RADIATIVE FORCING OF CLIMATE CHANGE BY AEROSOLS

WHY THIS IS IMPORTANT AND HOW WELL IT NEEDS TO BE KNOWN

Stephen E. Schwartz

Upton, New York, USA

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ENGINEERING AND PUBLIC POLICY

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The Greenhouse Effect

Some solar radiation is reflected by the Earth and the atmosphere.

Solar radiation passes through the clear atmosphere.

Most radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted from the Earth's surface.

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.
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

\[
\frac{1}{4} S_0 (1 - \alpha) = \sigma T^4
\]

\[69\% = 1 - \alpha\]

\[\alpha = 31\%\]

\[106\]

\[390 \approx 288 K\]

\[343\]

\[237 \approx 254 K\]

\[237\]

\[327\]

\[169\]

\[68\]

\[1/4 S_0\]

Rayleigh

Aerosol

H₂O, CO₂, CH₄...

Atmosphere

Schwartz, 1996, modified from Ramanathan, 1987
ATMOSPHERIC RADIATION

Energy per area per time

Power per time

Unit:
Watt per square meter
W m$^{-2}$
ATMOSPHERIC RADIATION

Energy per area per time

Power per time

Unit: Watt per square meter
W m$^{-2}$
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

\[ \frac{1}{4} S_0 (1 - \alpha) = \sigma T^4 \]

\[ 69\% = 1 - \alpha \]

\[ \alpha = 31\% \]

\[ 1/4 S_0 \approx 254K \]

\[ \approx 288K \]

\[ H_2O, CO_2, CH_4 \ldots \]

Rayleigh

Aerosol

Schwartz, 1996, modified from Ramanathan, 1987
A change in a radiative flux term in Earth’s radiation budget, $F$, W m$^{-2}$. 

**RADIATIVE FORCING OF CLIMATE CHANGE**
ATMOSPHERIC CARBON DIOXIDE IS INCREASING

Global carbon dioxide concentration over the last thousand years

- Mauna Loa Hawaii
- Law Dome
- Adelie Land
- Siple
- South Pole

Polar ice cores

CO₂ concentration (ppm)

Year

Global carbon dioxide concentration over the last thousand years
Global carbon dioxide concentration and infrared radiative forcing over the last thousand years
GREENHOUSE GAS FORCINGS OVER THE INDUSTRIAL PERIOD

Forcing relative to 1850, W m$^{-2}$

Year

Total
CO$_2$
CH$_4$
N$_2$O
CFC-12
CFC-11
Other

Data: GISS
GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter

\[ \frac{1}{4} S_0 (1 - \alpha) = \sigma T^4 \]

\[ 69\% = 1 - \alpha \]

\[ 1/4 S_0 \approx 254 \text{K} \]

\[ 237 \approx 288 \text{K} \]

\[ 343 - 237 = 106 \]

\[ 2 \times \text{CO}_2 \approx + 4 \text{ W m}^{-2} \]

\[ \alpha = 31\% \]

\[ 169 + 16 = 185 \]

Schwartz, 1996, modified from Ramanathan, 1987
GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD

Base Period 1951-80

Data: GISS


Temperature Anomaly, K


Pinatubo

Krakatoa
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
CLIMATE CHANGE 2001
The Scientific Basis

Cambridge University Press, 2001
THE BIBLE OF CLIMATE CHANGE

It's big and thick.
Every household should have one.
No one reads it from cover to cover.
You can open it up on any page and find something interesting.

It was written by a committee.
It is full of internal contradictions.
It deals with cataclysmic events such as floods and droughts.
It has its true believers and its nonbelievers.
The global mean radiative forcing of the climate system for the year 2000, relative to 1750.

- **CO₂**
- **CH₄**
- **N₂O**
- **Halocarbons**
- **Tropospheric ozone**
- **Stratospheric ozone**

Radiative forcing (Watts per square metre)

Level of Scientific Understanding

**Summary for Policymakers**
A Report of Working Group I of the Intergovernmental Panel on Climate Change
The global mean radiative forcing of the climate system for the year 2000, relative to 1750

- **CO₂**
- **CH₄**
- **N₂O**
- **Halocarbons**
- **Stratospheric ozone**
- **Tropospheric ozone**

**Level of Scientific Understanding**

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

**Summary for Policymakers** A Report of Working Group I of the Intergovernmental Panel on Climate Change
CLIMATE RESPONSE

The change in global and annual mean temperature, $\Delta T$, K, resulting from a given radiative forcing.

