What is Aerosol?

A stable suspension of solid or liquid particles in a gas.

Gas (molecules)

Particle (a clump of molecules)

Particulate matter (PM) – a clump of particles
Example

Biomass Burning Aerosol
(in a state-of-the-art aerosol generator)

Biomass burning particulate matter collected on a standard particle filter
## Importance of Atmospheric Particles

<table>
<thead>
<tr>
<th>Species</th>
<th>Content</th>
<th>“Usefulness”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>21 %</td>
<td>Energy</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>78 %</td>
<td>Pressure</td>
</tr>
<tr>
<td>Water vapor</td>
<td>&lt; 3 %</td>
<td>Humidity &amp; Temperature ↑</td>
</tr>
<tr>
<td><strong>Liquid water</strong></td>
<td>&lt; 0.3 %</td>
<td>Irrigation &amp; Temperature ↓</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0.038 %</td>
<td>Plant food &amp; Temperature ↑</td>
</tr>
<tr>
<td>Trace Gases</td>
<td>&lt;10⁻³ %</td>
<td>Chemistry!</td>
</tr>
<tr>
<td><strong>Particles</strong></td>
<td>&lt; 10⁻⁵ %</td>
<td>Useless?</td>
</tr>
</tbody>
</table>

- **Chemistry** (photochemical smog, ozone hole)
- **Climate** (light scattering & absorption, effect on clouds)
- **Health** (asthma, mortality, lung cancer, depression, …)
Particles above ~10 μm are generally not considered as "aerosol" because they settle too quickly.
Atmospheric Particle Sizes: 

nm to $\mu$m

- Molecule (0.0001 $\mu$m)
- Typical smog particle (0.5 $\mu$m)
- Diesel particle (0.05 $\mu$m)
- Typical sea-salt spray particle (2.5 $\mu$m)
- Typical cloud droplet (100 $\mu$m)

(magnified by 25,000×)
Schematic Particle Size Distribution for Atmospheric Particles

particle Diameter, \( d_p \) (µm)

- 100
- 10
- 1
- 0.1
- 0.01
- 0.001

PM\(_{2.5}\)
PM\(_{10}\)

Particle Concentration
\( \frac{dN}{N_T}/\Delta \ln (d_p) \)

growth  accumulation  mechanical

Ultrafine  Fine  Coarse

Figure Adapted from Finlayson-Pitts & Pitts (2000)
Diversity of Aerosol Particles

- Many different types of particles
  - Soot, dust, organic aerosols, ice, ...
- High degree of chemical heterogeneity
- Highly disordered surfaces
  - One “huge surface defect”
- Continuously evolving
  (as a result of chemical reactions, evaporation and condensation, interactions with clouds, and with solar radiation)
Sea salt particles

Soot aggregates

Soot particles coated with secondary organic material

Inorganic salts coated with secondary organic material
Volcanoes can emit large amounts of H$_2$S and SO$_2$ in the air.

Burning **coal** releases similarly large amounts of SO$_2$ in the air.

Sulfur compounds get oxidized to produce aerosol particles rich in sulfuric acid.

$\text{SO}_2 \rightarrow \text{H}_2\text{SO}_4 \rightarrow \text{aerosol} \leftrightarrow \text{clouds}$
According to "IPCC Climate change 2001 - Synthesis report" there has been a significant increase in the global aerosol particle emission rate by anthropogenic sources.
Primary Organic Aerosol (POA)

Natural and anthropogenic sources

POA

COOKING

TRAFFIC

OCEAN
Secondary Organic Aerosol (SOA)

Earth Sciences
- 
  \[ \text{VOC} = \text{Volatile Organic Compounds} \]

Chemistry
- \( \text{OH, O}_3, \text{NO}_x, \ldots \)

Physics
- Condensation

Natural and anthropogenic sources

Oxidized VOC

SOA particles

BIOGENIC EMISSIONS

INDUSTRY and TRAFFIC
Biomass burning refers to fires in forests, grasslands, woodlands, etc. Smoke produced by such fires contains a variety of different kinds of particles, including:

- "Tar balls" and other organic aerosol
- Leaf debris
- Soot / ash

Fire in the wetlands vegetation at the Merritt Island National Wildlife Refuge, Kennedy Space Center, Florida. Even wetlands can catch on fire!

SEM image of a particle sampled from a fire smoke. This particular particle happens to be a fragment of a leaf.
Dust

Dust storms commonly carry large amounts of crustal particles over large distances. It is not uncommon to find dust from Sahara in the air in the middle of US or Europe. Unlike particles produced in biomass and fuel burning, dust particles are relatively harmless. However, dust particles produced in areas with heavy agriculture (e.g., Fresno County in California) are known to amplify symptoms of asthma and related diseases.
Several major classes of aerosol particles result from fuel burning:

- Diesel particles - fractal-like agglomerates of 5-10 soot balls that are emitted directly by diesel engines. Compared to other type of PM, diesel PM is especially harmful to health; they are known to cause cancer and asthma.

- Secondary Organic Aerosol (SOA) is produced together with ozone from VOCs (Volatile Organic Compounds) in photochemical smog. Their health effects are not understood.
Biological Aerosols

Airborne spores, pollens, and viruses are frequently found in the air, including cloud and in fog water. Although not scientifically proven, such "bioaerosols" are frequently associated with symptoms of allergy, asthma, and related diseases.

