AEROSOLS AND CLIMATE

THE SCIENTIFIC BASIS

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Workshop on Climate Change Impacts and Integrated Assessment

Snowmass, Colorado

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OUTLINE

• Radiative forcing of climate change
• The role of aerosols
• Estimates of aerosol forcing and uncertainties
• Implications of these uncertainties
Our useful efforts to reduce sulfur emissions may have actually increased warming, because sulfate particles reflect sunlight, bouncing it back into space."

Kyoto also failed to address two major pollutants that have an impact on warming: black soot and tropospheric ozone. Both are proven health hazards. Reducing both would not only address climate change, but also dramatically improve people's health."
The Greenhouse Effect

Solar radiation passes through the clear atmosphere. Some solar radiation is reflected by the Earth and the atmosphere. Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.

Most radiation is absorbed by the Earth's surface and warms it. Infrared radiation is emitted from the Earth's surface.
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

$1/4 S_0 (1 - \alpha) = \sigma T^4$

$69\% = 1 - \alpha$

$\alpha = 31\%$

$1/4 S_0 = 343$ W/m$^2$

$237 \approx 254K$

$390 \approx 288K$

$327$ W/m$^2$

$68$ W/m$^2$

$169$ W/m$^2$

$90$ W/m$^2$

$16$ W/m$^2$

$106$ W/m$^2$

$\alpha = 31\%$

H$_2$O, CO$_2$, CH$_4$...

Rayleigh

Aerosol

Atmosphere

Schwartz, 1996, modified from Ramanathan, 1987
RADIATIVE FORCING

A change in a component of the Earth’s radiation budget.

Working hypothesis:

On a global basis radiative forcings are additive and fungible.

- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.
GLOBAL CARBON DIOXIDE OVER THE INDUSTRIAL PERIOD

CO₂ Mixing Ratio, µmol/mol(air) [ppm]

Forcing, W m⁻²


ICE CORES
SIQUE LANTARCTICA

MAUNA LOA HAWAII

C. D. Keeling
GREENHOUSE GAS MIXING RATIOS OVER THE INDUSTRIAL PERIOD

- **CO₂**
  - Ice core (↓)
  - In situ (←)
- **CH₄**
  - Ice core (↓)
  - Greenland (↓)
  - Antarctica (↑)
- **N₂O**
  - Ice core (↓)
- **CFCs**
  - CFC-11
  - CFC-12
  - Other trace gas forcing (converted to CFC-11 amount)

Hansen et al., PNAS. 1998
NORTHERN HEMISPHERE TEMPERATURE TREND (1000-1998)
From tree-ring, coral, and ice-core proxy records
As calibrated by instrumental measurements

Reconstruction (AD 1000-1980)
Instrumental data (AD 1902-1998)
Calibration period (AD 1902-1980) mean
Reconstruction (40 year smoothed)
Linear trend (AD 1000-1850)

Mann et al., GRL, 1999
GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD

Temperature Anomaly, K

GISS
East Anglia
AEROSOL INFLUENCES ON RADIATION BUDGET AND CLIMATE

Direct Effect (Clear sky)
Light scattering -- Cooling influence
Light absorption -- Warming influence, depending on surface

Indirect Effects (Aerosols influence cloud properties)
More droplets -- Brighter clouds (Twomey)
More droplets -- Enhanced cloud lifetime (Albrecht)

Semi-Direct Effect
Absorbing aerosol heats air and evaporates clouds
DIRECT EFFECT
SEAWIFS IMAGE OF MEDITERRANEAN AEROSOL

Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

http://www.nrlmry.navy.mil/aerosol/satellite/seawifs/med/200107/2001071612_med.jpg
SEAWIFS IMAGE OF MEDITERRANEAN AEROSOL

Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

http://www.nrlmry.navy.mil/aerosol/satellite/seawifs/med/200107/2001071812_med.jpg
Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

http://www.nrlmry.navy.mil/aerosol/satellite/seawifs/med/200108/2001080112_med.jpg
DIRECT RADIATIVE FORCING DUE TO ANTHROPOGENIC SULFATE AEROSOL

\[
\overline{\Delta F_R} = \frac{1}{2} F_T T^2 (1 - A_c)(1 - R_s)^2 \cdot \overline{\beta} \alpha_{SO_4^{2-}} f(RH) \cdot Q_{SO_2} Y_{SO_4^{2-}} \left( \frac{MW_{SO_4^{2-}}}{MW_S} \right) \tau_{SO_4^{2-}} \frac{1}{A}
\]

\(\overline{\Delta F_R}\) 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\(^2\)