Working hypothesis:
The change in global mean temperature depends on the magnitude of the forcing, not its nature or its spatial distribution.

$$\Delta T = \lambda F$$

CLIMATE SENSITIVITY

The change in global and annual mean temperature per unit forcing, $\lambda$, K/(W m$^{-2}$).
TOP-LEVEL QUESTION IN CLIMATE CHANGE SCIENCE

• How much will the global mean temperature change?

\[ \Delta T = \lambda F \]

where \( F \) is the forcing and \( \lambda \) is the climate sensitivity.

- A forcing is a change in a radiative flux component, W m\(^{-2}\).
- Forcings are thought to be additive and fungible.

• What is Earth’s climate sensitivity?

- U.S. National Academy Report (Charney, 1979):

  “We estimate the most probable global warming for a doubling of CO\(_2\) to be near 3 degrees C, with a probable error of plus or minus 1.5 degrees.”

- Intergovernmental Panel on Climate Change (IPCC, 2001):

  “Climate sensitivity [to CO\(_2\) doubling] is likely to be in the range 1.5 to 4.5°C.

This level of uncertainty is not very useful for policy planning.
HOW CAN CLIMATE SENSITIVITY BE DETERMINED?

Climate sensitivity $\lambda = \Delta T / F$

- *Climate models* evaluated by performance on prior climate change, and/or

- *Empirical determination* from prior climate change.

- Either way, $\Delta T$ and $F$ must be determined with sufficiently small uncertainty to yield an uncertainty in $\lambda$ that is useful for informed decision making.
# Climate Change Sensitivity
Summary of 15 Current Models

<table>
<thead>
<tr>
<th>Quantity, Unit</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$, K/(W m$^{-2}$)</td>
<td>0.87</td>
<td>0.23</td>
<td>0.5 - 1.25</td>
</tr>
<tr>
<td>$\Delta T_{2\times}$, K</td>
<td>3.5</td>
<td>0.9</td>
<td>2 - 5</td>
</tr>
</tbody>
</table>

*IPCC Climate Change 2001, Cambridge University Press, 2001*
EMPIRICAL CLIMATE SENSITIVITY

Greenhouse forcing over the industrial period is 2.5 W m\(^{-2}\)

Temperature increase over the industrial period is 0.6 K.

Empirical Sensitivity:

\[ \lambda = \frac{dT}{dF} = \frac{0.6 \text{ K}}{2.5 \text{ W m}^{-2}} = 0.24 \text{ K} \div (\text{W m}^{-2}) \quad \text{or} \quad \Delta T_{2\times} = 1 \text{ K} \]

*Why is the empirical sensitivity so much lower than model-based estimates?*
THE “WHITEHOUSE EFFECT”

RADIATIVE FORCING OF CLIMATE CHANGE BY AEROSOLS

Diagram showing the process of sulfate haze formation and its interaction with clouds, SO$_2$ (gas), DMS, and marine phytoplankton.
AEROSOL INFLUENCES ON RADIATION BUDGET AND CLIMATE

Direct Effect (Cloud-free 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
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

\[ \frac{1}{4} S_0 = 343 \text{ watts/m}^2 \]

\[ \alpha = 31\% \]

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

\[ 69\% = 1 - \alpha \]

\[ 237 \text{ watts/m}^2 \approx 254K \]

\[ 237 \text{ watts/m}^2 \]

\[ 390 \text{ watts/m}^2 \approx 288K \]

\[ 327 \text{ watts/m}^2 \]

\[ 169 \text{ watts/m}^2 \]

\[ 90 \text{ watts/m}^2 \]

\[ 16 \text{ watts/m}^2 \]

\[ \text{H}_2\text{O, CO}_2, \text{CH}_4 \ldots \]

\[ \text{Atmosphere} \]

\[ \text{Modified from Ramanathan, 1987} \]
GLOBAL ENERGY BALANCE
Global and annual average energy fluxes in watts per square meter

1/4 S₀ = 343 W/m²

237 W/m² ≈ 254K

69% = 1 - α

1/4 S₀ (1-α) = σT⁴

α = 31%

Rayleigh

Aerosol

25 W/m²

68 W/m²

H₂O, CO₂, CH₄...

