Climate Modelling and Data Analysis

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Schedule

1. **What are models?**
   Exercise: Python Skills

2. **Energy budget of the Earth**
   Exercise: Simple Energy Balance Model

3. **Nonlinearity, Feedback, and Predictability**
   Exercise: Nonlinearity and Feedbacks
   Exercise: Revised Energy Balance Model

4. **Parametrization and Sensitivity**

5. **Radiative budget**
   Exercise: 1-layer greenhouse model
   Exercise: 2-layer greenhouse model

6. **Introduction to fluid dynamics**
   Exercise: Analytical katabatic flow model

7. **Finite difference method**
   Exercise: Advection-Diffusion Equation
   Exercise: Boundary layer Evolution
   Exercise: Numerical katabatic flow model
   Exercise: Heat Equation

8. **Implicit finite difference methods**
   Exercise: Boundary layer evolution

9. **Optimization problem**
   Exercise: Surface energy balance
   Exercise: Sublimation

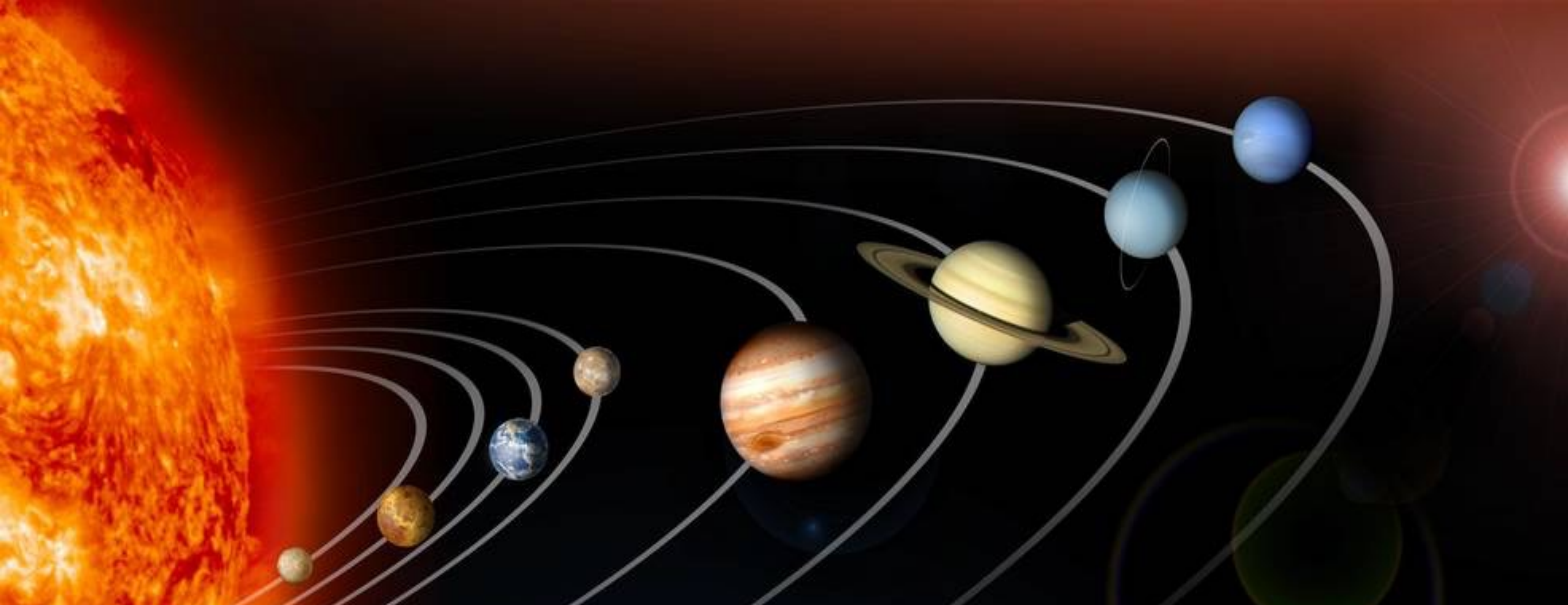
10. **COSIPY snow model**
    Exercise: Simulations with COSIPY

11. **Introduction to PALM**
    Exercise: Simulations with PALM

12. **How to write an article**

Learning objectives

- Global surface emission temperature
- What is transmissivity
- Equilibrium temperature
- Equilibrium states in the Earth system
- Greenhouse effect
- Develop a simple conceptual model
- Integrate a model in time
- How to set up sensitivity runs