Charlson, Schwartz, Hales, Cess, Coakley, Hansen & Hofmann, Science, 1992
EVALUATION OF GLOBAL MEAN DIRECT RADIATIVE FORCING DUE TO ANTHROPOGENIC SULFATE

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Central Value</th>
<th>Units</th>
<th>Uncertainty Factor</th>
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<tbody>
<tr>
<td>$F_T$</td>
<td>1370</td>
<td>W m$^{-2}$</td>
<td>—</td>
</tr>
<tr>
<td>$1-A_C$</td>
<td>0.4</td>
<td>—</td>
<td>1.1</td>
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<tr>
<td>$T$</td>
<td>0.76</td>
<td>—</td>
<td>1.15</td>
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<tr>
<td>$1-R_S$</td>
<td>0.85</td>
<td>—</td>
<td>1.1</td>
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<tr>
<td>$\bar{\beta}$</td>
<td>0.29</td>
<td>—</td>
<td>1.3</td>
</tr>
<tr>
<td>$\alpha^*$</td>
<td>8.5</td>
<td>m$^2$ (g SO$_4^{2-}$)$^{-1}$</td>
<td>—</td>
</tr>
<tr>
<td>$\alpha_{SO_4^{2-}}$</td>
<td>5</td>
<td>m$^2$ (g SO$_4^{2-}$)$^{-1}$</td>
<td>1.5</td>
</tr>
<tr>
<td>$f(RH)$</td>
<td>1.7</td>
<td>—</td>
<td>1.2</td>
</tr>
<tr>
<td>$Q_{SO_2}$</td>
<td>80</td>
<td>Tg S yr$^{-1}$</td>
<td>1.15</td>
</tr>
<tr>
<td>$Y_{SO_4^{2-}}$</td>
<td>0.4</td>
<td>—</td>
<td>1.5</td>
</tr>
<tr>
<td>$\tau_{SO_4^{2-}}$</td>
<td>0.02</td>
<td>yr</td>
<td>1.5</td>
</tr>
<tr>
<td>$A$</td>
<td>$5 \times 10^{14}$</td>
<td>m$^2$</td>
<td>—</td>
</tr>
<tr>
<td>$\Delta F_R$</td>
<td>-1.1</td>
<td>W m$^{-2}$</td>
<td>2.4</td>
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</tbody>
</table>

Total uncertainty factor evaluated as $f_t = \exp\left[\sum (\log f_i)^2\right]^{1/2}$  
Penner, Charlson, Hales, Laulainen, Leifer, Novakov, Ogren, Radke, Schwartz & Travis, BAMS, 1994
DIRECT AEROSOL FORCING AT TOP OF ATMOSPHERE

Dependence on Aerosol Optical Thickness

Comparison of Linear Formula and Radiation Transfer Model

Particle radius $r = 85$ nm; surface reflectance $R = 0.15$; single scatter albedo $\omega_0 = 1$.

Global-average AOT 0.1 corresponds to global-average forcing $-3.2$ W m$^{-2}$. 
LIGHT SCATTERING EFFICIENCY

Dependence on particle radius

Ammonium Sulfate, 530 nm

Data of Ouimette and Flagan, 1982
WATER UPTAKE AND LIGHT SCATTERING COEFFICIENT

Dependence on relative humidity

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

D. Imre, T. Onasch, BNL
LIGHT SCATTERING EFFICIENCY OF (NH₄)₂SO₄: DEPENDENCE ON PARTICLE SIZE AND RH

\[
\alpha^*, \text{m}^2 (\text{g} \text{SO}_4^{2-})^{-1}
\]

\[
10^{-18} \quad 10^{-17} \quad 10^{-16} \quad 10^{-15} \quad 10^{-14}
\]

moles(SO₄²⁻)/particle

\[
(NH_4)_2 \text{SO}_4
\]

Dry Radius, \(R_0\) (μm)
**UPSCATTER FRACTION**

**SCATTERING OF SOLAR RADIATION BY AEROSOL PARTICLE**

*Upscatter fraction* $\beta$ is the fraction of radiation scattered into the upward hemisphere/}

$$
\beta = \frac{\int P(\theta, \phi) d\Omega} {\int P(\theta, \phi) d\Omega} = \frac{\int P(\theta, \phi) d\Omega} {4\pi}$$
For sun at horizon $\beta = 0.5$ (by symmetry).

