Lecture 24.

Total radiative heating/cooling rates.

Objectives:

1. Solar heating rates.

2. Total radiative heating/cooling rates in a cloudy atmosphere.

3. Total radiative heating/cooling rates in different aerosol-laden conditions: Examples.

Required reading:

L02: 3.5, 4.5.2, 4.6.1, 4.6.2, 4.7, 8.2.4

Additional reading:

Heating rates in dust-laden conditions:

Quijano A.L., Sokolik I.N. and O.B. Toon. Radiative heating rates and direct radiative forcing by mineral dust in cloudy conditions. J. Geophys. Res. , D10, 12,207-12,219, 2000 (see figs. below)
Huang. J., et al. Taklimakan dust aerosol radiative heating derived from CALIPSO observations using the Fu-Liou radiation model with CERES constraints. Atmos. Chem. Phys., 9, 4011-4021, 2009.

Heating rates in cloudy conditions:

Liou, K.N., and Q. Zheng, 1984: A numerical experiment on the interactions of radiation, clouds and dynamic processes in a general circulation model. *J. Atmos. Sci.*, 41, 1513-1535. (see figs below)

Heating rates in smoke-laden conditions:

Stone, R. S., G. P. Anderson, E. P. Shettle, E. Andrews, K. Loukachine, E. G. Dutton, C. Schaaf, and M. O. Roman III (2008), Radiative impact of boreal smoke in the Arctic: Observed and modeled, J. Geophys. Res., 113, D14S16,doi:10.1029/2007JD009657.

!!more examples in class project presentations

1. Solar heating rates.

Recall that IR radiative cooling rates in the cloud-free conditions were discussed in Lecture 11.

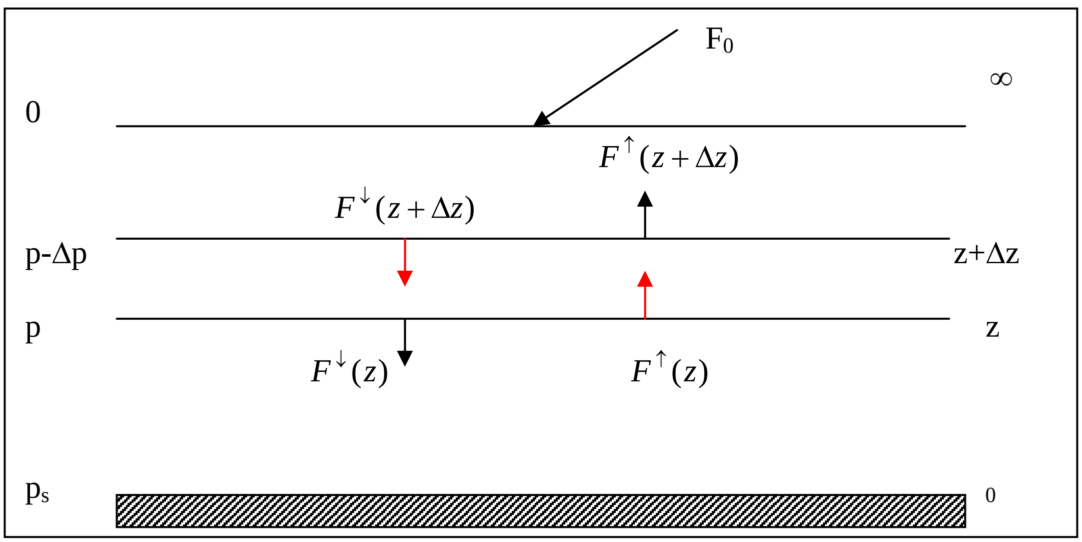
No emission in the solar (i.e., SW) => no cooling, only heating due to absorption

The net SW flux is often defined as

$$F_{net}(z) = F^{\uparrow}(z) - F^{\downarrow}(z) \qquad [24.1]$$

so the net SW flux divergence is $\Delta F_{net} = F_{net}(z + \Delta z) - F_{net}(z)$

$$\left(\frac{dT}{dt}\right)_{sw} = -\frac{1}{c_p \rho}\frac{dF_{net}}{dz} = \frac{g}{c_p}\frac{dF_{net}}{dp} \qquad [24.2]$$



NOTE: Instantaneous heating/cooling rates are the rates calculated for a given moment of time (e.g., at a given sun angle for solar heating). Hourly, diurnally, monthly and annually averaged rates are also used.

