Aerosols and climate

Rob Wood, Atmospheric Sciences
What are aerosols?

• Solid or liquid particles suspended in air

• Sizes range from a few nm to a few thousand nm
  ⇒ Huge range of masses
Where do aerosols come from?
# Estimate of Present-Day Global Emission of Major Aerosol Types (in Tg/year)

<table>
<thead>
<tr>
<th>Source</th>
<th>Present flux</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
<td>Best</td>
<td></td>
</tr>
<tr>
<td><strong>Natural</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Primary</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil dust (mineral aerosol)</td>
<td>1,000</td>
<td>3,000</td>
<td>1,500</td>
<td></td>
</tr>
<tr>
<td>Sea salt</td>
<td>1,000</td>
<td>10,000</td>
<td>1,300</td>
<td></td>
</tr>
<tr>
<td>Volcanic dust</td>
<td>4</td>
<td>10,000</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Biological debris</td>
<td>26</td>
<td>80</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td><strong>Secondary</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfates from biogenic gases</td>
<td>60</td>
<td>110</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Sulfates from volcanic SO$_2$</td>
<td>4</td>
<td>45</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Organic matter from biogenic NMHC$^*$</td>
<td>10</td>
<td>200</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Nitrates from NO$_x$</td>
<td>10</td>
<td>40</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td><strong>Anthropogenic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Primary</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial dust etc.</td>
<td>40</td>
<td>130</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Black carbon (soot and charcoal)</td>
<td>10</td>
<td>30</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td><strong>Secondary</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulphates from SO$_2$</td>
<td>120</td>
<td>180</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Biomass burning (w/o black carbon)</td>
<td>50</td>
<td>140</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Nitrates from NO$_x$</td>
<td>20</td>
<td>50</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Organics from anthropogenic NMHC$^*$</td>
<td>5</td>
<td>25</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>
Aerosols and light scattering

- Scattering of solar radiation **per unit mass** is maximum when particle size is close to solar wavelengths ($\lambda \sim 400$-$800 \text{ nm}$)
- Particles in the size range 200-2000 nm are most efficient scatterers
- Particle **surface area** more important than mass
Surface area and mass

- $M = \left(\frac{4\pi}{3}\right) \rho \ r^3$
- $A = 4\pi \ r^2$
- $A/M \propto 1/r$

- when $r \ll \lambda$ scattering efficiency increases with $r^4$
  $\Rightarrow r<100 \text{ nm particles don’t matter}$
Aerosols and light scattering

• If aerosol particle is soluble then size will depend upon water uptake
• Water uptake depends upon relative humidity (RH)
• For given number of particles, scattering will increase with RH
• But with no particles there is no scattering despite what the RH is
Size as a function of RH

![Graph showing size as a function of relative humidity](image)

- $r_0 = 0.045 \mu m$
- $r_0 = 3.10 \mu m$

Relative humidity (%) vs. $n/r_0$
Chemical composition affects growth

Marine airmass

Polluted airmass

growth factor $r/r_{\text{dry}}$

RH
What determines scattering?

- For particles of size > 200 nm, surface area determines scattering from one particle
- Multiply this by the number concentration of particles to get overall scattering per unit volume of air
- $A_{\text{tot}} \propto N r^2, M_{\text{tot}} \propto N r^3$
  \[ \Rightarrow A_{\text{tot}} \propto N^{1/3} M^{2/3} \]
- Need to know both total aerosol mass and the number concentration
Importance of sulfate

- Sulfate aerosols dominate the scattering over continental regions
- Anthropogenic sources comparable to natural sources
- Regionally, this scattering can seriously degrade visibility
- Globally, this scattering reduces solar radiation entering the climate system by $\approx 2 \text{ W m}^{-2}$
- Studies suggest that about 0.3-0.8 W m$^{-2}$ of this scattering are from anthropogenic aerosols, mostly sulfate ("direct" effect of aerosols)
Beijing after rain

Beijing during dry period
Solar radiation reaching the surface

The graph shows the percentage of solar radiation transmitted over time. Key volcanic eruptions are indicated: Agung (8.3 S, VEI 4), Fuego (14.5 N, VEI 4), Pinatubo (15.1 N, VEI 6), and El Chichón (17.4 N, VEI 5).
Global Sulfur Budget
Rates in Tg S yr\(^{-1}\)