390 W/m² ≈ 288K

327 W/m²

90 W/m²

169 W/m²

16 W/m²

Modified from Ramanathan, 1987
DIRECT EFFECT
AEROSOL: A suspension of particles in air

Atmospheric aerosols may result from primary emissions (dust, smoke) or from gas to particle conversion in the atmosphere (haze, smog).
BIOMASS BURNING AND WIDESPREAD AEROSOL
Northeastern Oklahoma, 2000-12-01
**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>
</tr>
</thead>
<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>
</tr>
<tr>
<td>$T$</td>
<td>0.76</td>
<td>—</td>
<td>1.15</td>
</tr>
<tr>
<td>1-$R_s$</td>
<td>0.85</td>
<td>—</td>
<td>1.1</td>
</tr>
<tr>
<td>$\bar{\beta}$</td>
<td>0.29</td>
<td>—</td>
<td>1.3</td>
</tr>
<tr>
<td>$\alpha^* = 8.5$ m(^2) (g SO(_4)(^{2-}))(^{-1})</td>
<td></td>
<td></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>$5 \times 10^{14}$ m(^2)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\Delta F_R$</td>
<td>-1.1</td>
<td>W m(^{-2})</td>
<td>2.4</td>
</tr>
</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
Forcing is highly sensitive to modest aerosol loadings. Global-average AOT 0.1 corresponds to global-average forcing -3.2 W m⁻². Linear model is accurate and convenient, especially for error budgets.
AEROSOL OPTICAL DEPTH
Determined by sunphotometry
North central Oklahoma - Daily average at 500 nm

Variability is due to variability in tropospheric aerosols.
Optical depth variability of 0.1 is common even at a rural mid-continental site.

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

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

Ångström Exponent $\alpha$
$\alpha = -d \ln \tau / d \ln \lambda$
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

![Graph showing water uptake by hygroscopic particle as a function of relative humidity. The x-axis represents relative humidity (%) ranging from 20 to 90, and the y-axis represents moles of water/moles of solute ranging from 0 to 18. The data points represent the uptake of (NH$_4$)$_2$SO$_4$ at various relative humidities.]
Scattering, optical depth, and forcing are highly sensitive to particle size and to hygroscopic growth, which depends on composition.
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.

Benkovitz et al., JGR, In press, 2004
# Statistics of Several Sulfate CTMs

<table>
<thead>
<tr>
<th>Model</th>
<th>F96</th>
<th>L97</th>
<th>R98</th>
<th>K99</th>
<th>R00</th>
<th>C00</th>
<th>B97</th>
<th>B04</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SO₂ Sink Rate (%/day)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry Deposition</td>
<td>26</td>
<td>10</td>
<td>8</td>
<td>17</td>
<td>16</td>
<td>26</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Wet Deposition</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>0</td>
<td>4x10⁻⁴</td>
</tr>
<tr>
<td>Gas Conversion</td>
<td>11</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>9</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>Aqueous Conversion to sulfate</td>
<td>22</td>
<td>26</td>
<td>27</td>
<td>15</td>
<td>29</td>
<td>15</td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td>Oxidation &amp; immediate wet dep</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>21</td>
</tr>
<tr>
<td><strong>Sulfate Sink Rate (%/day)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry Deposition</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Wet Deposition</td>
<td>20</td>
<td>14</td>
<td>17</td>
<td>14</td>
<td>23</td>
<td>15</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td><strong>Inverse Lifetime (%/day)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO₂</td>
<td>63</td>
<td>43</td>
<td>42</td>
<td>38</td>
<td>53</td>
<td>56</td>
<td>36</td>
<td>90</td>
</tr>
<tr>
<td>Sulfate</td>
<td>23</td>
<td>19</td>
<td>21</td>
<td>18</td>
<td>25</td>
<td>17</td>
<td>21</td>
<td>15</td>
</tr>
<tr>
<td><strong>Sulfate yield, %</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>76</td>
<td>82</td>
<td>55</td>
<td>68</td>
<td>43</td>
<td>66</td>
<td>50</td>
</tr>
<tr>
<td><strong>Burden (Tg S)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO₂</td>
<td>0.33</td>
<td>0.56</td>
<td>0.61</td>
<td>0.56</td>
<td>0.4</td>
<td>0.43</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>0.43</td>
<td>1.05</td>
<td>0.96</td>
<td>0.73</td>
<td>0.60</td>
<td>0.63</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td><strong>Sulfate Potential (days)</strong></td>
<td>2.1</td>
<td>4.4</td>
<td>3.7</td>
<td>3.4</td>
<td>2.5</td>
<td>2.7</td>
<td>3.3</td>
<td></td>
</tr>
</tbody>
</table>

