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Albuquerque NM
March 22, 2004
NEW ASP SCIENCE FOCUS

Aerosol radiative forcing of climate

Enhance the scientific knowledge needed to simulate and predict radiative forcing and other climatic effects of aerosols
AEROSOL FORCING OF CLIMATE AND CLIMATE CHANGE

Aerosol forcing of climate is difference between radiative flux with aerosol minus radiative flux without aerosol.

Aerosol forcing of climate change is difference between radiative flux with present aerosol minus radiative flux with preindustrial aerosol.

Determination of aerosol forcing of climate change requires:

• Attribution of aerosol to anthropogenic vs. natural, and

• Determination of aerosol forcing for natural and total aerosol.

This inherently involves atmospheric chemistry [and aerosol microphysics and optical properties and cloud microphysics] as well as atmospheric radiation.
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

The global mean radiative forcing of the climate system
for the year 2000, relative to 1750

Level of Scientific Understanding

The diagram includes contributions from various sources:
- Halocarbons
- N₂O
- CH₄
- CO₂
- Tropospheric ozone
- Black carbon from fossil fuel burning
- Mineral Dust
- Aviation-induced Contrails Cirrus
- Solar
- Stratospheric ozone
- Sulphate
- Organic carbon from fossil fuel burning
- Biomass burning
- Aerosol indirect effect
- Land-use (albedo) only

Radiative forcing (Watts per square metre)

Summary for Policymakers
A Report of Working Group I of the Intergovernmental Panel on Climate Change
DIRECT EFFECT
\[ \overline{\Delta F_R} = \frac{1}{2} F_T T^2 (1 - A_c) (1 - R_s)^2 \cdot \overline{\beta} \alpha_{SO_4^{2-}} f(RH) \cdot Q_{SO_2} Y_{SO_4^{2-}} \left( \frac{MW_{SO_4^{2-}}}{MW_S} \right) \tau_{SO_4^{2-}} / A \]

\( \overline{\Delta F_R} \) is the area-average shortwave radiative forcing due to the aerosol, W m\(^{-2}\)

\( F_T \) is the solar constant, W m\(^{-2}\)

\( A_c \) is the fractional cloud cover

\( T \) is the fraction of incident light transmitted by the atmosphere above the aerosol

\( R_s \) is the albedo of the underlying surface

\( \overline{\beta} \) is upward fraction of the radiation scattered by the aerosol,

\( \alpha_{SO_4^{2-}} \) is the scattering efficiency of sulfate and associated cations at a reference low relative humidity, m\(^2\) (g SO\(_4^{2-}\))\(^{-1}\)

\( f(RH) \) accounts for the relative increase in scattering due to relative humidity

\( Q_{SO_2} \) is the source strength of anthropogenic SO\(_2\) g S yr\(^{-1}\)

\( Y_{SO_4^{2-}} \) is the fractional yield of emitted SO\(_2\) that reacts to produce sulfate aerosol

\( MW \) is the molecular weight

\( \tau_{SO_4^{2-}} \) is the sulfate lifetime in the atmosphere, yr

\( A \) is the area of the geographical region under consideration, m\(^2\)

DIRECT AEROSOL FORCING

Comparison of linear formula and radiation transfer model
Particle radius $r = 85$ nm; surface reflectance $R = 0.15$; single scatter albedo $\omega_0 = 1$.

Forcing is highly sensitive to modest aerosol loadings.
Global-average AOT 0.1 corresponds to global-average forcing $\sim -3 \text{ W m}^{-2}$.
Linear model is accurate and convenient, especially for error budgets.
Forcing per optical depth depends on particle size.
Top-of-atmosphere forcing depends on single scattering albedo and surface reflectance.
AEROSOL OPTICAL DEPTH
Determined by sunphotometry
North central Oklahoma - Daily average at 500 nm

J. Michalsky et al., JGR, 2001
MONTHLY AVERAGE AEROSOL JUNE 1997
Polder radiometer on Adeos satellite

Optical Thickness $\tau$
$\lambda = 865$ nm

Ångström Exponent $\alpha$
$\alpha = -d \ln \tau / d \ln \lambda$
## UNCERTAINTY BUDGET FOR *DIRECT FORCING BY INDUSTRIAL AEROSOLS*

