Objectives

During the course of this lab we will investigate some basic connections between aerosols and climate. We will look at the aerosol scattering of incoming solar radiation to understand the relationship between sky color, visibility, and aerosols in the atmosphere. We will investigate how particle size affects light transmission and scattering. Also we will study how aerosol composition affects cloud formation due to variations of how water vapor condenses onto an aerosol particle (deliquescence).

At the end of this lab, you should be able to:
- understand what atmospheric aerosols are, and know their sources and sinks;
- perform calculations of aerosol concentrations, particle size, and mass;
- understand how aerosols scatter light of different wavelengths;
- understand how aerosols affect Earth’s radiative balance and cloud formation;
- know the mechanisms of the aerosols influence on climate and understand the uncertainties of current estimates of such an influence.

Theoretical background

Atmospheric aerosols are microscopic solid and liquid particles of both natural and anthropogenic origin suspended in the atmosphere (Figure 1). They vary in size from the “superfine” particles with diameters of a few nanometers (nm), to “coarse mode” particles, which reach several micrometers (µm) in diameter.

Some aerosols are produced by natural processes – evaporation of sea spray; strong winds blowing over desert areas; volcanic gases, eruptions and explosions; forest and grassland fires, emission of organic substances by vegetation, etc. Human activities also generate aerosols, both directly (e.g. burning of fossil fuels produces sulfur dioxide (SO₂) which makes very important sulfate aerosols; black carbon particles are produced by diesel engines) and indirectly, via changing the land and vegetation properties. Presently the human contribution of aerosols to the atmosphere equals the quantity emitted by natural sources (Tarbuck at al., 2009).

Figure 1. Aerosol particles larger than about 1 micrometer in size are produced by windblown dust and sea salt from sea spray and bursting bubbles. Aerosols smaller than 1 micrometer are mostly formed by condensation processes such as conversion of sulfur dioxide (SO₂) gas (released from volcanic eruptions) to sulfate particles and by formation of soot and smoke during burning processes. After formation, the aerosols are mixed and transported by atmospheric motions and are primarily removed by cloud and precipitation processes. (http://earthobservatory.nasa.gov/Library/Aerosols/).
Aerosols have a relatively short life, ranging from days to weeks; they are removed from the atmosphere by several processes:
- coagulation (small particles collide and then undergo deposition);
- precipitation (particles are captured by cloud droplets);
- dry deposition (sedimentation of large heavy particles).

“Fine” or “accumulation mode” aerosols, with diameters from about 0.1 µm to a few µm have the most effect on climate. This specific group of aerosols is important because the particle size is comparable to the wavelength of visible light and near infrared radiation. When radiation interacts with aerosols of this particular size, the photons of sunlight are scattered (e.g. 5% backscattered by the atmosphere, as shown in Figure 2, is mostly due to aerosols). Aerosols of this size have relatively long atmospheric residence times and are able to affect cloud properties, because they work very efficiently as **Cloud Condensation Nuclei (CCN)**.

![Figure 2. Balance of the incoming Solar energy](image)

In densely populated and industrial regions natural sources of fine mode atmospheric aerosols are overwhelmed by anthropogenic sources. Similarly, biomass burning in rural areas creates more aerosols than are produced by natural sources. Within polluted regions high concentrations of anthropogenic aerosols can negatively affect human health, visibility, and alter climate.
There are four main mechanisms through which changes in atmospheric aerosol concentrations can affect climate:

1) the ‘**direct effect**’ – increase in scattering of the incoming solar radiation back to space by increased concentration of aerosols in the upper atmosphere;
2) the ‘**first indirect effect**’ - increase of the cloud albedo due to (a) a decrease of droplet size and (b) increase in number of droplets per unit volume for a fixed total water content; these changes are due to increased availability of the aerosol CCN.
3) the ‘**second indirect effect**’ - increase in the lifetime, frequency of occurrence and vertical thickness of clouds as the result of an aerosol-induced increase in the number of droplets per unit volume;
4) the ‘**semi-direct effect**’ – increase in the absorption of solar radiation by dark aerosol particles, which warms the atmosphere and suppresses formation of clouds.

These mechanisms effect climate differently - the first three mechanisms tend to have a cooling effect on surface temperatures, while the fourth one results in a warming effect. Similarly, while the second indirect effect acts to increase cloud cover, the semi-direct effect leads to a decrease in cloud cover.

