Chapter 2. The Energy balance, hydrological and carbon cycles

2.1 The Earth's energy budget

2.1.1 The heat balance at the top of the atmosphere: a global view

Nearly all the energy entering the **climate system** comes from the Sun in the form of **electromagnetic radiation**. Additional sources are present, such as geothermal heating for instance, but their contribution is so small that their influence can safely be neglected. At the top of the Earth's atmosphere, a surface at the mean Earth-Sun distance perpendicular to the rays receives about 1368 W/m^2 (see also Figure 5.27). This is often called the **Total Solar Irradiance (TSI)** or **solar constant** S_0. A bit less than half of this energy comes in the form of radiation in the visible part of the **electromagnetic spectrum**, the remaining part being mainly in the near infrared, with a smaller contribution from the ultraviolet part of the spectrum (Fig. 2.1).

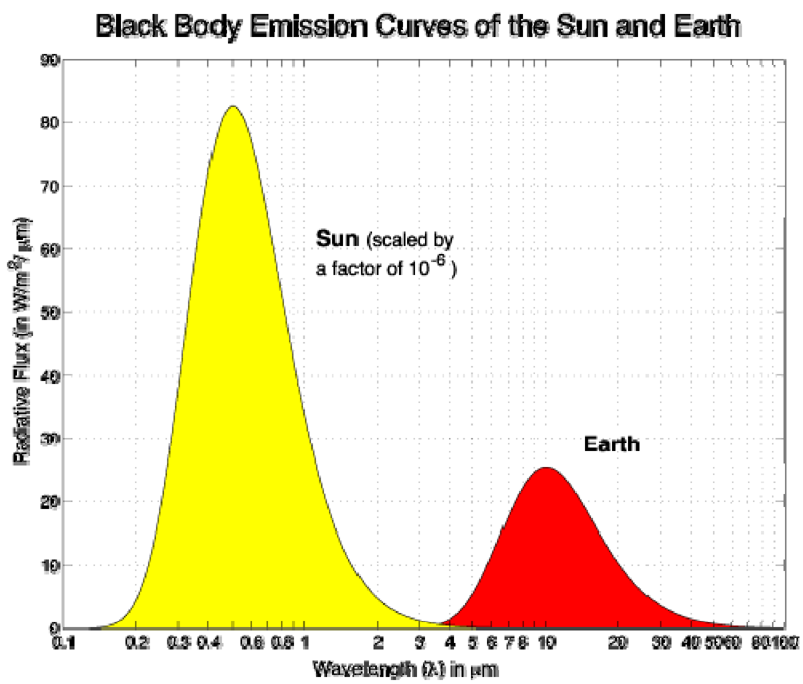

Figure 2.1: **Spectrum** of the energy received from the Sun and emitted by the Earth at the top of the atmosphere. Figure from Y. Kushnir available at http://www.ldeo.columbia.edu/~kushnir/MPA-ENVP/Climate/lectures/energy/. Reproduced with permission.

On average, the total amount of incoming solar energy outside the Earth's atmosphere (Fig 2.2) is the **solar constant** times the cross-sectional surface (i.e., the surface that intercepts the solar rays, which corresponds to a surface πR^2 where R is the Earth's radius of 6371 km^2). For simplicity and because it is a reasonable approximation, we will neglect the thickness of the atmosphere compared to the Earth's radius in our computations of distances or surfaces. Some of this incoming flux is reflected straight back to space by the atmosphere, the clouds and the Earth's surface. The fraction of the radiation that is reflected is called the **albedo** of the Earth or planetary albedo (α_p). In present-day conditions, it has a value of about 0.3.

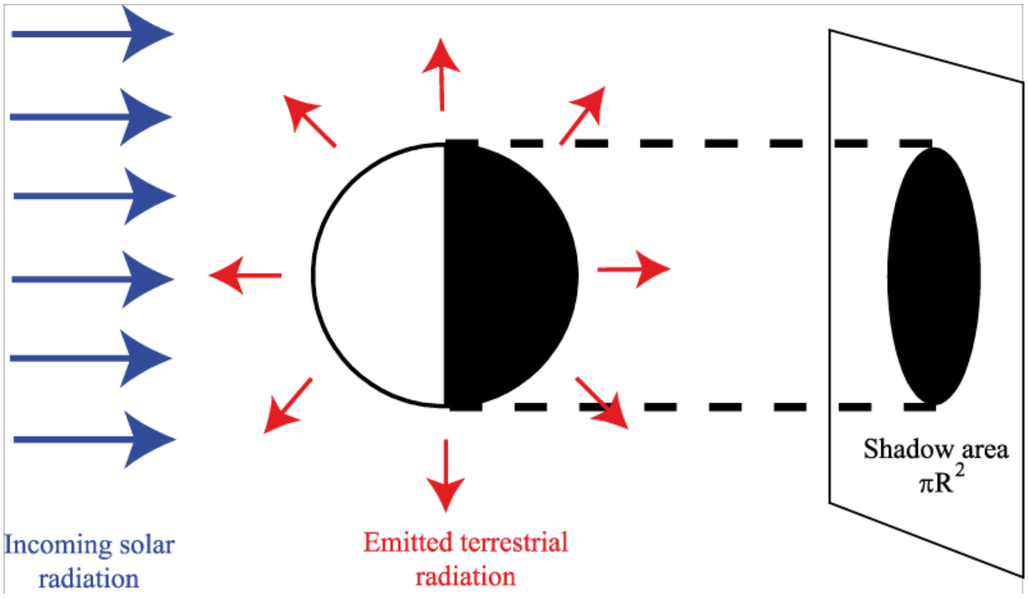

Figure 2.2: Heat absorbed and emitted by the Earth.