For small particles, $r \ll \lambda$, upscatter fraction approaches that for Rayleigh scattering (0.5).
HEMISPHERIC DISTRIBUTION OF SULFATE COLUMN BURDEN

Vertical integral of concentration

July 14, 1997, 1800 UTC

Brookhaven National Laboratory Chemical Transport Model
COMPARISON OF MODEL AND OBSERVATIONS

Comparisons for 24-hr sulfate mixing ratio at surface

MANITOBA, CANADA

DEUSELBACH, GERMANY

JUNGFRAUJOCH, SWITZERLAND

JARCZEW, POLAND
## COMPARISON OF MODEL AND OBSERVATIONS

### Statistics of Comparisons

<table>
<thead>
<tr>
<th>Comparison</th>
<th>$N$</th>
<th>Median Spread</th>
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</thead>
<tbody>
<tr>
<td>Obs-Obs</td>
<td>503</td>
<td>1.5</td>
</tr>
<tr>
<td>Model-Obs</td>
<td>503</td>
<td>1.9</td>
</tr>
<tr>
<td>Same locations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model-Obs All locations</td>
<td>7907</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Benkovitz and Schwartz, *JGR*, 1997
AEROSOL OPTICAL DEPTH

Determined by Sunphotometry

North Central Oklahoma

J. Michalsky, PNNL
MONTHLY AVERAGE AEROSOL JUNE 1997

Optical Thickness at 865 nm

Ångström Exponent

Polder/Adeos CNES/NASDA LOA/LSCE
Influence of Pinatubo Eruption on Aerosol Forcing and Global Temperature
CLOUDS AND AEROSOLS DURING INDOEX PROJECT

21 March, 1999: Arabian Sea; thick haze (9.2°N, 73.5°E)

25 March, 1999: clouds under thick haze (3.0°N, 74.5°E)

24 February, 1999: just north of ITCZ; haze extends up to top of Cu (0.5°N, 73.3°E)

24 March, 1999: south of ITCZ; almost pristine clouds (7.5°S, 73.5°E)

Satheesh and Ramanathan, Nature, 2000
AEROSOL DIRECT SHORTWAVE FORCING

Global Average for Nonabsorbing Aerosol

$$\Delta F = -\frac{1}{2} F_0 T^2 (1 - A_c)(1 - R)^2 \beta \tau$$

$$\tau = \int \alpha C dz = \int \sigma_{sp} dz$$

- Light Scattering Coefficient
- Mass Concentration
- Mass Scattering Efficiency
- Aerosol Optical Depth
- Mean Upscatter Fraction
- Surface Reflectance
- Cloud Fraction
- Atmospheric Transmittance
- Solar Constant
- Change in Net TOA Flux

Global Average for Absorbing Aerosol

$$\Delta F = -\frac{1}{2} F_0 T^2 (1 - A_c)(1 - R)^2 \beta \tau \omega \left\{ 1 - \frac{2R}{(1 - R)^2 \beta \omega} \left( \frac{1 - \omega}{\beta \omega} \right) \right\}$$

- Single Scattering Albedo
RADIATIVE FORCING OF ABSORBING AEROSOL
Sulfate with uniformly admixed absorber
Dependence on imaginary component of refractive index $k$ and surface reflectance $R_s$

Compare to single scattering albedo $\omega$ in north central Oklahoma, $0.92 \pm 0.06$ (one s.d.; 10,000 2-hour averages of 1-minute data).
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

\[ \Delta (\text{Global Mean Shortwave Forcing}, \, \text{W m}^{-2}) \]

\[ \Delta (\text{Global Mean Albedo}) \]

\[ 0.02 \quad 0.04 \quad 0.06 \quad 0.08 \]

\[ \Delta (\text{Top-of-Atmosphere Albedo}) \]

\[ 0.00 \quad 0.02 \quad 0.04 \quad 0.06 \quad 0.08 \]

\[ \Delta (\text{Cloud-Top Albedo}) \]

\[ 0.00 \quad 0.02 \quad 0.04 \quad 0.06 \quad 0.08 \]

Relative Number Density of Cloud Drops

Schwartz and Slingo (1996)
CLOUD DROPLET NUMBER CONCENTRATION

Dependence on Non-Seasalt Sulfate

CDNC (cm⁻³)

nss–sulfate (µg SO₄ / m³)

Leaitch, 1992
Quinn, 1993
Hegg, 1993
Berresheim, 1993
Van Dingenen, 1995

Boucher and Lohmann, 1995
CLOUD MICROPHYSICAL PROPERTIES AND SATELLITE VISIBLE RADIANCE

ASTEX, Northeast Atlantic, June, 1992

Albrecht et al., BAMS, 1995
LATITUDE DEPENDENCE OF CLOUD DROP RADIUS

Test for Anthropogenic Influence in Northern Hemisphere vs. Southern Hemisphere as Control

Han, Rossow, and Lacis, J. Climate, 1994
INDIRECT FORCING OF SULFATE AEROSOL

Annual-mean loss of solar irradiance, W m\(^{-2}\)

LMD model; Boucher and Lohmann, 1995
SHORTWAVE FORCING, ANNUAL AVERAGE
GHG’s + O₃ + Sulfate (Direct and Indirect)
Two Formulations of Cloud Droplet Concentration

Kiehl et al., JGR, 2000
The greatest uncertainty about the aerosol climate forcing—indeed, the largest of all the uncertainties about global climate forcings—is probably the indirect effect of aerosols on clouds.

