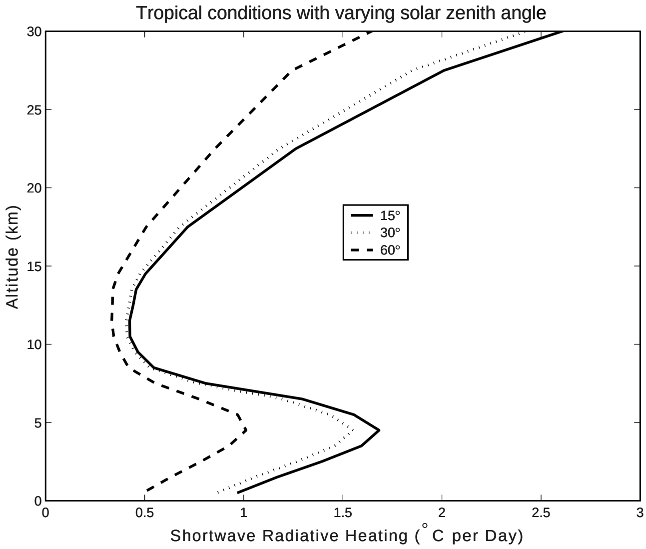

Fig. 10.7: Typical heating profiles due to solar absorption in a cloud-free tropical atmosphere at three different solar zenith angles. The heating profile for $\theta_s = 30^\circ$ corresponds to the sum of the three profiles in Fig. 10.6. *(Figure courtesy of S. Ackerman.)*

is created by the action of UV-C radiation on molecular oxygen. In fact, the stratosphere itself, which is *defined* by the general increase of temperature with height starting around 10–15 km owes its very existence to the absorption of solar radiation by ozone. *If there were no molecular oxygen in the atmosphere, there would be no ozone layer. Without ozone, there would be very little solar heating of the middle atmosphere and therefore no stratosphere!*

- Carbon dioxide is evenly mixed throughout the atmosphere, because atmospheric sources and removal mechanisms for CO_2 operate very slowly in comparison to those for water vapor and ozone.

Problem 10.2: Actual water vapor mixing ratios in the standard tropical atmosphere continue to increase all the way to the surface.

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Yet the heating rate associated with water vapor peaks at an altitude near 5 km and then decreases sharply below that level. Explain why.

Total shortwave heating rates are of course the sum of those contributed by the individual constituents. Profiles of total heating due to the absorption of solar radiation in a tropical atmosphere are shown in Fig. 10.7. The different profiles correspond to different solar zenith angles. Not surprisingly, when the sun is lower in the sky, overall heating rates are reduced.

Of course, the heating profiles described above include only contributions due to *direct* absorption of shortwave radiation. In the absence of clouds, solar radiation not absorbed by the atmosphere reaches the surface, where a fraction equal to one minus the surface albedo gets absorbed. Much of that energy *indirectly* heats the atmosphere by way of three mechanisms: (1) emission and reabsorption of longwave radiation (discussed below), (2) direct conduction of heat from the surface to the overlying air, followed by convective mixing, and (3) evaporation of water from the surface, followed by latent heat release in clouds.

Longwave Cooling

In the longwave band, each part of the atmosphere is simultaneously emitting and absorbing radiation. Where absorption dominates, there is net heating; where emission dominates, there is net cooling. Profiles of heating / cooling in the longwave band are more difficult to interpret because all four of the terms in (10.65) are potentially significant.

Fig. 10.8 shows longwave heating profiles for a tropical atmosphere, again segregated according to the responsible constituent. Water vapor is actually represented here by two curves, one for the heating contribution due to its rotation / vibration bands near 6.3 μm and beyond 15 μm; the other due to the relatively weak but pervasive continuum component that dirties up the spectral “windows” between conventional absorption bands.

Here is a brief rundown of the major features seen in this plot:

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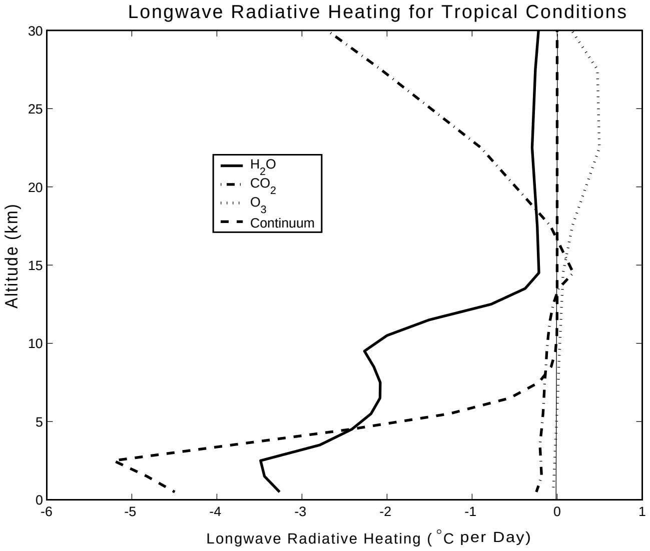

Fig. 10.8: Typical heating rate profiles due to longwave (thermal IR) radiative transfer in a cloud-free tropical atmosphere, segregated according to the responsible atmospheric constituents ozone (O_3), carbon dioxide (CO_2), water vapor resonant absorption (H_2O), and water vapor continuum. Negative values represent cooling. *(Figure courtesy of S. Ackerman, with modifications.)*

CO$_2$ Because of the high opacity of the pressure broadened 15 μm band, carbon dioxide contributes rather little to net radiative heating in the troposphere. Radiation emitted at one level is reabsorbed at nearby level having almost the same temperature. Only at the tropopause (near 15 km), where the temperature profile has a minimum, is there a small amount of net heating. At higher altitudes, pressure broadening is much weaker and the band "opens up," allowing emitted radiation to escape to space with little compensating radiation downward from higher levels. This is of course the *cooling to space* previously discussed in connection with term (B) in (10.65).

H$_2$0 Because water vapor is concentrated at low altitudes, the cooling-to-space effect kicks in strongly between 3 and 10 km altitude, with maximum cooling rates between 2 and 3.5 K/day. The two peaks in the profiles are associated with