Due to the complex nature of these interactions and our limited knowledge of the relative magnitudes of the aerosol climatic effects, the changes in atmospheric aerosol concentrations represent one of the largest uncertainties in our current understanding of possible climate change. Quantification of the aerosol feedbacks and their incorporation into climate models is one of the greatest challenges of climate forecasting.

The amount of aerosols at any specific location is usually characterized in terms of three parameters:

1) \( N \) - number of aerosol particles per unit volume;
2) \( D_{\text{mean}} \) - mean diameter of the aerosol particles;
3) \( M \) - mass of aerosol particles per unit volume of air.

The interconnection between these parameters is described by the following equation:
\[ M = \rho \cdot N \cdot \left[ \frac{4}{3} \pi \cdot \left( \frac{D_{\text{mean}}}{2} \right)^3 \right] \]

where \( \rho \) is the density of the particles. Aerosol particles typically have a density close to the density of water, therefore in simple calculations \( \rho \) is often considered to be \( \sim 1 \text{ g cm}^{-3} \).

As mentioned above, aerosol particles in the atmosphere are important for the process of cloud formation. Aerosols serve as centers of condensation for water vapor and aid the formation of cloud droplets. Aerosol particles are often deliquescent, that is they readily absorb water at relative humidities below 100\%, and dissolve in this water, forming a solution.

The value of relative humidity which is required for water droplets to start forming in the absence of CCN, in general, is higher than 100\% (i.e. supersaturated conditions are required), because of several effects too complex to be considered here. Presence of CCN (especially deliquescent ones) lowers that value and allows for the formation of cloud droplets under conditions that are frequently observed in the troposphere. These small droplets collide with each other to form larger droplets and, over time, to form a cloud.

**Scattering of the visible light by aerosols.** Aerosol scattering preferentially removes the short-wavelength light (violet and blue colors), leaving the longer wavelengths (green, yellow, red, etc.) unaffected; selective removal of the shorter wavelengths leaves the average color of the remaining light redder than original light.

![Figure 4. Scattering and reflection of light (images thanks to Prof. I. Sokolik, Dr. Haiyan Jiang and http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html)](image)

The conditions for this preferential removal of the short-wave light are more often met when the path of light in the atmosphere is longer (e.g., at sunset) or when the aerosol load is higher (windy conditions, polluted areas), as shown in Figure 5.

![Figure 5. Change in color of the sky and Sun under different conditions.](image)
Blue color of the sky is also explained by scattering of the Sun’s light. But, in this case the blue light we see actually is a short-wave part of the spectrum scattered by the atmosphere and re-directed into our eyes, while the red color of the sunset is the part of the spectrum left after the blue light has been removed from the sunlight.

Look at the illustration bellow (Figure 6). The image on the left shows an unpolluted cloud. Over time and under the right conditions, its larger droplets collide to form even bigger droplets that eventually fall out as rain. The image on the right shows a polluted cloud, that formed with excessive amount of available CCN. Notice the smaller size of droplets: it is less probable that they will collide frequently and become large enough to precipitate. As the result of increased availability of aerosol CCN, polluted clouds are less likely to produce rain.

![Figure 6](image)

Figure 6. Increased cloud albedo (reflectivity) of the cloud (panel B) is due to large amount of anthropogenic aerosol particles acting as cloud condensation nuclei that creates larger amount of smaller cloud droplets.

Under equal conditions (identical amount of water in each cloud) the polluted cloud (with larger number of small droplets) appears whiter and scatters more light then the darker unpolluted cloud with fewer, larger droplets.

Besides affecting optical properties of the clouds, which is important for radiative balance, scattering of the visible light by aerosols can change visibility. Background light, when scattered into the observer’s eye along the line of sight by aerosol particles, reduces the visibility of the object (Figure 7). The maximum visible range \( L \) is defined as the distance between an observer and a barely discernable object, at some specific atmospheric conditions. At this distance, if the object were moved slightly further away from the observer, or a small amount of scattering particles were added, the object would no longer be visible. At this borderline situation the amount of light from the object is only slightly higher than the amount of “masking” background light.
Figure 7. Reduction of visibility due to haze: (1) light from the object reaching observer; (2) light from object scattered out of the observer’s line of sight; (3) light from the sun scattered by the particles into the line of sight; (4) light from other distant objects.