In order to achieve a heat balance, the heat flux coming from the Sun must be compensated for by an equivalent heat loss. If this were not true, the Earth's temperature would rapidly rise or fall. At the Earth's temperature, following **Wien's Law**, this is achieved by radiating energy in the infrared part of the electromagnetic spectrum. As the radiations emitted by the Earth have a much longer wavelength than those received from the Sun, they are often termed **longwave radiation** while those from the Sun are called **shortwave radiation**. Treating the Earth as a **black body**, the total amount of energy that is emitted by a 1 m^2 surface ($A\uparrow$) can be computed by **Stefan-Boltzmann's** law:

$$A\uparrow = \sigma T_e^4 \tag{2.1}$$

where σ is the Stefan Boltzmann constant (σ=5.67 10^{-8} W m^{-2} K^{-4}). This equation defines T_e , effective emission temperature of the Earth. The Earth emits energy in the directions, so the total amount of energy emitted by the Earth is $A\uparrow$ times the surface of the Earth, 4 π R^2. To achieve equilibrium, we must thus have (Fig. 2.3):

Absorbed solar radiation = emitted terrestrial radiation

$$\pi R^2 \left(1-\alpha_p\right) S_0 = 4\pi R^2 \sigma T_e^4 \tag{2.2}$$

This leads to

$$\frac{1}{4}\left(1-\alpha_p\right) S_0 = \sigma T_e^4 \tag{2.3}$$

and finally to

$$T_e = \left(\frac{1}{4\sigma}\left(1-\alpha_p\right) S_0\right)^{1/4} \tag{2.4}$$

This corresponds to T_e=255 K (=-18°C). Note that we can interpret Eq. (2.3) as the mean balance between the emitted terrestrial radiation and the absorbed solar flux for 1 m^2 of the Earth's surface. As shown above, the factor 1/4 arises from the spherical geometry of the Earth, because only part of the Earth's surface receives solar radiation directly.

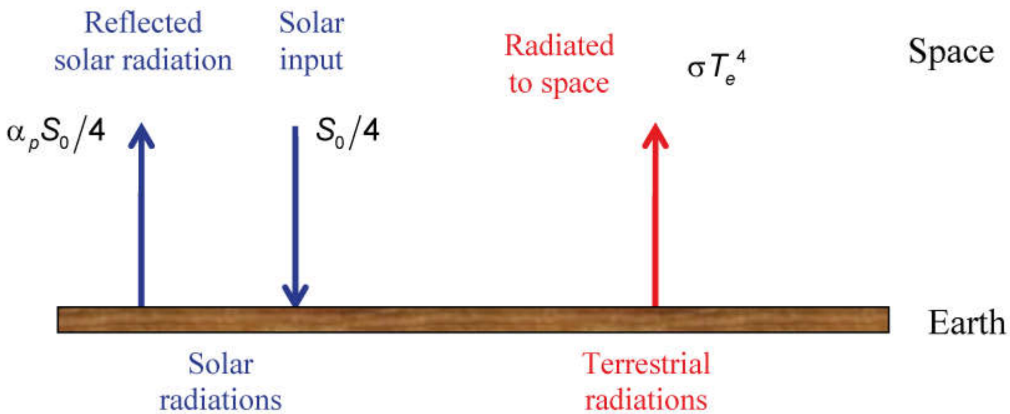

Figure 2.3: Simple heat balance of the Earth (assuming it behaves like a perfect blackbody).

The temperature T_e is not a real temperature that could be measured somewhere on Earth. It is only the black body temperature required to balance the solar energy input. It can also be interpreted as the temperature that would occur on the Earth's surface if it were a perfect black body, there were no atmosphere, and the temperature was the same at every point.

2.1.2 The greenhouse effect

The atmosphere is nearly transparent to visible light, absorbing about 20% of the incoming solar radiation. As a consequence, the majority of the absorption takes place at Earth's surface (see section 2.1.6). On the other hand, the atmosphere is almost opaque across most of the infrared part of the **electromagnetic spectrum**. This is related to the radiative properties of some minor constituents of the atmosphere, especially water vapour, carbon dioxide, methane and ozone. Those gases constitute only a small fraction of the atmospheric composition, while the two dominant components (molecular nitrogen and oxygen, see section 1.2) play nearly no part in this opacity. Nevertheless, a significant fraction of the energy emitted by the Earth's surface is absorbed by the atmosphere and re-emitted, significantly increasing the temperature of the system.

In a garden greenhouse, panes of glass are transparent to visible light but opaque to infra-red radiation, 'trapping' part of the energy emitted by the surface and resulting in a warming of the air. By analogy, the alteration of the energy budget by some minor atmospheric constituents described above is called the greenhouse effect and those minor constituents the greenhouse gases. However, the climate system is much more complex than a greenhouse and in a garden greenhouse a significant fraction of the warming is related to the reduction of the turbulent heat exchanges with atmosphere, not in the modification of the radiative fluxes. The analogy should be used with caution.

The greenhouse effect can be illustrated by a very simple model in which the atmosphere is represented by a single homogenous layer of temperature T_a, totally transparent to the solar radiation and totally opaque to the infrared radiations emitted by the Earth's surface (Fig. 2.4). Because of this opacity of the atmosphere to surface radiation, all the energy radiated to space is from the atmosphere. Using Equation 2.3, the balance at the top of the atmosphere is thus:

$$\sigma T_a^4 = \frac{1}{4}\left(1-\alpha_p\right)S_0 = \sigma T_e^4 \tag{2.5}$$