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Central Value</th>
<th>2/3 Uncertainty Range</th>
<th>Uncertainty Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total emission of anthropogenic OC from fossil fuel burning (Tg/yr)</td>
<td>20</td>
<td>10 to 30</td>
<td>3.0</td>
</tr>
<tr>
<td>Atmospheric burden of OC from fossil fuels (Tg)</td>
<td>0.48</td>
<td>0.33 to 0.70</td>
<td>2.1</td>
</tr>
<tr>
<td>Total emission of anthropogenic BC from fossil fuel burning (Tg/yr)</td>
<td>7</td>
<td>4.67 to 10.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Atmospheric burden of BC from fossil fuel burning (Tg)</td>
<td>0.133</td>
<td>0.11 to 0.16</td>
<td>1.5</td>
</tr>
<tr>
<td>Total emission of anthropogenic sulfate from fossil fuel burning (Tg/yr)</td>
<td>69</td>
<td>57.5 to 82.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Atmospheric burden of sulfate from fossil fuel burning (Tg S)</td>
<td>0.525</td>
<td>0.35 to 0.79</td>
<td>2.3</td>
</tr>
<tr>
<td>Fraction of light scattered into upward hemisphere, β</td>
<td>0.23</td>
<td>0.17 to 0.29</td>
<td>1.7</td>
</tr>
<tr>
<td>Aerosol mass scattering efficiency (m²g⁻¹), αᵢ</td>
<td>3.5</td>
<td>2.3 to 4.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Aerosol single scattering albedo, co-albedo (dry), ω₀, 1 - ω₀</td>
<td>0.92</td>
<td>0.85 to 0.97</td>
<td>1.1, 5</td>
</tr>
<tr>
<td>Tₐ, atmospheric transmittance above aerosol layer</td>
<td>0.87</td>
<td>0.72 to 1.00</td>
<td>1.4</td>
</tr>
<tr>
<td>Fractional increase in aerosol scattering efficiency due to hygroscopic growth at RH=80%</td>
<td>2.0</td>
<td>1.7 to 2.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Fraction of Earth not covered by cloud</td>
<td>0.39</td>
<td>0.35 to 0.43</td>
<td>1.2</td>
</tr>
<tr>
<td>Mean surface albedo, co-albedo</td>
<td>0.15</td>
<td>0.08 to 0.22</td>
<td>2.8, 1.2</td>
</tr>
<tr>
<td>Result: If central value is –0.6 Wm⁻² the 2/3 uncertainty range is from 0.1 to 1.0 Wm⁻².</td>
<td></td>
<td></td>
<td><strong>10.0</strong></td>
</tr>
</tbody>
</table>

*Modified from Penner et al., IPCC, 2001*

- Greatest uncertainties are in chemical, microphysical, and optical properties.
INTERCOMPARISON OF BROADBAND SHORTWAVE FORCING BY AMMONIUM SULFATE AEROSOL

Normalized global-average forcing: $W \text{ m}^{-2} / g(\text{SO}_4^{2-}) \text{ m}^{-2}$ or $W / g(\text{SO}_4^{2-})$

Aerosol optical depth 0.2; surface albedo 0.15

Standard deviation $\sim 8\%$ for 15 models at radius $\sim 200$ nm.

*Boucher, Schwartz and 28 co-authors, JGR, 1998*
LIGHT SCATTERING EFFICIENCY

Dependence on particle radius -- Size matters!

Ammonium Sulfate, 530 nm

Data of Ouimette and Flagan, 1982
WATER UPTAKE BY HYGROSCOPIC PARTICLE
Dependence on relative humidity

\[ (\text{NH}_4)_2\text{SO}_4 \]

Moles Water/Moles Solute

Relative Humidity, %

D. Imre, T. Onasch, BNL
LIGHT SCATTERING EFFICIENCY OF (NH$_4$)$_2$SO$_4$
DEPENDENCE ON PARTICLE SIZE AND RH

Nemesure et al., JGR, 1995
UPSCATTER FRACTION
Dependence on solar zenith angle and particle radius

For sun at horizon $\beta = 0.5$ (by symmetry).

For small particles, $r \ll \lambda$, upscatter fraction approaches that for Rayleigh scattering (0.5).
AEROSOL OPTICAL AND MICROPHYSICAL PROPERTIES DURING ARM ACP AEROSOL IOP MAY 2003

\( N \) from condensation nucleus counter.

RH as measured in nephelometer.

Index of refraction from optical particle counter on particles selected by DMA; RH dependence from TDMA.

Wang (BNL); Collins, Gasparini (TAMU); Ogren, Sheridan (NOAA)

**Aerosol loading, and microphysical and optical properties exhibit a rich variability, which must be understood and represented in models.**
HEMISPHERIC DISTRIBUTION OF SULFATE COLUMN BURDEN

Vertical integral of concentration

July 14, 1997, 1800 UTC

Brookhaven National Laboratory Chemical Transport Model
MODEL-OBSERVATION COMPARISONS

5083 24-Hour sulfate mixing ratio in BNL CTM driven by assimilated meteorological data - June-July 1997

56% of comparisons within factor of 2. 92% within factor of 5.
SULFATE MODEL INTERCOMPARISON
Annual average non-seasalt sulfate in 11 chemical transport models and comparison with observations at nine stations.

