10

Longwave Radiative Transfer in Inhomogeneous Cloud Layers

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10.1 Introduction

The solar energy absorbed by the Earth-atmosphere system is balanced in the long term by radiant loss of energy by the system to space in the thermal infrared. The manner by which this loss to space occurs involves absorption, scattering and thermal emission by the surface and the gaseous and suspended matter (i.e., clouds and aerosols) within the atmosphere. These complex processes in the thermal infrared comprise the "atmospheric greenhouse effect," which makes the Earth's surface warmer than it would be if the atmosphere were not present and leads to a complex vertical temperature profile.

The Earth-atmosphere thermal radiative processes are non-linear in atmospheric properties, and there are complex radiation-climate feed back mechanisms. Furthermore, unlike solar radiation, thermal radiative processes occur continuously in time. Thus, realistic modeling of the climate system, as well as remote sensing techniques to accurately infer properties of the atmosphere, require accurate models of the various radiative processes that occur in the thermal infrared.

When absorption, thermal emission and scattering occur, the equation of radiative transfer under local thermodynamic equilibrium may be written as (see Chap. 3)

$$\begin{aligned}\boldsymbol{\Omega} \bullet \nabla I = &- \sigma_{\mathrm{e}}(\boldsymbol{x}) I(\boldsymbol{x}, \boldsymbol{\Omega}) \\ &+ \sigma_{\mathrm{s}}(\boldsymbol{x}) \int\limits_{4\pi} p(\boldsymbol{x}, \boldsymbol{\Omega}' \rightarrow \boldsymbol{\Omega}) I(\boldsymbol{x}, \boldsymbol{\Omega}') \mathrm{d}\boldsymbol{\Omega}' + \sigma_{\mathrm{a}}(\boldsymbol{x}) B_{\mathrm{v}}(T(\boldsymbol{x}))\end{aligned} \tag{10.1}$$

where σ_e, σ_s, and σ_a are the transport coefficients for extinction, scattering, and absorption respectively. Here, $\sigma_e = \sigma_s + \sigma_a$ and p is scattering phase function (normalized in such a way that its integral over 4π steradians is unity); ϖ_0, the albedo of single scattering, is defined as the ratio of σ_s to σ_e. Finally, B_v is the Planck function depending on local temperature T, an isotropic source term. Neglecting incident solar radiation in the longwave portion of the spectrum (wavelength $\lambda \gtrsim 3\mu$m), solutions of this equation for the entire atmosphere are usually sought by assuming as boundary conditions zero incident radiation at the top of the atmosphere (TOA), and thermal emission and reflected incident radiation at the base. The effects of the solar longwave radiation, if important, are typically calculated separately, by means discussed in previous chapters. For downward flux considerations, this term is typically the order of 10 $\mathrm{Wm^{-2}}$, on the order of a few percent of the thermal longwave flux incident on the surface.

When only gases are considered, ϖ_0 is essentially 0 in the thermal infrared due to the λ^{-4} decrease of the molecular scattering coefficient. For this case, the radiation field depends only on the absorption properties, amounts and distributions of the active gases, the temperature distribution, and the emission properties of the underlying surface. Due to the relative opacity of the atmosphere and the generally slow horizontal variation of temperature and absorbing gases, clear-sky radiation calculations are generally performed assuming a horizontally homogeneous atmosphere.

The main difference in the treatment of shortwave and longwave radiation is due to the spectral absorption of atmospheric gases. Figure 10.1 is a low-resolution depiction of the major absorption features of the dominant active gases and the approximate spectral distributions of incoming solar energy and terrestrial radiation emitted by the atmosphere. In the solar portion of the spectrum ($\lambda \lesssim 4\,\mu$m), there is little gaseous absorption across large regions of the spectrum, particularly the region from 0.3 to 1 μm, a region containing more than 50% of the incident solar radiation. This region is particularly sensitive to the presence of clouds since ϖ_0 for cloud particles is close to 1, and thermal emission by the gases is practically 0.

In the longwave, the atmosphere as a whole is nearly opaque to energy incident on its boundaries due to the strong vibration-rotation bands of H_2O, CO_2, O_3, CH_4 and N_2O. The major exception is the interval from 8 to 12 μm or 1250 to 833 $\mathrm{cm^{-1}}$ (wavenumber in $\mathrm{cm^{-1}}$ is 10^4 times the reciprocal of wavelength λ in μm and vice-versa). Spectral intervals of significant transmission (lower absorption) are called windows. The primary window is the 8–12 μm interval; this is where clouds and 3D radiative transfer have their largest effects. There is also a “dirty” window centered near 500 $\mathrm{cm^{-1}}$ (20 μm) which becomes significant in dry atmospheres.