NOTE: L02 defines the **solar** net flux as $F_{net}(z) = F^{\downarrow}(z) - F^{\uparrow}(z)$. This definition is commonly used in the literature. Then divergence is calculated as

$\Delta F_{net} = F_{net}(\Delta z) - F_{net}(z + \Delta z)$ and heating rates are calculated with Eq.[24.2].

- In cloud- and aerosol-free conditions, the main absorbers of solar radiation are ozone, water vapor and some CO_2.

NOTE: To first order, the differences in heating profiles in Fig.24.1 (see below) mirror the differences in mixing ratios of these gases.

- In cloud- and aerosol-free conditions, total solar heating is the sum of solar heating due to individual gases.

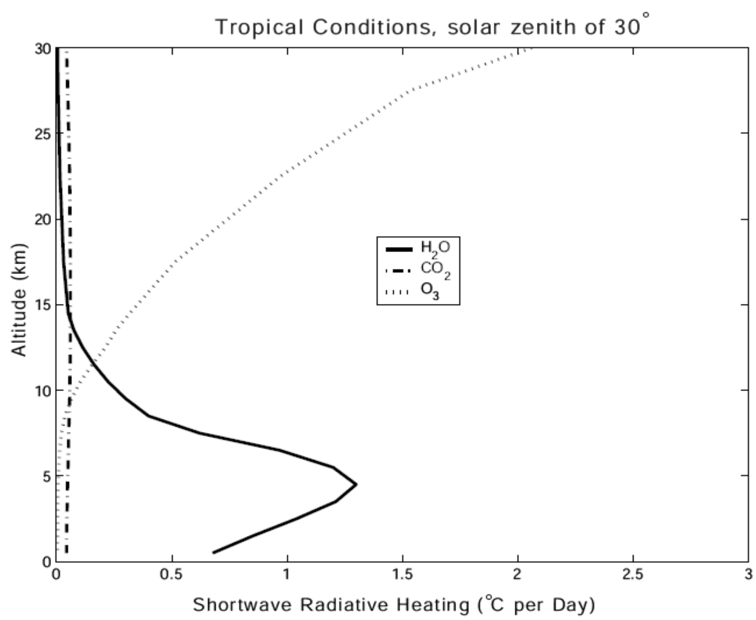


Figure 24.1 Representative heating profiles due to solar absorption in a cloud-free tropical atmosphere for H_2O, O_3 and CO_2.

<u>2. Total radiative heating/cooling rates in a cloudy atmosphere.</u>

Total rates = solar rates + IR rates

- ✓ Because rates can have different signs in solar and IR, one needs to be careful while computing total rates.
- ✓ **Total** rates are often called **net** rates.
- ✓ Depending on a sign of total radiative rates, an atmospheric layer experiences either radiative heating or cooling.

IR and solar radiative heating/cooling rates of clouds with different vertical distribution:

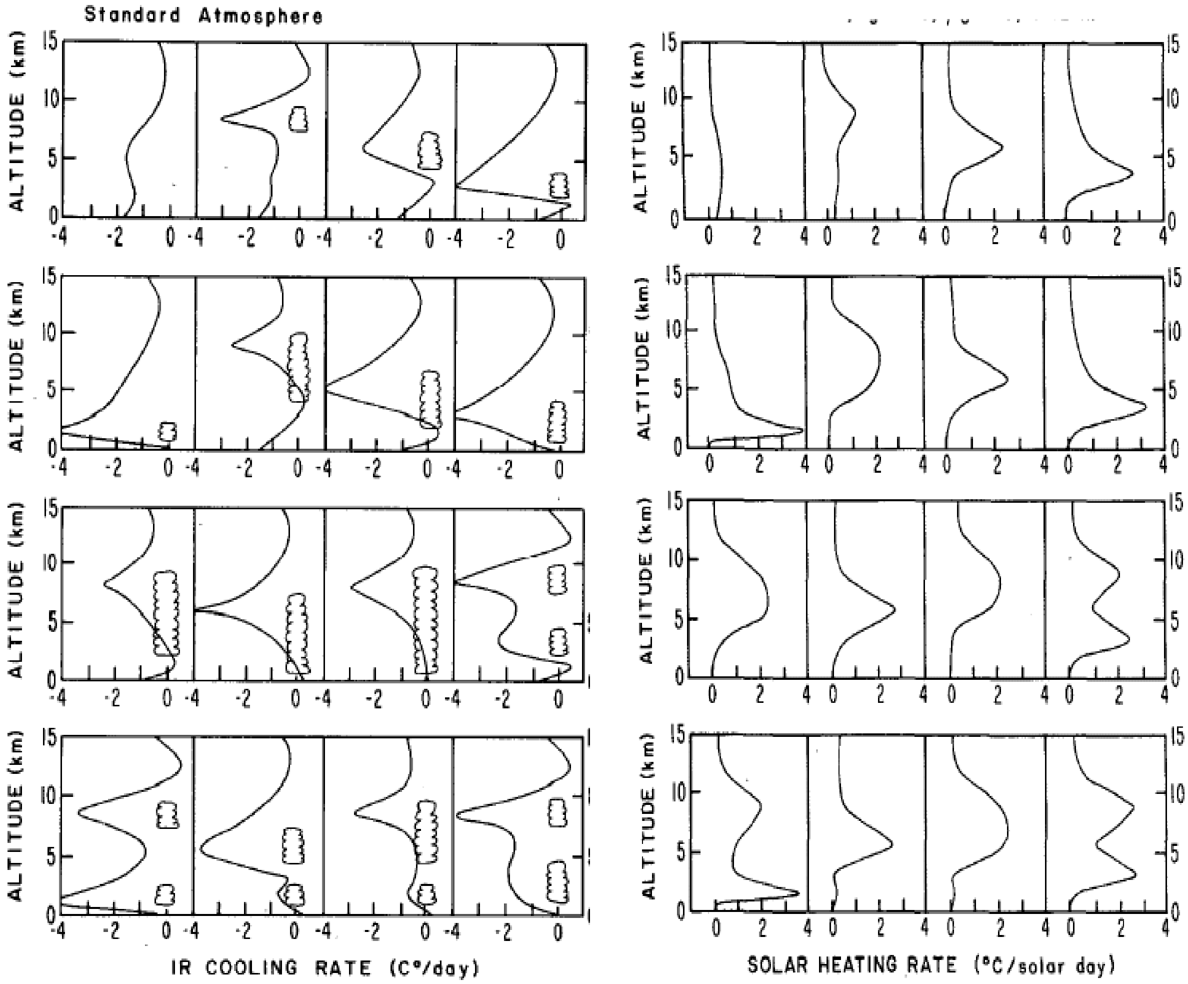


Figure 24.2 IR and solar heating/cooling rate profiles for clear and various cloudy atmospheric conditions. 100% cloud cover is assumed. Solar heating rates were calculated for a solar constant of 1360 W/m^2, surface albedo of 0.15, cosine of solar zenith angle 0.5 and solar time duration of 12 hours (modified from Liou and Zheng, 1984).

