Visibility Overview

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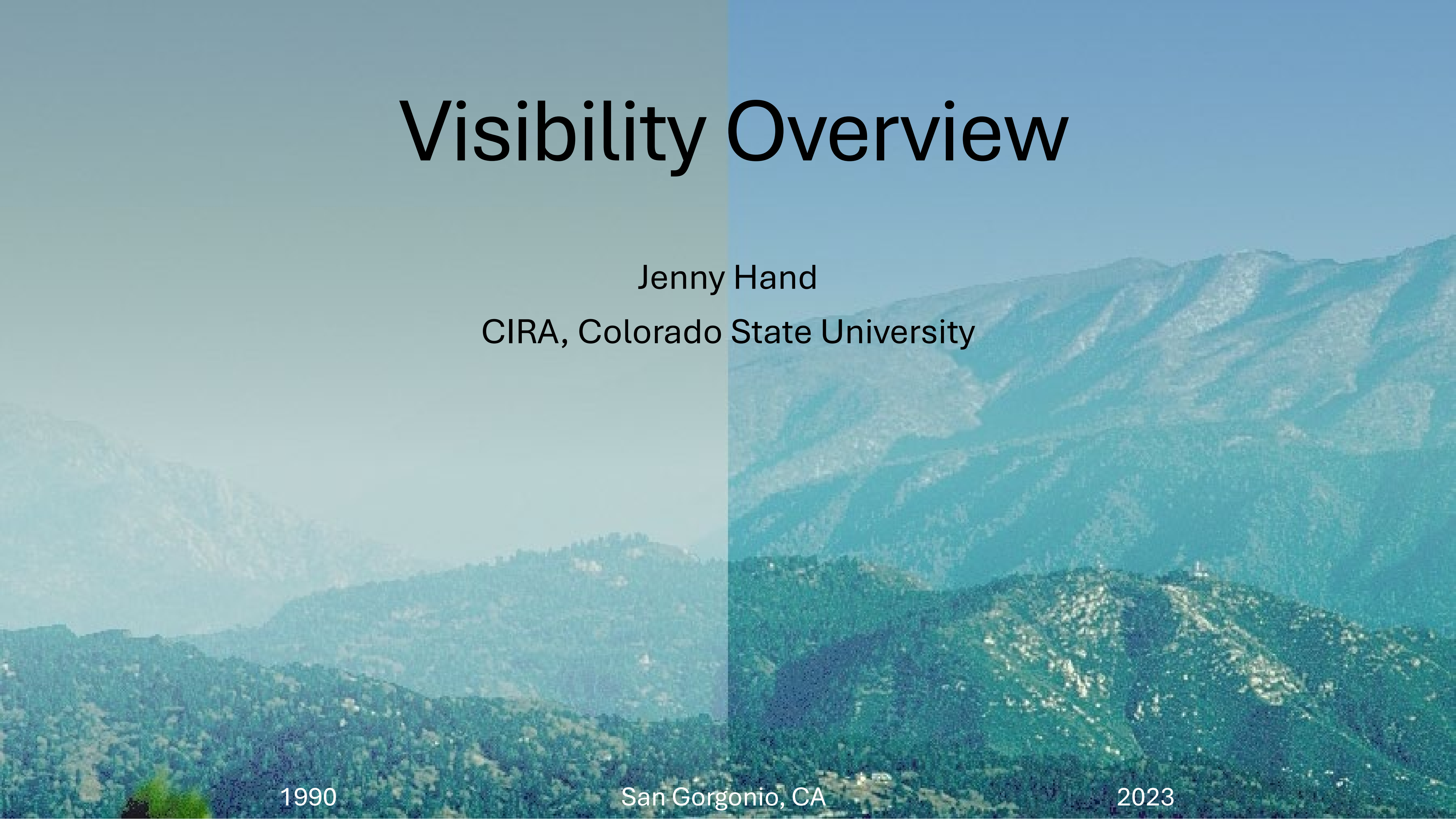


We’ll talk about:

1. What is visibility?
2. What causes haze?
3. What is light extinction?
4. Visibility measurements
5. 2nd IMPROVE Equation
6. Other visibility parameters (visual range, deciview)

1. What is Visibility?

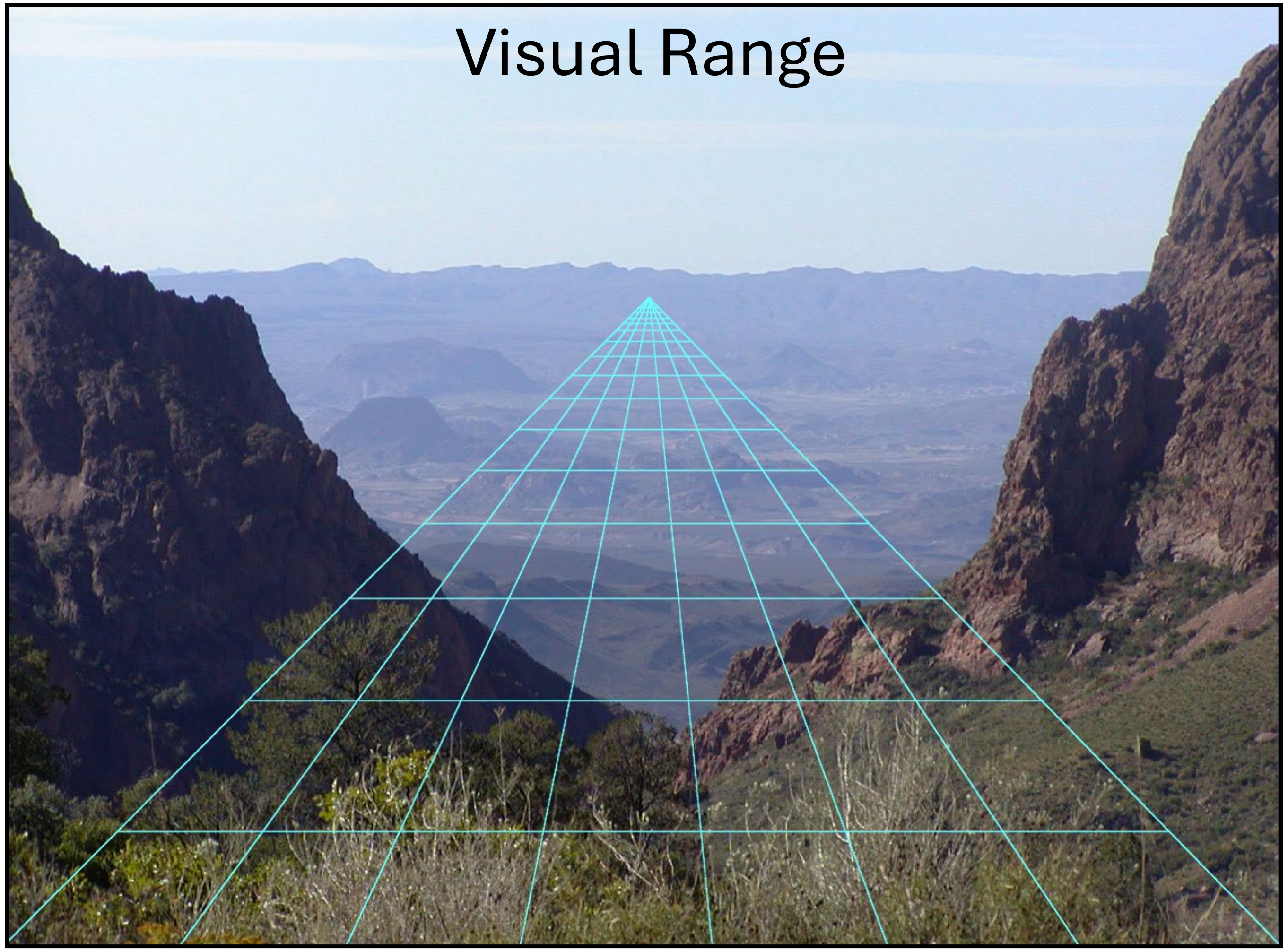
Visibility is historically defined as visual range:

"the farthest distance one can see a large black object against the background sky."

-Useful for aviation, doesn't account for changes in scene, such as loss of texture or discoloration as haze increases.

Visibility is more than just how far we can see.

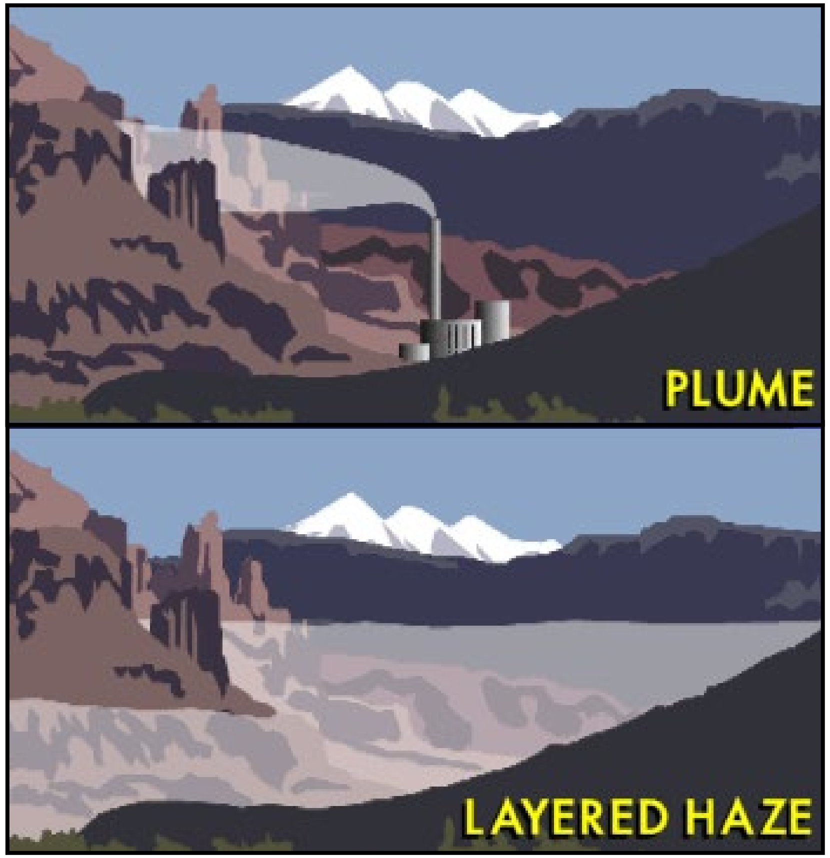
-It is better described as how "well" we can see and appreciate the colors, textures, forms, and detail in distant landscape features.



Theoretical limit of visual range is 243 miles

Types of Haze

How impairment manifests depends upon the extent and distribution of particles and gases in the atmosphere.



Visibility Impairment: generally associated with discoloration, haziness, and loss of color and detail.

Uniform Haze: Pollutants are uniformly distributed from the ground to a height well above the highest terrain feature.

Plume: Pollutants are constrained in a tight elevated layer that can often be traced to a nearby source.

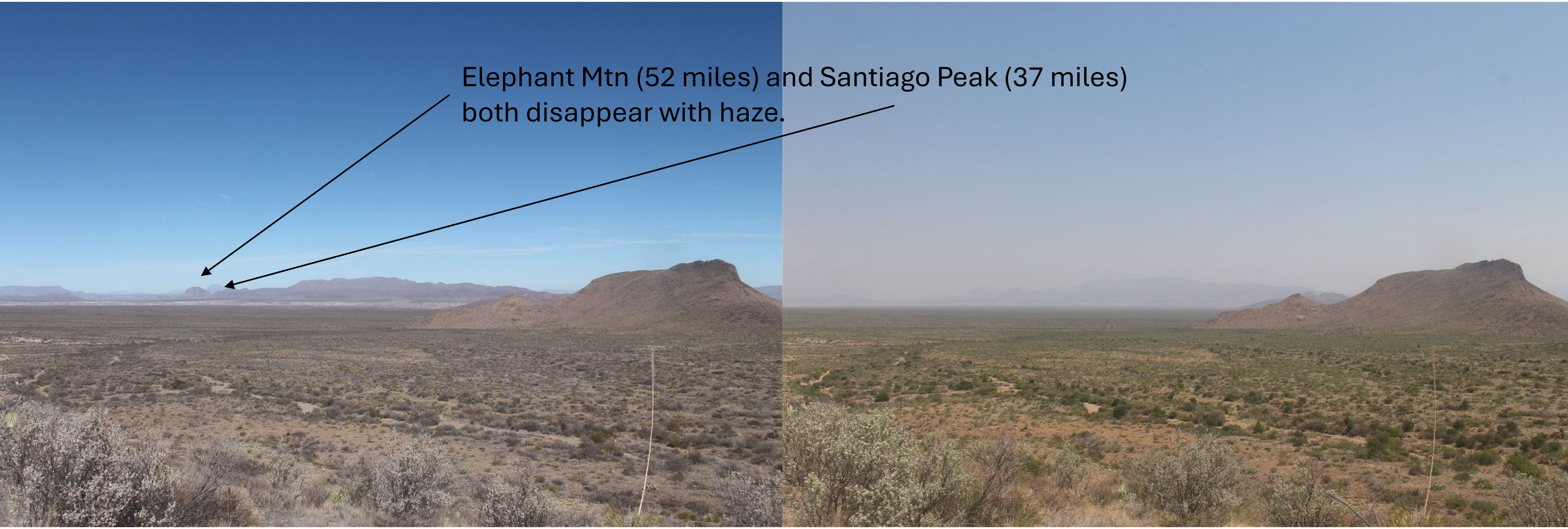
Layered Haze: Pollutants are often trapped near the ground beneath a temperature inversion. The top edge of the pollutant layer is visible.

Examples of different types of haze layers

Grand Canyon National Park, Arizona

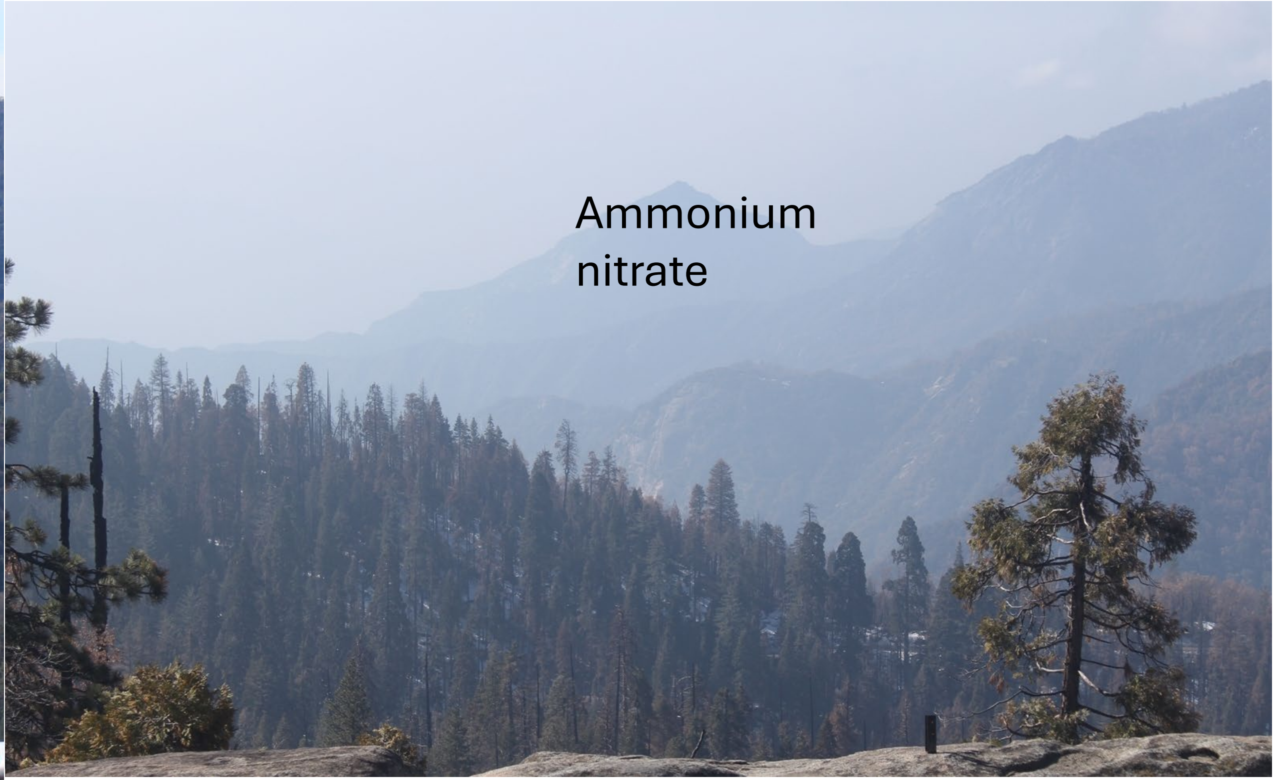
Great Smoky Mountains National Park, TN

Big Bend National Park, TX



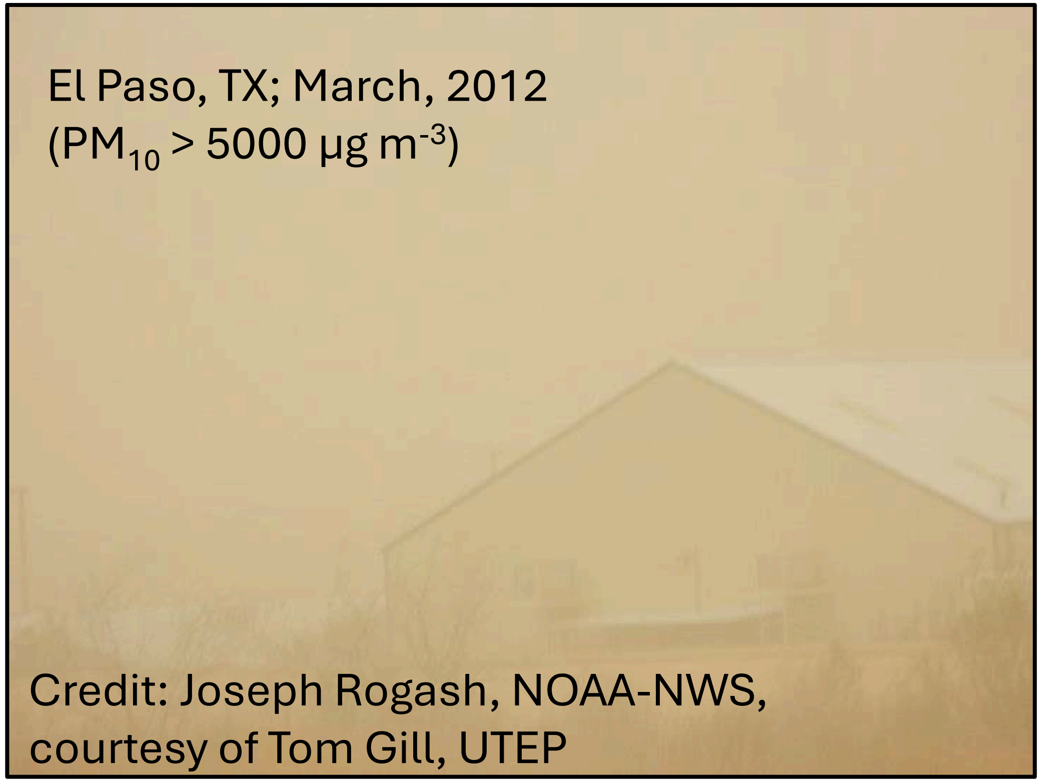
Sequoia & Kings Canyon National Park, CA

