \text{ g}$ of carbon per year [3]), yet over much less surface area. The highly productive rainforest ecosystems are thus a good reference point for understanding which factors constrain their high rates of photosynthesis

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https://doi.org/10.1016/j.bbaio.2020.148303

Received 15 May 2020; Received in revised form 21 July 2020; Accepted 27 August 2020
Available online 11 September 2020
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Radiative controls by clouds and thermodynamics shape surface temperatures and turbulent fluxes over land

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Edited by Kerry Emanuel, Massachusetts Institute of Technology, New Harbor, ME; received December 1, 2022; accepted June 3, 2023

Land surface temperatures (LSTs) are strongly shaped by radiation but are modulated by turbulent fluxes and hydrologic cycling as the presence of water vapor in the atmosphere (clouds) and at the surface (evaporation) affects temperatures across regions. Here, we used a thermodynamic systems framework forced with independent observations to show that the climatological variations in LSTs across dry and humid regions are mainly mediated through radiative effects. We first show that the turbulent fluxes of sensible and latent heat are constrained by thermodynamics and the local radiative conditions. This constraint arises from the ability of radiative heating at the surface to perform work to maintain turbulent fluxes and sustain vertical mixing within the convective boundary layer. This implies that reduced evaporative cooling in dry regions is then compensated for by an increased sensible heat flux and buoyancy, which is consistent with observations. We show that the mean temperature variation across dry and humid regions is mainly controlled by clouds that reduce surface heating by solar radiation. Using satellite observations for cloudy and clear-sky conditions, we show that clouds cool the land surface over humid regions by up to 7 K, while in arid regions, this effect is absent due to the lack of clouds. We conclude that radiation and thermodynamic limits are the primary controls on LSTs and turbulent flux exchange which leads to an emergent simplicity in the observed climatological patterns within the complex climate system.

land-atmosphere interactions | radiation | thermodynamics | clouds

Land surface temperature (LST) is one of the most significant climatological variables, shaping the physical environment of terrestrial ecosystems and being most strongly affected by global warming. Regional and seasonal variations are strongly modulated by both, atmospheric conditions, such as clouds, humidity, and heat transport (1–5), and land surface conditions, such as soil moisture, land cover, and vegetation type (6–12). An emergent simple feature of this variability is associated with aridity as dry regions and periods are typically associated with warmer temperatures (13, 14). On the one hand, it can be looked upon as a reflection of reduced evaporative cooling related to water limitation. On the other hand, these regions are also characterized by the absence of clouds, which enhances warming by altering the local radiative conditions. Alternatively, clouds cool the humid regions by reducing the solar absorption at the surface while the surface also cools by increased evaporation. While these two mechanisms are not entirely independent of each other (15–17) they do have a different impact on the surface energy budget of the region. Due to the highly coupled nature of the surface–atmosphere system (8, 18), it becomes almost impossible to separate the role of these effects. This leads to a key question: How much do soil water limitation and clouds affect surface temperatures across dry and humid regions?

To answer this question, we need to understand the impact of changes in radiative forcings on the turbulent flux exchange of sensible and latent heat between the surface and the atmosphere. However, these fluxes seem to be strongly coupled to highly heterogeneous land surface characteristics and appear unconstrained by the energy balance alone. With limited observations of land surface variables, they further remain uncertain in climate models and are generally described using a bulk aerodynamic approach and separating changes in partitioning with increasing aridity. Owing to this inherent complexity, there remains substantial intermodel disagreement and biases in their estimates (22–24). This further makes it difficult to separate the roles of evaporation, turbulent fluxes, and local radiative conditions in shaping surface temperatures.

To address this challenge, we provide an alternative approach by viewing turbulent land surface exchange in the framework of a thermodynamic system. The key idea is to explicitly consider the second law of thermodynamics in addition to surface energy balance (25–28). The second law sets the direction of energy conversions and limits the total power generated out of a heating difference by requiring an overall increase in entropy. This outcome is then reflected in the well-established Carnot limit of heat

Significance

Land surface temperatures are a key characteristic of climate. Yet, understanding the main factors that shape them remains challenging because of the apparent dependence on many factors, such as radiation, turbulence, water availability, and vegetation. We use a fundamental, physical approach starting with radiation as the main forcing and constraining turbulent fluxes by their ability to perform maximum work to generate convective motion. This approach works very well in predicting observed climatological variations in surface temperatures, showing that arid regions are typically warmer due to the stronger solar heating in the absence of clouds. The implication is that the climatological variations of surface temperatures are predominantly shaped by radiation, clouds, and thermodynamic limits.

