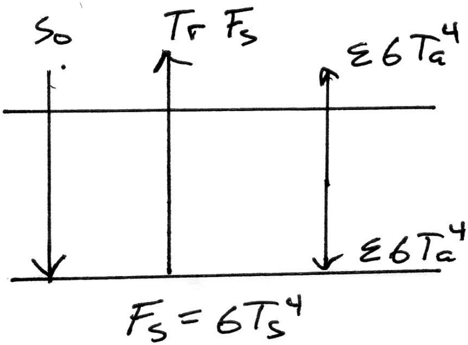
Radiative equilibrium

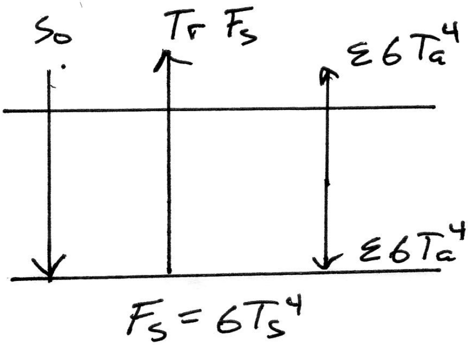
1. Coverage: W&H 116-122
2. Introduce heating rate, radiative equilibrium, brightness temperature
3. Extend the discussion of black atmospheric layers in WH Fig 4.9 page 122 to include *grey* layers.

One layer grey atmosphere



This figure shows a grey atmosphere with a transmissivity of Tr, an emissivity of ϵ and tempeature T_a over a black surface with temperature T_s. There is a downward shortwave flux of S_0 and no atmospheric absorption of solar photons

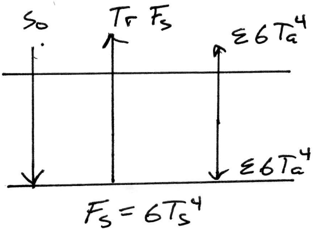
One layer atmosphere – cont.



If we ignore the S_0 contribution for the moment and want to know how fast the atmosphere and surface are cooling in the longwave, we need the the upward flux leaving the top of the atmoshere:

$$\text{longwave flux leaving the top} = F_{T,\uparrow} = TrF_s + \epsilon\sigma T_a^4$$
$$= (1-\epsilon)\sigma T_s^4 + \epsilon\sigma T_a^4 = \sigma T_s^4 - \epsilon\sigma(T_s^4 - T_a^4)$$

Greenhouse effect



The *Greenhouse effect* is defined as the difference in the upward flux to space caused by the presence of an absorbing/emitting atmosphere with a temperature that's different from the surface:

$$G = F_{B,\uparrow} - F_{T,\uparrow} = \sigma T_s^4 - (\sigma T_s^4 - \epsilon\sigma(T_s^4 - T_a^4))$$
$$G(\mathrm{W\,m^{-2}}) = \epsilon\sigma(T_s^4 - T_a^4))$$

Note that $G > 0$ (positive, heating) only if the atmosphere is colder than the surface. Also note that increasing the emissivity/absorptivity (ϵ) increases the heating.

Heating rate

- How fast is the atmosphere heating/cooling? That depends on the *net flux divergence*, $\frac{dF_N}{dz}$, where $F_N = F_\uparrow - F_\downarrow$ at a particular height.
- For this one layer atmosphere with no shortwave absorption,

$$F_{N,T} = F_{T,\uparrow} - F_{T,\downarrow} = TrF_s + \epsilon\sigma T_a^4 = (1-\epsilon)\sigma T_s^4 + \epsilon\sigma T_a^4$$
$$F_{N,B} = F_{B,\uparrow} - F_{B,\downarrow} = \sigma T_s^4 - \epsilon\sigma T_a^4$$
$$\Delta F_N = F_{N,T} - F_{N,B} = (1-\epsilon)\sigma T_s^4 + \epsilon\sigma T_a^4 - (\sigma T_s^4 - \epsilon\sigma T_a^4) =$$
$$\Delta F_N = 2\epsilon\sigma T_a^4 - \epsilon\sigma T_s^4$$

where positive ΔF_N means the layer is cooling

some representative numbers:

$T_a = 250$ K, $T_s = 280$ K, $\epsilon = 0.8$

which gives $\Delta F_N = 75\,\mathrm{W\,m^{-2}}$

Heating rate – cont.

- What does $\Delta F_N = 75\,\mathrm{W\,m^{-2}}$ mean in terms of temperature change? Suppose the average air density is $\overline{\rho} = 1\ \mathrm{kg\,m^{-3}}$ and the total mass of a 1 $\mathrm{m^2}$ column is M=10,000 kg. The column is losing 75 J/s, and since the heat capacity of air is $c_p = 1004\ \mathrm{J, kg^{-1}\,K^{-1}}$, the cooling rate is:

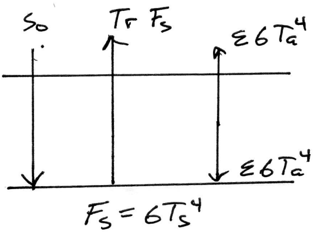
$$\text{cooling rate} = \Delta F_N = -M \times c_p \times \frac{dT}{dt} = -\overline{\rho} \times \Delta z \times c_p \times \frac{dT}{dt}$$

$$\text{or rearranging :}$$

$$\frac{dT}{dt} = -\frac{1}{\overline{\rho} c_p} \frac{\Delta F_N}{\Delta z}$$

So this atmosphere loses 75 $\mathrm{W\,m^{-2}}$ and cools at 75 $\mathrm{W\,m^{-2}}$ /1004 $\mathrm{J, kg^{-1}\,K^{-1}}$ /10000 m = 0.6 K/day

Equilibrium temperature



- Note that the atmosphere and surface will stop cooling when the outgoing longwave balances the incoming sortwave at each level.

Summary

- We can make a rough calculation of the heating/cooling in an isothermal layer if we know the transmission, absorption and reflection of the flux through the layer
- A layer that is neither heating or cooling is in equilibrium, at a temperature at which absorption and emission are in balance.