Sequoia & Kings Canyon National Park, CA

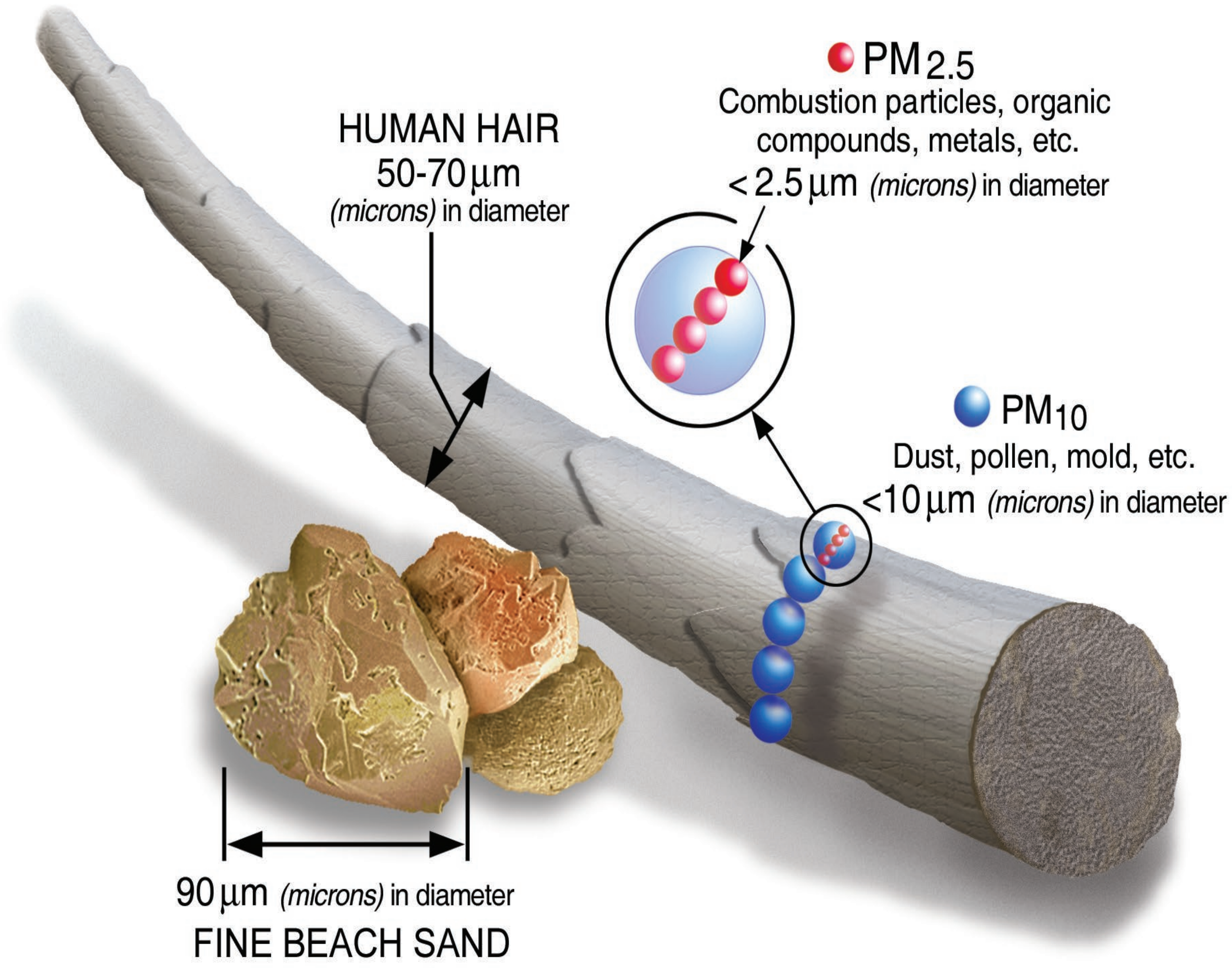


Dinosaur National Monument, CO

Anthropogenic and Natural Sources of Haze

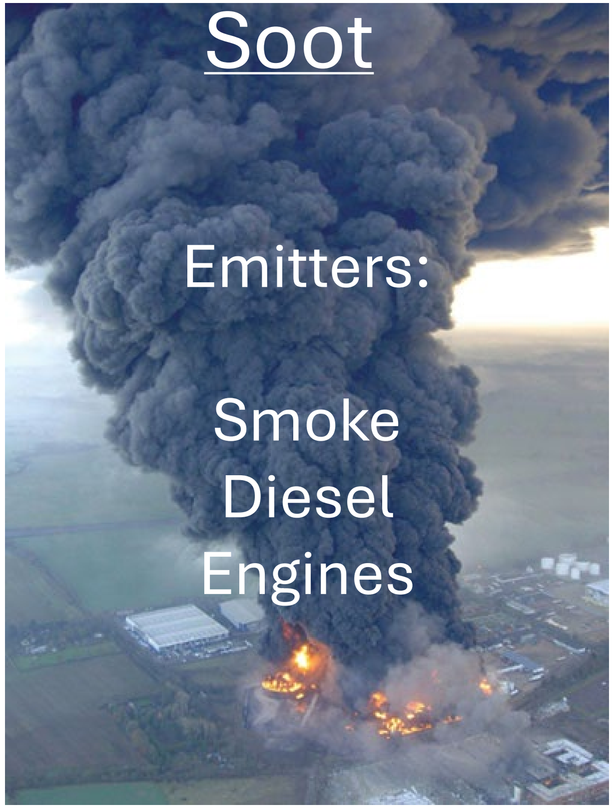


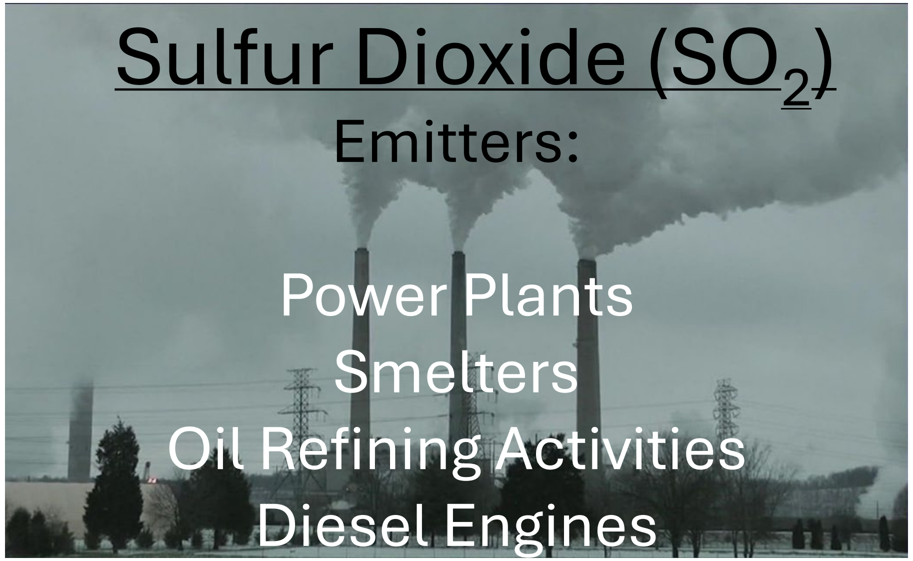
2. Causes of Haze: Atmospheric Aerosols

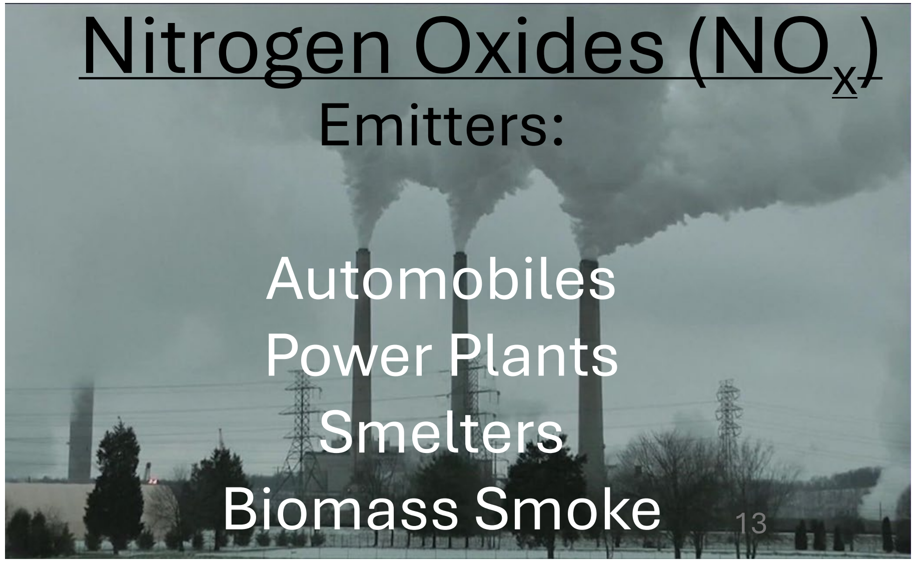


Source: EPA

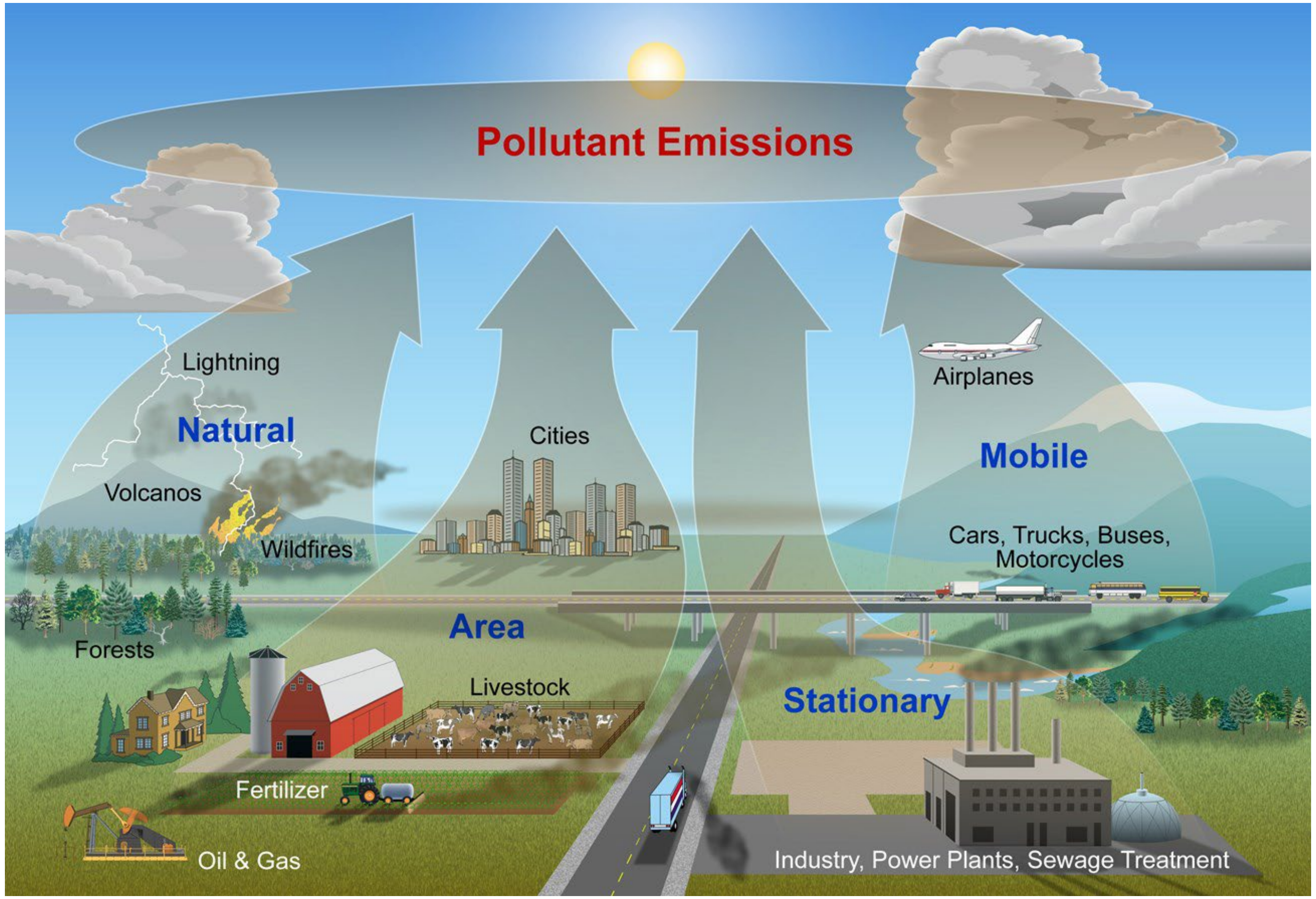
Sources of Aerosols: Natural and Anthropogenic







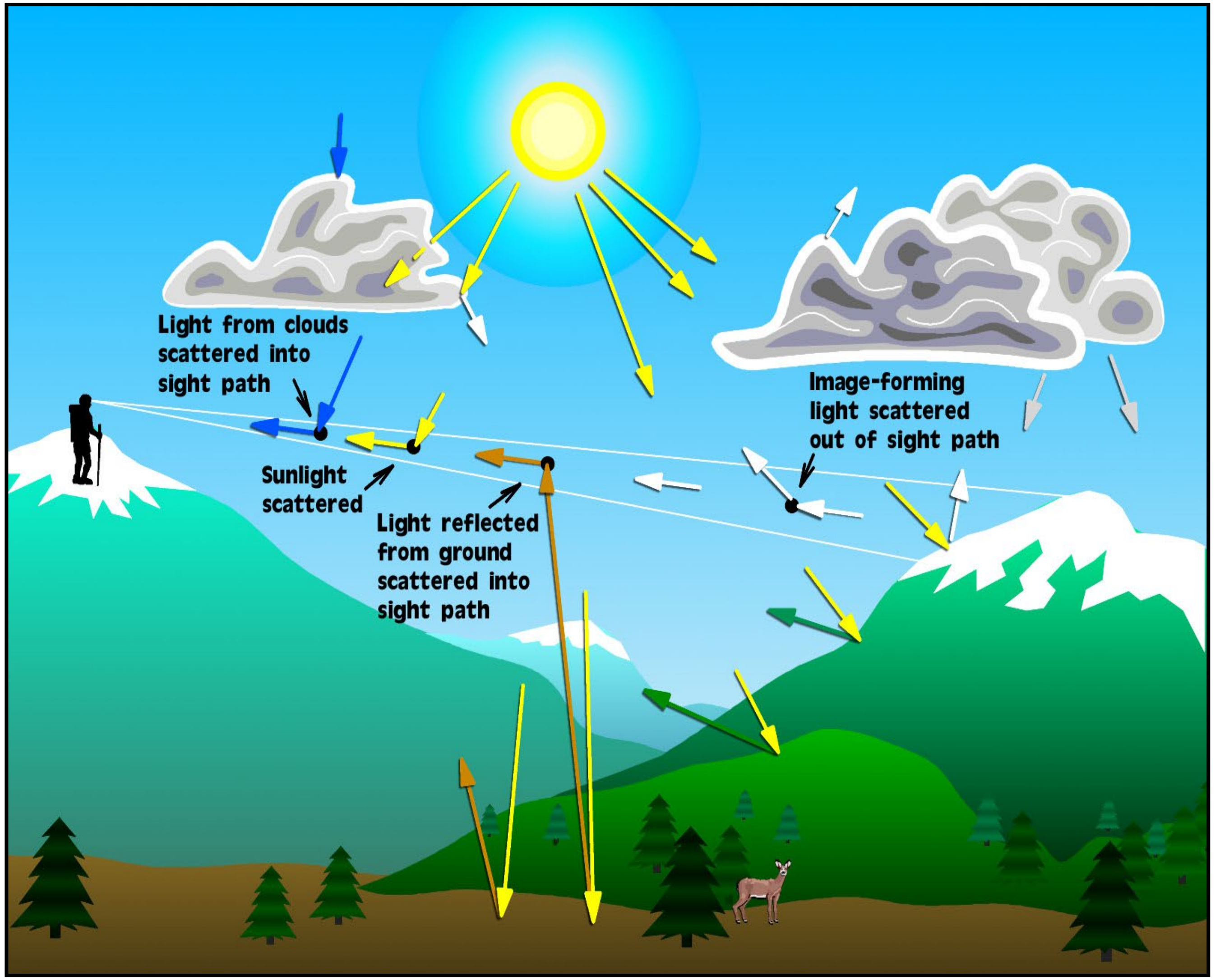
Secondary Particle Formation



Precursor emissions disperse in the atmosphere, convert into secondary particles through complex atmospheric chemical reactions, then travel long distances to deposit in remote areas far from their source.

How Pollutants Cause Haze

Scattering in the Atmosphere



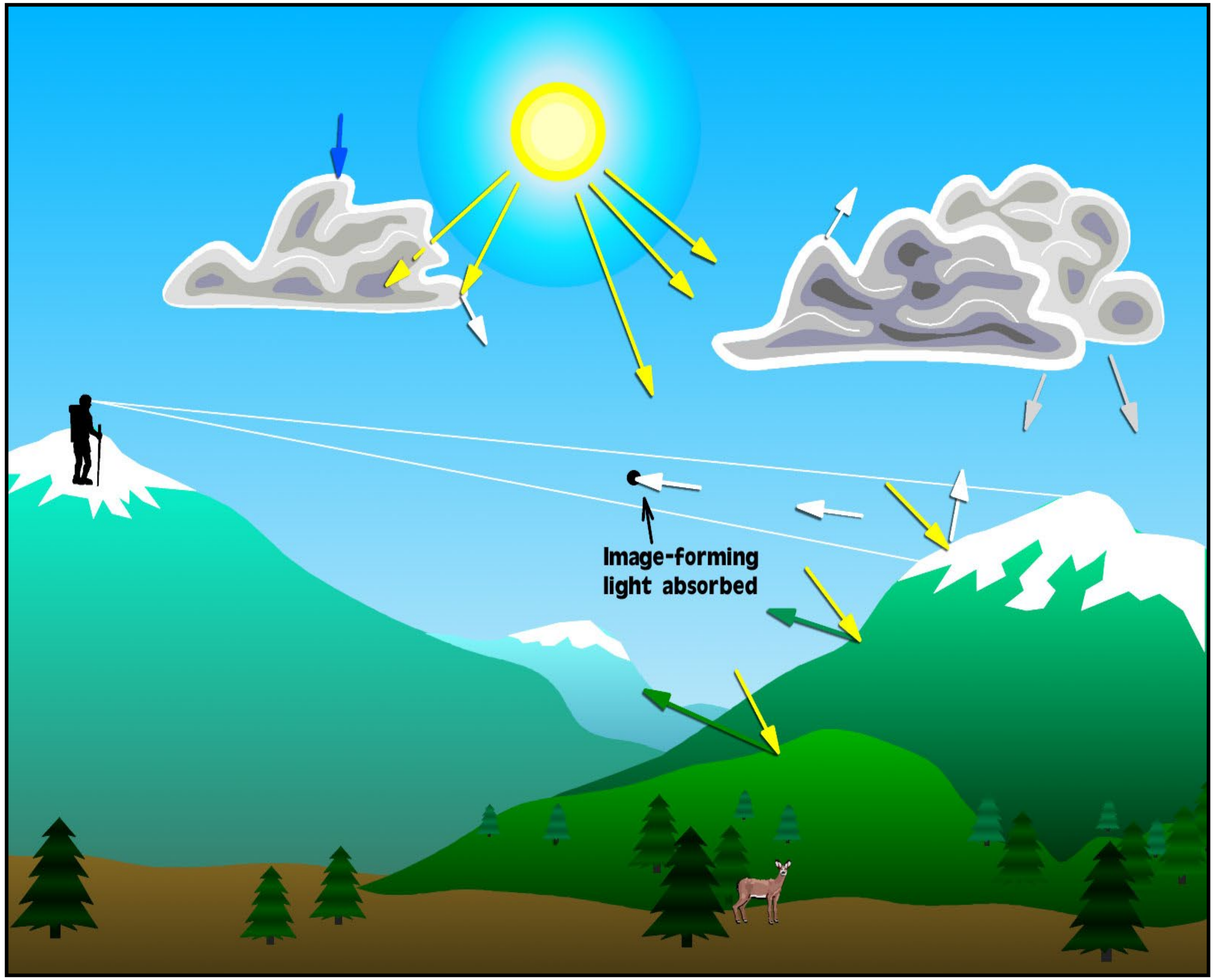
Particles and gases in the atmosphere can scatter or redirect image-forming light as it travels to the eye.