Author contributions: S.A.G., E.Z., and A.K. designed research; S.A.G. performed research; Y.T. and A.K. contributed new reagents/analytic tools; S.A.G. analyzed data; Y.T. helped in the interpretation of the results and writing of the manuscript; E.Z. helped in the interpretation of the results and writing of the manuscript; A.K. helped in the interpretation of the results and writing of the manuscript; and S.A.G. wrote the paper. The authors declare no competing interest. This article is a PNAS Direct Submission. Copyright © 2023 the Author(s). Published by PNAS. This open access article is distributed under Creative Commons Attribution License 4.0 (CC BY).

To whom correspondence should be addressed. E-mail: sghauser@bgc-jena.mpg.de. This article contains supporting information online at <https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2224001120/-/DCSupplemental>. Published July 10, 2023.

PNAS 2023 Vol. 120 No. 29 e222400120

<https://doi.org/10.1073/pnas.222400120> 1 of 8

Earth Syst. Dynam., 4, 455–465, 2013
www.earth-syst-dynam.net/4/455/2013/
doi:10.5194/esd-4-455-2013
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A simple explanation for the sensitivity of the hydrologic cycle to surface temperature and solar radiation and its implications for global climate change

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Received: 30 July 2013 – Published in Earth Syst. Dynam. Discuss.: 14 August 2013
Revised: 15 October 2013 – Accepted: 25 October 2013 – Published: 5 December 2013

Abstract. The global hydrologic cycle is likely to increase in strength with global warming, although some studies indicate that warming due to solar absorption may result in a different sensitivity than warming due to an elevated greenhouse effect. Here we show that these sensitivities of the hydrologic cycle can be derived analytically from an extremely simple surface energy balance model that is constrained by the assumption that vertical convective exchange within the atmosphere operates at the thermodynamic limit of maximum power. Using current climatic mean conditions, this model predicts a sensitivity of the hydrologic cycle of $2.2\% \text{ K}^{-1}$ to greenhouse-induced surface warming which is the sensitivity reported from climate models. The sensitivity to solar-induced warming includes an additional term, which increases the total sensitivity to $3.2\% \text{ K}^{-1}$. These sensitivities are explained by shifts in the turbulent fluxes in the case of greenhouse-induced warming, which is proportional to the change in slope of the saturation vapor pressure, and in terms of an additional increase in turbulent fluxes in the case of solar radiation-induced warming. We illustrate an implication of this explanation for geoengineering, which aims to undo surface temperature differences by solar radiation management. Our results show that such an intervention compensates surface warming, it cannot simultaneously compensate the changes in hydrologic cycling because of the differences in sensitivities for solar vs. greenhouse-induced surface warming. We conclude that the sensitivity of the hydrologic cycle to surface temperature can be understood and predicted with very simple physical considerations but this needs to reflect on the different roles that solar and terrestrial radiation play in forcing the hydrologic cycle.

Published by Copernicus Publications on behalf of the European Geosciences Union.

Earth Syst. Dynam., 8, 849–864, 2017
https://doi.org/10.5194/esd-8-849-2017
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An explanation for the different climate sensitivities of land and ocean surfaces based on the diurnal cycle

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Received: 5 May 2017 – Discussion started: 19 May 2017
Revised: 23 August 2017 – Accepted: 27 August 2017 – Published: 25 September 2017

Abstract. Observations and climate model simulations consistently show a higher climate sensitivity of land surfaces compared to ocean surfaces. Here we show that this difference in temperature sensitivity can be explained by the different means by which the diurnal variation in solar radiation is buffered. While ocean surfaces buffer the diurnal variations by heat storage changes below the surface, land surfaces buffer it mostly by heat storage changes above the surface in the lower atmosphere that are reflected in the diurnal growth of a convective boundary layer. Storage changes below the surface allow the ocean surface–atmosphere system to maintain turbulent fluxes over day and night, while the land surface–atmosphere system maintains turbulent fluxes only during the daytime hours, when the surface is heated by absorption of solar radiation. This shorter duration of turbulent fluxes on land results in a greater sensitivity of the land surface–atmosphere system to changes in the greenhouse forcing because nighttime temperatures are shaped by radiative exchange only, which are more sensitive to changes in greenhouse forcing. We use a simple, analytic energy balance model of the surface–atmosphere system in which turbulent fluxes are constrained by the maximum power limit to estimate the effects of these different means to buffer the diurnal cycle on the resulting temperature sensitivities. The model predicts that land surfaces have a 50 % greater climate sensitivity than ocean surfaces, and that the nighttime temperatures on land increase about twice as much as daytime temperatures because of the absence of turbulent fluxes at night. Both predictions compare very well with observations and CMIP5 climate model simulations. Hence, the greater climate sensitivity of land surfaces can be explained by its buffering of diurnal variations in solar radiation in the lower atmosphere.

