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and
Atmospheric Radiative Transfer

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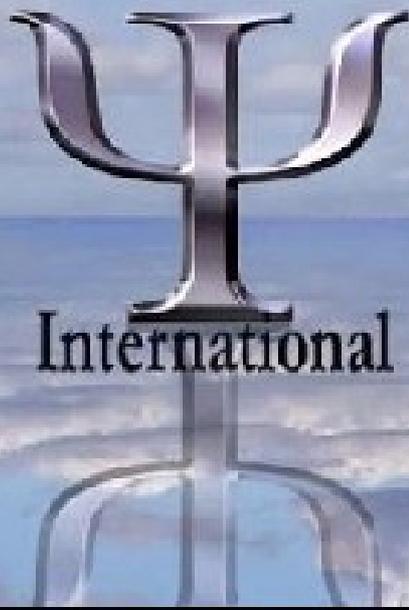
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The Planck Blackbody Equation and Atmospheric Radiative Transfer

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There appears to be a lot of confusion over the use of the terms 'blackbody absorption' and 'equilibrium' in the derivation and use of the Planck equation, particularly for atmospheric radiative transfer.

First, it is important to understand the history of blackbody radiation. A good description is in R. W. Wood's book 'Physical Optics'. The original 1905 edition is available on line at
http://www.unz.org/Pub/WoodRobert-1911?View=ReadIt

[Use the scroll bar at the bottom to get to page 454, Chapter 19 'The Laws of Radiation'.]

The basic idea that (thermal) absorption and emission are equivalent goes back to the 1850's and the work of Bunsen and Kirchoff on sodium D line reversal in flames. Wood states Kirchoff's law (1859) as

At a given temperature, the ratio between the absorptive and emissive power for a given wavelength is the same for all bodies. [1934 Edition of Physical Optics]

In other words $B = e/A$, where B is the blackbody emission, e is the emissivity and A is the absorption. This of course assumes thermal radiation and A for gases can change very rapidly with wavelength. Thermal radiation means that the population of the emitting states follows the Maxwell-Boltzmann distribution law, including the various quantum degeneracy terms.

Planck correctly derived the value of the constant B for any T and lambda with $A = 1$ using a quantized form of the electric dipole oscillator. This laid the foundation for quantum theory, but it did not change Kirchoff's Law.

Planck started from a description of the experiments used to measure thermal radiation in the late nineteenth century – a small hole in a heated enclosure (furnace) internally coated with graphite. The term 'cavity' also needs to be used with care. This is not a resonant cavity in the sense of a passive laser cavity. All of the light that is emitted by the surface is absorbed by the surface without reflection.

Plank also used the term 'equilibrium' in a rather specific way to define a uniform temperature. The rate of emission of the surface within his cavity is the same as the rate of absorption. This is just a precise way of saying that the interior surface is at a uniform temperature.

If a 1 cm^2 hole is added to a spherical 'blackbody' cavity, then the thermal emission from the hole is equivalent to the emission from the missing surface. In the limit of a large thin sphere, this is just a circular flat surface with an area of 1 cm^2.

If it is necessary to maintain the temperature of the sphere with the hole, then sufficient thermal energy has to be added to replace the 1 cm^2 emission at σT^4 as required by Stefan's Law.

Now Planck's law applies at any temperature. If the sphere is not heated, it will cool. If the cooling is slow enough to maintain a uniform surface temperature within the sphere, the cooling rate will depend on the heat capacity of the sphere and the thermal emission through the hole. The result will just be the usual exponential thermal decay curve.

If the temperature during cooling is non uniform, Planck's law still applies at each temperature and for each internal area of the sphere with the same temperature.

Planck's Law has to be modified to account for any refractive index effects at the surface. These can be added as a second surface interface. This was clearly understood by Wood in his discussion. Planck's Law also has to be modified to include other quantum mechanical oscillator effects such as the 2J+1 fold degeneracy of molecular rotation states. However, these modify the absorption as well as the emission and are really part of Kirchoff's Law, not Planck's.

When refractive index effects are included, the absorption and emission have to be measured along the same optical path (and with the same polarization).