*Benkovitz & Schwartz, 2004*
SULFATE MODEL INTERCOMPARISON

Annual average non-seasalt sulfate in 11 chemical transport models and comparison with observations at nine stations

Non-seasalt Sulfate (µg/m³)

Heimaey, Iceland 63.4°N
Mace Head, Ireland 53.3°N
Bermuda 32.3°N
Izaña Tenerife 28.3°N
Miami, Florida, USA 25.8°N
Ragged Point, Barbados 13.2°N
Cape Point, South Africa 34.4°S
King George Island 62.2°S
Palmer Station, Antarctica 64.8°S

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.”
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_

_Radiation transfer models agree closely for well specified aerosol._
**UNCERTAINTY BUDGET FOR DIRECT FORCING BY ANTHROPOGENIC SULFATE AEROSOL**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Central Value</th>
<th>2/3 Uncertainty Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total emission of anthropogenic sulfate from fossil fuel burning (Tg/yr)</td>
<td>69</td>
<td>57.5 to 82.8</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>
</tr>
<tr>
<td>Fraction of light scattered into upward hemisphere, $\bar{\beta}$</td>
<td>0.23</td>
<td>0.17 to 0.29</td>
</tr>
<tr>
<td>Aerosol mass scattering efficiency (m$^2$g$^{-1}$), $\alpha_s$</td>
<td>3.5</td>
<td>2.3 to 4.7</td>
</tr>
<tr>
<td>Aerosol single scattering albedo, co-albedo (dry), $\omega_0, 1-\omega_0$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$T_a$, atmospheric transmittance above aerosol layer</td>
<td>0.87</td>
<td>0.72 to 1.00</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>
</tr>
<tr>
<td>Fraction of Earth not covered by cloud</td>
<td>0.39</td>
<td>0.35 to 0.43</td>
</tr>
<tr>
<td>Mean surface albedo, co-albedo</td>
<td>0.15</td>
<td>0.08 to 0.22</td>
</tr>
</tbody>
</table>

Result: Central value of forcing is $-0.5$ Wm$^{-2}$, the uncertainty range is from $-0.25$ to $-1.0$ Wm$^{-2}$.

*Modified from Penner et al., IPCC, 2001*
The global mean radiative forcing of the climate system for the year 2000, relative to 1750

- **Halocarbons**
- **N₂O**
- **CH₄**
- **CO₂**
- **Tropospheric ozone**
- **Stratospheric ozone**
- **Sulphate**

Radiative forcing (Watts per square metre)

Level of Scientific Understanding

---

Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change
The global mean radiative forcing of the climate system for the year 2000, relative to 1750

<table>
<thead>
<tr>
<th>GHG's and aerosol direct effects</th>
<th>Level of Scientific Understanding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halocarbons</td>
<td>Very Low</td>
</tr>
<tr>
<td>N₂O</td>
<td>Very Low</td>
</tr>
<tr>
<td>CH₄</td>
<td>Very Low</td>
</tr>
<tr>
<td>CO₂</td>
<td>Very Low</td>
</tr>
<tr>
<td>Tropospheric ozone</td>
<td>Medium</td>
</tr>
<tr>
<td>Stratospheric ozone</td>
<td>Medium</td>
</tr>
<tr>
<td>Sulphate</td>
<td>Low</td>
</tr>
<tr>
<td>Organic carbon from fossil fuel burning</td>
<td>Low</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>Very Low</td>
</tr>
<tr>
<td>Black carbon from fossil fuel burning</td>
<td>Low</td>
</tr>
<tr>
<td>Aerosols</td>
<td>Low</td>
</tr>
</tbody>
</table>

Radiative forcing (Watts per square metre)