Through scattering, some image-forming light is removed from the view path.

In addition, extra light, sunlight, and light reflected from the clouds and ground are added to the sight path, which interferes with the ability to view the scene.

How Pollutants Cause Haze

Absorption in the Atmosphere



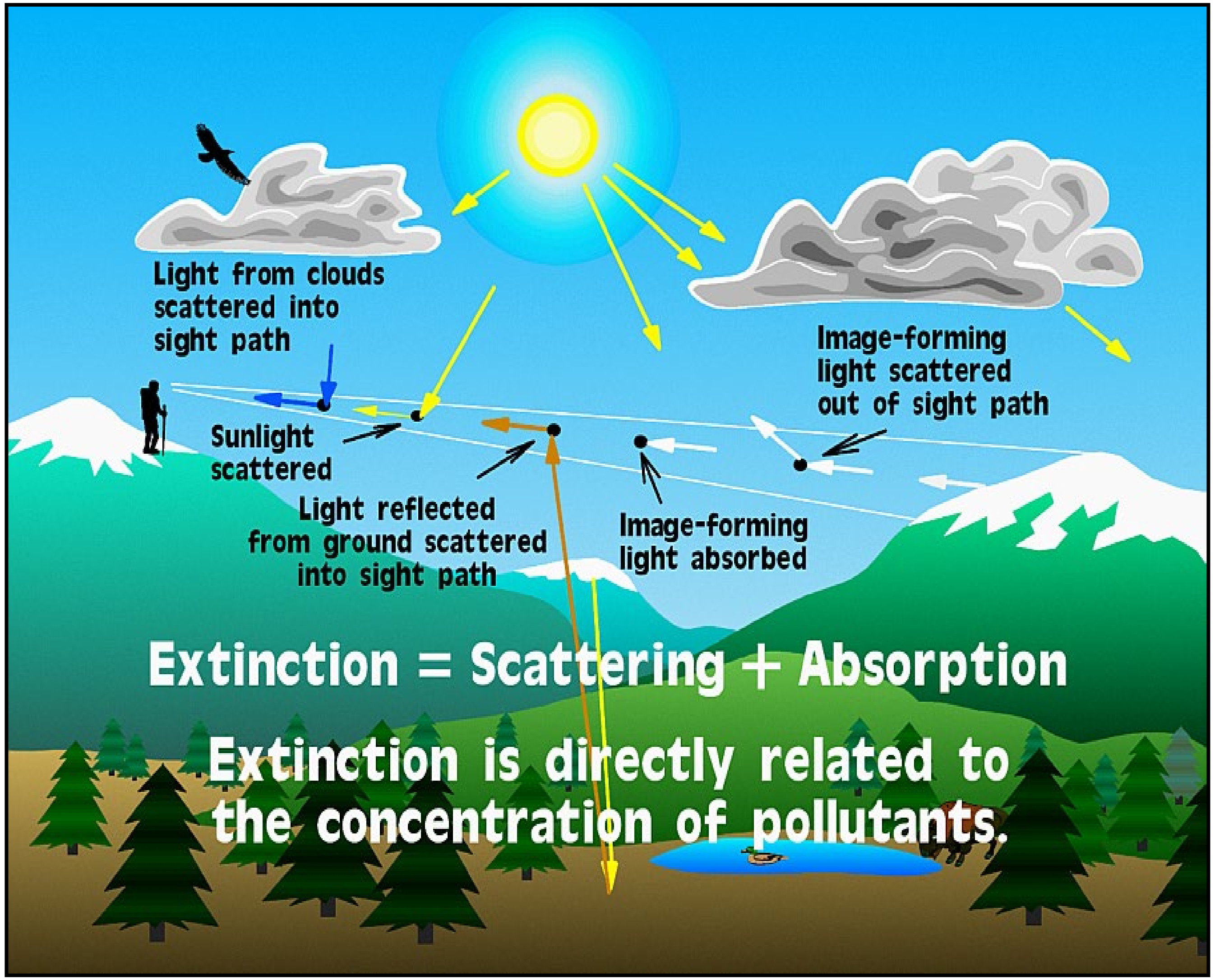
Another cause of visibility impairment is absorption.

Particles and gases in the atmosphere absorb or remove image-forming light before it ever reaches the viewer’s eye.

Although significant, absorption usually is less important than scattering processes when we talk about visibility impairment.

How Pollutants Cause Haze

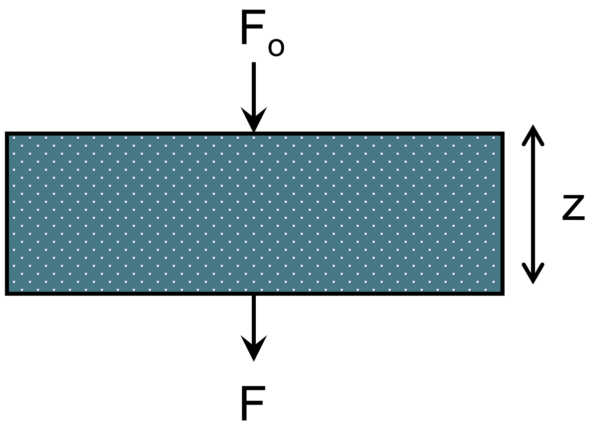
Extinction in the Atmosphere



Extinction is a visibility metric used to describe the combined effect of scattering and absorption. It is proportional to the total amount of light removed as light passes through the atmosphere and is related to the concentration of pollutants.

3. Light Extinction Coefficients

Attenuation of incident light by scattering and absorption as it passes through a layer is described by Beer's law:



$$\frac{F}{F_o} = \exp(-b_{ext} z)$$

F_o = incident light
F = transmitted light
b_{ext} is the extinction coefficient (Mm^{-1})
z is path length

$$\mathbf{b_{ext} = b_{sp} + b_{ap} + b_{sg} + b_{ag}}$$

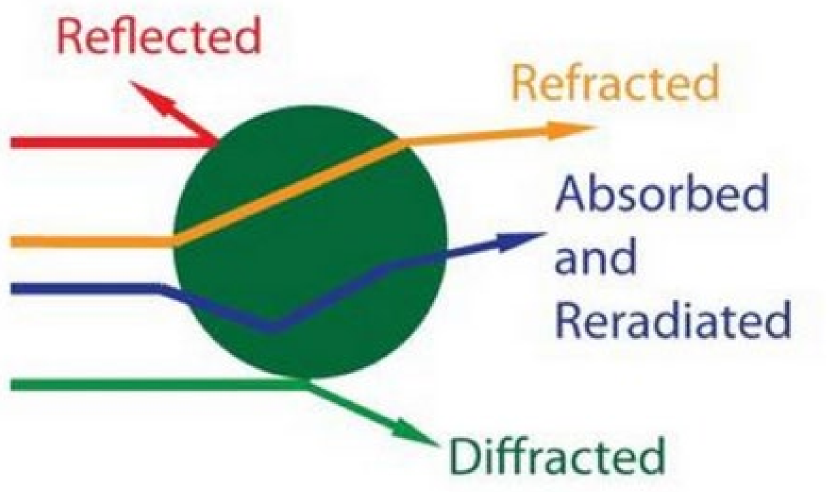
b_{sp}, b_{ap}: Scattering and absorption by particles

b_{sg}, b_{ag}: Scattering and absorption by gases
Rayleigh scattering by molecules, NO_2 absorption in visible wavelengths

Aerosol Radiative Effects

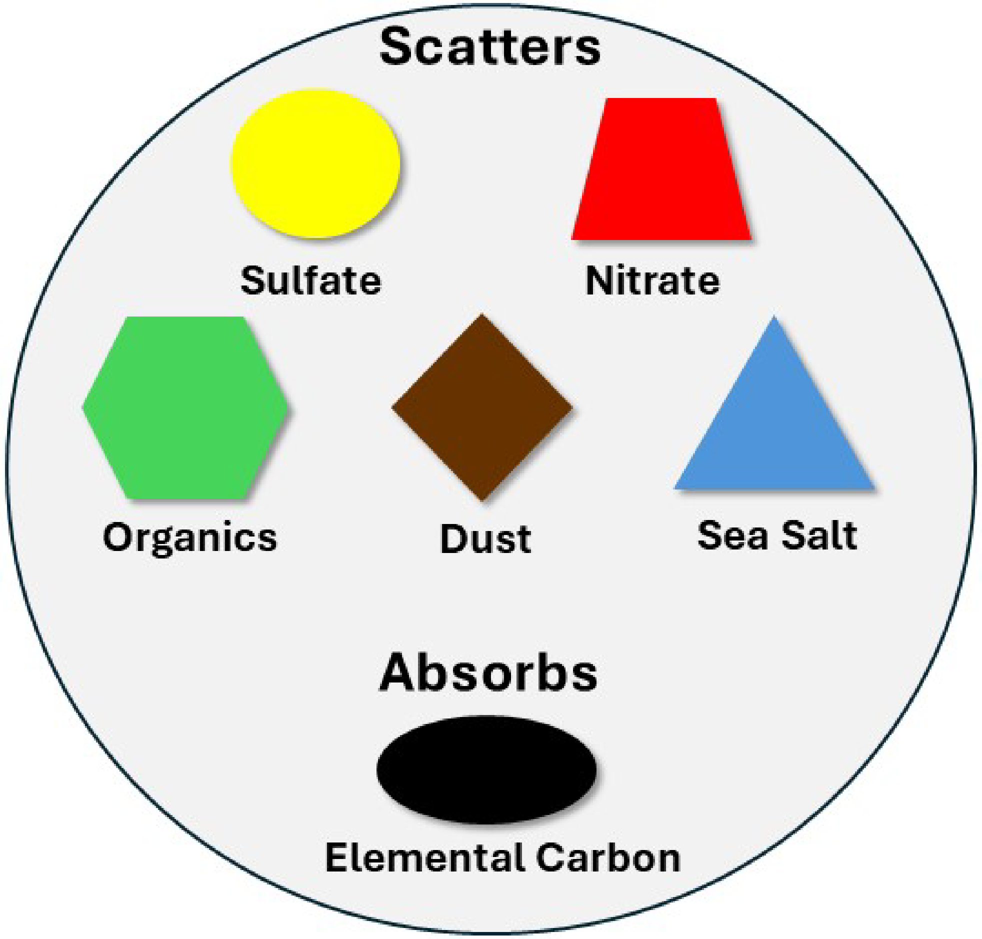
Aerosol interaction with solar radiation depends on:

- particle composition (scattering/absorbing)
- particle size
- ability to absorb water (hygroscopicity)
- particle shape



Aerosol Composition

Degree of scattering (or absorption) depends on optical properties (refractive index)



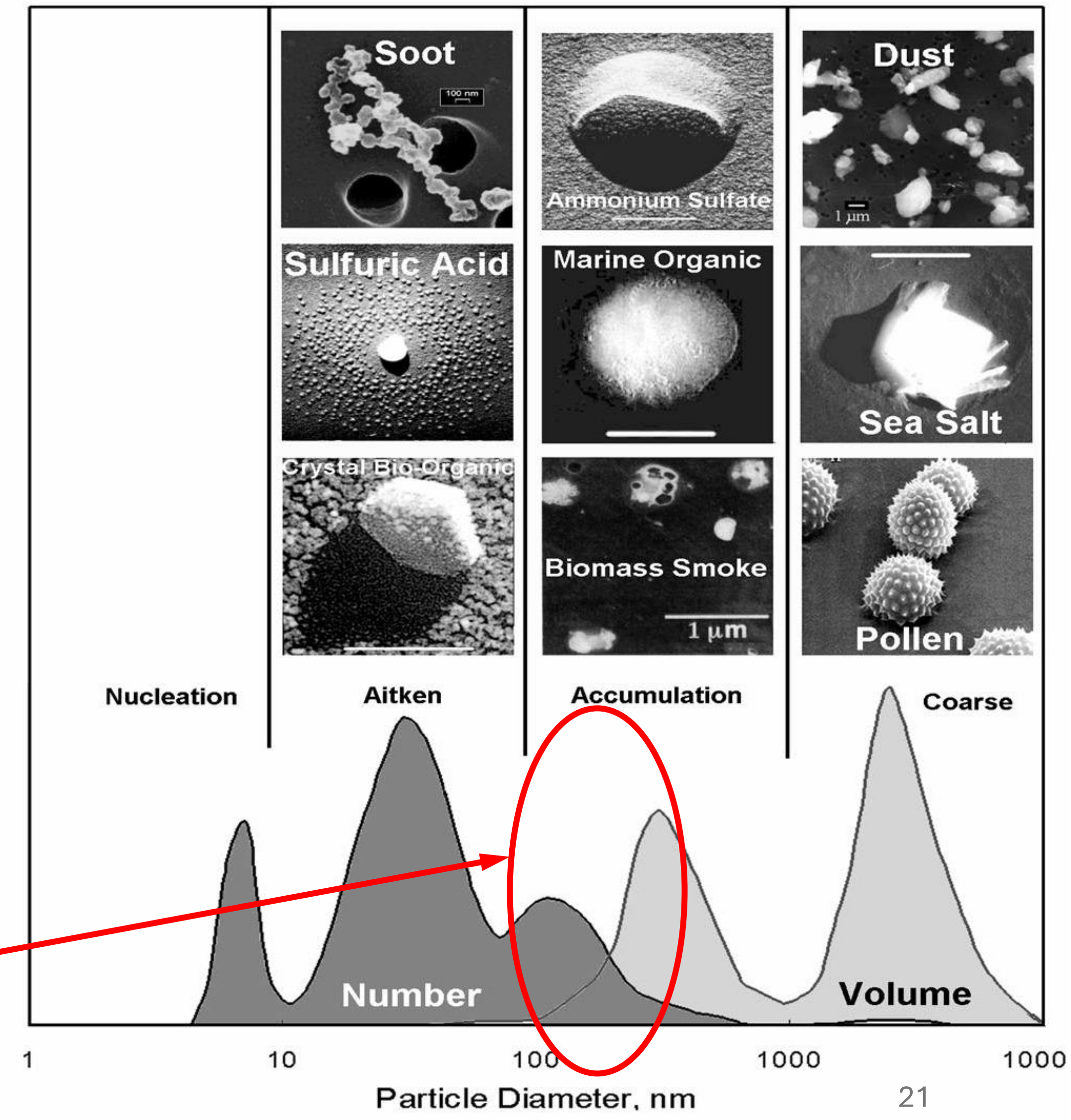
Aerosol Size

$PM_{2.5}$ (Fine Particles):

- Particles with aerodynamic diameters less than 2.5 μm.
- These particles can stay suspended for weeks and are transported far from their source.

PM_{10} (Coarse Particles):

- Particles with aerodynamic diameters less than 10 μm.
- These particles usually deposit out of the air close to their source.



This size range interacts most efficiently with solar radiation

Particle Size Effects on Haze

Base Case:

1 μg m^{-3} Ammonium Sulfate
1 μg m^{-3} Coarse Mass
$b_{ext} = 13\ Mm^{-1}$

Coarse mass:
Increase has less effect

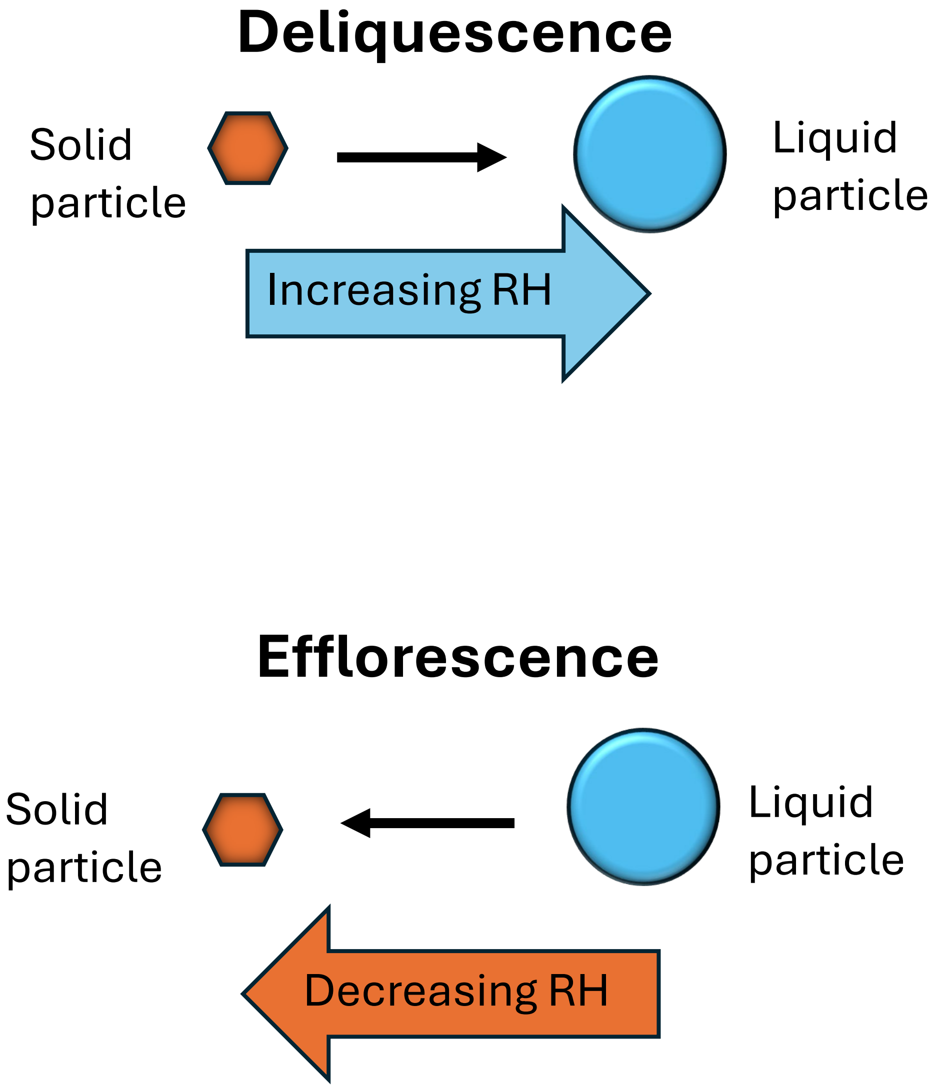
1 μg m^{-3} Ammonium Sulfate
20 μg m^{-3} Coarse Mass
$b_{ext} = 24\ Mm^{-1}$