In normal engineering use, the Planck equation is used to define the rate of thermal radiation (flux) emitted from a surface. There is no equilibrium requirement. The absolute temperature and the surface absorption are the minimum properties needed to define the radiative surface flux at a given wavelength. Since the spectroscopic and total emission properties are temperature dependent, the emission properties may be used to measure the surface temperature at the time of the measurement. However, the surface flux really defines the rate of cooling and the change in temperature over a period of time t is just

$$\Delta T = C \Delta Q$$

Where C is the heat capacity and ΔQ is the heat (enthalpy) lost to thermal radiation.

The heat radiated from the surface is only one part of the thermal energy balance. The heat absorbed by the surface from the surroundings, the convection and the latent heat changes also have to be considered.

Application to Atmospheric Radiative Transfer

The fundamental error that was made by the IPCC [and Carl Sagan and others] is the climate equilibrium assumption. In order to maintain a stable climate, conservation of energy requires that the solar flux absorbed by the climate system be re-radiated to space as LWIR radiation. However this does not impose an exact flux balance requirement. The solar flux absorbed at the surface varies significantly on both a daily and a seasonal time scale. The sun does not illuminate the surface at night. The absorbed heat is stored by the climate system and released to space at a much more uniform rate than it is received. However, there are still significant variations in the spatial and temporal values of the LWIR flux emitted to space.

The basic climate energy transfer process for returning sunlight to space as LWIR flux involves 3 steps. First, the solar flux is absorbed at the land surface, or just below the surface for the oceans (~90% in the first 10 m layer). Second, the surface heat is transported up through the troposphere by (moist) convection. Third, the heat is stored in the troposphere and radiated to space, mainly by the water bands in the middle troposphere. The troposphere acts as two independent thermal reservoirs with a boundary at about 2 km, so the heat at the surface is decoupled from the heat released to space [Clark 2013a,b].

The surface temperature is determined mainly by the energy balance between the wind driven ocean surface evaporation and the solar heating of the ocean. Climate changes induced by the El Nino Southern Oscillation (ENSO) change the extent of the equatorial Pacific warm pool, but they do not change the 30 C upper limit to the ocean surface temperature. Much of the ocean heat is removed by evaporation and released into the middle troposphere by condensation.

The basic misunderstanding over ocean heating comes from the blackbody surface equilibrium assumption, not from the thermal emission. The water surface is a good blackbody emitter at normal ocean temperatures. However, it is almost transparent to the incident solar flux. The net LWIR flux balance at the water surface defines the net radiative cooling rate. However, the solar heating occurs below the surface where the thermal radiation is not well defined. There is no simple connection between the average local solar flux and the average local LWIR emission. The balance of the surface cooling is determined by the wind driven evaporation, which is a momentum transport process, not a simple thermal transport process. Ocean evaporation and LWIR absorption/emission are limited to a thin layer close to the surface. Small changes in the net LWIR flux cannot be separated and averaged independently of the total cooling flux. It is the total water mass flux, determined by the sinking and convective mixing of cooled water from the surface that actually cools the oceans.

The atmospheric temperature profile in the troposphere is set by convective mixing. As the moist convection rises from the surface, the air expands and cools. The atmospheric thermal gradient is known as the lapse rate. The cooling is produced because the rising air mass has to overcome the gravitational potential. The required potential energy is lost

from the internal energy of the air molecules. The expansion of the air reduces the number density of the IR absorbers ('greenhouse gases'). As the absorption decreases, then the corresponding thermal emission must also decrease. This is in addition to the decrease in thermal emission from the change in temperature.

When the atmospheric temperature and species profiles are defined, HITRAN, or equivalent spectroscopic databases can be used to calculate the atmospheric LWIR flux. This provides a 'snapshot' of the LWIR flux for the specific atmospheric profile used. However, the LWIR flux is fully coupled to the local air mass. The local cooling is determined by the net loss of heat over a given period of time and the corresponding change in temperature is determined by the heat capacity of the local air mass. In addition, a change in temperature of the local air mass leads to a change in density. If this changes the buoyancy of the air parcel, the temperature will change as the air expands or contracts with variations in altitude. Furthermore, at low humidity in the upper troposphere, the lapse rate is close to the dry air value of -9.8 K km^{-1}. As the air sinks, it warms up.

