Haze and Visibility

Review of Aerosol Basics

- We know there is a variety of particles present in the atmosphere and their importance to many phenomena
- Many sources of particulate matter; anthropogenic generally much less than natural
- Classification of particles by size (and, to some extent, sources)

Objectives

- Some aerosol formation processes
- Explore the interaction of light with particles
- Discuss the concept of visibility

Application

- Problem 9 (handed out in class). Visibility and Particulate Matter

Aerosol Formation Processes

We typically discuss two general classes of aerosols.

Those that are produced directly are called “Primary particles.” These are produced in a variety of ways, among them:

- Mechanical processes (like winds suspending materials, like dust), which can be natural or man-made
- Breaking waves and bubbles (e.g., sea spray)
- Manufacturing – friction (machining processes)
- Volcanic eruptions (e.g., ash)
- Combustion, biomass burning (“smoke”)

Those that are produced by chemical reactions and condensation of low-volatility compounds are called “secondary particles.”

Secondary particles - chemical transformation of gases

Sulfate particles

$$SO_2 + OH + M \rightarrow HSO_3 + M$$
$$HSO_3 + O_2 \rightarrow HO_2 + SO_3$$
$$SO_3 + H_2O \rightarrow H_2SO_4$$
$$H_2SO_{4(g)} \rightarrow H_2SO_{4(aq)}$$

Or

$$SO_2 + \text{particles} \rightarrow\rightarrow H_2SO_4$$

Nitrate particles

$$NO_2 + OH + M \rightarrow HNO_3 + M$$
$$HNO_{3(g)} \rightarrow HNO_{3(aq)}$$

Hydrocarbon particles

$$RH + O_3 \rightarrow\rightarrow\rightarrow \text{particles}$$

The Denver "Brown Cloud"

Two things contribute to the brown color of the sky:

(1) Absorption of light by nitrogen dioxide (NO_2)

(2) Scattering of light by particles

Small particles are typically secondary - generated from ammonia and sulfates, nitrates: $(NH_4)_2SO_4$; NH_4NO

Large particles tend to be dust and airborne dirt (why roads aren't "sanded" here!)

Haze and Visibility

What is haze?

- Particulate pollution (mostly small particles)
- Haze (particulates) ≠ PHOTOCHEMICAL Smog (ozone, NO_2, PAN), although they often occur at the same time.

Why should we care about haze?

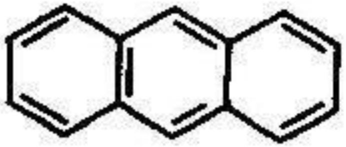
Aesthetics: it affects visibility - our ability to see objects in the distance.

Health: small particles can be inhaled and can lodge in lung tissue or deposit hazardous substances there.

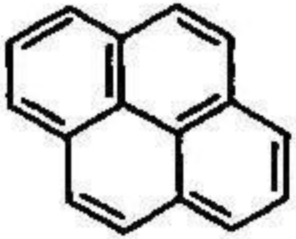
For example: Soot - mostly elemental carbon, comes from combustion

Contain (or have on surface) small amounts of other combustion by-products, especially polycyclic aromatic hydrocarbons (PAHs)

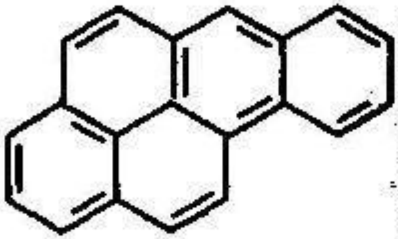
PAHs are known to be carcinogenic or mutagenic! Studies have shown high incidence of lung cancer among urban residents, probably related to PAHs



