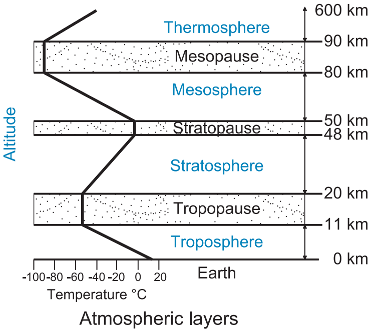
Atmospheric Structure

The atmosphere is commonly divided into two major regimes—the **atmospheric boundary layer** (ABL) and the **free atmosphere**. The ABL is that region roughly 1–2 km above the Earth's surface where heating of the surface leads to convective instability, resulting in thermal plumes and strong **optical turbulence** (i.e., refractive-index fluctuations). The first couple of hundred meters above ground define the surface layer, roughly the first 10% of the ABL, where its properties are determined by the air-to-ground differences in atmospheric parameters. The free atmosphere refers to that portion of the atmosphere above the ABL in which the effect of the Earth's surface friction on the air motion is negligible.

The atmosphere can cause a variety of interesting effects on light. Sunlight shining on dust or ice crystals in the atmosphere can produce a host of optical spectacles—rainbows, halos, blue sky, red sunset, coronas, green flash, and many more atmospheric optics phenomena. Also, it is well known that rain, snow, sleet, fog, haze, pollution, etc., are atmospheric factors that affect our viewing of distant objects. These latter harmful factors can also affect the transmission of electromagnetic radiation through the atmosphere, particularly optical waves.

The three primary atmospheric processes that affect optical wave propagation are **absorption**, **scattering**, and **refractive-index fluctuations**. Absorption is a mechanism by which the atmosphere is heated. Scattering occurs in the visible and infrared (IR) wavelengths when the radiation propagates through certain air molecules and particles. Both absorption and scattering by the constituent gases and particulates of the atmosphere give rise primarily to **attenuation** of an optical wave. Index-of-refraction fluctuations lead to **irradiance fluctuations**, **beam broadening**, and **loss of spatial coherence** of the optical wave, among other effects. Clearly, such deleterious effects have far-reaching consequences on **astronomical imaging**, **free-space optical communications**, **remote sensing**, **laser radar**, and other applications that require the transmission of optical waves through the atmosphere.

Atmospheric Structure with Altitude



Atmospheric layers

The atmosphere is a gaseous envelope that surrounds the Earth and extends to several hundred kilometers above the surface. Over 98% of the atmosphere by volume consists of nitrogen and oxygen. Based primarily on temperature variations, the Earth's atmosphere is divided into four primary layers separated by three isothermal boundaries.

The **troposphere** extends up to 11 km and contains roughly 75% of the Earth's atmospheric mass. Maximum air temperature occurs near the surface of the Earth, but decreases with altitude to −55 °C. The **tropopause** between 11 and 20 km is an isothermal layer where air temperature remains constant at −55 °C.

The **stratosphere** extends from 20 km up to 48 km. The air temperature in this layer increases with altitude because the ozone gas absorbs ultraviolet sunlight, thereby creating heat energy. The ozone layer, which protects life from harmful ultraviolet radiation, is concentrated between 10 and 50 km. Separating the mesosphere from the stratosphere is the **stratopause**, another isothermal layer between 48 and 50 km.

The **mesosphere** extends from the stratopause at 50 km up to 80 km. Temperature generally decreases at a constant rate down to −90 °C, the coldest in the atmosphere. The **mesopause** is the third isothermal layer and lies between 80 and 90 km.

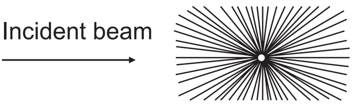
The **thermosphere** extends from the mesopause to roughly 600 km. Air temperature increases quite strongly above 90 km. This layer includes most of the **ionosphere** and the **exosphere**, the latter being the outermost region of the atmosphere.

Absorption and Scattering

Absorption and **scattering** refer to wavelength-dependent **attenuation** of electromagnetic radiation. Absorption is fundamentally a quantum process where atmospheric molecules absorb energy from incident photons. Scattering results from photons colliding with atmospheric particles. The single-scattering theories below are based on the assumption of spherical-shaped, non-interacting particles.

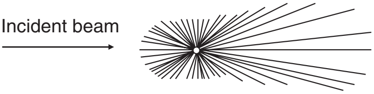
Water vapor, CO_2, NO_2, CO, and ozone are the primary radiation absorbers. Absorption by the ozone O_2 and O_3 essentially eliminates propagation of ultraviolet radiation when $\lambda < 0.2$ μm, but little absorption occurs at visible wavelengths (0.4 to 0.7 μm) except for H_2O absorption between 0.65 and 0.85 μm. Both CO_2 and water vapor are radiation absorbers at IR wavelengths.