The LWIR flux observed at the top of the atmosphere has to be interpreted as a cooling flux that originates from various levels within the atmosphere. This is illustrated in Figure 1 [Mlynczak et al, 2002]. This shows the spectrally resolved cooling of the atmosphere as a function of pressure (related to height) for mid latitude summer. The units are mK per day per cm^{-1}. If the cooling were all green at 1 mK day 1/cm^{-1} near 500 mbar, the total cooling rate over the full 2000 cm^{-1} spectrum would be 2000 x 1 mK = 2 K per day at an altitude near 3 km. [The color temperature scale here is logarithmic. Negative values mean heating instead of cooling]. The orange/red heating bands are from high altitude ozone.
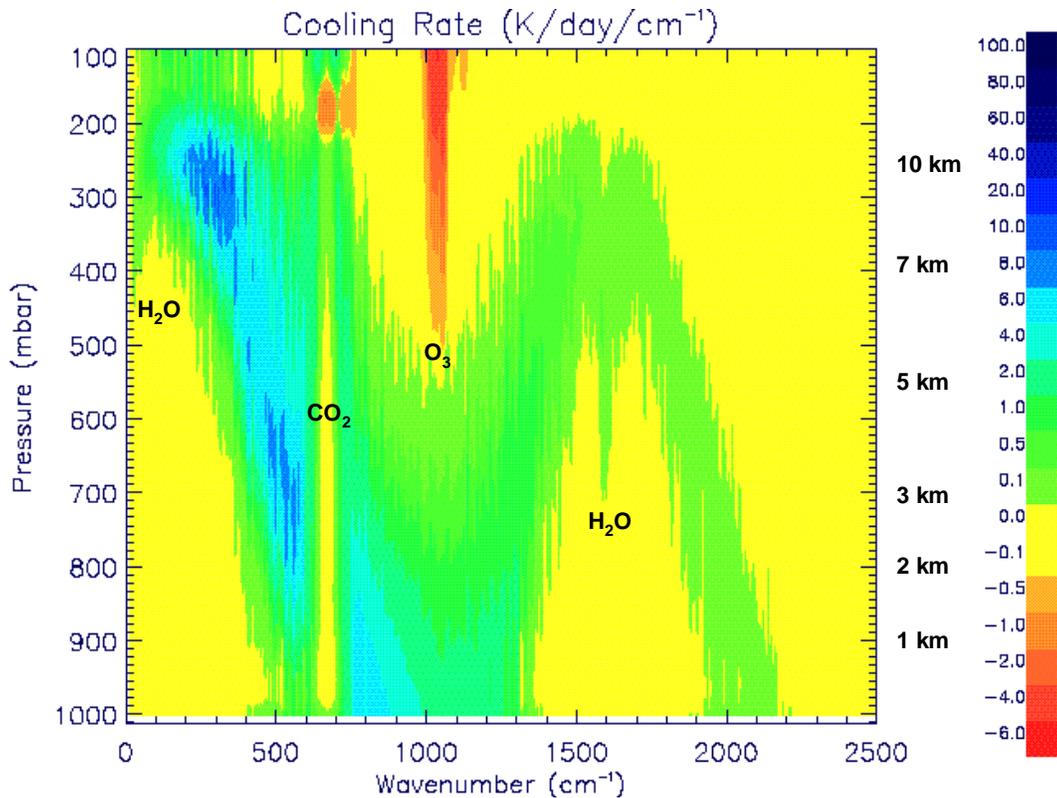
Figure 1: Spectrally resolved atmospheric cooling rates (mK per day per cm^{-1}) vs. atmospheric pressure (altitude).