The maximum visual range $L$ is inversely proportional to the aerosol number concentration ($N$) and to the square of the particle diameter ($D_p$):

$$L = \frac{1}{N \times D_p^2}$$

**Online exercises/activities**

A good introductory-level resources on aerosol and climate basics:

http://www.nasa.gov/centers/langley/news/factsheets/Aerosols.html
http://earthobservatory.nasa.gov/Features/Aerosols/

**Safety precautions**

- Handle hot water with care;
- Never look directly at the sun even if you are wearing sunglasses;
- Be careful when handling glass beakers;
- Clean all spills immediately.
Equipment and procedures in the lab

Part I: Atmospheric Aerosols, Deliquescence and Droplet Formation

Procedure:

1. You will be provided with four types of particles that are typically found in the atmosphere: sea salt, soil dust, ammonium sulfate, and soot. Add a small pinch of each type of particles on one side of the divided Petri dish, as shown in Figure 8. Do not allow the particles to mix.

2. Carefully pour some hot water into the other side of the Petri dish, without wetting the particles. A squirt bottle is very effective for this purpose. Cover the dish with the undivided Petri dish lid. Hot water within a confined space will ensure high relative humidity required for droplet formation.

3. This experiment will require about 30 to 60 minutes to produce any results. Place a lamp ~20 cm above the Petri dish and plug it in. Return back to this section in 30 min.

4. After at least 30 minutes, look at your nuclei in the Petri dish. Note and write down any changes you see. Answer the questions 1-6 below.

Figure 8. Experimental setup for Part 1.
Questions.

**Question 1.** List all the particles that remained dry. Choose from the following and enter all the letters that correspond to your answer into Clicker in alphabetic order, e.g. enter ABD if your answers are A, B and D. (2 pts).

A. Soot  
B. Ammonium sulfate  
C. Soil dust  
D. Sea salt

**Question 2.** List the particle that changed the most. Choose one from the following and enter the letter that corresponds to your answer into Clicker (2 pts).

A. Soot  
B. Ammonium sulfate  
C. Soil dust  
D. Sea salt

**Question 3.** From the selection of aerosol particles in your experiment, which one is the most likely to act as cloud condensation nuclei? Choose one from the following and enter the letter that corresponds to your answer into Clicker (3 pts).

A. Soot  
B. Ammonium sulfate  
C. Soil dust  
D. Sea salt

**Question 4.** What kind of particles (name two) from your experiment would be important in terms of the “direct effect” (i.e. scattering of the solar radiation back to space)? Choose from the following and enter the letters that correspond to your answers into Clicker in alphabetical order, e.g. AB (2 pts).

A. Soot  
B. Ammonium sulfate  
C. Soil dust  
D. Sea salt

**Question 5.** From the selection of aerosol particles in your experiment, which one would be the most important in terms of the “first indirect effect” of the aerosols? Choose from the following and enter the letter that corresponds to your answer into Clicker (3 pts).

A. Soot  
B. Ammonium sulfate  
C. Soil dust  
D. Sea salt
**Question 6.** From the selection of aerosol particles in your experiment, which one would be the most important in terms of the “semi-direct effect” of the aerosols? Choose from the following and enter the letter that corresponds to your answer into Clicker (3 pts).

A. Soot
B. Ammonium sulfate
C. Soil dust
D. Sea salt

**Part II: Aerosol Scattering**

**Procedure:**

1. Fill the provided 500 ml beaker 3/4 full with water.
2. Place the beaker on the desktop and let the water become still.
3. Once the water is still, turn on the flashlight and shine it through the side of the container. Observe:
   a) the scattered light from the side and top (at 90° to the light beam) and
   b) the light that passed straight through the container.
4. In order to do this, hold the provided index card 10-20 cm away from the container and directly opposite to the source of light (as shown in Figure 9). Observe the light as it projects straight onto the card. Also, using the card, look at the scattered light as seen from the side of the container, at 90° to the light beam, or from the top. **Note: the lights in the room should be dimmed or turned off to provide better conditions for this experiment.**

![Figure 9. Experimental setup for aerosol scattering experiment - Part 2.](image)

5. Add 3 drops of milk from the pipette into the beaker. Stir well using the provided glass stirring rod. Observe for eventual change in the color of the transmitted and scattered light with the index card.
6. Record your observations.
7. Repeat steps 3-6.
8. Continue to add drops of milk to the container until the light no longer passes through the water. Record any changes you see.
9. Answer the questions 7-13 below.
Question 7. What was the color of the light as you viewed it on the index card while the light was passing straight through the container of clear water? Choose one from the following and enter the letter that corresponds to your answer into Clicker (1 pt).