➢ Cirrus clouds

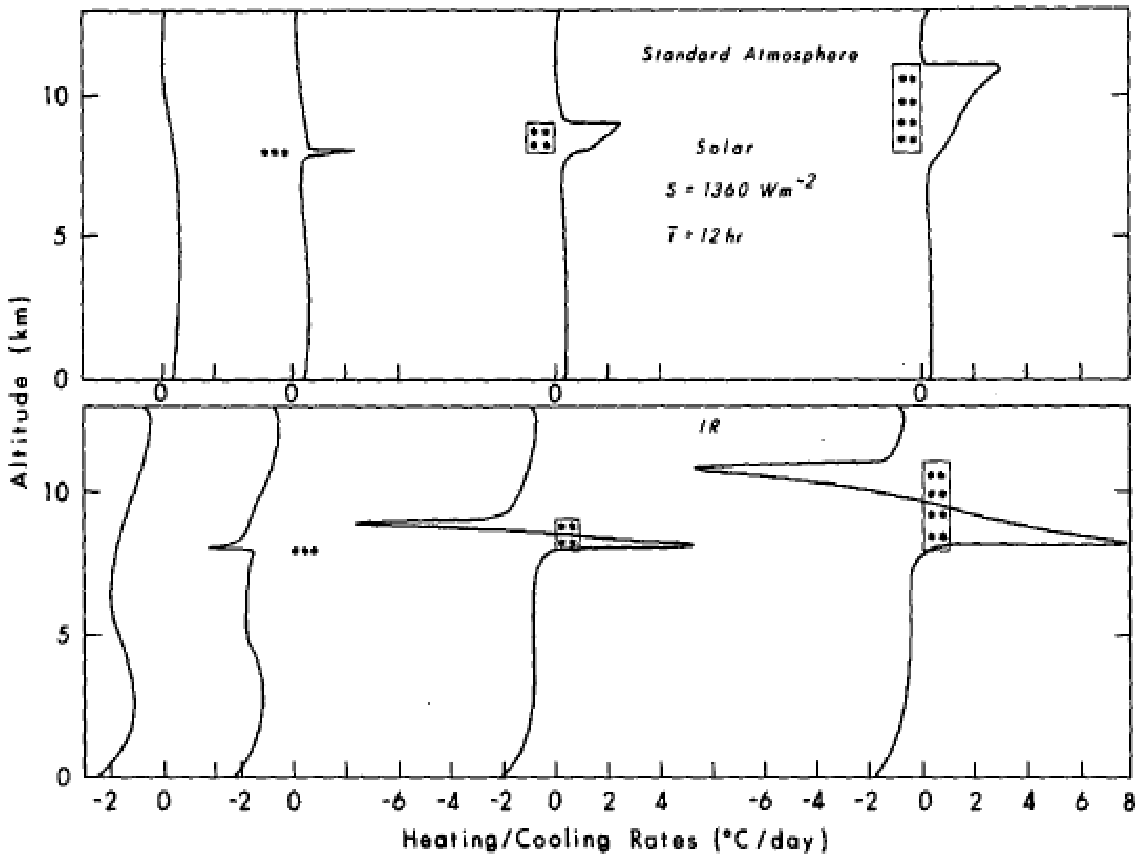


Figure 23.2 Solar and IR radiative heating/cooling rates for clear sky and for a cirrus cloud with thickness of 0.1, 1 and 3 km. The cloud base is fixed at 8 km. Solar heating rates were calculated for a solar constant of 1360 W/m^2, surface albedo of 0.15, cosine of solar zenith angle 0.5 and solar time duration of 12 hours (Liou, 1986).

Main features:

- ✓ Strong IR cooling above a cirrus cloud and strong warming below.
- ✓ Maximum of solar heating occurs at the top of a cirrus cloud.

3. Total radiative heating/cooling rates in an aerosol-laden atmosphere.

- Radiative heating/cooling rates in an aerosol-laden atmosphere depend on optical properties of aerosols and their vertical distribution, solar angle (for solar heating rates), surface albedo (for solar heating rates), and atmospheric conditions (e.g., presence of clouds)