Now consider Figure 1 in more detail. Starting at ground level (1000 mbar), the yellow regions from 0 to 500 cm^{-1}, 600 to 700 cm^{-1} and 1400 to 1900 cm^{-1} show no cooling and perhaps a little warming. These are the regions of the most intense absorption from H_2O and CO_2. At low altitudes within these bands, all of the LWIR flux from the surface is absorbed and replaced by LWIR emission from the IR emitters in the air parcel. This is illustrated in Figure 2. The net cooling (or warming) for a given air parcel is produced by the net balance of four flux terms. This is illustrated in Figure 3. The upward flux from below and the downward flux from above are partially absorbed by the air parcel. Flux is also emitted upwards and downward from the air parcel. The upward and downward emitted fluxes are equal. [This assumes a plane parallel atmosphere]. Within the intense absorption bands, the four flux terms balance out and there is little or no cooling.
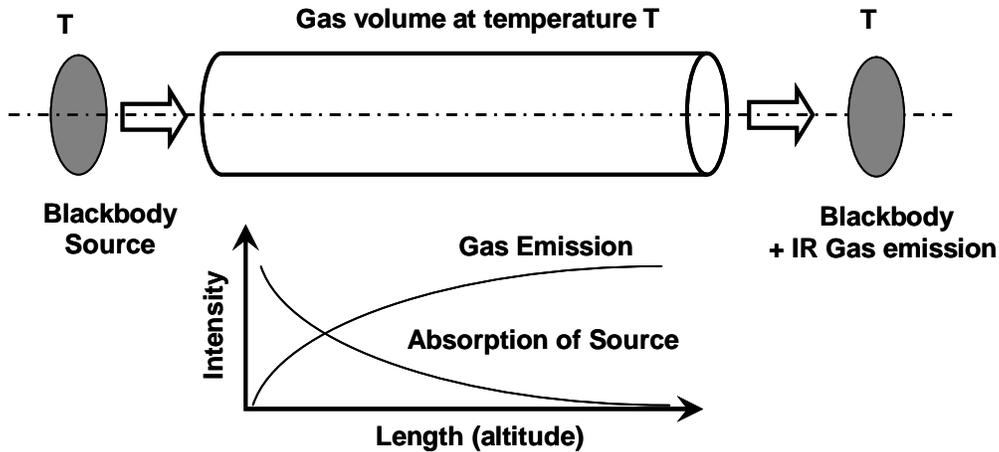
Figure 2: Gaseous absorption and emission: In this case, at a high absorption wavelength, all of the blackbody emission from the source is absorbed and replaced by emission from the IR active species ('greenhouse gas') in the air volume. The source and gas volume are at the same temperature T.
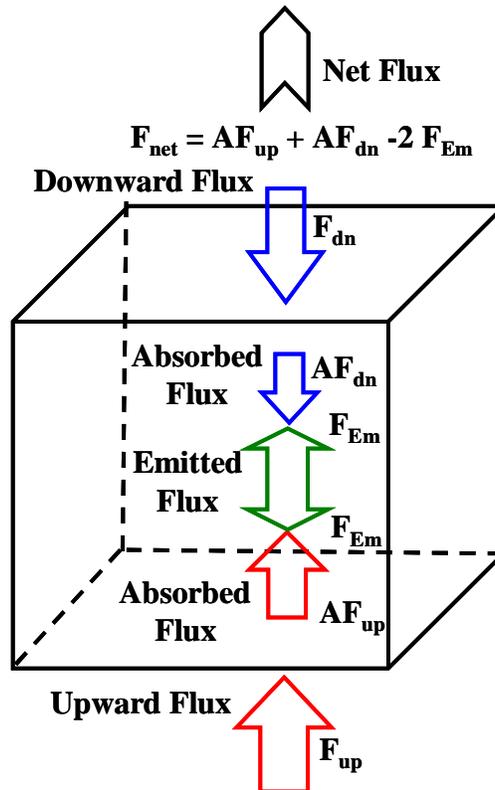
Figure 3: Radiative transfer energy balance for an air parcel in the troposphere: part of the upward and downward fluxes incident on the air parcel are absorbed and the air parcel emits LWIR thermal radiation at its local temperature T. The net cooling (heating) is determined by the balance between these terms. The change in temperature over time t is determined by the time integrated net flux balance and the heat capacity of the air parcel.

For a 100 m increase in altitude at an average lapse rate of -6.5 K km^{-1}, the decrease in total blackbody emission is approximately 3 W m^{-2}. This explains the slight warming observed within the low altitude, high absorption bands. The absorbed flux from below

is sufficient to offset the net cooling from the air parcel emission and the absorption of the downward flux from above.

Most of the cooling (blue/dark blue regions) originates from the water bands. The region of maximum cooling flux shows a shift to lower energy as the altitude and therefore the temperature decreases. The cooling process involves a reduction in the water vapor concentration as the temperature decreases. This decreases the absorption of the water vapor lines which in turn reduces the emission. This follows from Kirchoff's Law. The detailed relationship between the absorption and emission then follows from Planck's Law – applied at each wavelength/wavenumber. The spectral resolution has to be high enough to give an accurate line profile. The Planck blackbody emission has to be scaled by the absorption at each wavelength/wavenumber.