Ragweed pollen

Tuber Rufum spore
Highly Unnatural Particles

The plume of chemicals emitted as a result of the September 11, 2001 terrorist attack in New York contained an array of rather nasty toxins in the form of gases and particles.
Lab-Generated Aerosols

- Such aerosols are produced to mimic various types of particulates
- Gas phase species may react in a chamber to form non-volatile species that condense into liquid or solid phase
- \( \text{NH}_3(g) + \text{HCl}(g) \rightarrow \text{NH}_4\text{Cl}(s) \)
- \( \text{SO}_3(g) + \text{H}_2\text{O}(g) \rightarrow \text{H}_2\text{SO}_4(l) \)
- \( \text{Ozone}_{(g)} + \text{terpene}_{(g)} \rightarrow \text{SOA}_{(l \text{ or } s)} \)
How Much Do We Inhale?

- **Example:** 10 µg of particulates per m³ of air
- **Breathing:** ? m³ per day or ? m³ per year
- **Retention:** 50% particles deposited in the lungs
- **Result:** ? grams of particles per year
  ? grams of particles per day
- **Compare:**
  Prof. Nizkorodov weighs 86,936 g
  His favorite meal weighs 945 g
  *It takes very little to upset the lungs (as opposed to the stomach)!*
Particulate Matter and Health

INITIAL 6-city study
An Association between Air Pollution and Mortality in Six U.S. Cities

FOLLOW-UP 6-city study

From a number of similar studies:
In US, 10 µg/m³ increase in PM results in:
• 4% increase in general morbidity
• 6% increase in cardio-pulmonary mortality
• 8% increase in cancer mortality

P = Portage, WI
T = Topeka, KS
W = Watertown, MA
L = St. Louis, MI
H = Harriman, TN
S = Steubenville, OH
Lower case = follow up study
How Can Particles Affect Climate?

- **Greenhouse effect**: \( \text{CO}_2, \ \text{CH}_4, \ \text{N}_2\text{O}, \ \text{H}_2\text{O}, \ \text{O}_3, \ \text{and CFCs} \) strongly absorb infrared radiation while transmitting visible radiation ⇒ **surface heating**

- **Whitehouse effect**: Clouds and aerosol particles reflect (on average) solar radiation back to space ⇒ **surface cooling**

Adopted from: IPCC 2007 Report (Frequently Asked Questions)

http://ipcc-wg1.ucar.edu/wg1/wg1-report.html
Dual Role of Atmospheric Water

- **Water vapor**: the most important natural greenhouse gas
- **Liquid water (clouds and fogs)**: the most important cooling mechanism (close to 23% of incoming radiation bounces off clouds back into space)
Climate Effects of Aerosol Particles

Cloud droplets **ALWAYS** need a particle to nucleate

- **Direct Effects**
  - Scattering of incoming solar radiation back to space
  - Absorption of incoming solar radiation
- **Indirect Effects**
  - More particles ⇒ longer precipitation lifetimes of clouds
  - More particles ⇒ higher reflectivity (albedo) of clouds
Direct Effect of Particles

- **Light Absorption → heating:** Photon is taken up and converted into heat by particle. Soot particles efficiently absorb all visible light.
- **Light Scattering → cooling:** Photon is taken up but immediately re-emitted in a different direction. Blue light is scattered more efficiently than red.
  - Rayleigh scattering (particle size $\ll \lambda$) $\Rightarrow$ fairly isotropic; all angles
  - Mie scattering (particle size $\sim \lambda$) $\Rightarrow$ complicated function of scattering angle
  - Geometric scattering (particle size $\gg \lambda$) $\Rightarrow$ mostly forward
  - Geometric reflection (cloud droplets) $\Rightarrow$ reflected as if by a curved mirror

![Diagram of light scattering](attachment:light_scattering_diagram.png)
Indirect Effect of Particles

Particle → Cloud → Climate

From 2007 IPCC Fourth Assessment Report
http://www.ipcc.ch/
### Aerosols and Climate (IPCC 2007)

#### Global Mean Radiative Forcings

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF values (W m⁻²)</th>
<th>Spatial scale</th>
<th>LOSU</th>
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</thead>
<tbody>
<tr>
<td>Long-lived greenhouse gases</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>1.66 [1.49 to 1.83]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.48 [0.43 to 0.53]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.16 [0.14 to 0.18]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>0.34 [0.31 to 0.37]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Ozone</td>
<td></td>
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<tr>
<td>Stratospheric</td>
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<tr>
<td>Tropospheric</td>
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<td>Stratospheric water vapour from CH₄</td>
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<tr>
<td>Surface albedo</td>
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<tr>
<td>Land use</td>
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<td>Black carbon on snow</td>
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<td>Direct effect</td>
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<tr>
<td>Black carbon on snow</td>
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<tr>
<td>Total Aerosol</td>
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<tr>
<td>Cloud albedo effect</td>
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<td>Linear contrails</td>
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<tr>
<td>Natural</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Solar irradiance</td>
<td>0.12 [0.06 to 0.30]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Total net anthropogenic</td>
<td>1.6 [0.6 to 2.4]</td>
<td></td>
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</tr>
</tbody>
</table>

**Negative values:** surface cooling  
**Positive values:** surface heating

- IPCC – summary for policy makers
- IPCC – full reports