1 Introduction

It has long been reported that the sensitivity of near-surface air temperatures over land is greater than over ocean, with land surfaces warming about 50 % more strongly than ocean surfaces (Huntingford and Cox, 2000; Sutton et al., 2007; Boer, 2011; Byrne and O’Gorman, 2013). This phenomenon has also been found in observations, with the ratio remaining surprisingly constant through time (Lambert and Chiang, 2007). Several explanations have been put forth to explain this robust feature, including the role of heat transport (Boer, 2011), a balancing effect of oceanic heat storage (Lambert and Chiang, 2007), changes in evapotranspiration (Sutton et al., 2007) and the climatological relative humidity over land as well as its change (Byrne and O’Gorman,

2013). Also, Joshi and Gregory (2008) showed that this effect depends on the nature of the forcing, so that the ratio of land warming to ocean warming of about 1.5 holds only for changes in the greenhouse forcing.

Here, we explain this phenomenon of a higher climate sensitivity over land by the different ways of how the strong diurnal variation in solar radiation is buffered within the system (see Fig. 1). This buffering is accomplished by heat storage changes within the surface–atmosphere system that are forced by the heating by absorption of solar radiation during the day. The build-up of heat storage during the day then allows for nighttime temperatures that are far warmer than those one would expect in the absence of solar radiative heating at night. For ocean surfaces, these heat storage changes

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



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

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(Manuscript received September 29, 2020; in revised form February 5, 2021; accepted February 15, 2021)

Abstract

How much wind energy does the atmosphere generate, and how much of it can at best be used as renewable energy? This review aims to give physically-based answers to both questions, providing first-order estimates and sensitivities that are consistent with those obtained from numerical simulation models. The first part describes how thermodynamics determines how much wind energy the atmosphere is physically capable of generating at large scales from the solar radiative forcing. The work done to generate and maintain large-scale atmospheric motion can be seen as the consequence of an atmospheric heat engine, which is driven by the difference in solar radiative heating between the tropics and the poles. The resulting motion transports heat, which depletes this differential solar heating and the associated, large-scale temperature difference, which drives this energy conversion in the first place. This interaction between the thermodynamic driver (temperature difference) and the resulting dynamics (heat transport) is critical for determining the maximum power that can be generated. It leads to a maximum in the global mean generation rate of kinetic energy of about 1.7 W m^{-2} and matches rates inferred from observations of about $2.1\text{--}2.5 \text{ W m}^{-2}$ very well. This represents less than 1 % of the total absorbed solar radiation that is converted into kinetic energy. Although it would seem that the atmosphere is extremely inefficient in generating motion, thermodynamics shows that the atmosphere works as hard as it can to generate the energy contained in the winds. The second part focuses on the limits of converting the kinetic energy of the atmosphere into renewable energy. Considering the momentum balance of the lower atmosphere shows that at large-scales, only a fraction of about 26 % of the kinetic energy can at most be converted to renewable energy, consistent with insights from climate model simulations. This yields a typical resource potential in the order of 0.5 W m^{-2} per surface area in the global mean. The apparent discrepancy with much higher yields of single wind turbines and small wind farms can be explained by the spatial scale of about 100 km at which kinetic energy near the surface is being dissipated and replenished. I close with a discussion of how these insights are comparable to established meteorological concepts, inform practical applications for wind resource estimations, and, more generally, how such physical concepts, particularly limits regarding energy conversion, can set the basis for doing climate science in a simple, analytical, and transparent way.

Keywords: Thermodynamics, Carnot limit, Maximum Entropy Production, maximum power limit, Lorenz energy cycle, Betz limit, wind energy, resource potential

1 Introduction

In the current transition to a sustainable energy system, renewable forms of energy, such as solar, wind energy, hydropower, and biofuels, play a central role. Wind energy, the use of the kinetic energy associated with atmospheric motion by wind turbines, is one of the more common forms of renewable energy that is used today. It has seen a rapid expansion in the recent two decades. In Europe, for instance, the installed capacity of wind turbines has more than doubled over the last decade from 77 GW at the end of 2009 to 205 GW at the end of 2019 (WindEurope, 2020). Some scenarios expect wind energy to continue to grow, considering 450 GW of installed capacity in offshore areas of Europe alone

in 2050, with about half to be installed in the North Sea (WindEurope, 2019). In Germany, wind energy on land has roughly doubled during the last decade, with an increase in installed capacity from 25.7 GW at the end of 2009 to 53.3 GW at the end of 2019, contributing more than 40 % of the renewably generated electricity in Germany (BMWi, 2020). Scenarios for 2050 envision the installed capacity of onshore wind energy in Germany to increase to 102–178 GW, with additional 51 GW–60 GW installed offshore (BDI, 2019; WWF, 2019).

Such an anticipated increased use of wind energy in the future raises questions about the limits to wind energy use. How much can wind energy, at most, contribute to human energy needs? Can wind energy meet the entire energy needs of industrialized countries? Is wind energy so abundant that it can continuously power all human civilization, as some scientists have argued

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