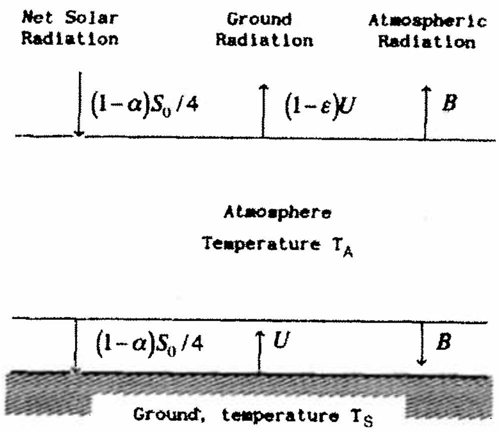
Climate Dynamics (NS-363-B) (test 1, 18 April 2012, 9:00-12:00)

In this test the symbols, if not explained, have their usual meaning. Answers may be given Dutch or English

Problem 1

Explain in words the meaning of "Radiative Forcing". Explain in words the meaning of "Equilibrium Climate Sensitivity". Why is the concept of "Radiative Forcing" employed more frequently by the IPCC than the concept of "Equilibrium Climate Sensitivity"?

Problem 2



Let us adopt a single slab model of the Earth-atmosphere system (see the figure above). The parameter, α, is the albedo of the Earth. The parameter, ε, is the emissivity of the atmosphere. The parameter S_0 is the Solar constant($=1366$ W m^{-2}).

(a) Derive an expression for the emission temperature, T_E of the Earth using Stefan-Boltzman's law, which states that the radiation emitted by a black body is proportional to the fourth power of the temperature of the emitting surface (constant of proportionality is $\sigma=5.67\cdot10^{-8}$ W m^{-2}K^{-4}). Assume that the earth is a black body.

(b) Show that, in radiative equilibrium,

$$T_{A0} = \left(\frac{1}{2-\varepsilon}\right)^{1/4} T_E$$

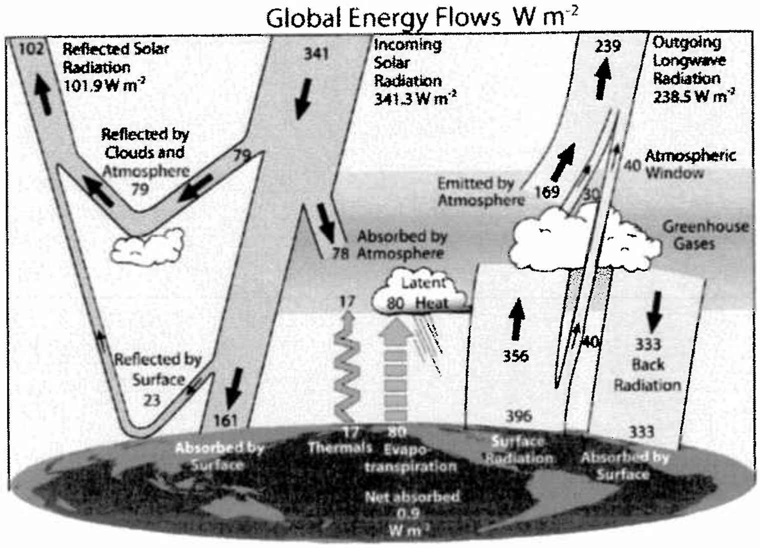
where the subscript 0 denotes the equilibrium state.

(c) Now, suppose that for some reason the atmospheric temperature is disturbed slightly away from the radiative equilibrium such that $T_A = T_{A0}+\Delta T_A$, with $\Delta T_A \ll T_{A0}$. Derive an approximate (linear) expression[1] for the time-rate of change of ΔT_A in terms of T_{A0} and ΔT_A. Assume that the Earth's surface has zero heat capacity and that $c_p p_s/g$ is the heat capacity of an atmospheric column of unit cross-sectional area. Here p_s is the pressure at the Earth's surface ($p_s=100000$ Pa); c_p is the specific heat at constant pressure ($=1004$ J K^{-1}kg^{-1}), and g is the acceleration due to gravity ($g=9.8$ m s^{-2}).

(d) According to the expression derived in (c) the temperature perturbation decays exponentially towards zero. Give an estimate of the time in days it takes for the temperature perturbation to decay from its maximum value to $1/e$ times this maximum value (e equals approximately 2.718 and assume that $\varepsilon=0.9$).

[1] Use the following approximation of Taylor's formula:
$f(x) \cong f(x_0) + (x - x_0)f'(x_0)$

Problem 3



The figure above shows the global annual mean energy for the periods of 2000-2004. Fluxes are indicated in W m^{-2}.

(a) Is the Earth's surface in radiative equilibrium?

(b) Approximately in which wavelength interval do we observe the "atmospheric window?

(c) Name three important constituents in the atmosphere that are responsible for the back-radiation of 333 W m^{-2}?

(d) Compute the global average emission coefficient of the Earth's surface if the global average temperature of the Earth's surface is 288 K.

Problem 4

According to Budyko, the equation governing the global average, yearly average temperature, T, of the Earth's surface can be approximated by the following equation:

$$C\frac{dT}{dt} = \frac{S_0}{4}(1-\alpha) - I_0 - bT.$$

S_0 is the Solar constant; C is a heat capacity.

(a) What physical processes are captured by this equation?

(b) Empirically, Budyko obtained $I_0 = 205$ W m^{-2} and $b = 2.23$ W m^{-2}°C^{-1}, with T expressed in °C. The parameter b is a measure of the strength of the greenhouse effect. What does an increase of b to a value of about 4.7 imply for the greenhouse effect?

(c) Within a certain range of surface temperatures $T_0<T<T_1$ the global average albedo, α, is temperature-dependent as follows:

$$\alpha = \alpha_0 \text{ if } T \le T_0;\ \ \alpha = \alpha_0 + \frac{T - T_0}{T_1 - T_0}(\alpha_1 - \alpha_0) \text{ if } T_1 \ge T > T_0;\ \ \alpha = \alpha_1 \text{ if } T \ge T_1.$$

The empirical parameters have the following values: $\alpha_0 = 0.6$; $T_0 = -10°C$; $\alpha_1 = 0.25$; $T_1 = 0°C$. In other words, three temperature intervals can be distinguished with different behaviour of the albedo. How many equilibrium states does the system have, given that S_0=1366 W m^{-2}?

(d) Calculate the radiative equilibrium temperature in the temperature range, $T_1>T>T_0$.