Rayleigh scattering (after Lord Rayleigh) is caused by air molecules and haze that are small compared to the wavelength λ of the radiation. The scattering coefficient is proportional to λ^{-4}, known as the **Rayleigh law**. For $\lambda > 3$ μm, scattering by air molecules is negligible. For $\lambda < 1$ μm, Rayleigh scattering produces the blue color of the sky because blue light is scattered much more than red light.



Rayleigh scattering

Mie scattering (after Gustav Mie) is scattering by particles comparable in size to, or even larger than, the radiation wavelength (also called aerosol scattering). It is confined mostly to the lower 4.5 km of the atmosphere. Dust, pollen, and smoke cause Mie scattering, which is larger in the forward direction than in the reverse direction. Mie scattering is the reason that sunsets appear red.



Mie scattering

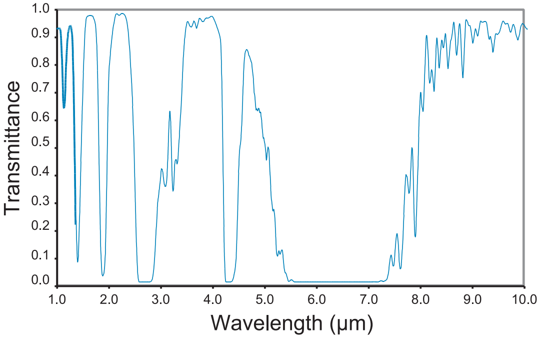
Transmittance, Optical Depth, and Visibility

The **transmittance** of laser radiation that has propagated a distance Z [km] is described by **Beer's law**:

$$\tau = \exp[-\alpha(\lambda)Z] \quad [\text{unitless}]$$

Here, $\alpha(\lambda) = A_a + S_a$ [1/km] is the **extinction coefficient**, where A_a is the absorption coefficient, and S_a is the scattering coefficient. Extinction is defined as the reduction or attenuation in the intensity of radiation passing through the atmosphere.

Software packages like LOWTRAN, MODTRAN, FASCODE, HITRAN (database), and PCLNWIN are commonly used to predict transmittance (attenuation) effects as a function of wavelength λ.



Typical atmospheric transmittance for a horizontal 1-km path. Height above ground is 3 m with no rain or clouds.

Optical depth is defined by the product $\alpha(\lambda)Z$.

Visibility (or **visual range**) corresponds to the range at which radiation at 550 nm is attenuated to 0.02 times its transmitted level. For a given wavelength λ [nm], the extinction coefficient is related to visibility V through the empirical formula

$$\alpha(\lambda) = \frac{3.912}{V}\left(\frac{550}{\lambda}\right)^q; \quad q = \begin{cases} 1.6, & V > 50\,\text{km} \\ 1.3, & 6\,\text{km} < V < 50\,\text{km} \\ 0.585V^{1/3}, & V < 6\,\text{km} \end{cases}$$

Meteorological Phenomena

Blue sky is caused by Rayleigh scattering of sunlight off of air particles (molecules), which induces more scattering at short wavelengths near the blue end of the spectrum.

A **rainbow** is caused by the dispersion of light within a water droplet after a rainstorm.

A **red sunset** occurs when sunlight near the horizon must pass through a greater thickness of air than when the sun is overhead. Shorter-wavelength sunlight is therefore scattered more out of the beam by the additional aerosols and particulate matter, leaving only the longer red wavelength to pass through to the observer.

A **green flash** is a rare phenomenon seen at sunrise and sunset where the curved Earth causes the atmosphere near the horizon to act like a prism in which some part of the sun suddenly changes color from red or orange to green or blue. It occurs just before the last part of the sun disappears from view.

A **green ray** is a rare kind of green flash in which a beam of green light is seen shooting up from the horizon where the sun has just set.

A **halo** occurs around the sun in cold climates as a result of ice crystals in the air. The familiar 22-deg halo or ring around the sun or moon occurs because of refraction in tiny hexagonal ice crystals in the air. The order of colors is reversed from that of diffraction (i.e., the inner circle is red).

A **corona** is a circle of light distinct from the 22-deg halo that can sometimes be seen around the sun or moon if there are thin clouds composed of water droplets or ice crystals of nearly uniform size. The appearance is often that of alternating blue-green and red circles. Coronas are caused in part by sunlight scattering off of free electrons and sunlight bouncing off of dust particles.

A **glory** is phenomenon seen from aircraft and involves a rainbow band around the shadow of the aircraft seen on a cloud below. Glories are another phenomenon of diffraction, with smaller droplets causing larger glories through Mie scattering.