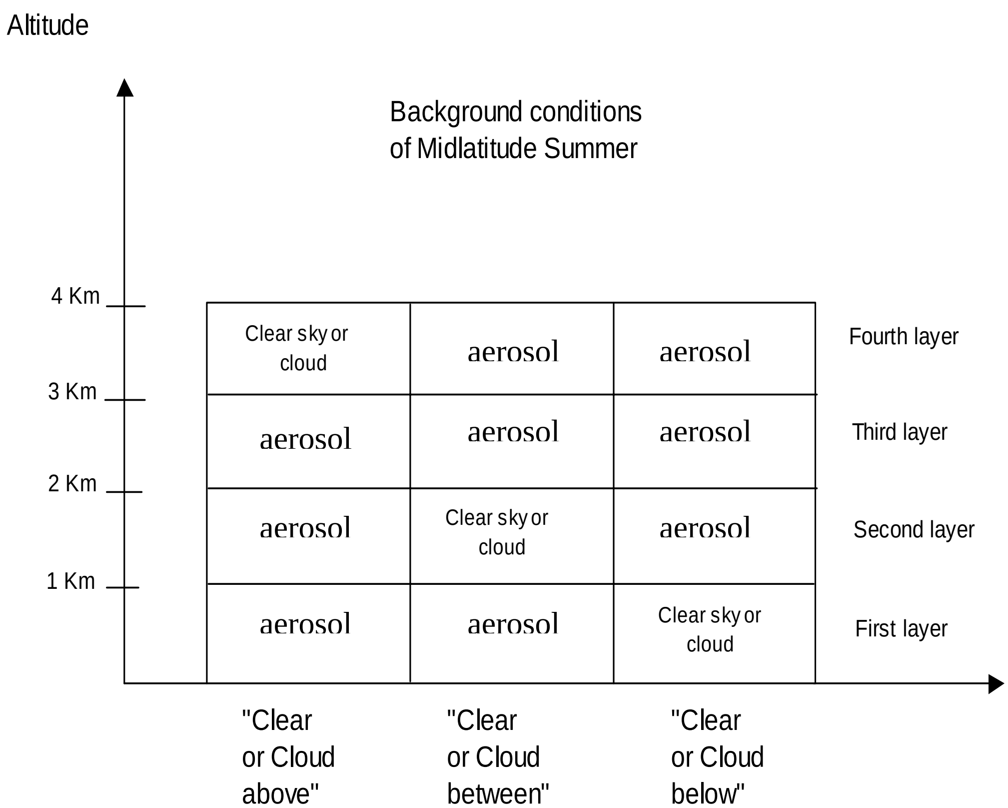


Figure 24.4 Schematic representation of the aerosol-cloud/clear sky vertical distribution for calculations of heating/cooling rates shown in figures 24.6-24.8 (see below).