Aerosols serve as condensation nuclei for cloud droplets. Thus, anthropogenic aerosols are believed to have two major effects on cloud properties, the increased number of nuclei results in a larger number of smaller cloud droplets, thus increasing the cloud brightness (the Twomey effect); and the smaller droplets tends to inhibit rainfall, thus increasing cloud lifetime and the average cloud cover on Earth. Both effects reduce the amount of sunlight absorbed by the Earth and thus tend to cause global cooling.
The existence of these effects has been verified in field studies, but it is extremely difficult to determine their global significance.

Climate models that incorporate the aerosol-cloud physics suggest that these effects may produce a negative global forcing on the order of 1 \( \text{W/m}^2 \) or larger.

*The great uncertainty about this indirect aerosol climate forcing presents a severe handicap both for the interpretation of past climate change and for future assessments of climate changes.*
• In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.
The global mean radiative forcing of the climate system for the year 2000, relative to 1750

Level of Scientific Understanding

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

- **CO₂**
- **CH₄**
- **N₂O**
- **Halocarbons**
- **Tropospheric ozone**
- **Stratospheric ozone**
- **Sulphate**
- **Organic carbon from fossil fuel burning**
- **Biomass burning**
- **Mineral Dust**
- **Aerosol indirect effect**
- **Aviation-induced Contrails Cirrus**
- **Solar**
- **Land-use (albedo) only**

Radiative forcing (Watts per square metre)

- **High**
- **Medium**
- **Low**

Level of Scientific Understanding

**Summary for Policymakers** A Report of Working Group I of the Intergovernmental Panel on Climate Change
IPCC-2001 STATEMENT AGAINST ADDING FORCINGS

• Some of the radiative forcing agents are well mixed over the globe, such as CO2, thereby perturbing the global heat balance. Others represent perturbations with stronger regional signatures because of their spatial distribution, such as aerosols. For this and other reasons, a simple sum of the positive and negative bars cannot be expected to yield the net effect on the climate system.
CLIMATE MODEL SIMULATIONS OVER THE INDUSTRIAL PERIOD (IPCC, 2001)

Annual global mean temperatures (1.5 m) with coupled ocean-atmosphere GCM

a. NATURAL FORCINGS

- 1990 = +0.5 W m\(^{-2}\)
- 1992 = -2.0 W m\(^{-2}\)

b. ANTHROPOGENIC FORCINGS

- 1990 = 1.0 W m\(^{-2}\)
- 1990 sulfate = -1.0 W m\(^{-2}\)

c. ALL FORCINGS
Simulations that include estimates of natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20th century (Figure 4). However, contributions from some additional processes and forcings may not have been included in the models. Nevertheless, the large-scale consistency between models and observations can be used to provide an independent check on projected warming rates over the next few decades under a given emissions scenario.
IPCC-2001 STATEMENTS ON DETECTION AND ATTRIBUTION OF CLIMATE CHANGE

• *Detection and attribution studies comparing model simulated changes with the observed record can now take into account uncertainty in the magnitude of modelled response to external forcing*, in particular that due to uncertainty in climate sensitivity.

• Most of these studies find that, over the last 50 years, the estimated rate and magnitude of warming due to increasing concentrations of greenhouse gases alone are comparable with, or larger than, the observed warming. *Furthermore, most model estimates that take into account both greenhouse gases and sulphate aerosols are consistent with observations over this period.*
The best agreement between model simulations and observations over the last 140 years has been found when all the above anthropogenic and natural forcing factors are combined, as shown in Figure 4 (c). These results show that the forcings included are sufficient to explain the observed changes, but do not exclude the possibility that other forcings may also have contributed.
The Emperor's New Clothes

A Fairy Tale by Hans Christian Andersen

Illustrated by Monica A. Storey
CONCLUSIONS

• Radiative forcing of climate change by aerosols is highly uncertain but not negligible.

• This uncertainty is limiting in present estimates of radiative forcing over the industrial period.

• Little confidence can be placed on empirical estimates of climate sensitivity, or on conformance of climate models with observations over the industrial period, unless and until the uncertainty in aerosol forcing is greatly reduced.