The upward and downward LWIR fluxes are not equivalent. The emission from the wings of the lines at lower altitudes is not re-absorbed at higher altitudes. The downward emission near line center from higher altitudes is re-absorbed at lower altitudes. This is illustrated in Figure 4. The atmospheric equilibrium assumption is incorrect. The LWIR emission to space is decoupled from the surface. Small changes in atmospheric LWIR emission at the top of the atmosphere have no effect on surface temperature. However, within the LWIR transmission window it is still possible to detect the thermal radiation from the surface.
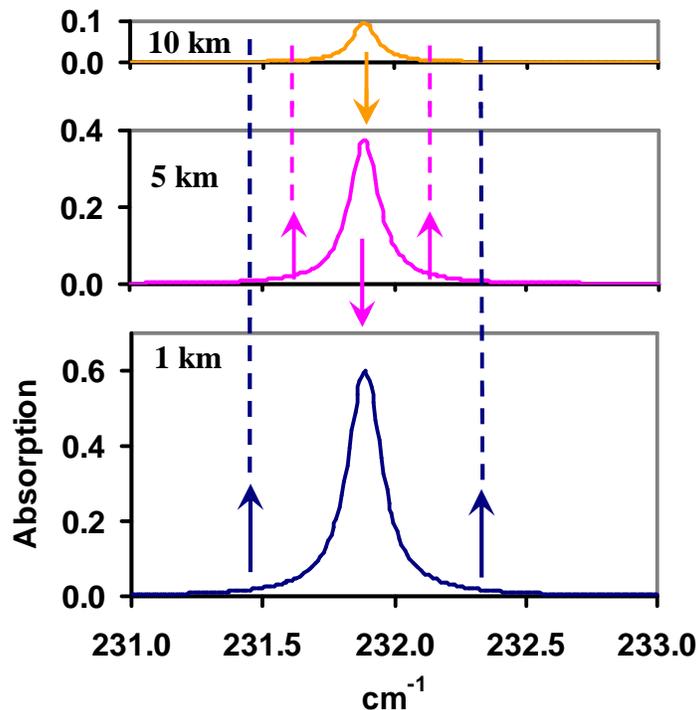
Figure 4: The effect of line narrowing on atmospheric absorption/emission. The emission from the wings of the lines at lower altitudes is not re-absorbed at higher altitudes. The downward emission near line center from higher altitudes is re-absorbed at lower altitudes. The line profile is calculated for a single water line near 232 cm^{-1}. The path length is 100 m.

