Aerosols and climate: the big climate impact of small particles

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Outline

- Introduction to aerosol – climate interactions
- Direct forcing & aerosol optical properties
- Cloud droplet nucleation
  - Aerosol size measurements & arctic observations
# Global Average Climate Forcing Estimates

<table>
<thead>
<tr>
<th>Emitted compound</th>
<th>Resulting atmospheric drivers</th>
<th>Radiative forcing by emissions and drivers</th>
<th>Level of confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CO₂</td>
<td>1.68 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂, H₂O, O₃, CH₄</td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>O₃, CFCs, HCFCs</td>
<td>0.18 [0.01 to 0.35]</td>
<td>H</td>
</tr>
<tr>
<td>N₂O</td>
<td>N₂O</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
<tr>
<td>Well-mixed greenhouse gases</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>CO₂, CH₄, O₃</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>NMVOC</td>
<td>CO₂, CH₄, O₃</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrate, CH₄, O₃</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
<tr>
<td>Anthropogenic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Mineral dust, sulphate, nitrate, organic carbon, black carbon</td>
<td>Cloud adjustments due to aerosols</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Albedo change due to land use</td>
<td>M</td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in solar irradiance</td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
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<tr>
<th>Year</th>
<th>Total anthropogenic RF relative to 1750 (W m⁻²)</th>
<th>Level of confidence</th>
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<tr>
<td>2011</td>
<td>2.29 [1.13 to 3.33]</td>
<td>H</td>
</tr>
<tr>
<td>1980</td>
<td>1.25 [0.64 to 1.86]</td>
<td>H</td>
</tr>
<tr>
<td>1950</td>
<td>0.57 [0.29 to 0.85]</td>
<td>M</td>
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Taken From: IPCC, 5th Assessment Report, 2013
Mount Ruapehu, New Zealand (Photograph ©2007 New Zealand GeoNet)

Precipitation & Water Cycles
Extinction of radiation

Scattering from milk, ink, and water on an overhead projector

Transmission through milk, ink, and water projected onto a screen
The Beer-Lambert law describes the attenuation of light as it passes through a medium.

\[ \frac{I(z)}{I_0} = e^{-b_{ext}z} \]

\[ b_{ext} = b_{scat} + b_{abs} \]

The extinction coefficient, $b_{ext}$, is the sum of the scattering and absorption coefficients, $b_{scat}$ and $b_{abs}$. All have units of $(m^{-1})$.

For milk $b_{ext} \approx b_{scat}$, and for ink $b_{ext} \approx b_{abs}$, and for water $b_{ext} \approx 0$.

Often single scattering albedo (SSA) is used as a metric to indicate the importance of scattering versus absorption:

\[ SSA = \frac{b_{scat}}{b_{ext}} = \frac{b_{scat}}{b_{scat} + b_{abs}} \]
Quiz! Clouds and soot...

Based on their appearance what you estimate is the value of SSA and the spectral dependence of $b_{\text{ext}}$ for

- a cloud

  \[ \text{SSA} \approx 1, \text{weak spectral dependence since color is white} \]

- diesel exhaust fumes

  \[ \text{Low SSA, weak spectral dependence since color is neutral} \]
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<th>Cloud Types Affected</th>
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<th>Sign of Change in TOA Radiation</th>
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<th>Scientific Understanding</th>
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Cloud albedo and lifetime effect (negative radiative effect for warm clouds at TOA; less precipitation and less solar radiation at the surface)

- More reflection → higher albedo
- Clean → polluted
- Higher optical depth → less radiation at the surface

IPCC
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**Diagram:**

Semi-direct effect (positive radiative effect at TOA for soot inside clouds, negative for soot above clouds)

- Absorption → Heating
- Less radiation at surface
- Evaporation of cloud droplets → Shrinking of cloud
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Glaciation effect (positive radiative effect at TOA and more precipitation), thermodynamic effect (sign of radiative effect and change in precipitation not yet known)
Surface temperature response to aerosols

Sand et al., *Nature Climate Change*, 2015, 6, 286.
Size distributions of particles

- Nucleation mode
- Aitken mode
- Accumulation mode
- Coarse mode

Seinfeld and Pandis "Atmospheric chemistry and physics: From air pollution to climate change", Wiley-Interscience
Scanning Mobility Particle Sizer (SMPS)

The SMPS allows measurement of nucleation mode and Aitken mode particles

The instrument contains two devices:
- A differential mobility analyzer used to generate monodisperse aerosols
- A condensation particle counter for measuring the number concentration
Scanning Mobility Particle Sizer (SMPS)

Differential Mobillity Analyzer
• Ambient polydisperse aerosol distribution

• Radiation source is used to give aerosols known charge distribution

• In the DMA column, particle-laden air passes along the column walls

• Sheath air flowing through the center of the column is particle free

• Electrostatic potential applied between center rod and column wall

• The trajectories of the particles are a function of particle size

• Selected diameter passes through the column exit port.
Condensation Particle Counter

- In the saturation block, the air flow is saturated in butanol
- Particles then pass to the condenser block where the air is cooled and becomes supersaturated
- The aerosols can now serve as condensation nuclei
- Light scattering is then used to count the concentration of droplets

Scanning Mobility Particle Sizer (SMPS)
Smaller particles will tend to have greater indirect rather than direct forcing.
Size distributions of Arctic aerosol

Cloud droplet nucleation by particles

- Process by which droplets (several microns in size) are formed from particles; also called heterogeneous nucleation
  - To what size will dry particles grow at a given atmospheric supersaturation?
  - Will the particles grow into large cloud droplets or will the particle diameters remain small (haze).
  - Koehler theory is used to address these questions
Cloud Nucleation: Kelvin Effect

Rate of evaporation increases with curvature of droplet due to reduced H-bonding.

Very high saturation vapor pressures over small droplet compared to flat water surface.
Raoult’s Law

\[ P_{H_2O,SAT}^o \]

\[ P_{H_2O,SAT} = x_{H_2O} P_{H_2O,SAT}^o \]

The presence of dissolved species on the surface of water reduced the speed of evaporation

- The saturation vapor pressure is proportional, \( P_{H_2O, SAT} \), is the product of the molar fraction of water and the saturation vapor pressure of pure water, \( P^o_{H_2O,SAT} \).
Koehler Theory: Cloud nucleation and particle diameter

ambient supersaturation, $s$
(set ambient condensation rate)

$s-s_k<0$

drop gets to $s_k=s$, and stops growing - haze!

$s_k$ (sets drop evaporation rate)

initial drop size

$s_c$
Larger initial dry particle sizes will favor cloud nucleation.
Arctic atmosphere sensitive to aerosol concentrations

Questions / Discussion