The temperature variation in the atmosphere is relatively small, so there is little contrast between the incident and emitted radiation. Scattering effects are most pronounced when the emission source is at a much higher temperature than the scattering medium as in the shortwave. Therefore, scattering is much less significant in

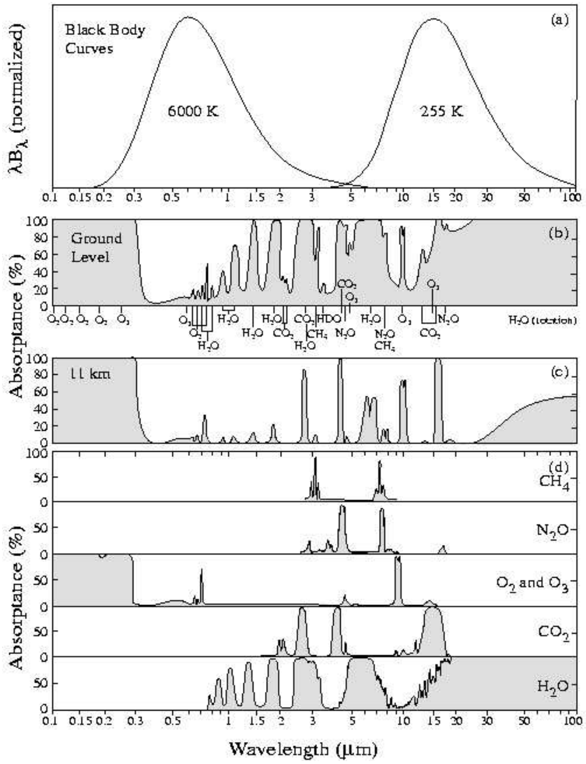

Fig. 10.1. (a) Planck function curves for approximate solar and terrestrial temperatures. **(b)** Absorption spectra for the entire vertical extent of the atmosphere. **(c)** Absorption spectra for the atmosphere above 11 km. **(d)** Atmospheric absorption spectra for the major active gases. From Thomas and Stamnes (1999), with permission.

the longwave than the shortwave. Because the gas concentrations, temperature and pressure vary with altitude, not every part of the atmosphere is opaque, and radiative transfer calculations are complicated by the structure of molecular line absorption.

The longwave optical properties of water clouds, shown in Fig. 10.2, are not nearly as spectrally detailed as those of the gases. ϖ_0 and extinction cross-sections vary strongly with particle size, but for typical cloud particle sizes, $\varpi_0 \approx 0.5$. However, the ϖ_0 to be used in calculations is that for the cloud-air mixture. Although cloud particles have non-zero scattering albedo across the longwave spectrum, the strong absorption by water vapor and other atmospheric gases reduces the effectiveness of scattering by cloud particles in the longwave compared to the shortwave. This is true even in the 8–12 μm window region, where the H_2O continuum absorbs a significant amount in humid atmospheres. Longwave 3D cloud scattering effects are reduced in those portions of the atmosphere where there is strong gaseous absorption.

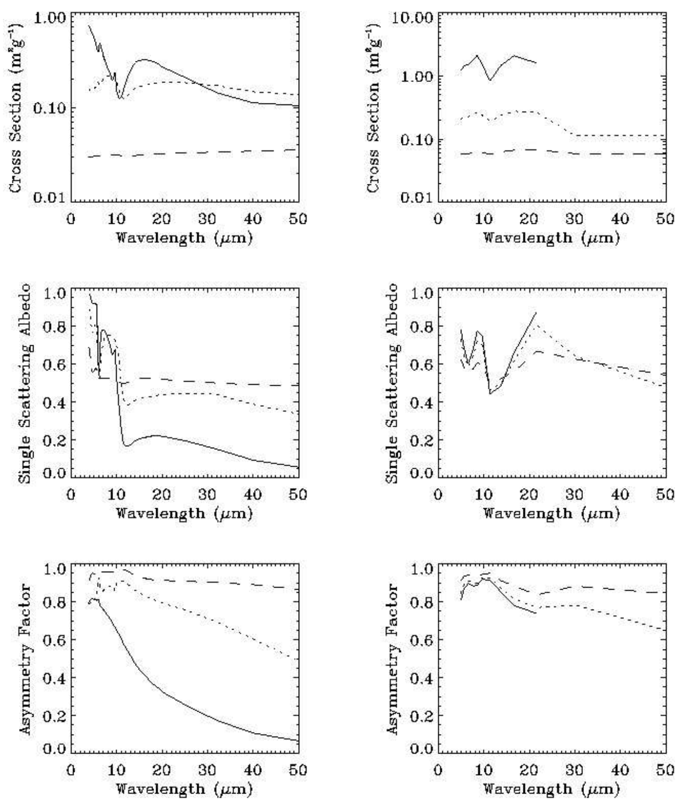

Fig. 10.2. Dependence of the cloud particle longwave optical properties on wavelength and effective radius, from Thomas and Stamnes (1999) with permission. The three left panels pertain to water clouds and the right panels to ice clouds. The curves in the left panels pertain to different effective cloud droplet radii; solid 3 μm; dotted 10 μm; dashed line 50 μm, The right panel curves correspond to different ice particle effective diameters; solid 6 μm; dotted 25 μm; dashed 100 μm.

As a result, 3D scattering effects are typically unimportant in climate models. The exception to this is for conditions typical of some cirrus clouds —thin cold clouds with large particles at low pressures where the concentrations of water vapor and the pressure broadening effects on line absorption are relatively small compared to the lower troposphere. Also, 3D scattering effects may be important for more detailed models such as cloud resolving models (CRMs) and large eddy simulations (LESs). Even in those cases, the spectroscopy of atmospheric gases plays a very large role in longwave 3D radiative transfer.

Although 3D cloud effects are potentially important for a variety of problems in remote sensing and climate studies, the discussion in this chapter is focused toward climate applications. In the material that follows we summarize information on the calculation of radiation quantities for a two dimensional, horizontally homogeneous atmosphere. Next, longwave Monte Carloc alculations are introduced with some results expanding on the two dimensional calculations and results for a 3D calculation.