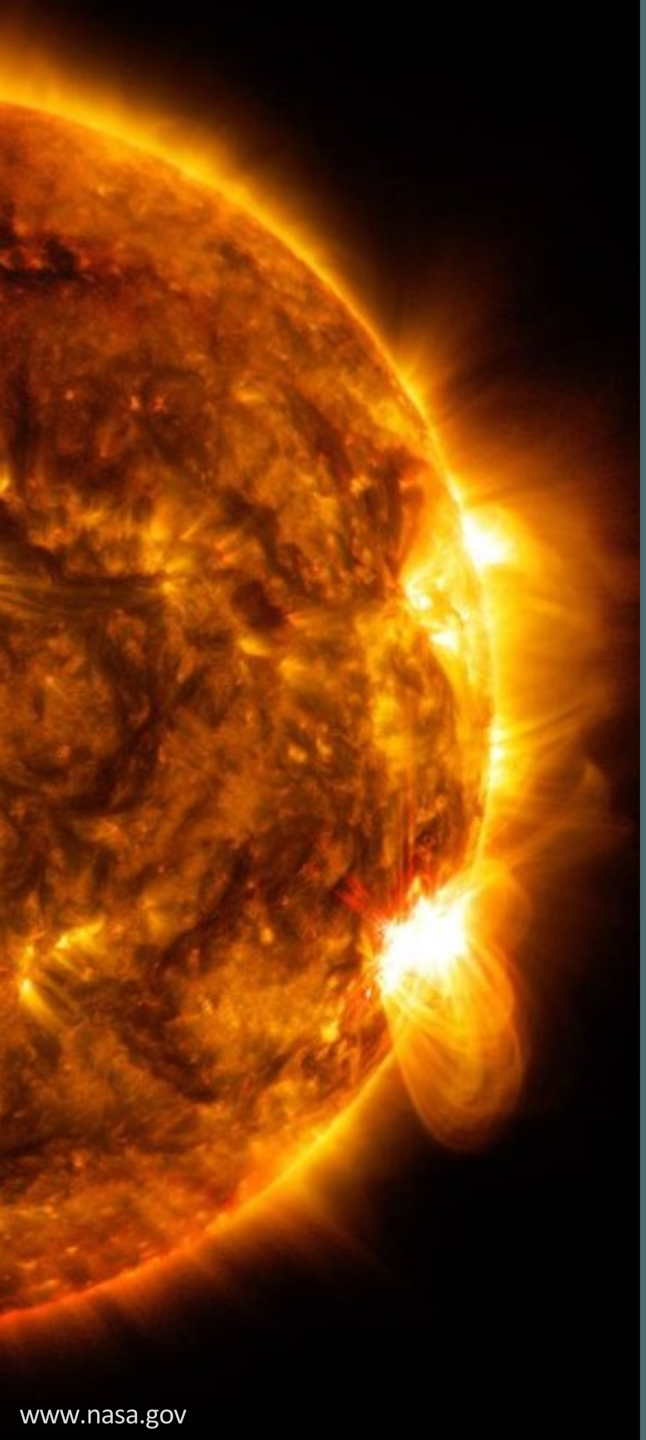


THE EARTH AS A PLANET IN THE SOLAR SYSTEM

Solar conditions, i.e. the position of the Earth as a planet in the solar system, are an important influence on climate

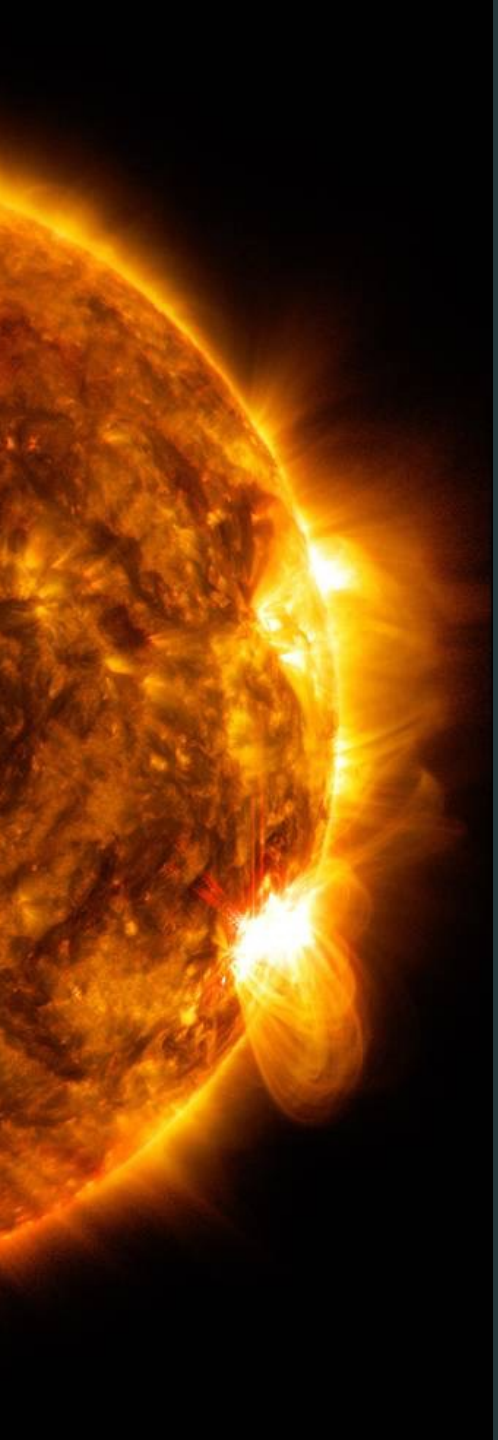
Reason: The energy of the sun is the primary driver for all climatic processes

Quelle: www.nasa.gov



Radiation is a physical process in which energy is transported without a material carrier. Thus, radiation has the ability to transfer energy from the sun to the earth through the "airless" space. Without the radiant energy from the sun, the earth would be a cold, inanimate lump of matter.