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

<table>
<thead>
<tr>
<th>GHG's and Aerosol Direct Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Halocarbons</strong></td>
</tr>
<tr>
<td><strong>N&lt;sub&gt;2&lt;/sub&gt;O</strong></td>
</tr>
<tr>
<td><strong>CH&lt;sub&gt;4&lt;/sub&gt;</strong></td>
</tr>
<tr>
<td><strong>CO&lt;sub&gt;2&lt;/sub&gt;</strong></td>
</tr>
<tr>
<td><strong>Tropospheric ozone</strong></td>
</tr>
<tr>
<td><strong>Black carbon from fossil fuel burning</strong></td>
</tr>
<tr>
<td><strong>Mineral Dust</strong></td>
</tr>
<tr>
<td><strong>Stratospheric ozone</strong></td>
</tr>
<tr>
<td><strong>Sulphate</strong></td>
</tr>
<tr>
<td><strong>Organic carbon from fossil fuel burning</strong></td>
</tr>
<tr>
<td><strong>Biomass burning</strong></td>
</tr>
<tr>
<td><strong>Level of Scientific Understanding</strong></td>
</tr>
<tr>
<td><strong>High</strong></td>
</tr>
<tr>
<td><strong>Medium</strong></td>
</tr>
<tr>
<td><strong>Medium</strong></td>
</tr>
<tr>
<td><strong>Low</strong></td>
</tr>
<tr>
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</tr>
<tr>
<td><strong>Very Low</strong></td>
</tr>
<tr>
<td><strong>Very Low</strong></td>
</tr>
</tbody>
</table>

**RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD**

IPCC (2001)

GHG's and aerosol direct effects

**Summary for Policymakers**

A Report of Working Group I of the Intergovernmental Panel on Climate Change
INDIRECT EFFECT
For a given liquid water path, cloud albedo is highly sensitive to cloud drop number concentration or radius.
For a given liquid water path, cloud albedo is highly sensitive to cloud drop number concentration or radius.
Indirect forcing is highly sensitive to small perturbations in cloud drop concentration.

A 30% increase in cloud drop concentration results in a forcing of ~1 W m$^{-2}$. 

Schwartz and Slingo (1996)
The large spread in the relation between aerosol particle and cloud drop number concentration leads to great uncertainty in modeled CDNC.
Indirect forcing is highly sensitive to the assumed relation between sulfate concentration and cloud droplet number concentration.
## UNCERTAINTY BUDGET FOR INDIRECT FORCING BY INDUSTRIAL AEROSOLS

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Central Value</th>
<th>2/3 Uncertainty Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background $N_d$ for Northern Hemisphere marine (cm$^{-3}$)</td>
<td>140</td>
<td>66 to 214</td>
</tr>
<tr>
<td>Perturbed $N_d$ for Northern Hemisphere marine (cm$^{-3}$)</td>
<td>217</td>
<td>124 to 310</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>
</tr>
<tr>
<td>Background sulfate concentration (g m$^{-3}$)</td>
<td>1.5</td>
<td>0.85 to 2.15</td>
</tr>
<tr>
<td>Cloud layer thickness (m)</td>
<td>200</td>
<td>100 to 300</td>
</tr>
<tr>
<td>Perturbed sulfate concentration (g m$^{-3}$)</td>
<td>3.6</td>
<td>2.4 to 4.8</td>
</tr>
<tr>
<td>Susceptible cloud fraction, $f_c$</td>
<td>0.24</td>
<td>0.19 to 0.29</td>
</tr>
<tr>
<td>Atmospheric transmission above cloud layer, $T_a$</td>
<td>0.92</td>
<td>0.78 to 1.00</td>
</tr>
<tr>
<td>Mean surface albedo</td>
<td>0.06</td>
<td>0.03 to 0.09</td>
</tr>
</tbody>
</table>

Result: If central value is $-1.4$ Wm$^{-2}$, the 2/3 uncertainty range is from 0 to $-2.8$ Wm$^{-2}$.

*Modified from Penner et al., IPCC, 2001*
The global mean radiative forcing of the climate system for the year 2000, relative to 1750.

- **Radiative forcing (Watts per square metre)**
- **Level of Scientific Understanding**

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

**GHG's and aerosol direct and indirect effects**

- **CO$_2$**
- **CH$_4$**
- **N$_2$O**
- **Halocarbons**
- **Tropospheric ozone**
- **Stratospheric ozone**
- **Sulphate**
- **Organic carbon from fossil fuel burning**
- **Biomass burning**
- **Black carbon from fossil fuel burning**
- **Mineral Dust**
- **Aerosols**
- **Aerosol indirect effect**

**Summary for Policymakers**

A Report of Working Group I of the Intergovernmental Panel on Climate Change
WHY SO LARGE UNCERTAINTY IN AEROSOL FORCING?