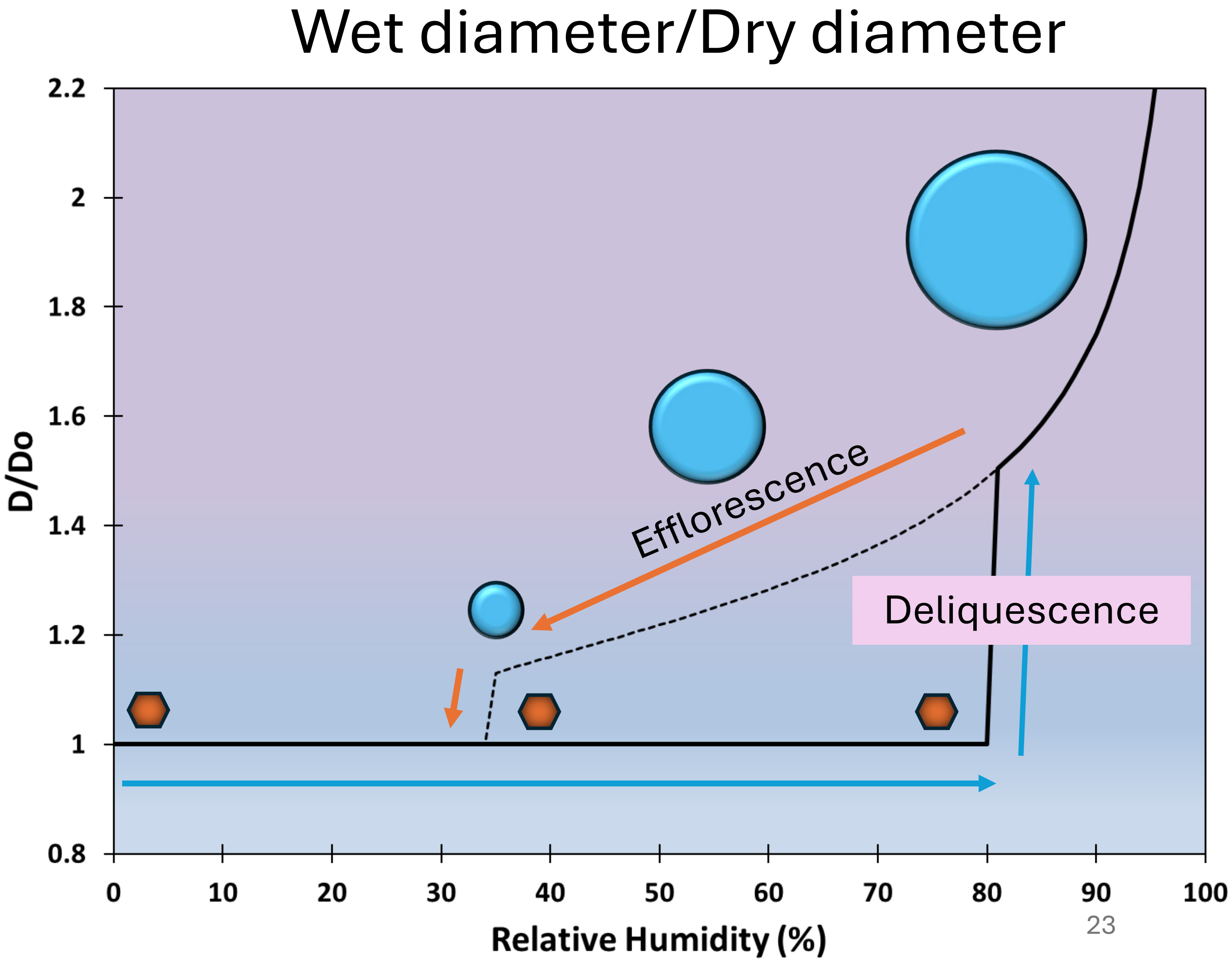
Fine mass:
Increase has bigger effect

20 μg m^{-3} Ammonium Sulfate
1 μg m^{-3} Coarse Mass
$b_{ext} = 107\ Mm^{-1}$

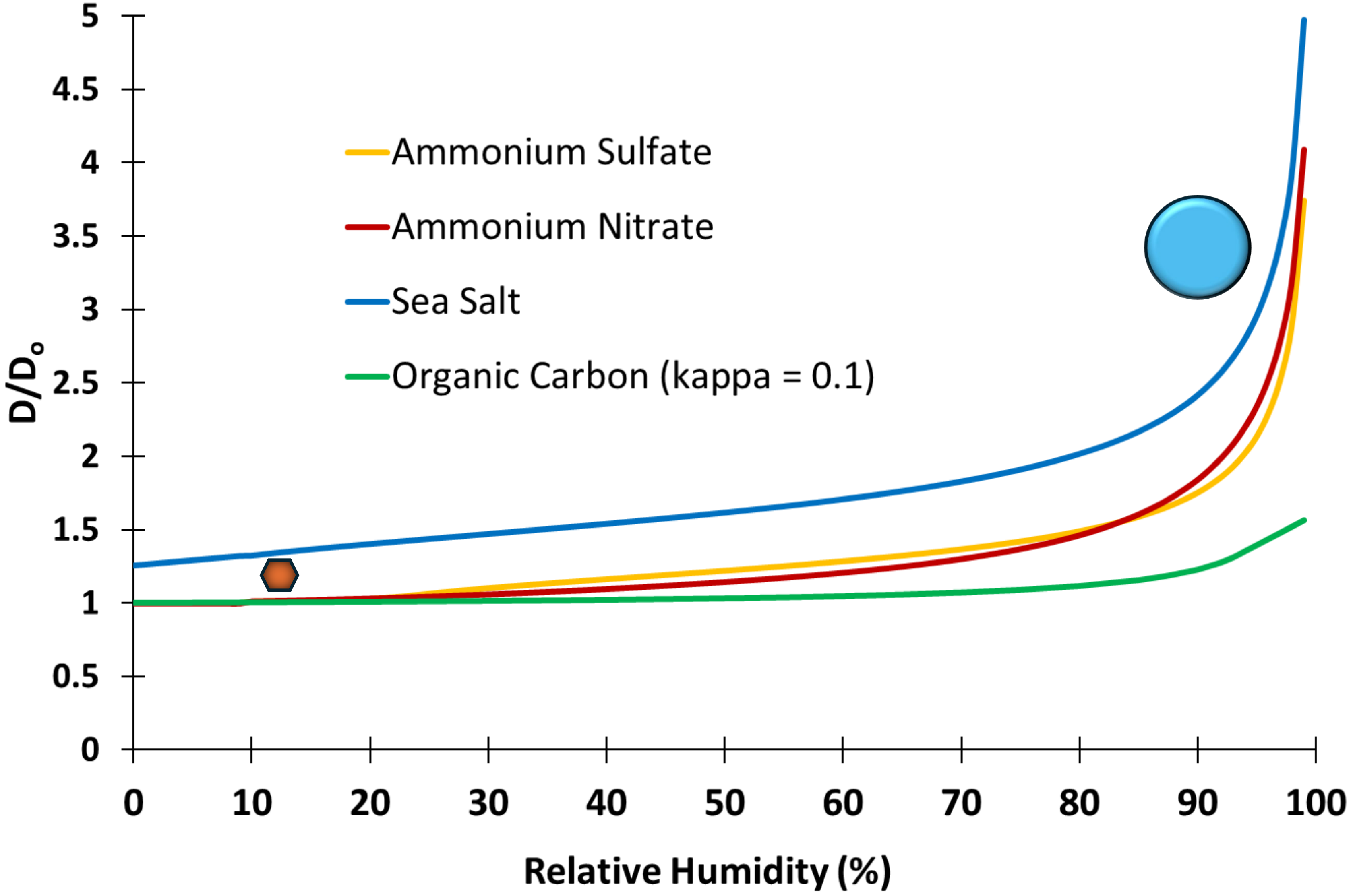
Modeled using WinHaze

Aerosol Growth Curves (Hygroscopicity, D/D_o)

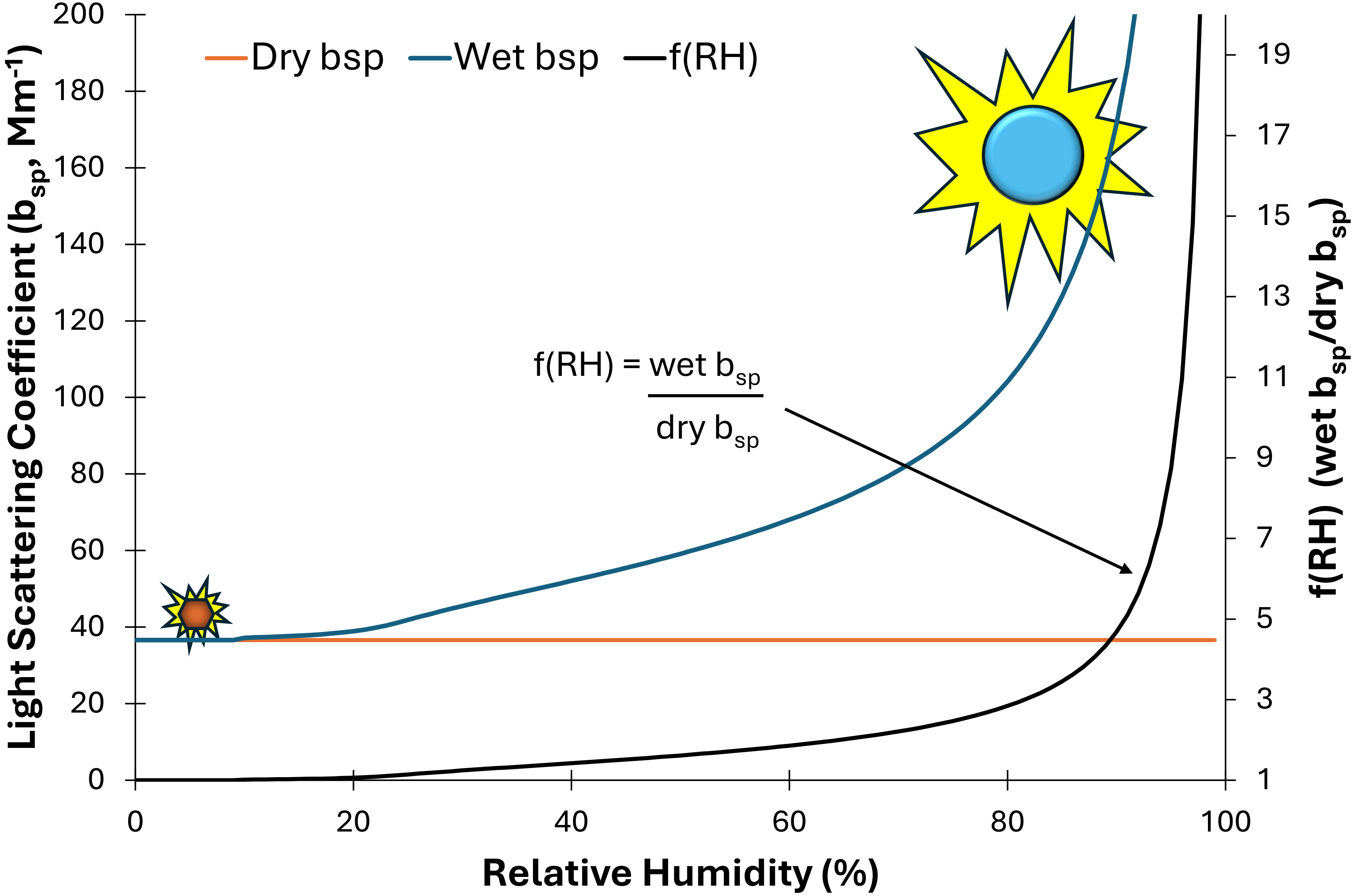




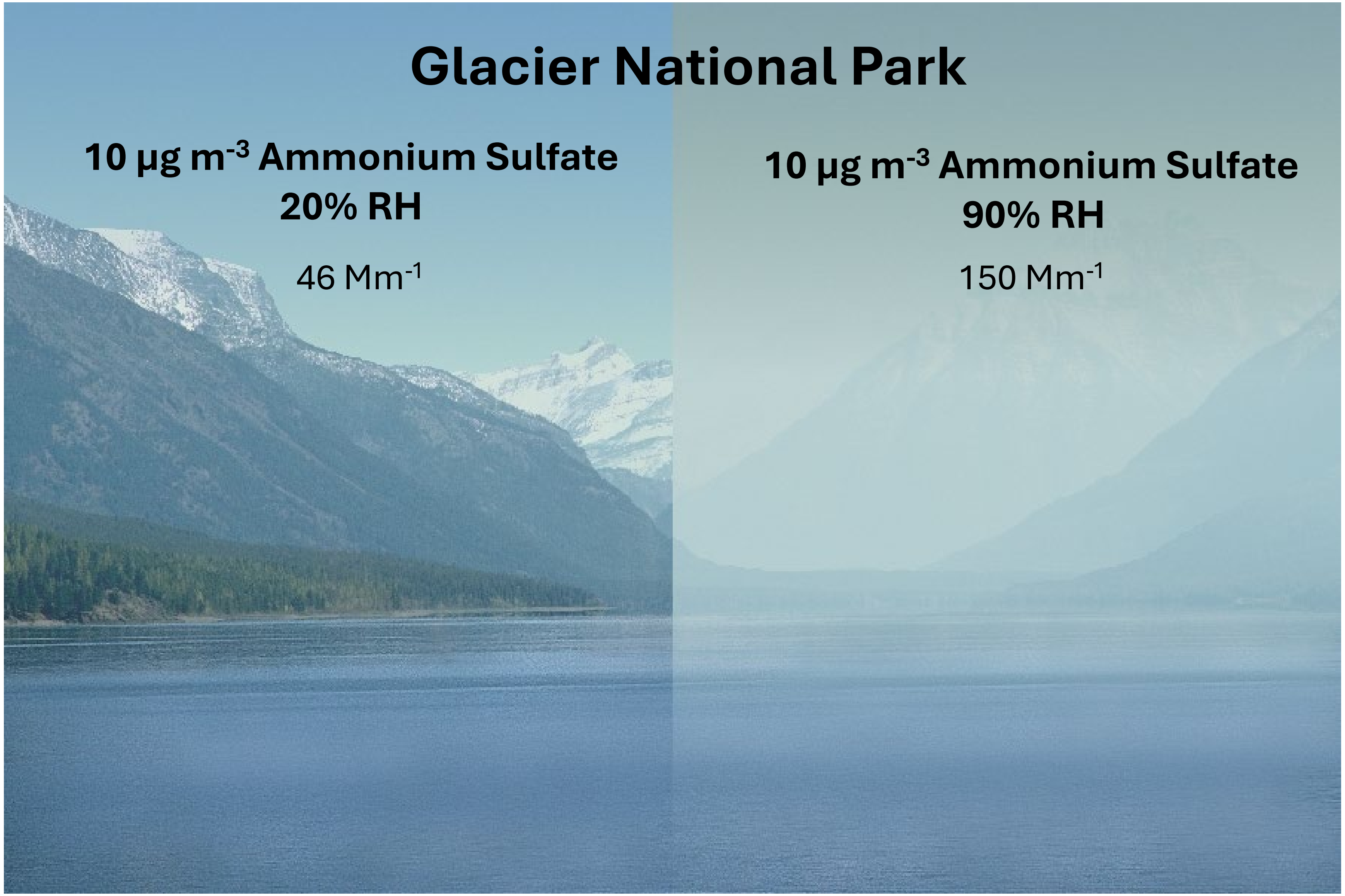
Aerosol Diameter Growth Curves (D/D_o)



Scattering Growth Curves (f(RH))

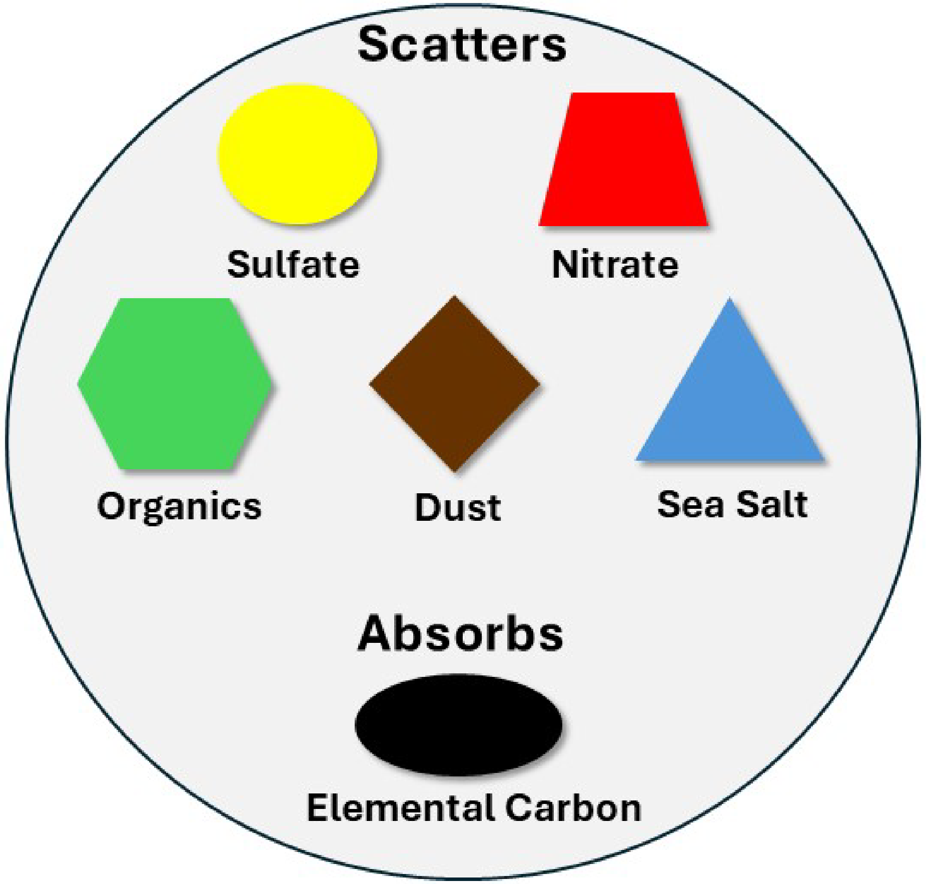


Relative Humidity Effects



Modeled using WinHaze

Light Extinction Coefficient (b_{ext})



Major Contributors

1st IMPROVE Equation

b_{ext} (Mm^{-1}) = 3.0 × f(rh) × [Ammonium Sulfate] +
3.0 × f(rh) × [Ammonium Nitrate] +
4.0 × [Organics] +
1.0 × [Fine Dust] +
0.6 × [Coarse Mass] +
10.0 × [Elemental Carbon] +
Rayleigh Scattering

Dry mass scattering efficiency ($m^2 g^{-1}$)

Rayleigh Scattering of light by gas molecules:
Depends on the density of the air so is most dependent on elevation above sea level
Ranges from ~9-12 Mm^{-1}
λ = 550 nm