Häckel, H. (2008[6]:161)



SOLAR CONSTANT

On 1 m^2 of irradiated surface at the upper atmospheric boundary, which is perpendicular to the direction of the radiation, a thermal energy of 1,368 W (=1368 J/s) is incident at a mean distance from the sun of 1.496 * 108 km.

Thus:

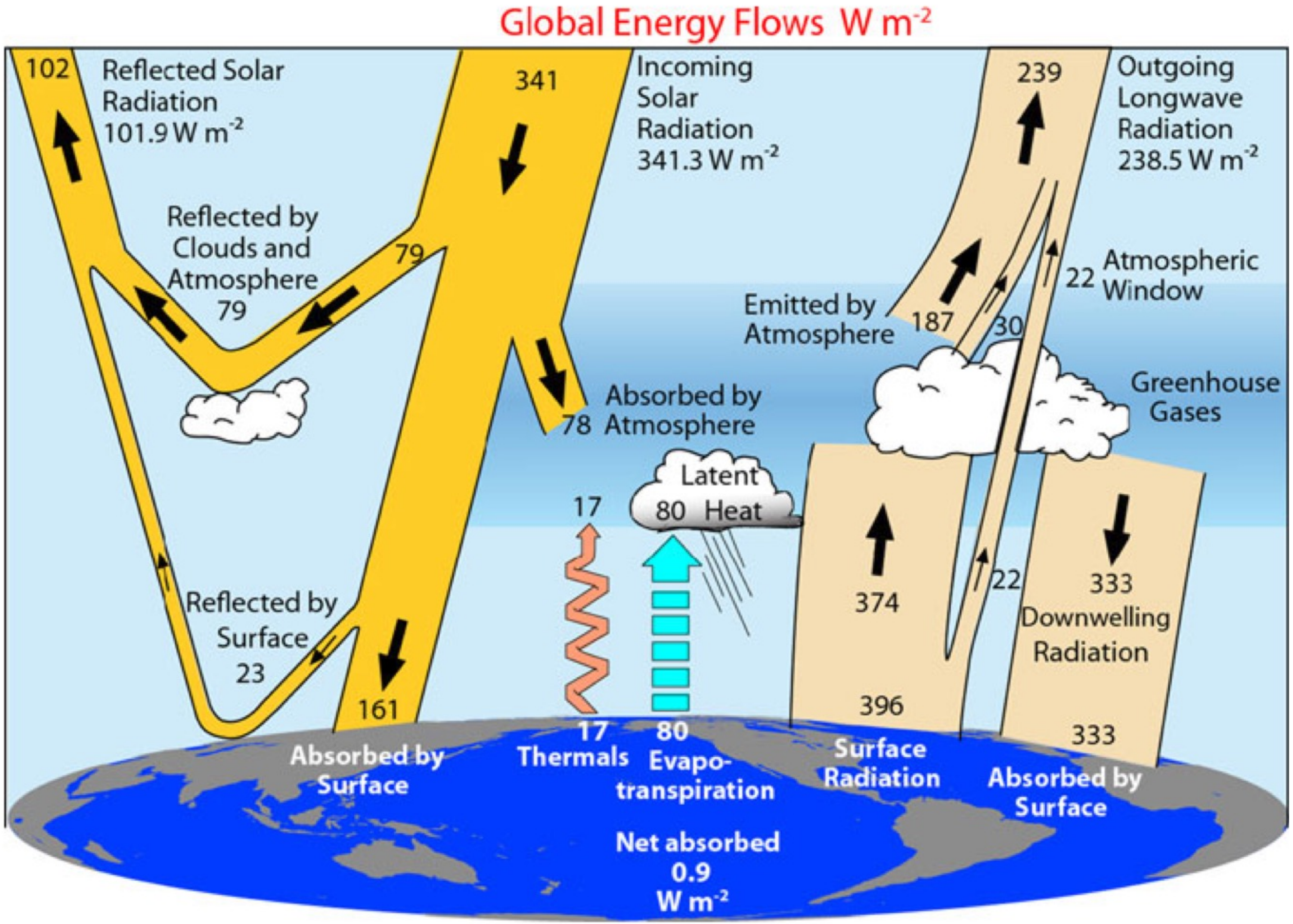
$$S_0 = 1368\ W/m^2 = 1.368\ KW/m^2$$

Fluctuations due to earth revolution:

Solar constant at perihelion: $S_0 = 1420\ W/m^2$

Solar constant at aphelion: $S_0 = 1319\ W/m^2$

The global energy budget



Trenberth and Fasullo (2012) Surv. Geophys.

