Lecture 26. Regional radiative effects due to anthropogenic aerosols. Part 2. Haze and visibility.

Objectives:

1. Attenuation of atmospheric radiation by particulates.
2. Haze and Visibility.

Readings: Turco: p. 55-68, 163-172; Brimblecombe: p. 73-80

1. Attenuation of atmospheric radiation by particulates.

Aerosol particles can scatter or/and absorb electromagnetic radiation at different wavelengths.

NOTE: aerosol particles also can emit thermal radiation.

NOTE: recall scattering and absorption of electromagnetic radiation; scattering and absorption coefficients introduced in Lecture 5.

Scattering is a process, which conserves the total amount of energy, but the direction in which the radiation propagates may be altered.

Absorption is a process that removes energy from the electromagnetic radiation field, and converts it to another form.

Extinction (or attenuation) is the sum of scattering and absorption, so it represents total effect of medium on radiation passing the medium.

- In the atmosphere: aerosol particles can scatter and absorb solar and infrared radiation altering air temperature and the rates of photochemical reactions.

Key parameters that govern the scattering and absorption of radiation by a particle:

(i) the wavelength λ of the incident radiation;

(ii) the size of the particles, expressed as a dimensional size parameter x:

$x=\pi D/\lambda$ (where D is the particle diameter);

(iii) complex refractive index (or optical constant) of a particle: **$m = n + i k$**

where **n** is the real part of the refractive index, **k** is the imaginary part of the refractive index. Both **n** and **k** depend on the wavelength.

Important to remember:

- complex refractive index of a particle is defined by its chemical composition;
- **real part , n**, is responsible for scattering.
- **imaginary part, k,** is responsible for absorption. If k is equal to 0 at a given wavelength thus a particle does not absorb radiation at this wavelength.

Table 26.1 Some refractive indices of atmospheric aerosol substances at $\lambda = 0.5$ µm.

Substance	n	k
Water	1.333	0
Hematite	2.6	1.0
Elemental carbon	1.96	0.66
Organic carbon	1.55	0
NaCl(s)	1.544	0
H_2SO_4(aq)	1.53	0
NH_4HSO_4(s)	1.53	0
$(NH_4)_2SO_4$(s)	1.52	0
SiO_2	1.55	0

NOTE: hematite is a mineral that is a main light absorbing components of mineral dust.

⇒ If a particle is made of a mixture of substances an effective refractive index must be calculated.

Mie theory is the basis for calculation of the scattering and absorption coefficients of a spherical particle having a given diameter and refractive index.

How it works:

For a particle with diameter **D** and refractive index **m** we can calculate the scattering efficiency Q_{sc}, absorption efficiency Q_{abs}, and extinction efficiency Q_{abs} at a given wavelength using Mie theory.

NOTE: $Q_{ext} = Q_{sc} + Q_{abs}$, and they are dimensionless.

Then we calculate cross sections as

$\sigma_{sc} = (\pi D^2/4)\ Q_{sc}$

$\sigma_{abs} = (\pi D^2/4)\ Q_{abs}$

$\sigma_{ext} = (\pi D^2/4)\ Q_{ext}$

NOTE: $\sigma_{ext} = \sigma_{sc} + \sigma_{abs}$, and they have the units of area.

And then we calculate scattering, absorption and extinction coefficients as

$\varepsilon_{sc} = N\ \sigma_{sc} = N\ (\pi D^2/4)\ Q_{sc}$

$\varepsilon_{abs} = N\ \sigma_{abs} = N\ (\pi D^2/4)\ Q_{abs}$

$\varepsilon_{ext} = N\ \sigma_{ext} = N\ (\pi D^2/4)\ Q_{ext}$

where N is the number concentration of the particles with diameter D.

NOTE: $\varepsilon_{ext} = \varepsilon_{sc} + \varepsilon_{abs}$, and they have the units of inverse length.

Important to remember:

- Mie theory is used when size parameter **x is about 1** (particle about the same size as the wavelength).
- If **x << 1** (particles small compared with the wavelength) we use Rayleigh regime, in which scattering and extinction coefficient are given by approximate expressions.

Rayleigh regime: $Q_{sc} \sim \lambda^{-4}$ **and** $Q_{abs} \sim \lambda^{-1}$

- If **x >> 1** (particles large compared with the wavelength) we use Geometric regime. If size parameter increases the extinction efficiency approaches 2.

In general, if we want to know how radiation will be attenuated in the atmosphere by aerosols, gases and/or clouds we need to solve a radiation transfer equation, which requires information on optical properties of the gases and particulates (such as extinction coefficients, single scattering albedo, scattering phase function, etc.).