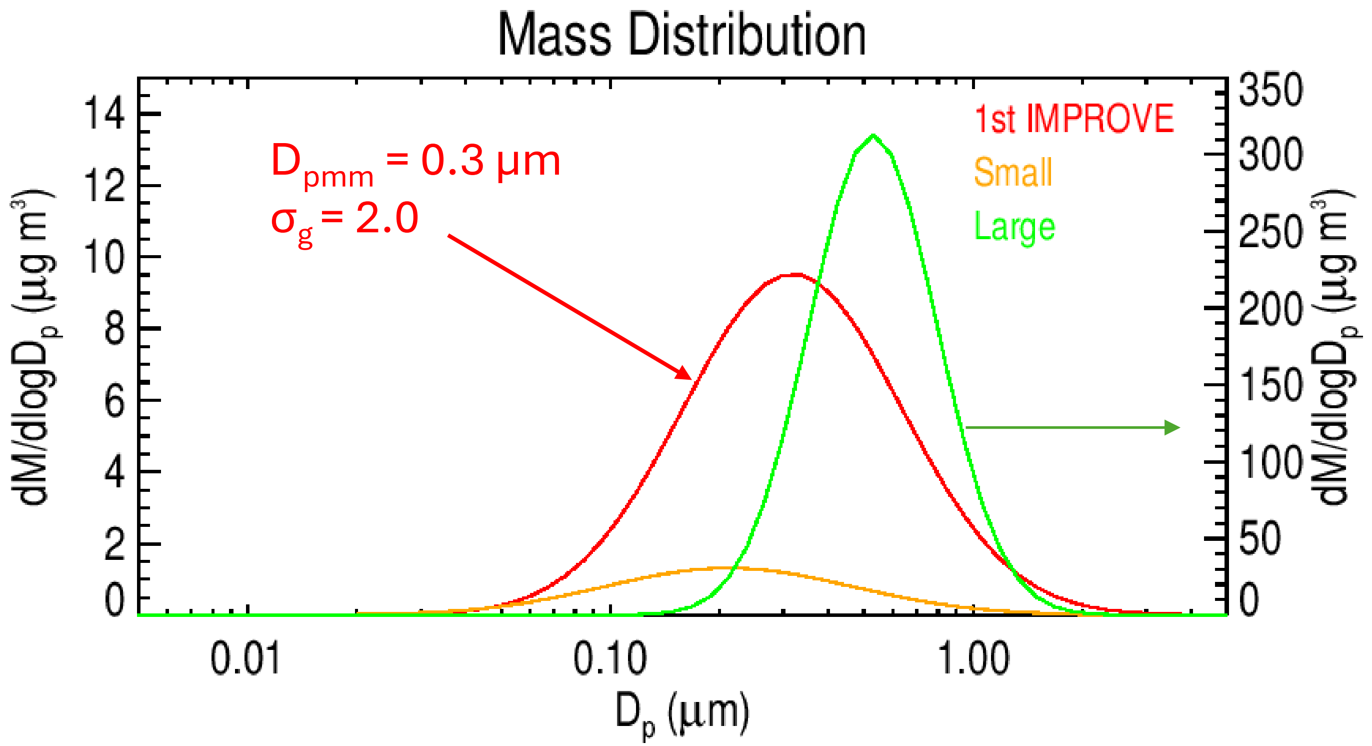
Malm et al. (1994)

Dry Mass Scattering Efficiency (α, m^2g^{-1})

Light scattering coefficient (b_{sp})

$$b_{sp} = \sum_i \frac{3}{2}\frac{M_i Q_{sp,i}}{D_{p,i}\rho} \qquad (Mm^{-1})$$

M_i = mass of particles in bin *i*
$D_{p,i}$ = diameter of bin *i*
$Q_{sp,i}$ = Mie scattering efficiency
ρ = species density ($g\ cm^{-3}$)

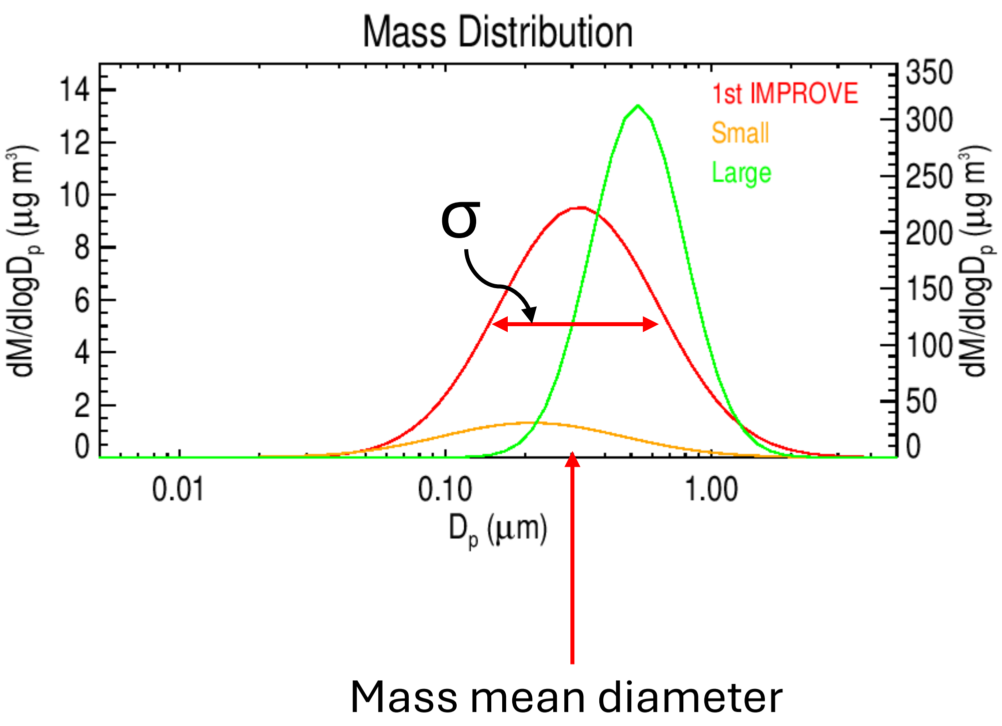


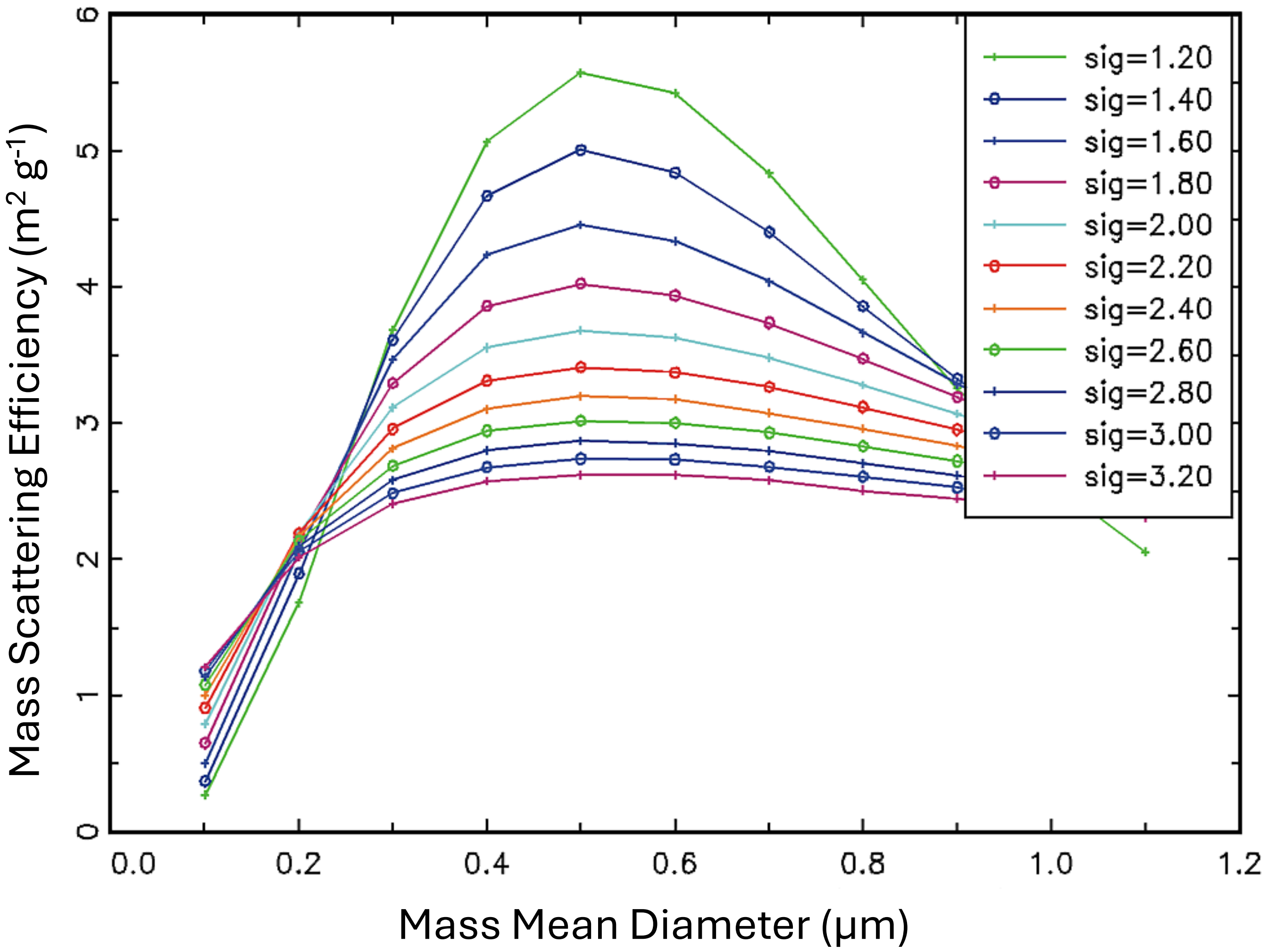
Mass scattering efficiency (α)

$$\alpha = b_{sp}/Mass \qquad (m^2\ g^{-1})$$

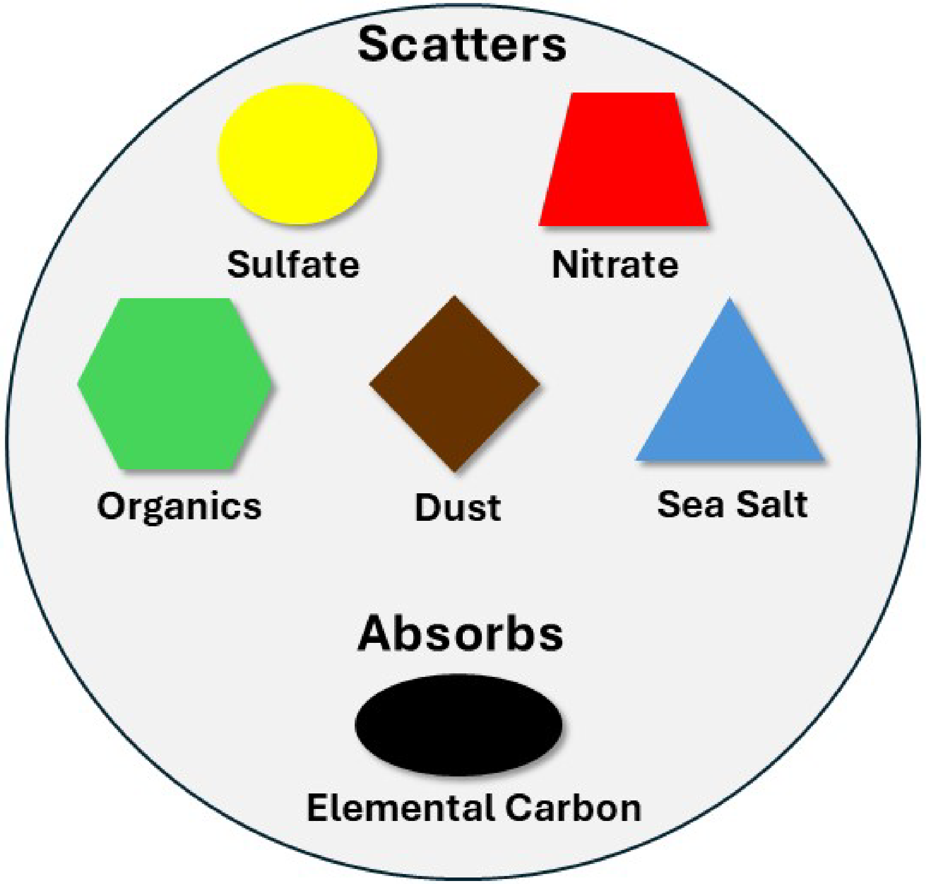
Mie scattering efficiency (Q_{sp}) is a function of refractive index, particle diameter, and wavelength, assuming spherical particles.

Mass Scattering Efficiency as Function of Size





Light Extinction Coefficient



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4.0 × [Organics] +
1.0 × [Fine Dust] +
0.6 × [Coarse Mass] +
10.0 × [Elemental Carbon] +
Rayleigh Scattering

Scattering growth curves

Malm et al. (1994)

Calculating f(RH)

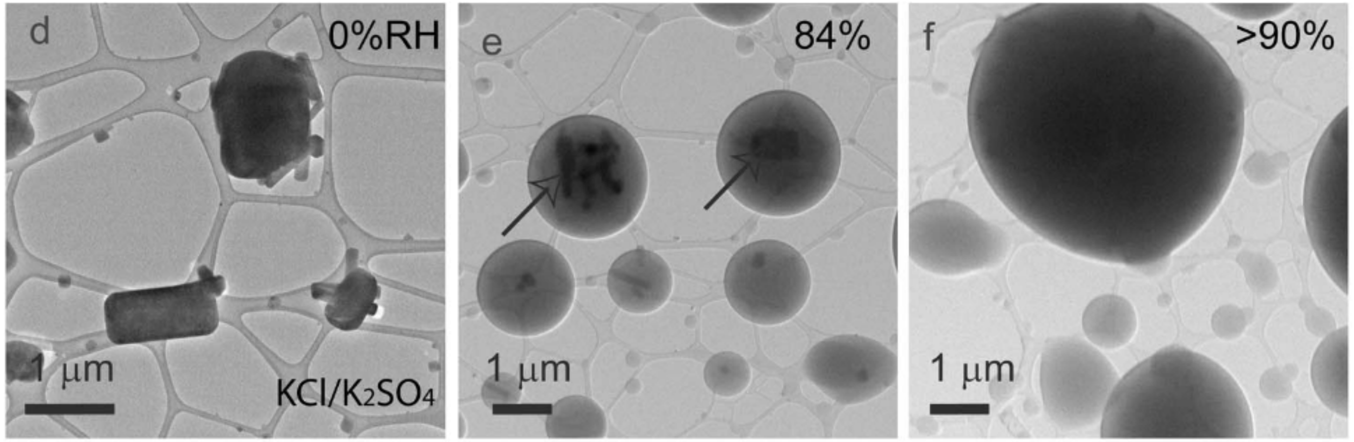
DRY light scattering coefficient (b_{sp})

$$b_{sp} = \sum_i \frac{3}{2} \frac{M_i Q_{sp,i}}{D_{p,i}\rho} \quad (Mm^{-1})$$

"Grow" the size distribution using D/Do and calculate a WET b_{sp}

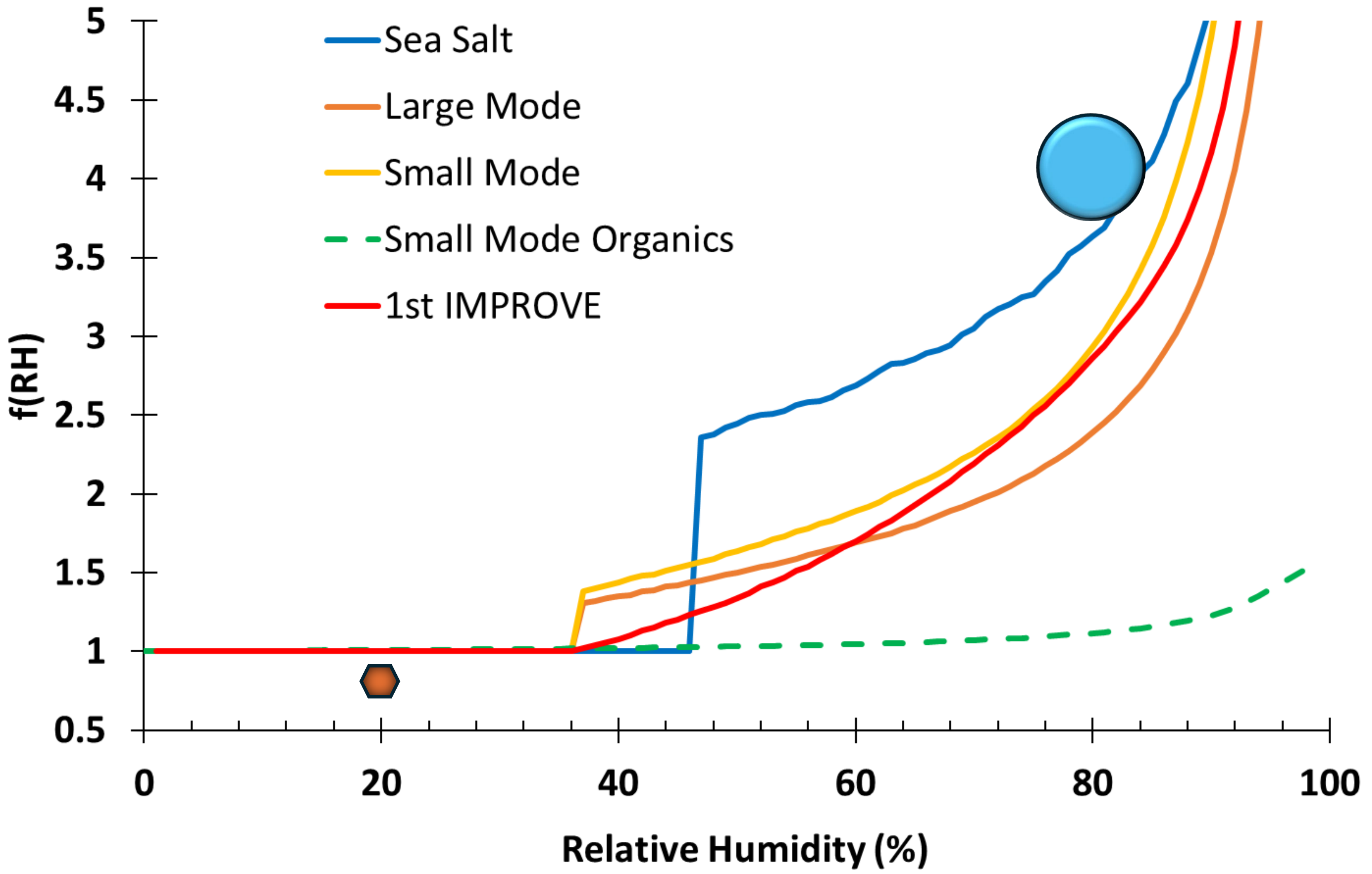
$$f(RH) = \frac{\text{wet } b_{sp}}{\text{dry } b_{sp}}$$

RH = 0 RH = 84% RH > 90%



Freney et al. (2010)

Scattering Growth Curves (f(RH))



https://vista.cira.colostate.edu/Improve/the-improve-algorithm/

Pitchford et al. (2007)

4. Visibility Measurements

Optec NGN-2 Nephelometer

Photo courtesy of Mackenzie Reed/NPS

Photo courtesy of Mark Tigges, ARS

Optec NGN2: started in 1992
Open Air nephelometer (total b_{sp})
Wavelength of 550 nm
Ambient scattering without affecting RH of sample
After 30 years, shut down on July 12, 2023