PLANCK'S LAW OF RADIATION

Planck (1900):

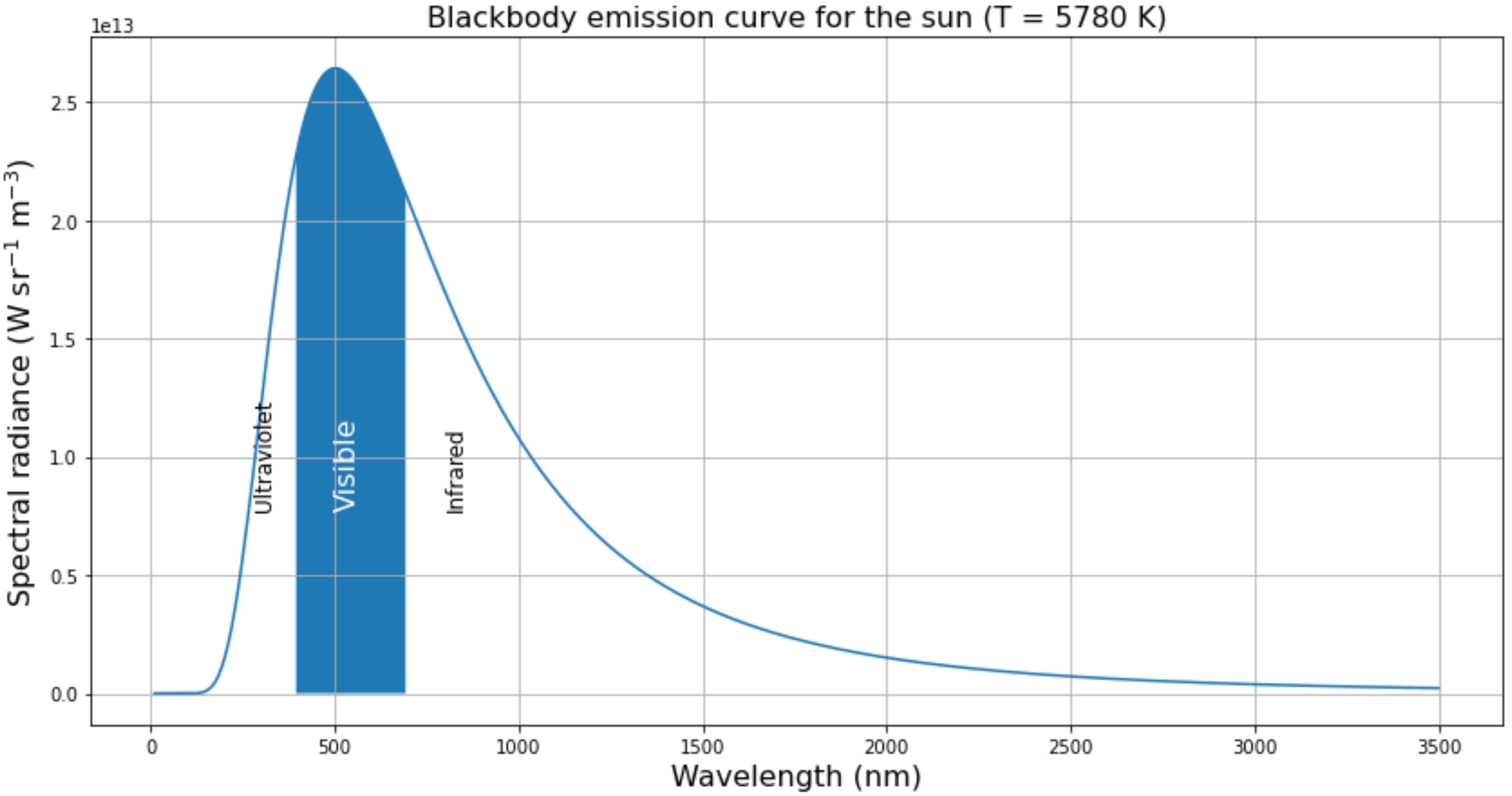
Every body emits thermal radiation (energy), which depends on the temperature of the radiating body.

Blackbody radiator:

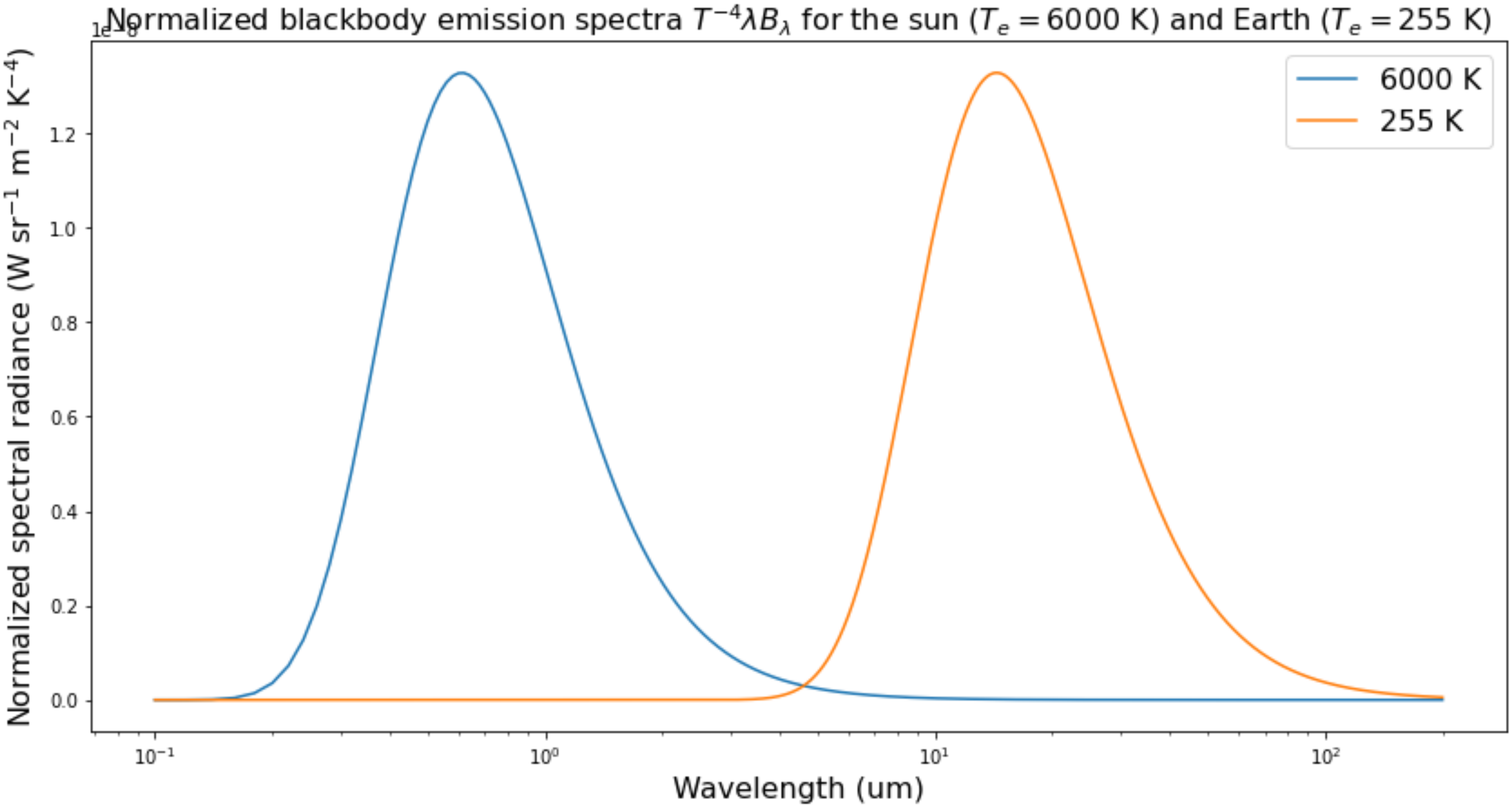
- Body that completely absorbs incident electromagnetic radiation.
- It emits at the respective temperature with the maximum possible radiation intensity.
- In the mid- and far-IR range, natural land surfaces behave approximately like black bodies.

$$\frac{\partial Q}{\partial \lambda} = \frac{2hc^2}{\lambda^5 \left[\exp\left(\frac{hc}{k\lambda T}\right) - 1\right]}$$

$h \approx 6.626*10^{-34}$ Js (Plank'sche Wirkungskonstante)
$k \approx 1.381*10^{-23}$ JK^{-1} (Boltzmann-Konstante)
$c \approx 2.9979*10^{8}$ ms^{-1} (Lichtgeschwindigkeit im Vakuum)
λ = Wellenlänge