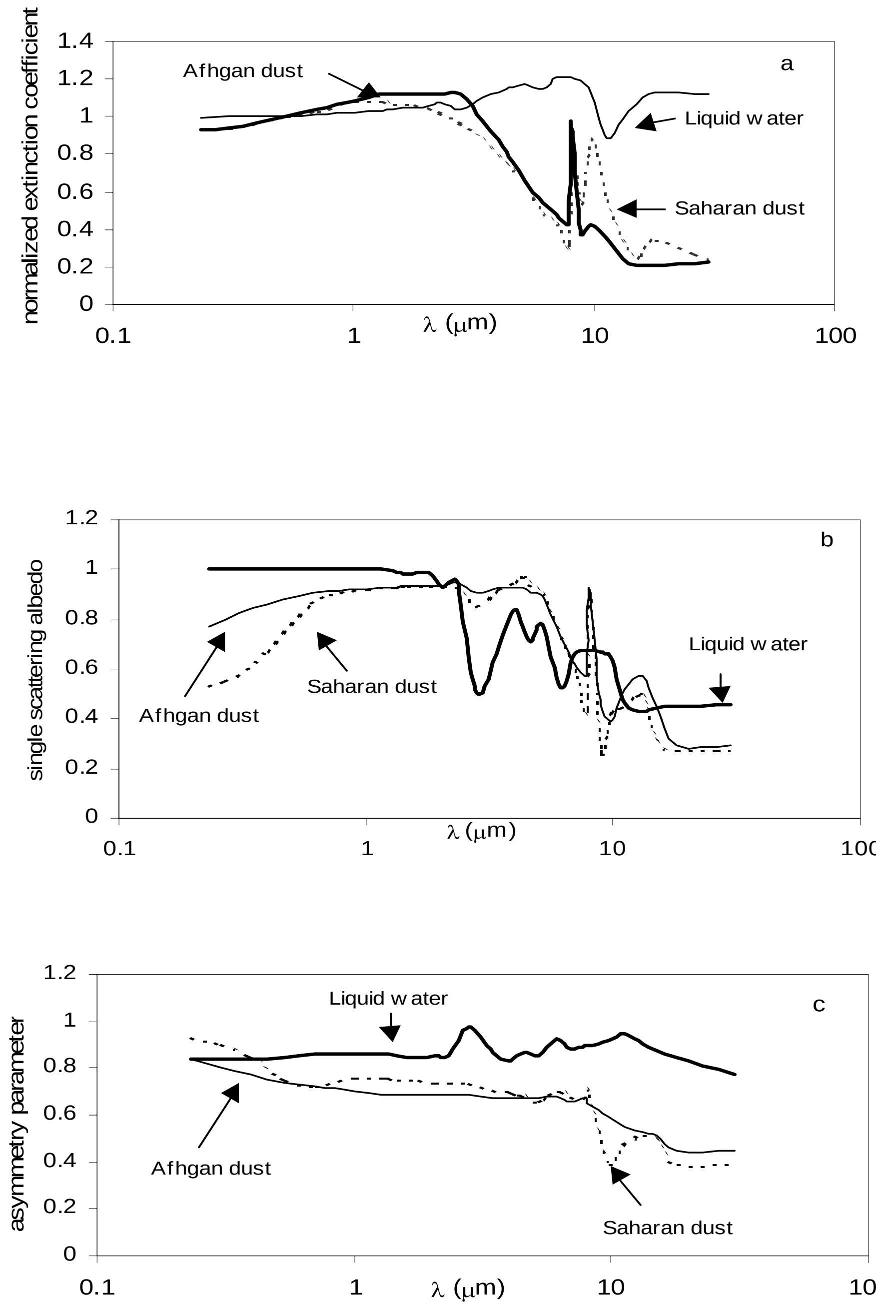


Figure 24.5 Spectra of (a) normalized extinction coefficient, Kext/Kext(0.5 μm), (b) single scattering albedo, ω_o, and (c) asymmetry parameter, g, calculated for strong absorbing dust (Saharan-like dust model), weak absorbing dust (Afghan-like dust model), and marine stratus cloud (Quijano, Sokolik, and Toon, 2000).

NOTE: Saharan dust model selected in this study has lower values of the single scattering albedo in the solar.

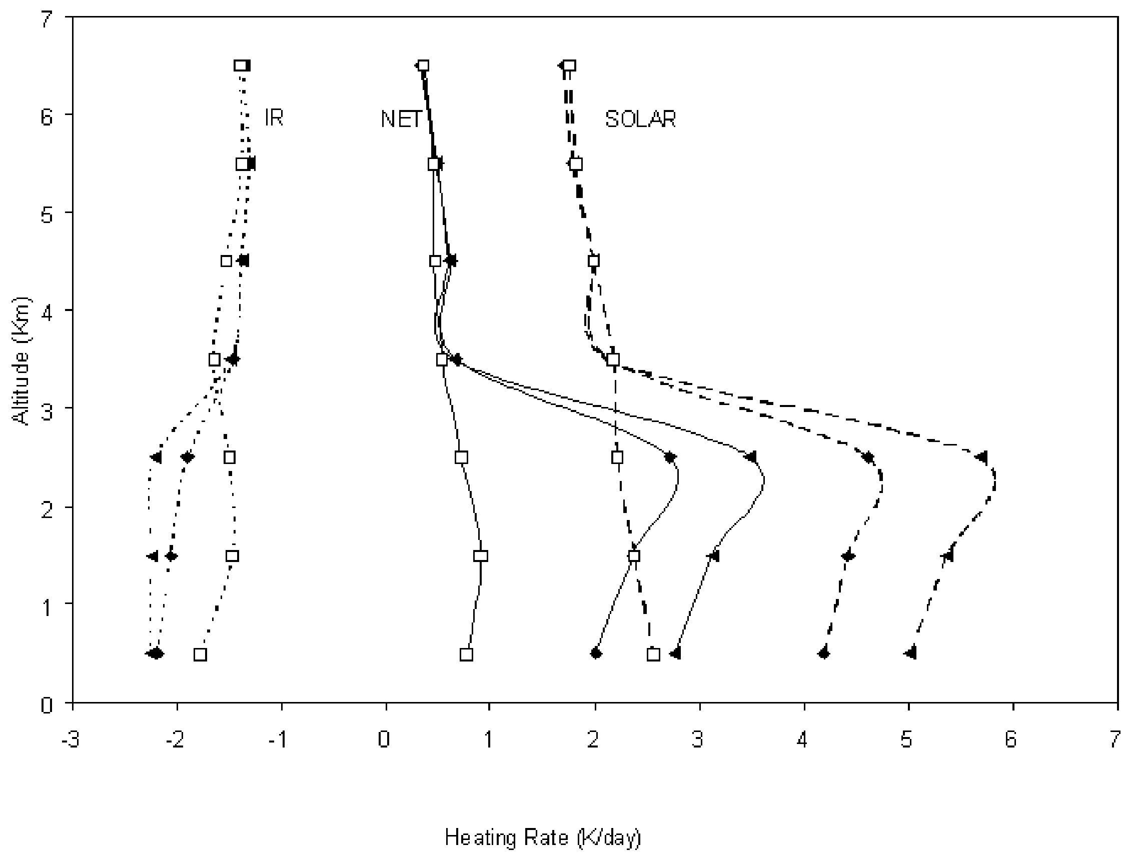


Figure 24.6 Solar (long-dashed lines), thermal IR (short-dashed lines), and total (solid lines) radiative heating rates of Saharan and Afghan dust and for clear sky, over the desert (r_s=0.3) at μo = 0.8; open squares are for clear sky; triangles are for Saharan dust; diamonds are for Afghan dust; "Clear above" and τ_{dust} (0.5 μm) = 0.5 (Quijano, Sokolik, and Toon, 2000).