For convenience, the emission properties of the troposphere may be illustrated by using lower resolution, 1 cm^{-1} spectra derived from the high resolution data. Figure 5 shows the effective absorption of a 100 m layer of air in the troposphere at 0.1, 3, 6 and 9 km. This is just the thermal emission divided by the blackbody emission using the high resolution data summed into 1 cm^{-1} 'bins'. The surface and air temperature at the surface are 288 K (15 C). The CO_2 concentration is 380 ppm and the surface relative humidity is 50%. The calculations are for $^1H_2^{16}O$ and $^{12}C^{16}O_2$ only with linestrengths above 10^{-23}. Spectral data is taken from the 2004 HITRAN database. For further details see Clark [2013a, b, 2011, 2010]. The water band absorption decreases faster with altitude than the CO_2 band. Figure 6 shows the cooling rate in mK per day per cm^{-1} for 100 m thick air layers at 0.1, 3, 6 and 9 km, corresponding to the absorption bands in Figure 5. Figure 7 shows the related cooling flux in W m^{-2}. In order to determine the cooling rate in mK/day, the LWIR flux in W m^{-2} has to be scaled to a daily rate and divided by the heat capacity of the air layer. Since the air density decreases with altitude, so does the heat capacity. A higher cooling flux is required at lower altitudes to produce the same cooling rate in mK day^{-1}. This can be seen by comparing the 3 and 6 km plots in Figures 6 and 7.
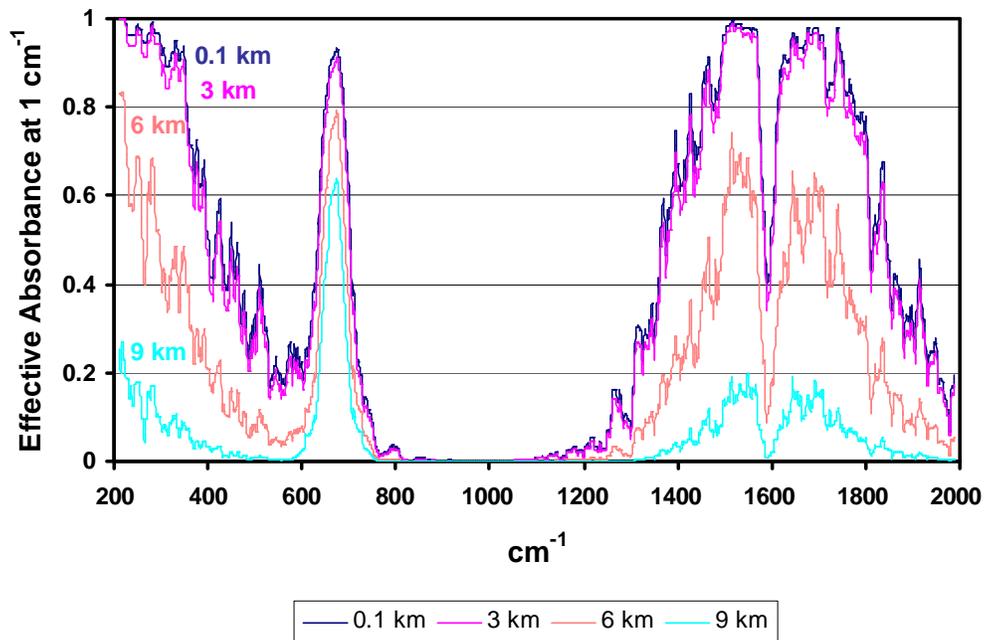
Figure 5: Effective atmospheric absorbance at low (1 cm^{-1}) spectral resolution for four selected altitudes and 100 m air layer thickness (path length).
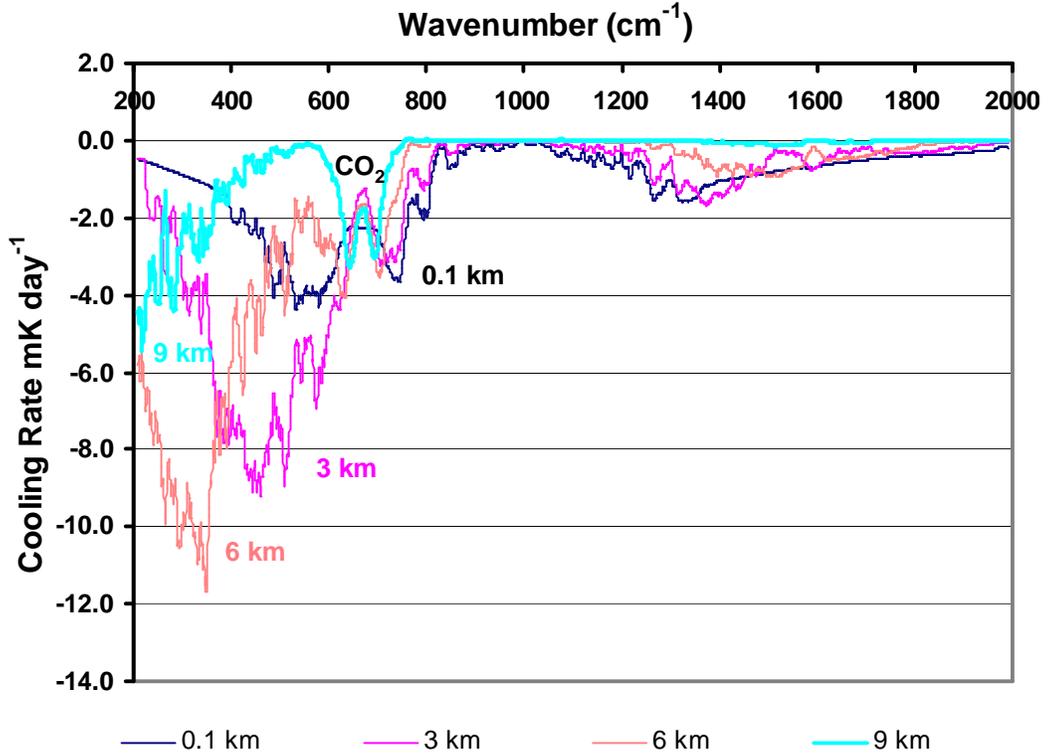
Figure 6: Spectrally resolved atmospheric cooling rates (mK day^{-1}/cm^{-1}) at low (1 cm^{-1}) spectral resolution for four selected altitudes and 100 m air layer thickness (path length).
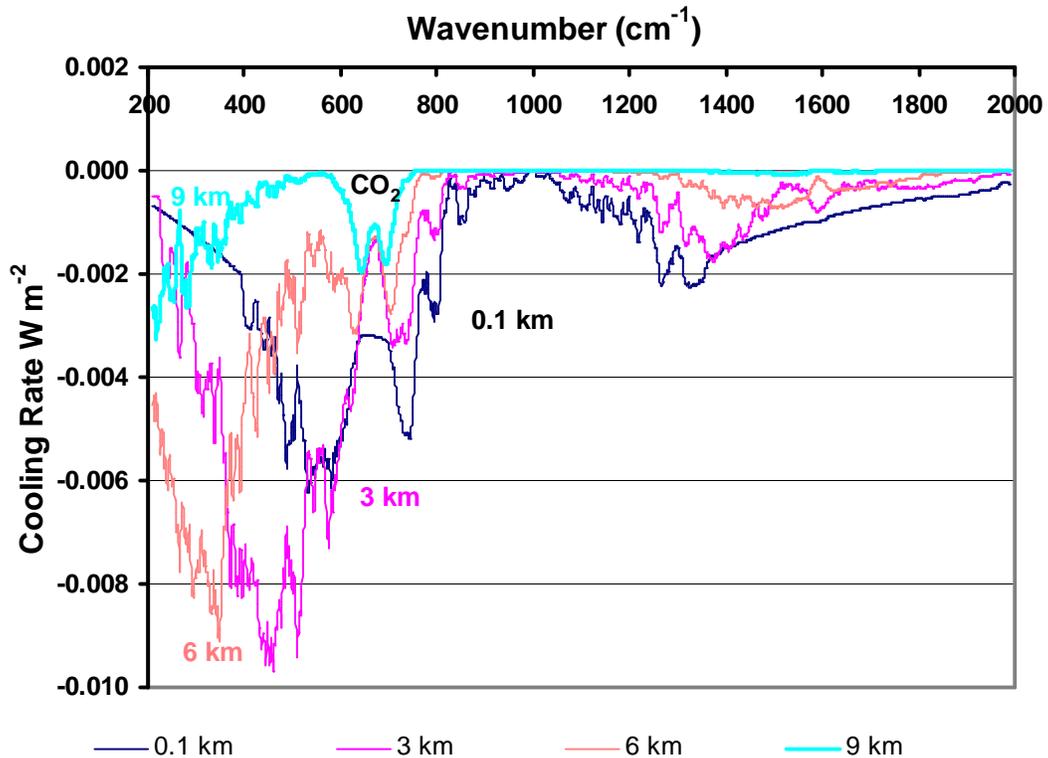
Figure 7: Spectrally resolved flux cooling rates (W m^{-2}/cm^{-1}) corresponding to Figure 3.