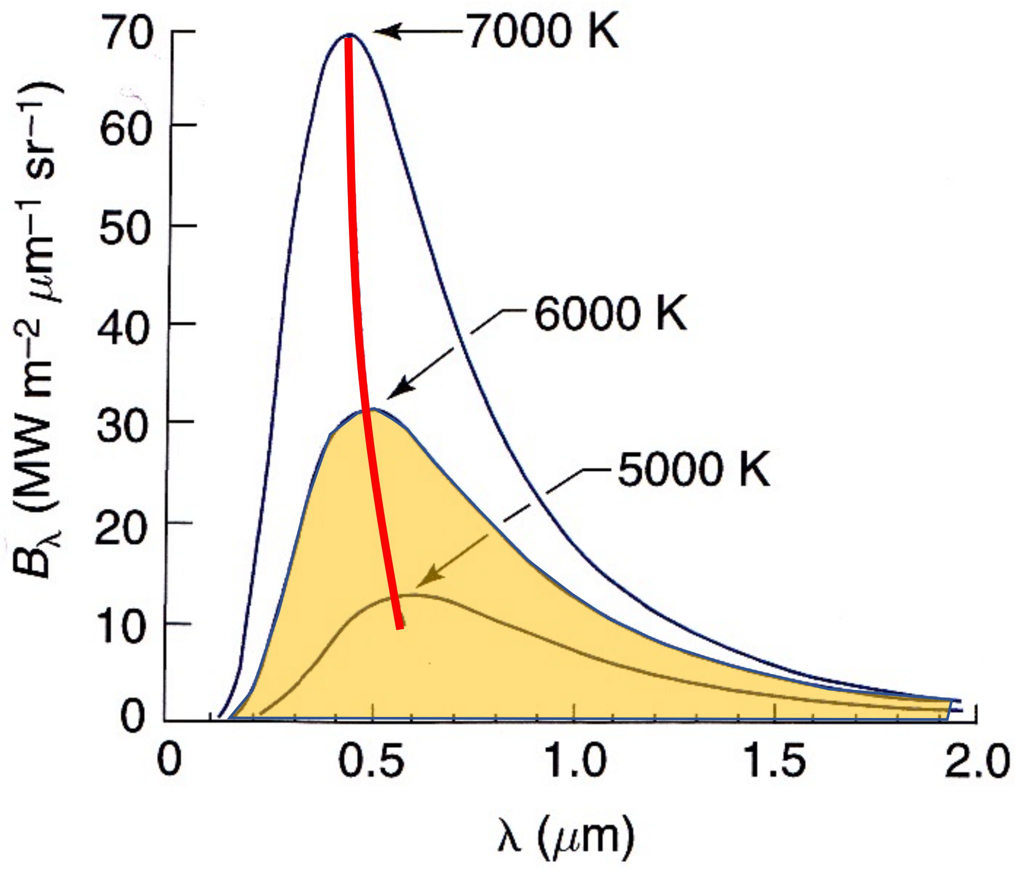


Source: Rose, 2020.



Source: Rose, 2020.

Stefan-Boltzmann Law



- The curves describe the distribution of the energy over the different wavelengths
- The areas under the curves describe the amount of radiated energy
- The radiated energy is temperature-dependent, namely to the 4th power of the absolute temperature, more precisely:

$$E = \sigma \cdot T^4 \qquad \text{mit } \sigma = 5.67 \cdot 10^{-8}\ [W/m^2K^4]$$

→ **Stefan-Boltzmann-Law**

- The position of the emission maximum shifts to shorter and shorter wavelengths with increasing temperatures. The product of temperature and wavelength of the emission maximum is constant:

$$\lambda_{max} \cdot T = 2880\ \mu m \cdot K$$

→ **Wien‘s law**

Quelle: Wallace & Hobbs 2006:117

Exercise: The global energy budget

Assume that the Earth behaves like a blackbody radiator with **effective global mean surface emission temperature** T_s. Use the Stefan-Boltzmann law to calculate the emission temperature using the observed **outgoing longwave radiation** (OLR) (see Fig. 1)

$$OLR = \sigma T_s^4 \tag{1}$$

with $\sigma = 5.67 \cdot 10^{-8}$ the Stefan=Boltzmann constant. Compare the value with the mean global surface temperature of the earth? Does the model assumption that the Earth is a blackbody radiator seem justified?

> **Task 1:** Write a Python function for the OLR and effective temperature for later use.

The emission into space is reduced due to the greenhouse effect. We make a simplified assumption that only part of the radiation is emitted into space and part of the energy remains in the system.

> **Task 2:** Extend the OLR function by a **transmissivity** constant τ which takes this effect into account. Determine the transmissivity for a global mean temperature of 288 K.

> **Task 3:** Determine the planetary albedo from the observations (Fig. 1) and write a function for the absorbed shortwave radiation (ASR), the part of the incoming sunlight that is not reflected back to space.

> **Task 4:** What additional amount of energy would have to remain in the system for the global temperature to rise by 4 K?

Exercise: The global energy budget

Before we turn to a time-dependent energy balance model, we want to deal with the concept of **equilibrium temperature**. It is based on the fundamental assumption that the energy balance in the Earth system is balanced, i.e.