Anthracene



Pyrene

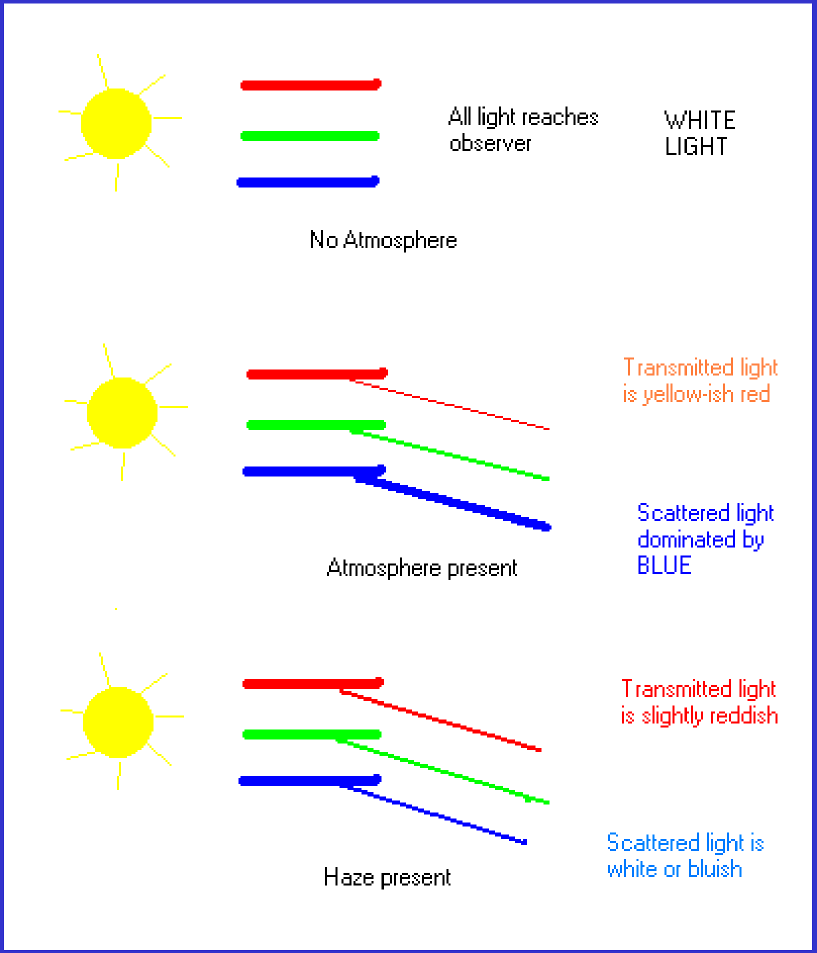


Benzo(a)pyrene

Interaction of Visible Light and Particles

The effect of this interaction depends on the nature and size of the particles present.

General rule: Particles efficiently scatter light with a wavelength that is about the same size as the particle diameter. (Mie scattering)



Quantifying Visibility

Visibility: The ability to distinguish a black object against a white background. Practically speaking, it is the ease with which features along the skyline can be distinguished from the sky itself

Extinction: Removal of light from a path by absorption and/or scattering. It is not always possible or practical to separate out the two processes; ultimately we really only care about how much light reaches the observer.

Beer's Law:

$$I = I_o \, exp[-(\sigma_{scat} n l + \sigma_{abs} n l)]$$

Note: “exp[x]” means e^{-x}

Actual photo near Mexico City, March, 2006

Enhanced contrast

“Dirty air”

Better?? - subjective

Since σ for absorption and scattering are likely to be different, we typically lump together these terms together:

$$I = I_o \, exp(-\varepsilon\ell)$$

ε is called the "extinction coefficient" and has units of cm^{-1}

Optical Depth: Another unit of measure; useful when the path length is not known or is ill-defined

$$I = I_o \, exp(-\tau)$$

Optical depth (τ) is a dimensionless number and can be thought of as the product of cross-section and column amount:

$$\tau = \sigma\ell n = \sigma N$$

Optical depth also describes the probability of removal of light:

$\tau < 0.1$	little attenuation
$0.1 < \tau < 0.5$	attenuation $\approx \tau$
$\tau > 1$	most light removed

Problem: The optical depth of the stratospheric aerosol layer is typically about 1 x 10^{-4} for wavelengths of 1 μm. Following the eruption of the Mt. Pinatubo volcano in 1991, the optical depth at 1 mm increased to 1 x 10^{-2}. How much more or less infrared light got through this layer? What do you think the consequences of this change might be?

Answer

From the restatement of Beer's Law above, we know that $I/I_o = e^{-\tau}$, where the ratio I/I_o represents the fraction of light getting to the detector or observer. We can make use of an approximation here: for small values of x, $e^{-x} \sim (1 - x)$. Both values for the optical depth are quite small, so we can approximate:

Typical: $I/I_o = e^{-(0.0001)} \sim (1 - 0.0001) \sim 1$

Post-volcano: $I/I_o = e^{-(0.01)} \sim (1 - 0.01) \sim 0.99$

The amount of light getting through the aerosol layer decreased following the volcanic eruption because the optical depth increased. Approximately 1% less light got through.

That "missing" 1% had to go somewhere - either be scattered by the particles or absorbed by them. In this case, it was likely absorbed. Evidence has shown that the enhanced aerosol layer following the Pinatubo eruption was responsible for slightly increasing the temperature of the lower stratosphere!

Quantifying Visibility (cont'd)

In clear air:

Visibility in the western US is typically 140 miles

Visibility in the eastern US is typically 90 miles

Why the difference? It is mainly related to relative humidity and particle composition. More typically, however:

Visibility in the western US is 35 - 90 miles

Visibility in the eastern US is 15 - 25 miles

Differences between clear air and common values is related to total amount of particulate matter in air: Total Suspended Particulate (TSP)

Empirically, ε (km^{-1}) = TSP/250

where TSP is in $\mu\mathrm{g\ m}^{-3}$.

That is, the extinction of light along a path is proportional to the amount of aerosol in the path. Intuitively this makes sense!

For convenience, we drop the use of the extinction coefficient (or ε) by defining the “Visibility Length” (or £) – that is, how far you can one discern objects) as the inverse of the “extinction” of light along the path

$$£\ (\mathrm{km}) = 3.9/\varepsilon \approx 1000/\mathrm{TSP}$$

Note that this very simple formula allows us to determine the total amount of aerosol (i.e., TSP – total suspended particulate) if we just have a way to measure how far one can see before light is scattered too much to discern any objects at a distance.

Example:

PM_{10} standard (24-hr average) = 150 $\mu g\ m^{-3}$. Under those conditions, £ (km) $\approx$ 1000/TSP = 6.7 km (about 4 mi).

For average "bad" Denver/Boulder conditions of 65 $\mu g\ m^{-3}$, £ (km) $\approx$ 1000/TSP = 15 km (about 10 mi).

Problem 9 – Use the same relationship to examine a set of photos on a bad day at the Grand Canyon

A more complicated problem that we will do in class: The visibility length in a certain fog is 0.5 km. Assuming that there are 100 spherical fog particles per cm^3 and that ρ_{H2O} is 1 g cm^{-3}, calculate the average radius of a fog droplet.