CHAPTER 12

Scattering and Absorption By Particles

In the previous chapter, we introduced the mathematical framework and terminology needed to account for radiative scattering in the atmosphere. It is safe to say that whenever you find yourself struggling with a thorny problem involving radiative scattering at microwave and shorter wavelengths, some kind of *particles* are to blame, whether they be molecules or hailstones.[1]

Formally, the scattering component of the radiative transfer equation (11.9) depends on the local extinction coefficient β_e (since $d\tau = \beta_\mathrm{e} ds$), single scatter albedo $\tilde{\omega}$ and the scattering phase function $p(\cos\Theta)$. These in turn depend both on wavelength and on the size, composition, shape and number of suspended particles, in addition to any absorption contributions by atmospheric gases. The purpose of this chapter is to examine some basic aspects of the relationship between a particle's physical and geometric properties and its absorption and scattering properties.

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[1] Weak scattering can also occur at radio wavelengths due solely to turbulent fluctuations in the index of refraction of air and / or due to the presence of electrically conducting ionized gases.

Table 12.1: Examples of atmospheric particle types, with representative dimensions and number concentrations. Note that actual values can vary far more widely than indicated here.

Type	Size	Number
Gas molecule	$\sim 10^{-4}\ \mu$m	$< 3 \times 10^{19}$ cm^{-3}
Aerosol, Aitkin	$< 0.1\ \mu$m	$\sim 10^4$ cm^{-3}
Aerosol, Large	0.1–1 μm	$\sim 10^2$ cm^{-3}
Aerosol, Giant	$>1\ \mu$m	$\sim 10^{-1}$ cm^{-3}
Cloud droplet	5–50 μm	10^2–10^3 cm^{-3}
Drizzle drop	$\sim 100\ \mu$m	$\sim 10^3$ m^{-3}
Ice crystal	10–10^2 μm	10^3–10^5 m^{-3}
Rain drop	0.1–3 mm	10–10^3 m^{-3}
Graupel	0.1–3 mm	1–10^2 m^{-3}
Hailstone	$\sim$1 cm	10^{-2}–1 m^{-3}
Insect	$\sim$1 cm	<1 m^{-3}
Bird	$\sim$10 cm	$<10^{-4}$ m^{-3}
Airplane	$\sim$10 m	<1 km^{-3}

12.1 Atmospheric Particles

12.1.1 Overview

The variety of particles encountered in the atmosphere is enormous. Examples include individual gas molecules, haze, smoke, dust and pollen particles, cloud droplets and ice crystals, rain drops, snowflakes, hailstones, insects, birds, and airplanes. Every one of these examples has at least some practical significance as a scatterer of EM radiation in the atmosphere.[2] Table 12.1 gives representative dimensions and number concentrations for some common atmospheric particles.

For the scattering of radiation by particles, *size matters*. The size of a particle is in fact its most important defining characteristic. In general, particles that are far smaller than the wavelength will scatter only very weakly, though they may still *absorb* radiation (e.g., the gas molecules discussed in Chapter 9). We will revisit the question of what “far smaller” means in a moment.

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[2] The last three of these are significant mainly for radar.

At the other extreme, if the particle is *very large* compared to the wavelength of the radiation, then the laws of reflection, refraction, and absorption presented for homogeneous media in Chapter 4 can be used to evaluate σ_e, $\tilde{\omega}$, and $p(\Theta)$ for the particle via the approximate technique known as *ray-tracing* or *geometric optics*.[3]

Unfortunately, many particles in the atmosphere fall in between the two extremes cited above. For these particles, more complex methods are needed in order to compute their scattering and absorption properties. Such methods generally have to consider the effects of diffraction, constructive and destructive interference and other wave-related phenomena.

In this book, we will discuss only those methods applicable to very small randomly oriented particles (Rayleigh theory) or to spheres of arbitrary size (Mie theory). Fortunately, a great many atmospheric particles, from molecules to haze droplets to cloud droplets to rain drops to hailstones, are reasonable (though not always perfect) candidates for one or both of these methods, so we can cover a fair amount of ground.

12.1.2 Relevant Properties

As already mentioned, the relationship between the size of a particle and the wavelength of the radiation of interest is of crucial importance to particle's optical properties as well as to the choice of a suitable method for calculating those properties. We therefore define the nondimensional *size parameter* as

$$\boxed{x \equiv \frac{2\pi r}{\lambda} \,,} \tag{12.1}$$

where r is the radius of a spherical particle. In the case of nonspherical particles, r might represent the radius of a sphere having the same volume or surface area, depending on the context.

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[3] Even for large particles, geometric optics gives results that are seemingly at odds with exact theories. The discrepancy is due to the inability of ray tracing alone to account for subtle bending of light waves passing *near* the particle. However, because the bending is slight, it is often acceptable to treat this radiation as if it had never been scattered at all, in which case the geometric optics approximation yields perfectly acceptable results.