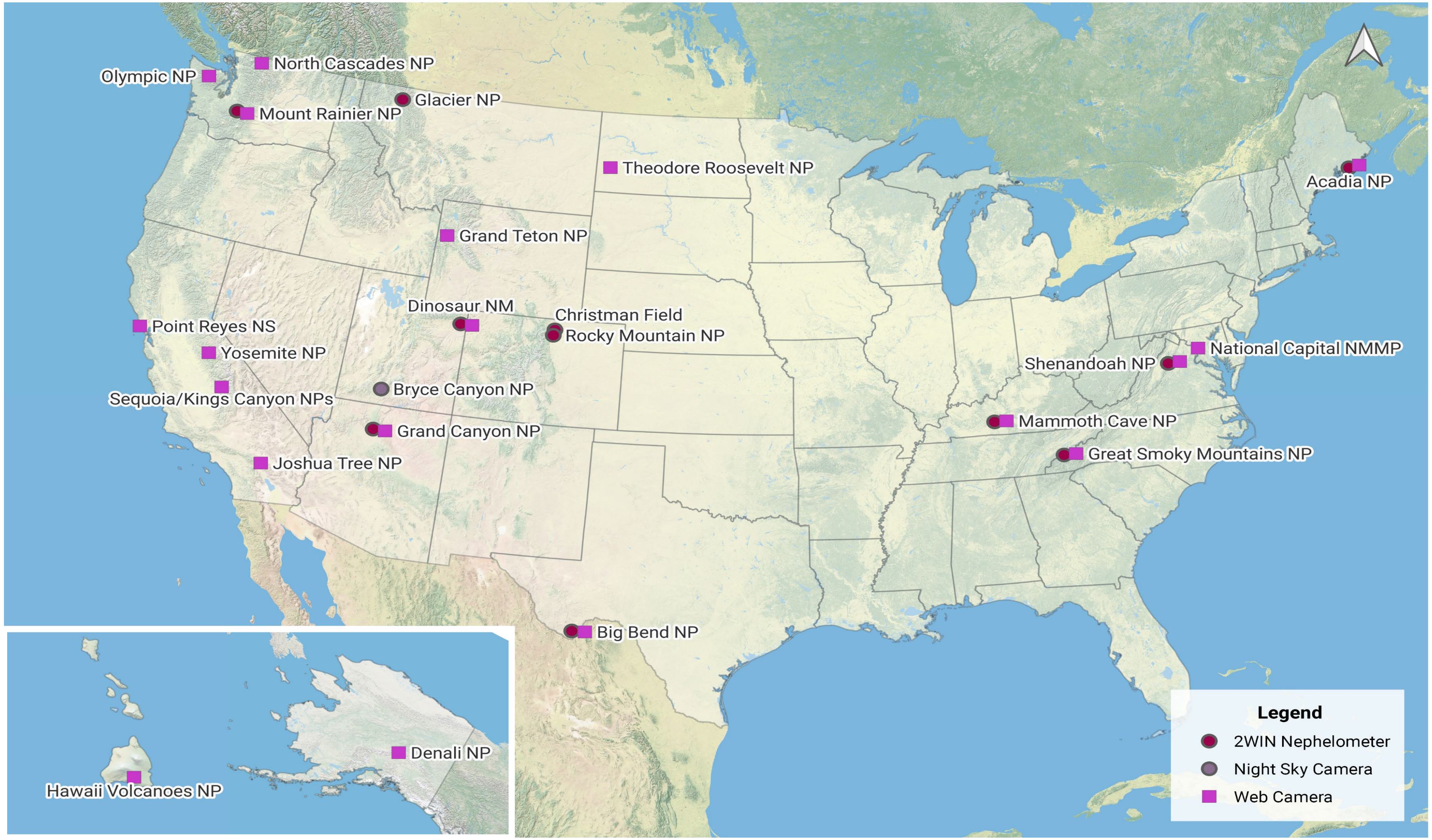
New Nephelometers

Ambilabs 2WIN Dual Wavelength nephelometer

Wavelength: 450nm, 525nm, and 635nm
(only two at any given time)
2.5 µm size cut

Photo courtesy of Mark Tigges, ARS

New Nephelometers

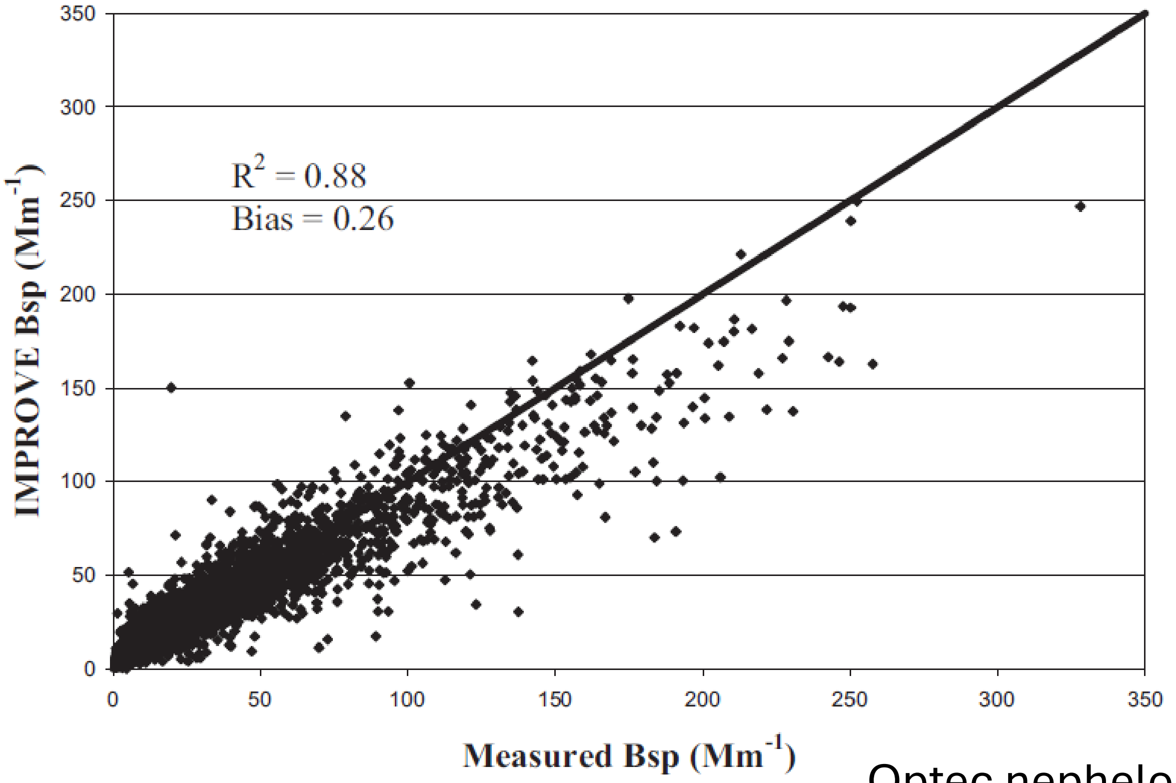


M. Tigges, ARS, 2024

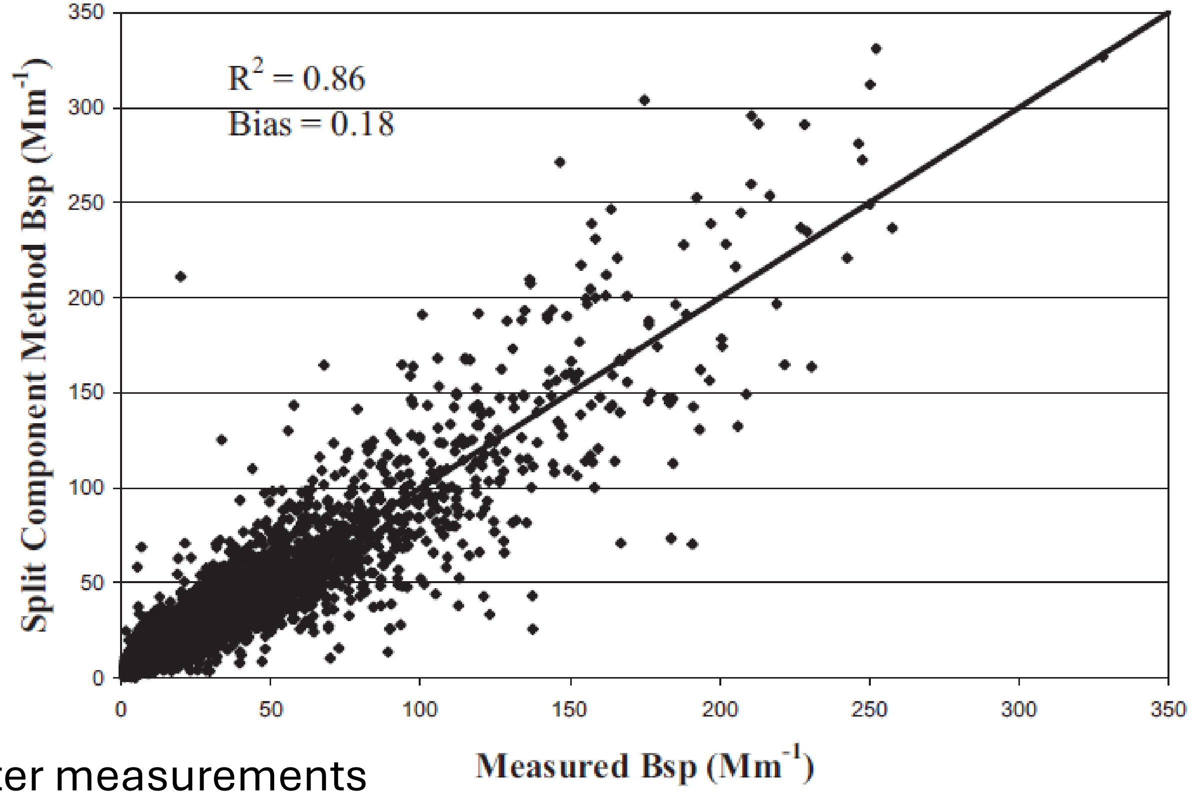
Measured and Calculated Scattering

(2001-2003)

1st IMPROVE Equation



2nd IMPROVE Equation



Optec nephelometer measurements

2nd IMPROVE Equation was designed to improve biases at low and high scattering values

Pitchford et al., 2007; 21 sites

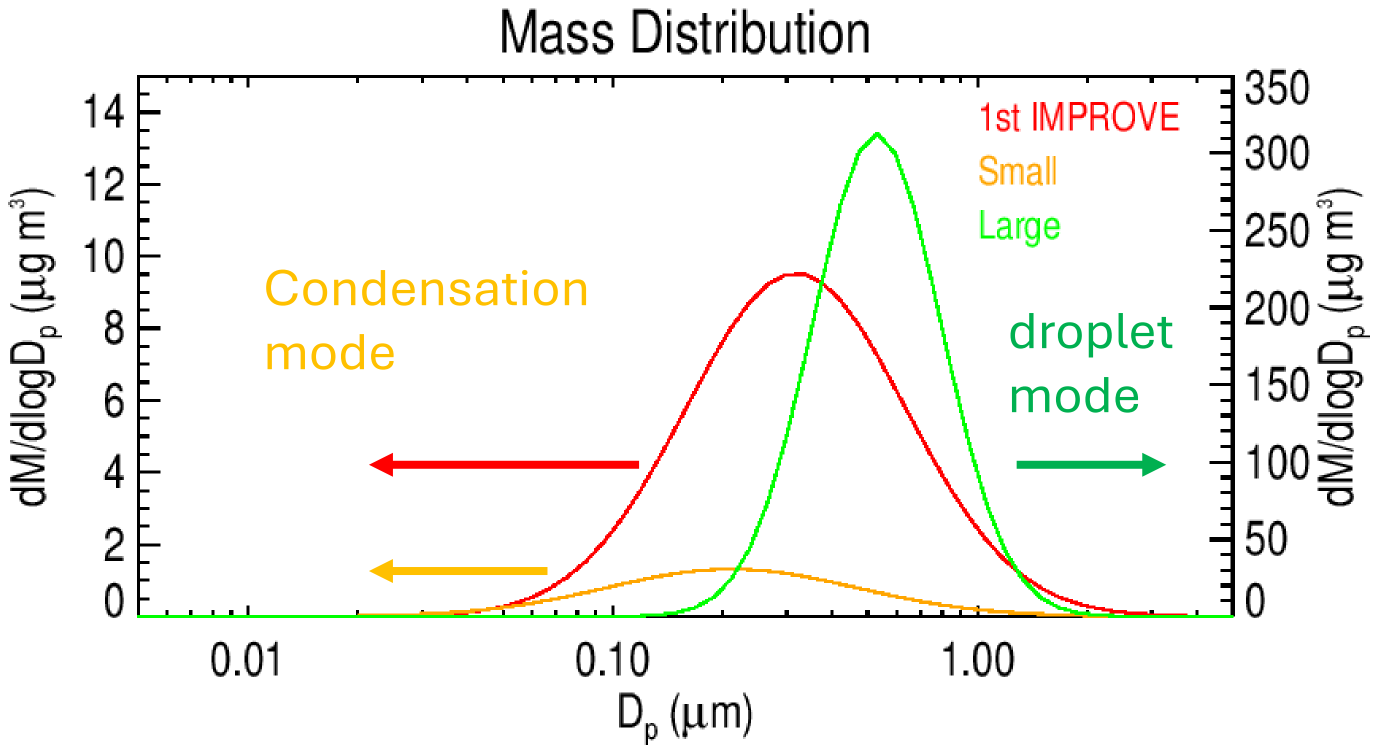
5. 2nd IMPROVE Equation

b_{ext} = **2.2 × f_s(RH) × [*Small* Ammonium Sulfate]** +
4.8 × f_L(RH) × [*Large* Ammonium Sulfate] +
2.4 × f_s(RH) × [*Small* Ammonium Nitrate] +
5.1 × f_L(RH) × [*Large* Ammonium Nitrate] +
2.8 × [*Small* Organic Mass] +
6.1 × [*Large* Organic Mass] +
1 × [Fine Dust] +
1.7 × f_{ss}(RH) × [Sea Salt] +
0.6 × [Coarse Mass] +
10 × [Elemental Carbon] +
Rayleigh Scattering (site specific)

https://vista.cira.colostate.edu/Improve/the-improve-algorithm/

2^{nd} IMPROVE Equation

The **2^{nd} IMPROVE Equation** is also known as the **"split mode"** or **"split component"** algorithm because it splits, or apportions, the component $PM_{2.5}$ mass into two size modes.



Mode	D_{pmm} (μm)	σ_g
1st IMPROVE	0.3	2.0
2nd IMPROVE (small)	0.2	2.2
2nd IMPROVE (large)	0.5	1.5
2nd IMPROVE (sea salt)	2.5	2.0

Split Component Algorithm

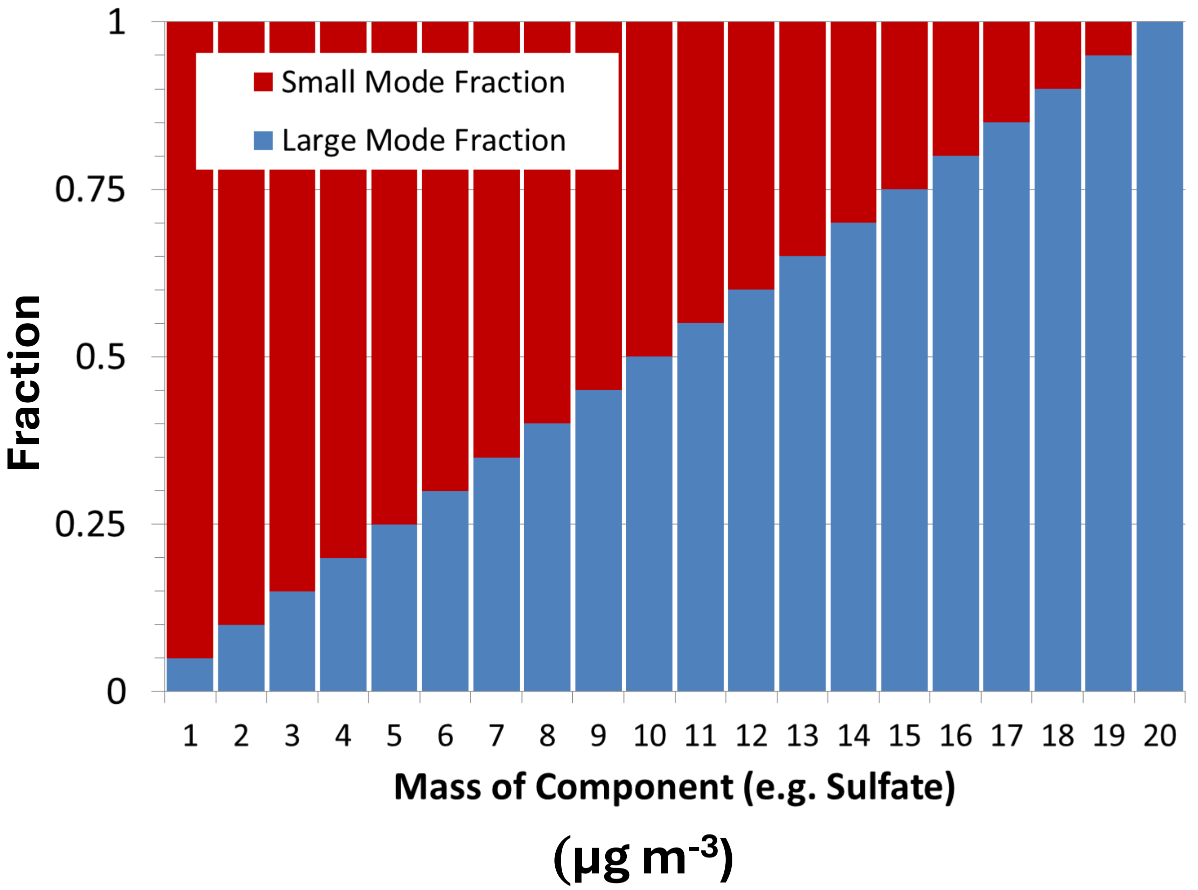
The mass in the two modes is apportioned using a "cut point" of 20 μg m^{-3}.

For example:

If the $PM_{2.5}$ ammonium sulfate mass (AS) is 4 μg m^{-3},

- "large mode" AS is one fifth (4/20) of the mass, or 0.8 μg m^{-3}
- "small mode" AS mass is 4 - 0.8 = 3.2 μg m^{-3}.

If the AS more than 20 μg m^{-3}, all of it is assumed to be in the "large mode".



Ammonium nitrate and organic mass are also apportioned using 20 μg m^{-3}.