$$ASR = OLR$$

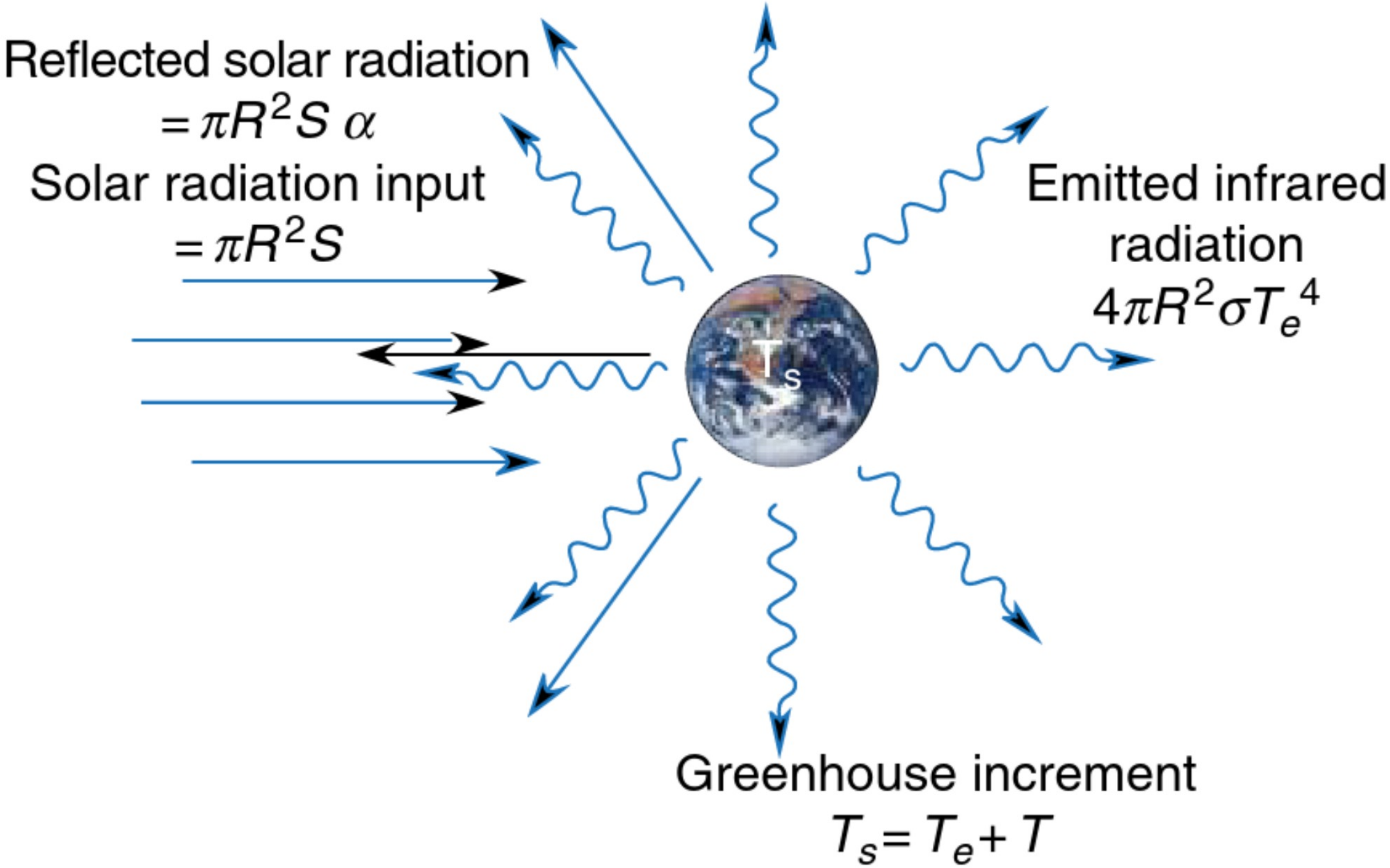
This condition can only be fulfilled if there is a corresponding equilibrium temperature that ensures that the OLR balances the short-wave radiation balance. It follows that

$$(1-\alpha) \cdot Q = \tau \sigma T_s^4. \tag{2}$$

> **Task 5:** Rearrange Eq (2) for the temperature denoting our equilibrium temperature. Substitute the observed values for insolation, transmissivity and planetary albedo and calculate the equlibrium temperature.