The rate of cooling to space is determined mainly by the radiative transfer properties of the water bands. The rate of heating is determined by the convective transport of heat from the surface. These two processes are essentially decoupled. At mid latitudes, the seasonal summer solar heating increases the height of the troposphere. The emission from the water bands simply shifts to higher altitude. As the troposphere cools in winter, the water band emission shifts to lower altitudes. These changes also alter the location of the polar jet stream. This was recently discussed by Tim Ball [2014]

In simple terms, the troposphere becomes more transparent as the altitude increases and the water vapor concentration decreases. The cooling occurs because the heating flux from the warmer air below is not absorbed in the first place. Kirchoff's Law then requires that less absorption produce less emission at a given temperature. The spectrally resolved emission is calculated from Planck's Law using the blackbody emission at the local air temperature scaled by the spectrally resolved molecular absorption over the path length of the local air parcel. The molecular quantum mechanics is part of Kirchoff's Law, not Planck's.

The surface heating and the LWIR emission to space are decoupled. There is no flux equilibrium. The atmosphere cools by LWIR emission to space and is independently heated by moist convection and advection. The equilibrium flux equations, forcings, feedbacks, climate sensitivities etc. are mathematical artifacts of the equilibrium modeling assumptions. They do not apply to planet Earth.

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[Further details also available at: http://www.venturaphotonics.com]

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