A. Bluish  
B. Red or orange  
C. White or slightly yellow  
D. Light green  

Question 8. Was there any light scattered (viewed from the side of the container, at 90° to the light beam) by clear water? Choose one from the following and enter the letter that corresponds to your answer into Clicker (1 pt).

A. Very little scattered light  
B. Significant scattered light  

Question 9. What color was the light on the index card as you viewed it passing straight through the container of water with milk, after you added just a few drops of milk? Choose one from the following and enter the letter that corresponds to your answer into Clicker (1 pt).

A. Blue  
B. Red  
C. Yellow  
D. Green  
E. White  

Question 10. What color was the light on the index card as you viewed it passing straight through the container of water with milk, after you added a lot of milk? Choose one from the following and enter the letter that corresponds to your answer into Clicker (1 pt).

A. Blue  
B. Red  
C. Yellow  
D. Green  
E. White  

Question 11. What color was the light scattered (viewed from the side of the container, at 90° to the light beam) by water with large amount of milk? Choose one from the following and enter the letter that corresponds to your answer into Clicker (1 pt).

A. Bluish-White  
B. Red or orange  
C. Yellow  
D. Green
**Question 12.** Compare the wavelength of the red- and the blue-color light. Choose one from the following and enter the letter that corresponds to your answer into Clicker (2 pts).

A. The wavelength of the blue light and the red light is the same  
B. The wavelength of the blue light is longer than the wavelength of the red light.  
C. The wavelength of the blue light is shorter than the wavelength of the red light.

**Question 13.** As you were adding more and more milk (i.e. microscopic droplets of fat), what was happening to the light passing through the beaker? Choose one from the following and enter the letter that best corresponds to your answer into Clicker (2 pts).

A. Short-wavelength light became scattered, while long waves were passing through without significant scattering  
B. Long-wavelength light became scattered, while short waves were passing through without significant scattering  
C. Both short- and long-wavelength light became scattered, so less light was passing through.  
D. Neither short- nor long-wavelength light became scattered, all light was able to pass through.

**Part III: Observing visibility and sky color**

**Procedure:**

1. **Estimate the visibility.** Go outside of the lab. Select as a reference point the Bank of America/BellSouth building. Take note of how distinctly you can see it and select one of the visibility categories below and record it on the Visibility and Sky Color Data Sheet.

2. **Observe the sky color.** Now look at the sky and find the part of it that is the darkest color. When you do this activity, be sure not to look directly at the sun even if it is partially obscured by clouds. Select a category for the sky color from the list below and record it on the Visibility and Sky Color Data Sheet.

3. Answer questions 14-18.
Visibility and Sky Color Data Sheet (5 points)

Observer: ______________________________________________

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Sky color (see below)</th>
<th>Visibility (see below)</th>
<th>Comments (weather conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sky color categories

<table>
<thead>
<tr>
<th>Deep blue</th>
<th>Unusually clear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>Clear</td>
</tr>
<tr>
<td>Light blue</td>
<td>Somewhat hazy</td>
</tr>
<tr>
<td>Pale blue</td>
<td>Very hazy</td>
</tr>
<tr>
<td>Milky</td>
<td>Extremely hazy</td>
</tr>
</tbody>
</table>

Questions.

**Question 14.** What type of aerosol is likely to be observed in Atlanta? Choose one from the following and enter the letter that best corresponds to your answer into Clicker (3 pts).

A. Volcanic
B. Ocean spray (sea salt)
C. Biomass and fossil fuel burning (anthropogenic)
D. Desert dust
**Question 15.** What type of aerosol is likely to be observed in arid non-urban areas of Arizona? Choose one from the following and enter the letter that best corresponds to your answer into Clicker (3 points)

A. Volcanic  
B. Ocean spray (sea salt)  
C. Biomass and fossil fuel burning (anthropogenic)  
D. Desert dust

**Question 16.** How would you relate the sky color at sunset to the strength of wind in remote areas? Choose one from the following and enter the letter that best corresponds to your answer into Clicker (3 points)

A. Stronger winds result in more dramatic red sunset/sunrise  
B. Stronger winds result in less pronounced red sunset/sunrise  
C. The sky color at sunset does not depend on wind

**Question 17.** Would you expect to have more or less aerosols in Atlanta on windy days? *(Hint: think of the main aerosol source in Atlanta).* Choose one from the following and enter the letter that best corresponds to your answer into Clicker (3 points)