Main features:

- Maximum solar and total heating rates occur at the top of an aerosol layer
- IR cooling rates < solar heating rates => total heating
- Total heating rates in an aerosol layer > total heating rates of clear sky

➢ **<u>Over dark surfaces</u>**

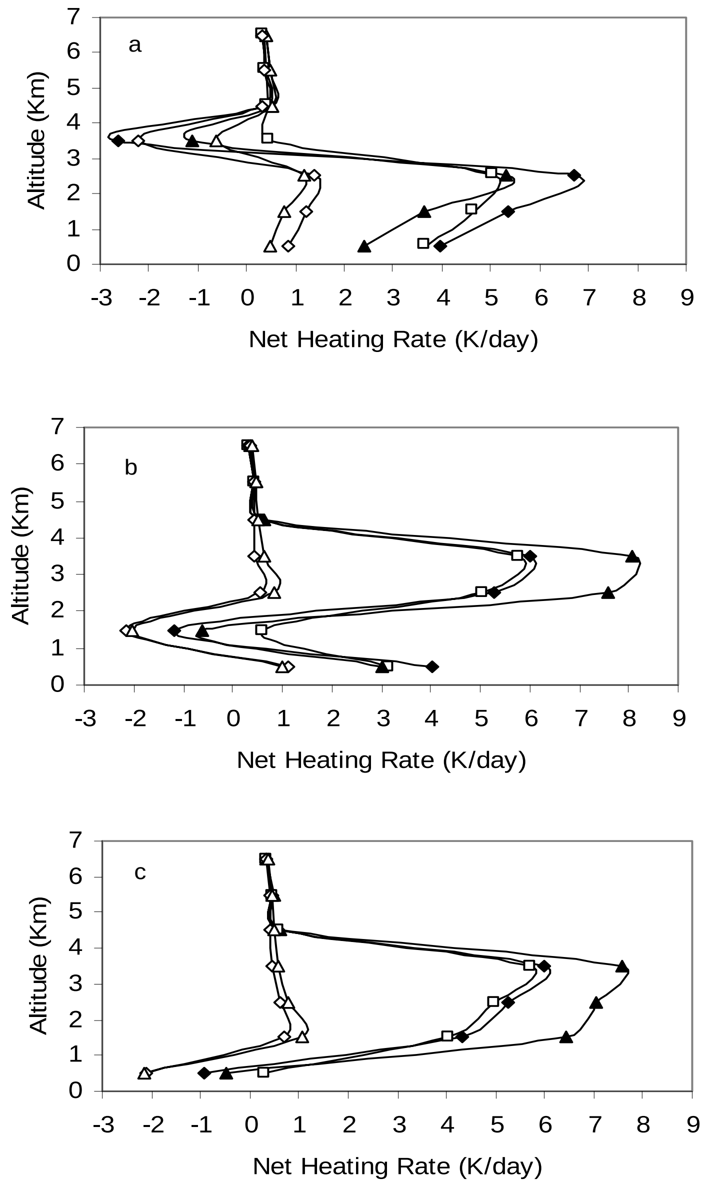


Figure 24.7 Total radiative heating rates by dust and cloud <u>over ocean</u> at μo = 0.8 for (a) "Clear or Cloud above", (b) "Clear or Cloud between", and (c) "Clear or Cloud below"; open diamonds are for "Only Thin Cloud"; open triangles are for "Only Thick Cloud"; open squares are for only dust; solid diamonds are for "Dust and Thin Cloud"; solid triangles are for "Dust and Thick Cloud"; Saharan dust and τ_{dust} (0.5 μm) = 1. (Quijano, Sokolik, and Toon, 2000).