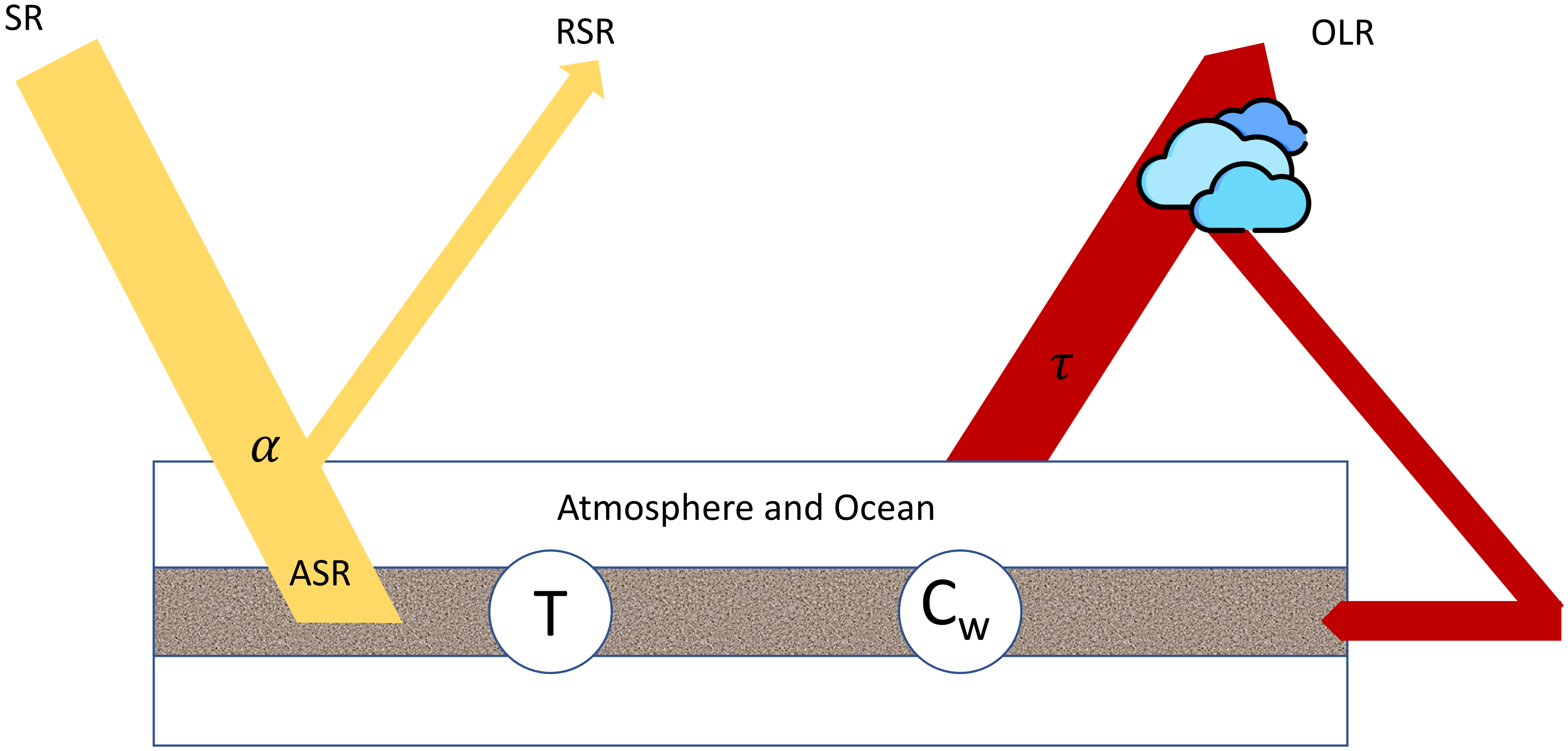
> **Task 6:** Conceptual approaches, such as equilibrium temperature, can be used to calculate simple scenarios like the relationship between the increase in albedo due to increased cloud cover and the associated decrease in transmissivity. For example, assume that the planetary albedo increases to 0.32 due to more cloud cover and that the transmissivity decreases to 0.57. What would be the new equilibrium temperature?

Energy Balance Models



Source: McGuffie and Henderson-Sellers, 2014.

Energy Balance Models



$$\frac{dE}{dt} = \frac{C_w \cdot dT_s}{dt} = ASR + OLR$$

How to solve model?

This simple model equation is a first-order Ordinary Differential Equation (ODE) for T_s as a function of time. Under certain conditions, analytical solutions exist for this type of equation. However in many cases, these equations must or are solved numerically. We will look at how these equations are discretised at a later stage.

In general, the derivative can be approximated by a finite difference, then the above equation can be rewritten as

$$\frac{dE}{dt} = \frac{C_w \cdot \Delta T_s}{\Delta t} = ASR + OLR, \tag{4}$$

where ΔT is the temperatur difference $\Delta T = T_2 - T_1$ between two discrete points in time $\Delta t = t_2 - t_1$. The Δt is called the **timestep**. Substituting the difference approach into the above equation we get

$$\frac{dE}{dt} = C_w \frac{T_2 - T_1}{\Delta t} = ASR + OLR. \tag{5}$$

Energy Balance Models

Task 7: Rearrange Eq. (5) so that you can predict future temperature.

Task 8: Write a function called *step_forward(T, dt)* that returns the new temperature given the old temepratature T and timestep dt. Assume an initial temperature of 288 K and integrate the function for three timesteps (choose dt = 1 year) and observe how the temperature changes.

Task 9: Integrate the equation over a time of 1000 years. Use the following initial and boundary conditions: S_0=1360 W m^{-2}, $T(0)$ = 273 K, C_w = 10^8 J/(m^2· K), α = 0.3, τ = 0.61. Describe in your own words what you observe.

Task 10: What happens if the intial temperature is set to 293 K?

Task 11: What changes do you observe with a higher C_w value (e.g. C_w =10·10^8 J/(m^2· K)?

Task 12: How does the result change when $\tau = 1$?

Task 13: What are the disadvantages of the energy balance model? How could it be improved?

Energy Balance Models

Summary

- We have looked at the global energy budget
- The surface temperature is higher than the emission temperature
- The atmosphere results in a temperature increase of 33 K due to the greenhouse effect
- The imbalance between ASR and OLR leads to temperature changes
- Zero-dimensional energy balance model calculates the mean surface temperature of the Earth
- The Earth has a so-called equilibrium temperature when ASR=OLR.
- If the mean surface temperature is lower than the equilibrium temperature, the Earth warms up.