Second IMPROVE Equation

$$
\begin{aligned}
b_{ext} = \; & 2.2 \times f_S(RH) \times [\textit{Small}\ \text{Sulfate}] + \\
& 4.8 \times f_L(RH) \times [\textit{Large}\ \text{Sulfate}] + \\
& 2.4 \times f_S(RH) \times [\textit{Small}\ \text{Nitrate}] + \\
& 5.1 \times f_L(RH) \times [\textit{Large}\ \text{Sulfate}] + \\
& 2.8 \times [\textit{Small}\ \text{Organic Mass}] + \\
& 6.1 \times [\textit{Large}\ \text{Organic Mass}] + \\
& 1 \times [\text{Fine Soil}] + \\
& 1.7 \times f_{SS}(RH) \times [\text{Sea Salt}] + \\
& 0.6 \times [\text{Coarse Mass}] + \\
& 10 \times [\text{Elemental Carbon}] + \\
& \text{Rayleigh Scattering (site specific)}
\end{aligned}
$$

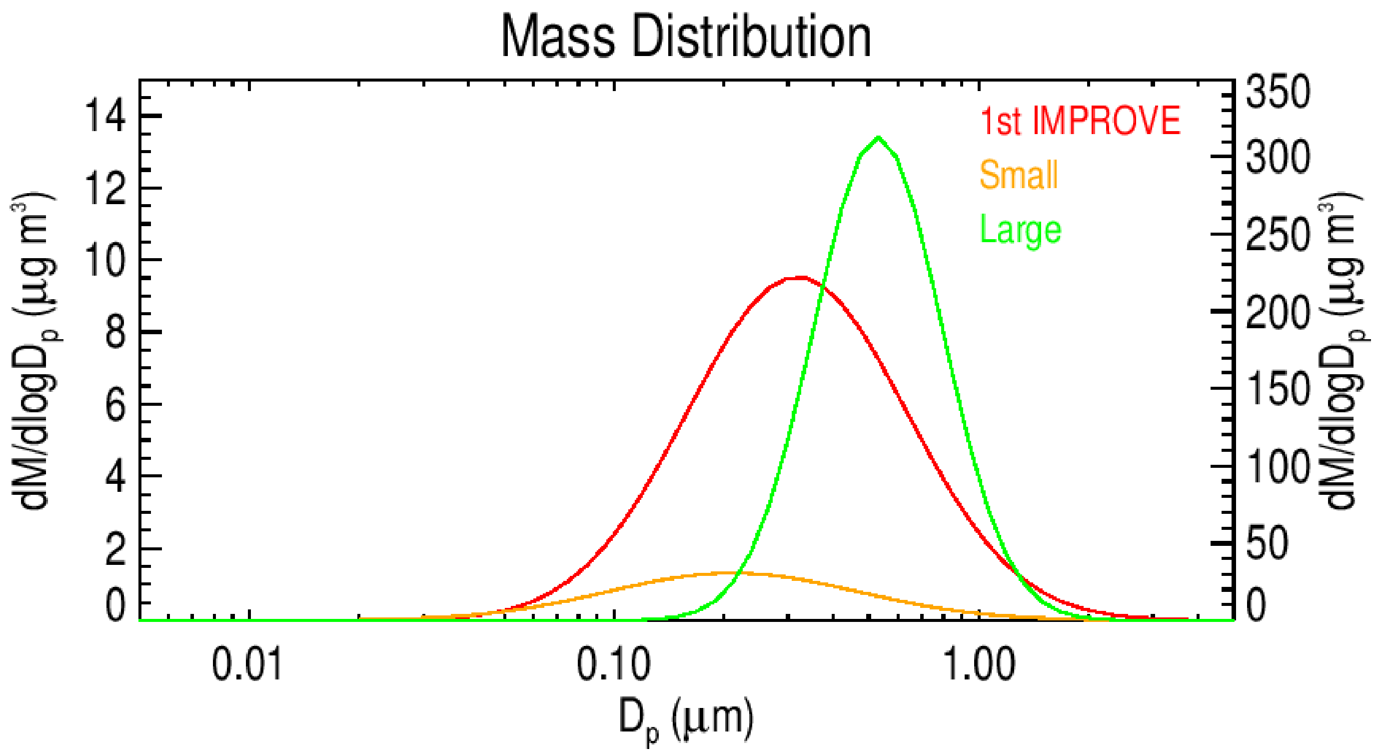
Dry mass scattering efficiency ($m^2\ g^{-1}$)

Split Component Mass Scattering Efficiencies

$$b_{sp} = \sum_i \frac{3}{2} \frac{M_i Q_{sp,i}}{D_{p,i}\rho} \quad (Mm^{-1})$$

M_i = mass of particles in bin *i*
$D_{p,i}$ = diameter of bin *i*
$Q_{sp,i}$ = Mie scattering efficiency
ρ = density ($g\ cm^{-3}$)

$$\alpha = b_{sp}/Mass \quad (m^2\ g^{-1})$$



Split Component f(RH)

$$
\begin{aligned}
b_{ext} = \; & 2.2 \times f_S(RH) \times [\textit{Small}\ \text{Sulfate}] + \\
& 4.8 \times f_L(RH) \times [\textit{Large}\ \text{Sulfate}] + \\
& 2.4 \times f_S(RH) \times [\textit{Small}\ \text{Nitrate}] + \\
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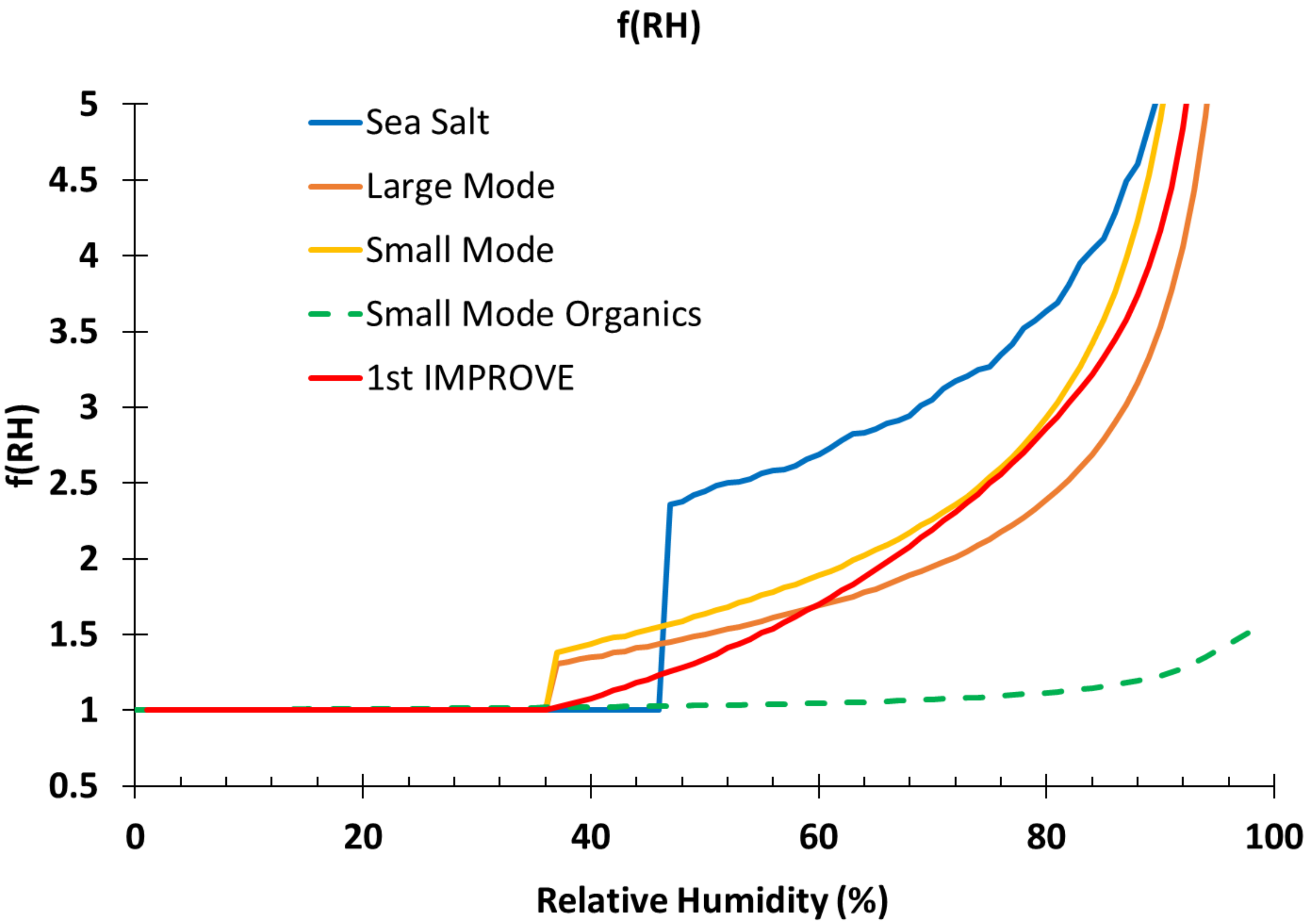
& 0.6 \times [\text{Coarse Mass}] + \\
& 10 \times [\text{Elemental Carbon}] + \\
& \text{Rayleigh Scattering (site specific)}
\end{aligned}
$$

Scattering growth curves

Split Component f(RH)

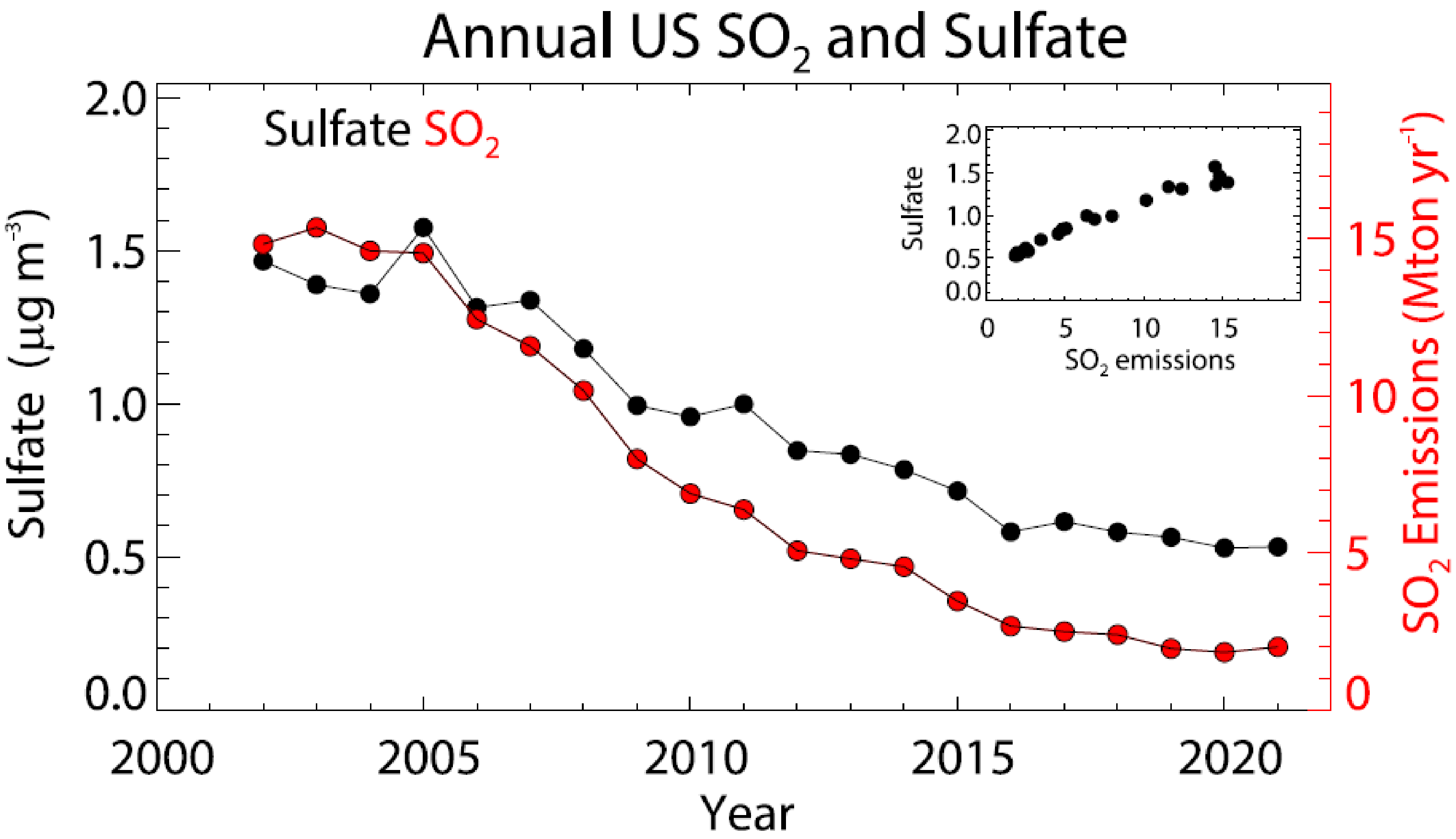


Pitchford et al. (2007)

2^{nd} IMPROVE Equation

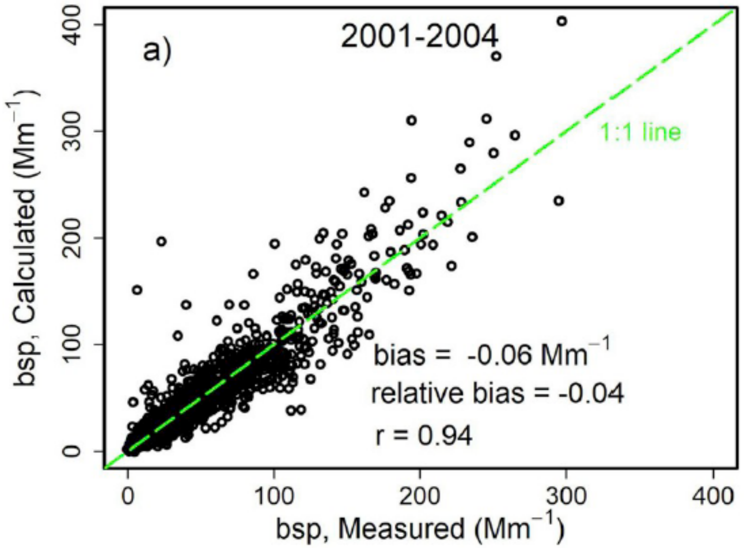
The “cut point” of 20 μg m^{-3} is empirically derived based on IMPROVE data from 2001-2003.

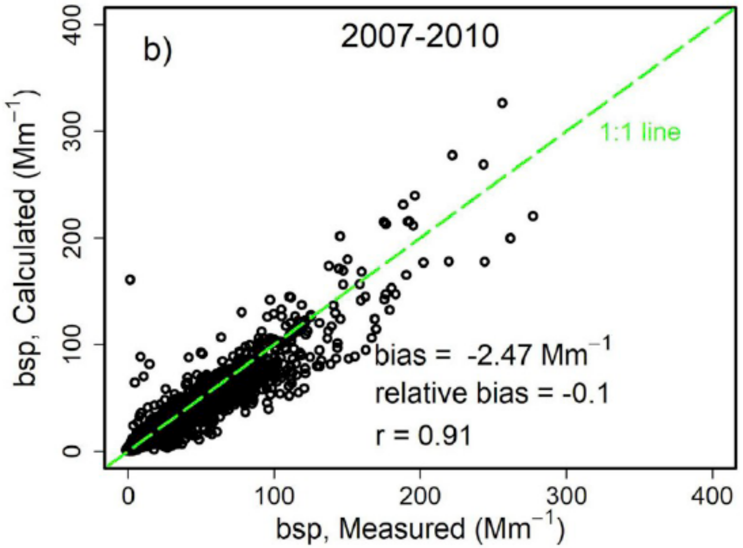
The atmosphere has changed significantly since then.



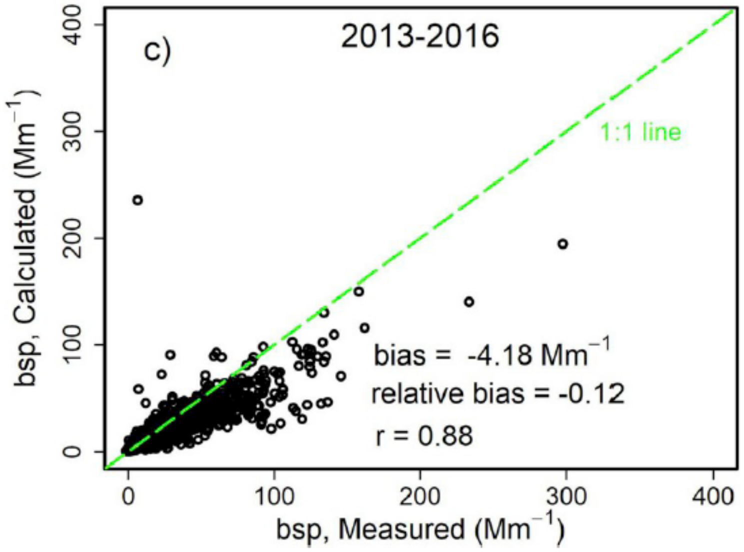
Hand et al. (2024)

Measured and Calculated Scattering





Optec nephelometer data & 2nd IMPROVE Equation (11 sites)

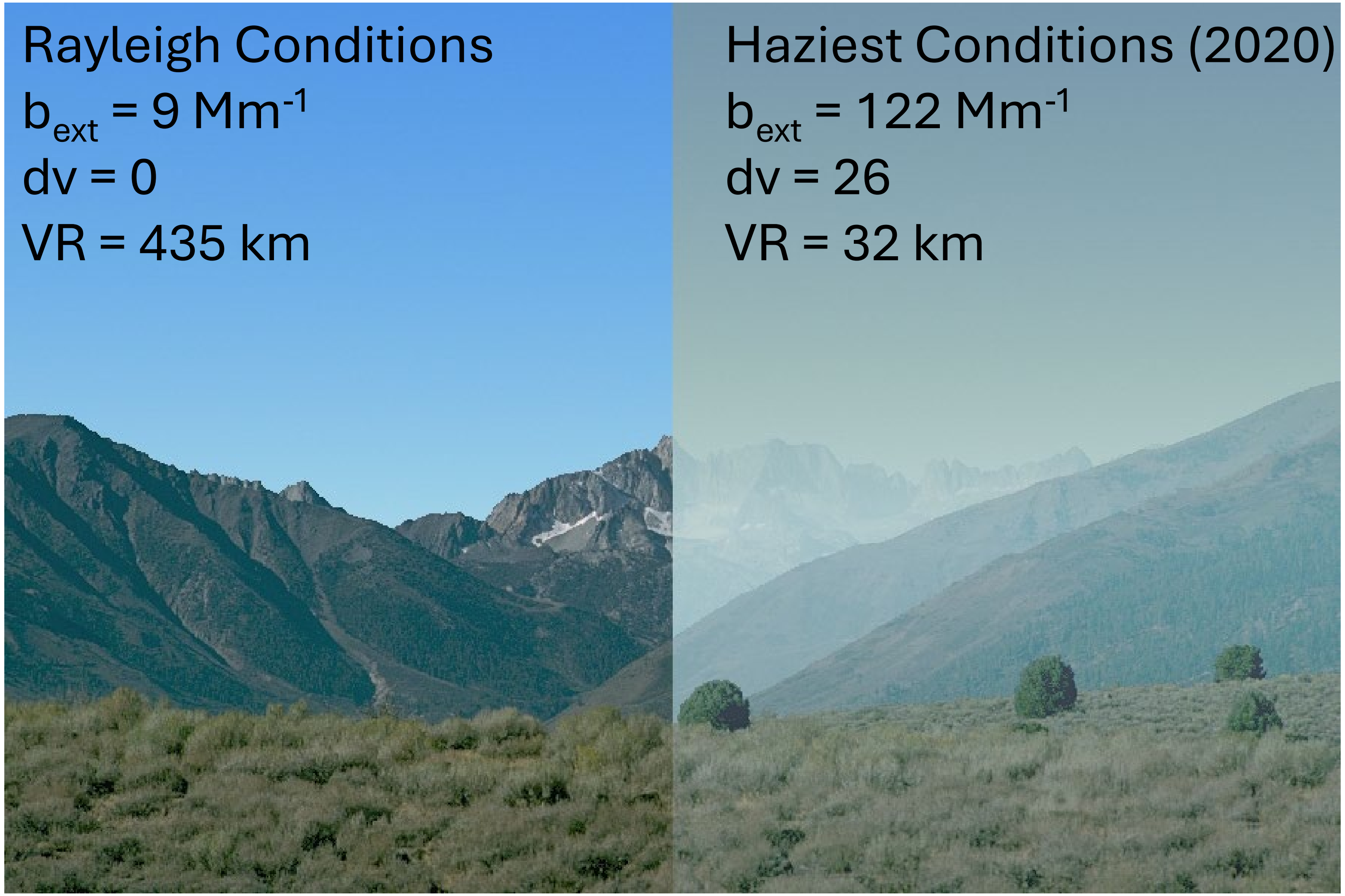


In recent years, we are underestimating reconstructed b_{ext} due to the split component aspect of the 2nd IMPROVE Equation.