➢ **<u>Over bright land surfaces</u>**

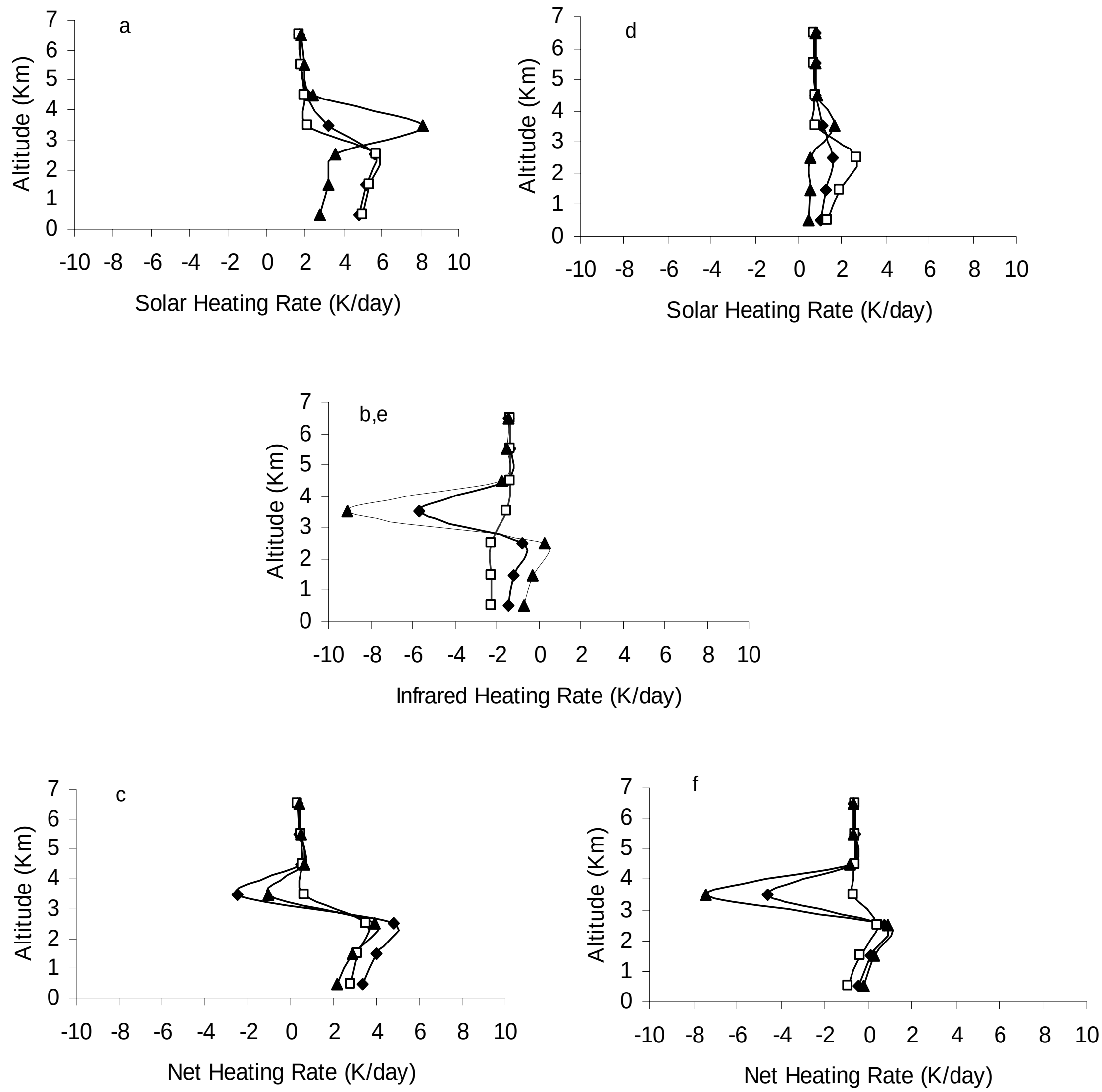


Figure 24.8 Radiative heating rates over the desert (r_s=0.3) of (a) solar, (b) infrared, and (c) net at μo = 0.8 and of (d) solar, (e) infrared, and (f) net at μo = 0.25; open squares are for "Clear above", diamonds are for "Thin cloud above"; triangles are for "Thick cloud above"; Saharan dust, and τ_{dust} (0.5 μm) = 0.5 (Quijano, Sokolik, and Toon, 2000).