Penner et al., IPCC, 2001

“Most models predict surface-level seasonal mean sulphate aerosol mixing ratios to within 20%.”
“We cannot be sure that these models achieve reasonable success for the right reasons.”
TIME SERIES COMPARISON FOR AEROSOL MOMENTS

Look Ridge, Great Smoky Mountains TN (84° W, 36° N; 900 m) during SEAVS

Yu, Kasibhatla, Wright, Schwartz, McGraw & Deng, JGR, 2003
SIZE DISTRIBUTIONS
Comparison of Measurement and Retrieval from Model
At 3 Altitudes near Nashville TN

--- Model --- Observation

Yu, Kasibhatla, Wright, Schwartz, McGraw & Deng, JGR, 2003
INDIRECT EFFECT
DEPENDENCE OF CLOUD ALBEDO ON CLOUD DEPTH

Influence of Cloud Drop Radius and Concentration

LWC = 0.3 g m$^{-3}$
g = 0.858

SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION

Schwartz and Slingo (1996)
CDNC depends on sulfate concentration but much other variance is not accounted for.
Indirect forcing is highly sensitive to the assumed relation between sulfate concentration and cloud droplet number concentration.
The variables controlling CDNC must be understood and represented in models much better than at present.
### Uncertainty Budget for Indirect Forcing by Industrial Aerosols

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Central Value</th>
<th>2/3 Uncertainty Range</th>
<th>Uncertainty Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background (N_d) for Northern Hemisphere marine (cm(^{-3}))</td>
<td>140</td>
<td>66 to 214</td>
<td><strong>3.2</strong></td>
</tr>
<tr>
<td>Perturbed (N_d) for Northern Hemisphere marine (cm(^{-3}))</td>
<td>217</td>
<td>124 to 310</td>
<td><strong>2.5</strong></td>
</tr>
<tr>
<td>Cloud mean liquid water content (LWC) (g m(^{-3}))</td>
<td>0.225</td>
<td>0.125 to 0.325</td>
<td><strong>2.6</strong></td>
</tr>
<tr>
<td>Background sulfate concentration (µg m(^{-3}))</td>
<td>1.5</td>
<td>0.85 to 2.15</td>
<td><strong>2.5</strong></td>
</tr>
<tr>
<td>Cloud layer thickness (m)</td>
<td>200</td>
<td>100 to 300</td>
<td><strong>3.0</strong></td>
</tr>
<tr>
<td>Perturbed sulfate concentration (µg m(^{-3}))</td>
<td>3.6</td>
<td>2.4 to 4.8</td>
<td><strong>2.0</strong></td>
</tr>
<tr>
<td>Susceptible cloud fraction, (f_c)</td>
<td>0.24</td>
<td>0.19 to 0.29</td>
<td><strong>1.5</strong></td>
</tr>
<tr>
<td>Atmospheric transmission above cloud layer, (T_a)</td>
<td>0.92</td>
<td>0.78 to 1.00</td>
<td><strong>1.3</strong></td>
</tr>
<tr>
<td>Mean surface albedo</td>
<td>0.06</td>
<td>0.03 to 0.09</td>
<td><strong>3.0, 1.1</strong></td>
</tr>
<tr>
<td>Result: If central value is (-1.4) Wm(^{-2}) the 2/3 uncertainty range is from 0 to (-2.8) Wm(^{-2}).</td>
<td></td>
<td></td>
<td><strong>∞</strong></td>
</tr>
</tbody>
</table>

*Modified from Penner et al., IPCC, 2001*

- Many of the greatest quantified uncertainties are in chemical properties.

- Some key uncertainties are at the interface of aerosols and clouds, such as relation between cloud drop concentration and aerosol loading, microphysical properties, and composition. These uncertainties are not quantified.
AEROSOL RESEARCH REQUIREMENTS
BY CCRD COMPONENT

Atmospheric Science Program
Abundance, composition, mixing state and optical and cloud-nucleating properties of atmospheric aerosols
   Observe - Model - Compare (local closure experiments)
Sources of aerosols and aerosol precursors (mass rates and size-dependent composition and mixing state)
   Measure - Understand - Quantify
Atmospheric chemical and microphysical transformation processes and three dimensional mixing and transport processes
   Experiment - Understand - Model - Compare (model evaluation)
Aerosol direct and indirect radiative forcing
   Model - Estimate

Atmospheric Radiation Measurement Program (ARM)
Aerosol-radiation interactions
Aerosol-cloud-radiation interactions

Climate Change Prediction Program (CCPP)
Represent aerosol influences in climate models
Determine climate sensitivity in models and compare with observations