Prenni et al. (2019)

6. Other Visibility Parameters

- Visual Range (VR)
- Deciview (dv)



Hoover, CA

Modeled using WinHaze

Visual Range

- The greatest distance that large dark objects can be seen.

- Visual range (VR) is the extinction-based index designed to estimate visual range.

- VR is defined by Koschmieder equation (VR in km and b_{ext} in Mm^{-1}):

$$\mathbf{VR = 3910/b_{ext}}$$

- Advantage: Useful for when only the distance is important (aviation)
- Disadvantage: Doesn’t account for loss of texture and discoloration with haze

Deciview (dv)

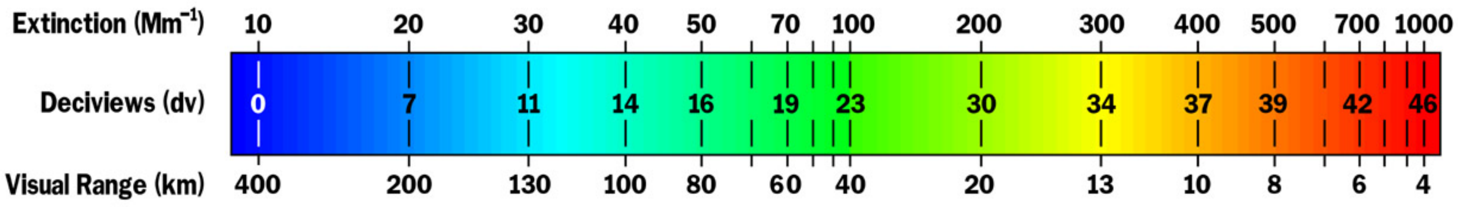
- Deciview is a haze index that expresses changes in scene quality.

$$\textbf{Haze Index (dv)} = 10\ln(b_{ext}/10)$$

where b_{ext} is in Mm^{-1}

- Linear with perceived changes in visibility.

- Haze index in deciview units is analogous to sound measured in decibel units in that they are both logarithmic transformation to produce perceptually linear parameters.



Pitchford and Malm (1994)

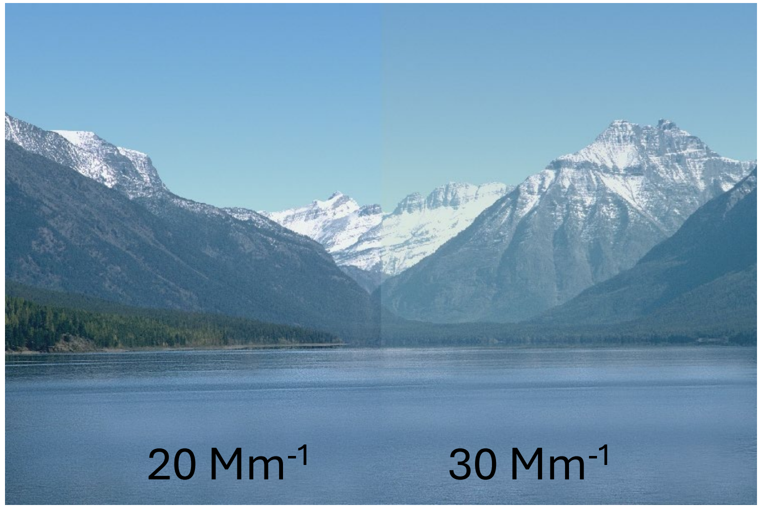
Deciview

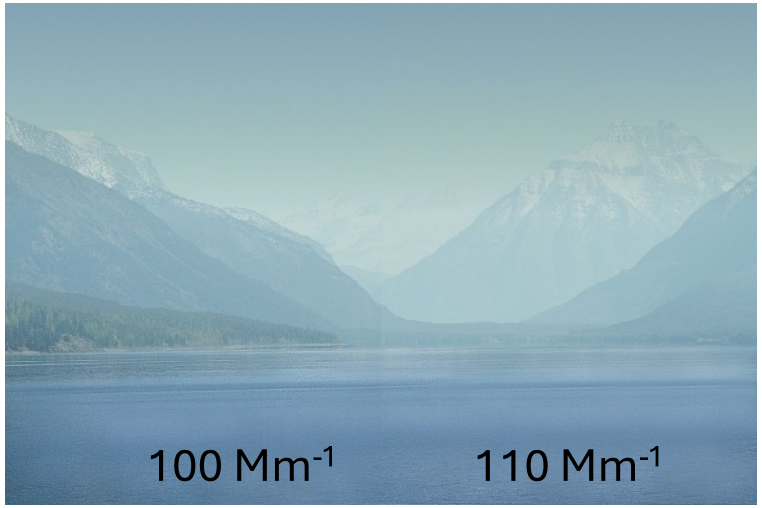
- b_{ext} is non-linearly related to a person's perception of changes in haze.
    - 10 Mm^{-1} increase in b_{ext} will have a larger perceived impact on a scene at b_{ext} of 20 Mm^{-1} than at b_{ext} = 100 Mm^{-1}.

Advantage: under many circumstances a 1 dv change will be perceived the same on clear and hazy days

Disadvantage: not easily related to gas and aerosol concentrations

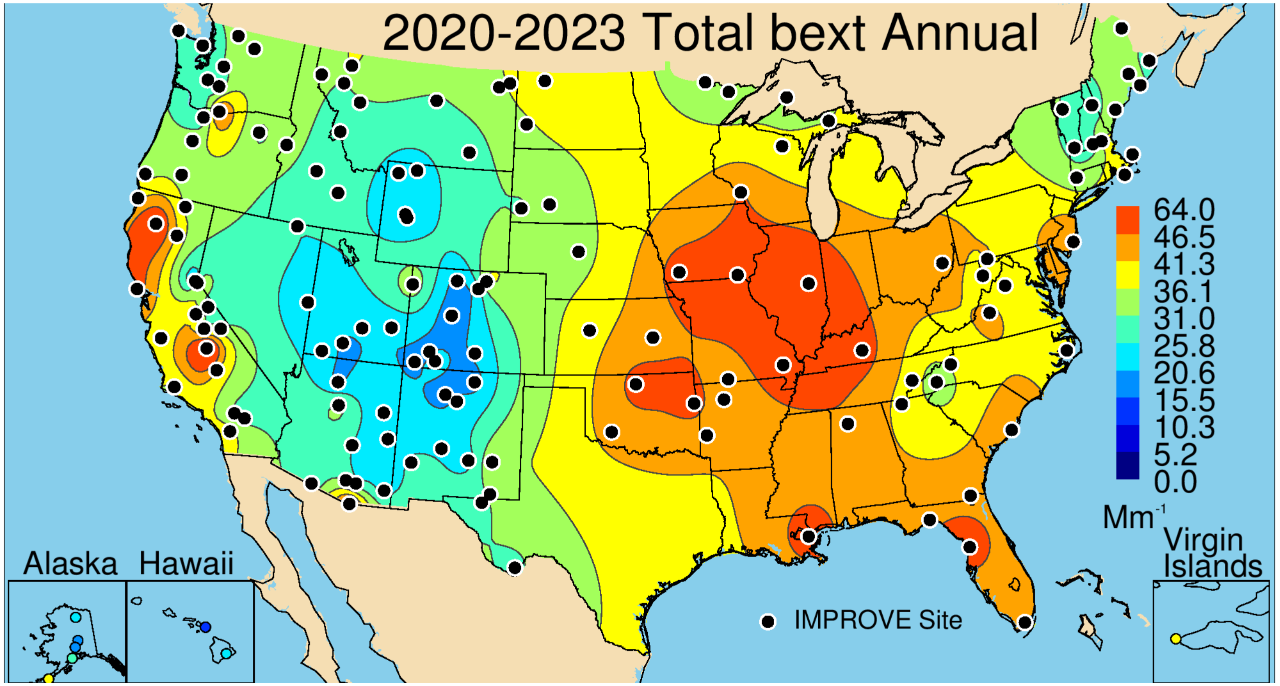
Glacier National Park

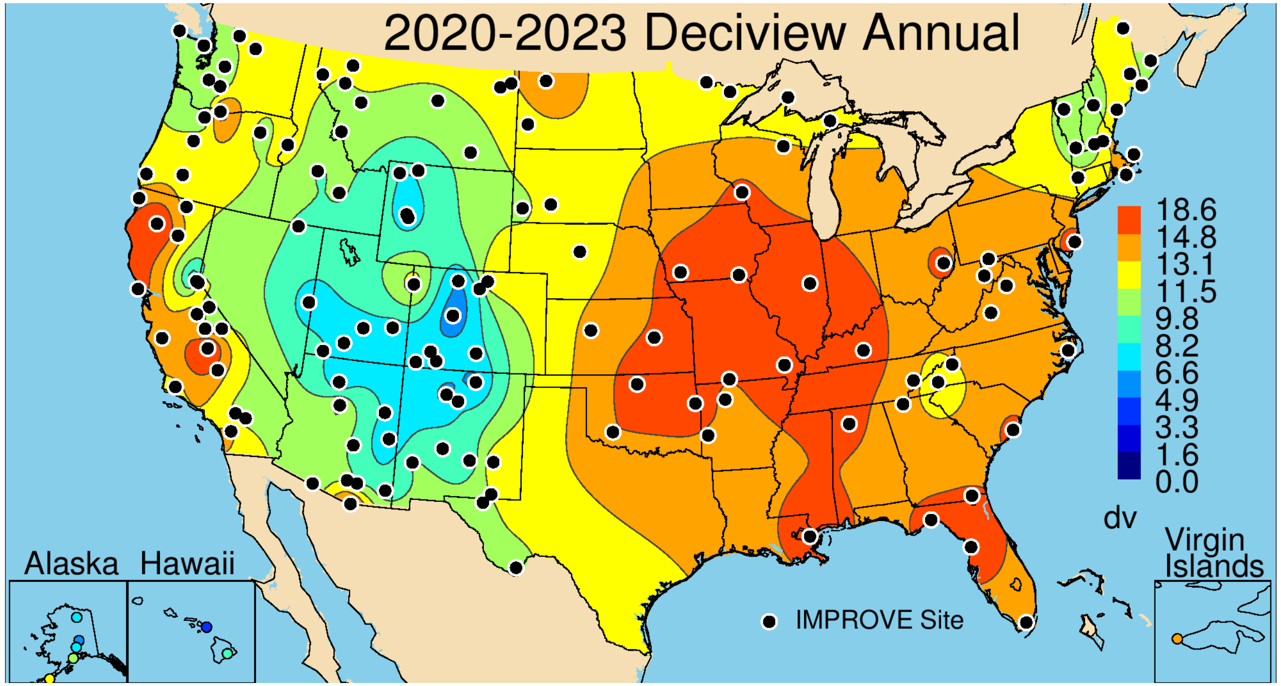




Modeled with Winhaze

2020-2023 Annual Mean Rural U.S. Visibility





https://vista.cira.colostate.edu/Improve/improve-reports/

Thanks!

Photo: Scott Copeland

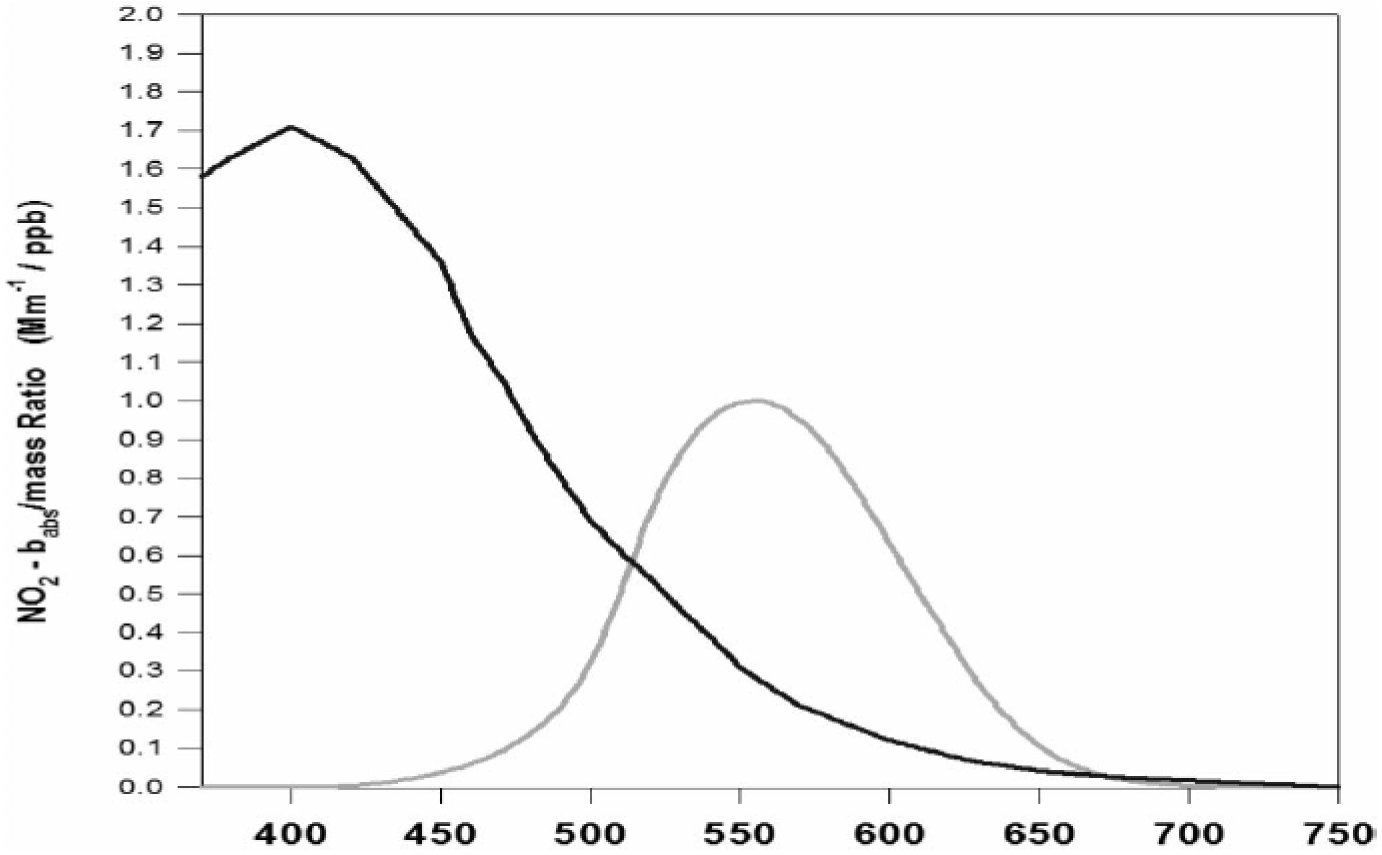
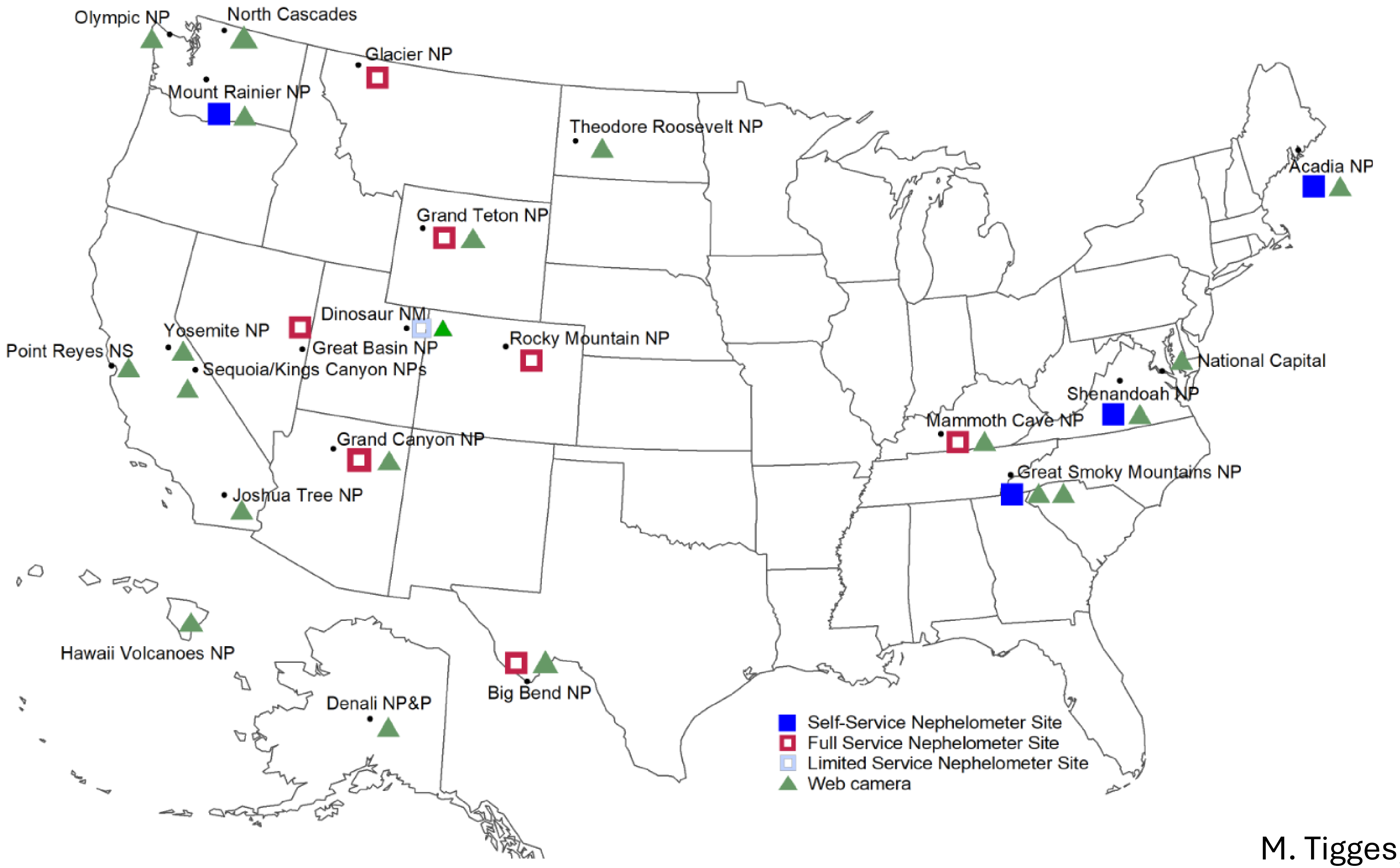


Figure 2. NO_2 absorption coefficient and 2° observer PR curves as a function of wavelength (ηm).

Previous NPS Optical Monitoring Network



M. Tigges, ARS, 2020