Scattering phase function describes the angle-dependent scattering of light incident on a particle. Phase function strongly depends on particle size and shape.

Single scattering albedo, ω_0, is defined as

$$\omega_0 = \varepsilon_{sc} / (\varepsilon_{sc} + \varepsilon_{abs})$$

which is fraction of total extinction that is due to scattering.

NOTE: single scattering albedo is a key aerosol optical characteristic in assessment the radiative effects due to aerosols (will be discussed in Lectures 39-41).

- There are many computational and analytical techniques to solve the radiation transfer equation accounting for multiple scattering, absorption and emission by atmospheric particulates and gases.

Under single scattering approximation we can employ the Beer-Lambert law to calculate the light intensity **I** at any distance **z** attenuated by the atmospheric aerosols with extinction ε_{ext} as

$$I/I_0 = \exp(-\varepsilon_{ext} z) = \exp(-\tau)$$

where $\tau = \varepsilon_{ext} z$ is the aerosol optical depth, and I_0 is the incident intensity.

NOTE: The Beer-Lambert law was discussed in Lecture 5.

2. Haze and Visibility.

Clean (background) atmospheric conditions: light is scattered and absorbed by natural gases and particulates (background aerosol).

Polluted atmospheric conditions: air pollutants (gases and particles) cause additional attenuation of light.

Haze is a form of air pollution consisting of small particles of dust, soot, sulfates, and other material.

- Haze has natural and anthropogenic sources.

Total suspended particulate (TSP) refers to the total mass concentration of aerosol particles present in the air.

- In heavily polluted cities, average TSP abundance is about 50-100 $\mu m/m^3$, with upper limits of about 1000 $\mu m/m^3$.

Two major problems caused by haze:

1) visibility reduction;
2) health effects

Visibility is generally used synonymously with "visual range", meaning the farthest distance at which one can see a large, black object against the sky at the horizon.

Some factors determining how far one can see through the atmosphere:

(i) optical properties of the atmosphere;
(ii) amount and distribution of light;
(iii) characteristics of the objects observed;
(iv) properties of the human eye.

- Visibility is reduced by the absorption and scattering of light by both gases and particles. However, light scattering by particles is the most important phenomenon responsible for visibility degradation.

Clean (background) atmospheric conditions: one can see over distances up to several hundred kilometers.

Polluted atmospheric conditions: visibility is up to 10 km.

Koschmieder equation:

relates visual range (visibility), x_v, and extinction coefficient , ε_{ext}, as

$$x_v = 3.912/\varepsilon_{ext}$$

NOTE: in Koschmieder equation the extinction coefficient is sum of extinction coefficients of all gases and particles, which attenuate light.

NOTE: in Koschmieder equation the extinction coefficient is averaged over visible wavelengths, however it is often taken at about 550-nm wavelength.

Problem.

Calculate visibility in the cleanest (Rayleigh) atmosphere, if the rayleigh scattering coefficient is $13.2\ 10^{-6}\ m^{-1}$ at $\lambda = 520$ nm wavelength.

Solution.

In the Rayleigh atmosphere light is attenuated by gas (Rayleigh) scattering, thus the extinction coefficient is equal to the rayleigh scattering coefficient. Using the Koschmieder equation we can calculate visibility, x_v, as

$$x_v = 3.912/\varepsilon_{ext} = 3.912/\ 13.2\ 10^{-6}\ m^{-1} = 296\ 10^{3}\ m = 296\ km$$

- **In polluted air** various species contribute to visibility reduction but their contributions are not equal.

Table 26.2 Contribution of chemical species to the extinction coefficient, $\boldsymbol{\varepsilon_{ext}}$, in Denver wintertime (data from Groblicki et al. 1981).

Fine particle species	**Mean percent contribution**
$(NH_4)_2SO_4$	**20.0%**
NH_4NO_3	**17.2%**
Organic carbon	**12.5%**
Elemental carbon (scattering)	**6.5%**
Elemental carbon (absorption)	**31.2%**
Other	**6.6%**
$NO_2(g)$	**5.7%**
Total	**100%**

Long Term Trends:

Visibility degradation has been analyzed using data collected since 1960 at 280 monitoring stations located at airports across the country. The maps below show U.S. visibility trends derived from such data. The dark blue color represents the best visibility and red represents the worst visibility.

Overall, these maps show that visibility degradation in the eastern U.S. increased greatly between 1970 and 1980, and decreased slightly in 1990. This follows the overall trends in emissions of sulfur oxides during these periods (recall Lecture 24).