- \((\text{CH}_3)_2\text{S}\) (DMS), \(\tau = 1.0\) d
- NO\(_3\)
- OH
- Volcanoes
- 
- SO\(_2\), \(\tau = 1.3\) d
- OH
- \(\text{H}_2\text{SO}_4(g)\)
- Cloud, 42
- Dep 27 dry, 20 wet
- Dep 6 dry, 44 wet
- Combustion/Smelters
- SO\(_4^{2-}\), \(\tau = 3.9\) d
- Phytoplankton
Global Sulfur Emission Patterns

Chin et al. [2000]
SO$_2$ sources by type

- Industry: 87%
- Transport: 12%
- Other: 1%
- Petroleum Refining: 18%
- Basic Non Ferrous Metal Manufacturing: 11%
- Basic Chemical Manufacturing: 1%
- Ceramic Product Manufacturing: 1%
- Other Industry: 1%
- Electricity Supply: 68%
Direct effect of aerosols upon solar radiation

- Aerosols scatter solar radiation
- More particles $\Rightarrow$ more scattering
- Some scattered radiation returns to space
- Reduction in amount entering climate system
- $\Rightarrow$ Cooling effect
Aerosol optical depth (measure of scattering)

Figure 2.11. Aerosol optical depth, $\tau_{\text{air}}$, at 0.55 $\mu$m (colour bar) as determined by the MODIS instrument for the January to March 2001 mean (top panel) and for the August to October 2001 mean (bottom panel). The top panel also shows the location of AERONET sites (white squares) that have been operated (not necessarily continuously) since 1996. The bottom panel also shows the location of different aerosol lidar networks (red: EARLINET, orange: ADNET, black: MPLNET).
How well do we understand human influence?

• Direct radiative forcing (effect of anthropogenic emissions on aerosol scattering) from different models

Figure 2.13. Estimates of the direct aerosol RF from observationally based studies, independent modelling studies, and AeroCom results with identical aerosol and aerosol precursor emissions. GISS_1 refers to a study employing an internal mixture of aerosol, and GISS_2 to a study employing an external mixture. See Table 2.4, Note (a) for descriptions of models.
Trends in U.S. NO$_x$ AND SO$_2$ Emissions
Aerosol-cloud-climate interactions
Figure 2.10. Schematic diagram showing the various radiative mechanisms associated with cloud effects that have been identified as significant in relation to aerosols (modified from Haywood and Boucher, 2000). The small black dots represent aerosol particles; the larger open circles cloud droplets. Straight lines represent the incident and reflected solar radiation, and wavy lines represent terrestrial radiation. The filled white circles indicate cloud droplet number concentration (CDNC). The unperturbed cloud contains larger cloud drops as only natural aerosols are available as cloud condensation nuclei, while the perturbed cloud contains a greater number of smaller cloud drops as both natural and anthropogenic aerosols are available as cloud condensation nuclei (CCN). The vertical grey dashes represent rainfall, and LWC refers to the liquid water content.
Cloud droplets form on aerosol particles

- For soluble aerosols, particle size increases with RH
- When a parcel of air rises, it cools and the RH increases
- When RH>1, the soluble aerosols can “activate” (grow unstably into much larger cloud droplets)
- The RH at which an aerosol activates is strongly dependent upon its size
- Larger aerosols activate first and can consume vapor, preventing the smaller ones from activating
- The number of cloud droplets is strongly controlled by the number of soluble aerosols
What determines $N$ in warm clouds?

Aerosol concentration ($r>0.1$ micron) [$\text{cm}^{-3}$] vs. Cloud droplet concentration [$\text{cm}^{-3}$]
Link between number of cloud droplets and cloud albedo

- Similar arguments as for light scattering due to aerosols
- For given amount of liquid water, increased N gives smaller average size of droplets
- Smaller droplets have larger surface area
- More reflective cloud, more albedo
• Most well-understood aerosol-cloud-climate effects *(indirect effects)*
Global Sulfur Emission Patterns

Chin et al. [2000]
Putting it all together