A. Stronger winds should result in more aerosols in Atlanta  
B. Stronger winds should result in less aerosols in Atlanta  
C. The wind velocity does not affect the amount of aerosols in Atlanta

**Question 18.** Would you expect to have more or less aerosols in the desert on windy days? Choose one from the following and enter the letter that best corresponds to your answer into Clicker (2 points)

A. Stronger winds should result in more aerosols in desert  
B. Stronger winds should result in less aerosols in desert  
C. The wind velocity does not affect the amount of aerosols in desert

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**Part IV: An indirect effect of atmospheric aerosols**

**Procedure:**

1. You will be provided with two 100 ml beakers and two different sets of glass beads with different sizes but with the same total mass (about 100 grams). The glass beads represent cloud droplets. We will assume that these glass “cloud droplets” do not absorb light. Each of the beakers represents a cloud with the same mass of water but different number of droplets.
2. Place the provided flashlight at the bottom of each beaker, and illuminate each beaker by shining the light up through the beads, as shown in Figure 10.

3. Observe the amount of light that is able to pass through. Also, observe the amount of scattered light, which is directed outward from the sides, away from the beaker (90 degrees from the direction of the light beam). You can use the index card put at the side of the beaker to see the scattered light. Describe your observations. Discuss with your team, what is the possible reason for any difference in the amount of scattered light from the small/large glass “cloud droplets”?


**Question 19.** Which glass beads scatter more light? Choose one from the following and enter the letter that best corresponds to your answer into Clicker (3 points)

A. Large beads scatter more light  
B. Small beads scatter more light

**Question 20.** Which glass beads transmit more light? Choose one from the following and enter the letter that best corresponds to your answer into Clicker (3 points)

A. Large beads transmit more light  
B. Small beads transmit more light
**Question 21.** The cloud with what size of droplets will have a higher albedo? Choose one from the following and enter the letter that best corresponds to your answer into Clicker (3 points)

A. The cloud with large droplets  
B. The cloud with small droplets

**Problems for individual work**

Take a look at the photos below (Figure 11) taken at Shenandoah National Park. The visual range for different days is given for each of the photos.

![Figure 11. Visibility at Shenandoah National Park.](http://www.epa.gov/air/airtrends/aqtrnd98/chapter6.pdf)

**Question 22.** Using the data from Figure 11 (visual range), estimate the Aerosol Number Concentration $N$ for a clean day (upper left photo). Assume that the average diameter of aerosol particles is 0.53 µm. *(Note also that 1 mile = 1609 m).* Enter the Aerosol Number Concentration into your Clicker in units of **millions of particles per m$^3$**, i.e. if your answer is $60 \times 10^6$ particles per m$^3$, enter 60 into Clicker. (5 points)
Question 23. Using the data from Figure 11 (visual range), estimate the Aerosol Number Concentration \( N \) for a “Dirty day” (lower left photo). Assume that average diameter of aerosol particles is 0.53 \( \mu \)m. (Note also that 1 mile = 1609 m). Enter the Aerosol Number Concentration into your Clicker in units of \textbf{millions of particles per m}^3, i.e. if your answer is 60\( \times \)10^6 particles per m\(^3\), enter 60 into Clicker. (5 points)

Question 24. Based on your estimates of Aerosol Number Concentration for questions 22 and 23, and the fact that the observed difference in \( N \) for the two left photos is due to a ~20 \( \mu \)g/m\(^3\) increase in mass of aerosol particles per unit volume of air, calculate the aerosol density \( \rho \). Enter your answer into Clicker in units of g/cm\(^3\) (6 points)

Question 25. The U.S. EPA has proposed Annual Averaged National Ambient Air Quality Standards for fine particulate matter (aerosols) concentration, which is equal to 15 \( \mu \)g m\(^{-3}\). Assuming a median aerosol diameter of 0.53 \( \mu \)m and density \( \rho = 1.3 \) g-cm\(^{-3}\), determine what maximum visual range \( L \) this standard would correspond to. Enter your answer into Clicker in km (8 points).

Conclusions

1. What conclusions about aerosols of anthropogenic origin can you draw based on your experiment with particle deliquescence (Part 1)? (5 pts.)
2. Think about the underlying physics of your experiment with water and milk (Part 2). How can you explain that the passing light changed color? (4 pts.)

3. In your opinion, what are the positive and negative consequences of current anthropogenic influence on aerosols? (5 pts.)