• Uncertainties in knowledge of atmospheric composition

  Mass loading and chemical and microphysical properties and cloud nucleating properties of anthropogenic aerosols, and geographical distribution.

  At present and as a function of secular time.

• Uncertainties in knowledge of atmospheric physics of aerosols

  Relating direct radiative forcing and cloud modification by aerosols to their loading and their chemical and microphysical properties.

The U.S. Department of Energy has initiated a new research program examining aerosol chemistry and physics pertinent to radiative forcing of climate change.
Welcome to the ASP website!

The Department of Energy's Atmospheric Science Program has as its long-term goal developing comprehensive understanding of the atmospheric processes that control the transport, transformation, and fate of energy related trace chemicals and particulate matter. The current focus of the program is aerosol radiative forcing of climate: aerosol formation and evolution and aerosol properties that affect direct and indirect influences on climate and climate change.

2005 Science Team Meeting

The first annual science team meeting of the reconfigured Atmospheric Science Program took place January 25-27 in Charleston, South Carolina. A key component of the meeting was a series of ten-minute presentations by each principal investigator. The purpose of these presentations was to convey to the rest of the Program participants the objectives of the individual projects (what the investigator intends to do), the approach (how he or she intends to do it), the requirements of the project (what is required from others--other science projects and program infrastructure) and the products (what it is intended to provide to others; who would use, or even better, rely on, what will be produced in the project).
Working Groups

- Gas-Particle Interaction
- New Particle Formation
- Aerosol Optical Properties
- Cloud-Aerosol Interactions

- Instrument Development
- Laboratory Studies
- Field Studies
- Model Development and Evaluation

- MASE 2005
- MAX-Mex 2006
- ? Houston 2006
- ? St. Louis 2007
The global mean radiative forcing of the climate system for the year 2000, relative to 1750

Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
ADDING UP THE FORCINGS
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

With total aerosol forcing

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

Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change
Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

With total aerosol forcing and total forcing

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

Radiative forcing (Watts per square metre)

Cooling

-2

-1

0

1

2

3

Warming

Total Forcing

Total Aerosol Forcing

Level of Scientific Understanding

High

Medium

Medium

Low

Very Low

Very Low

Very Low

Very Low

Very Low

Very Low

Very Low

Very Low

Very Low

Halocarbons

N₂O

CH₄

CO₂

Tropospheric ozone

Aerosols

Black carbon from fossil fuel burning

Mineral Dust

Aviation-induced

Contrails Cirrus

Solar

Stratospheric ozone

Sulphate

Organic carbon from fossil fuel burning

Biomass burning

Aviation-induced

Contrails Cirrus

Land-use (albedo) only

Aerosol indirect effect

Land-use (albedo) only
The global mean radiative forcing of the climate system for the year 2000, relative to 1750.

**Radiative Forcing Over the Industrial Period**

**IPCC (2001)**

With total aerosol forcing.

**Summary for Policymakers**

A Report of Working Group I of the Intergovernmental Panel on Climate Change
The global mean radiative forcing of the climate system for the year 2000, relative to 1750.
The global mean radiative forcing of the climate system for the year 2000, relative to 1750

Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change

Schwartz, JAWMA, 2005
REPRESENTING AEROSOL INFLUENCES IN CLIMATE MODELS
FORCING AND RESPONSE IN THE CANADIAN CLIMATE MODEL (2000)

Model sensitivity = 3.5 K per CO$_2$ doubling; sulfate direct forcing only, -1.0 W m$^{-2}$ (1990)

“Observed global mean temperature changes and those simulated for GHG + aerosol forcing show reasonable agreement.” -- Boer, et al., Climate Dynamics, 2000
The surface temperature time series from the five GHG-plus-sulfate integrations show an increase over the last century, which is broadly consistent with the observations.” -- Delworth & Knutson, Science, 2000

Model sensitivity = 2.18 K per CO₂ doubling; sulfate direct forcing only, -0.6 W m⁻² (1990)

FORCING AND RESPONSE IN THE UK MET OFFICE MODEL (2000)

Model sensitivity = 3.45 K per CO2 doubling; sulfate + indirect forcing, -1.1 W m\(^{-2}\) (1990)

“The ALL ensemble \textit{captures the main features} of global mean temperature changes observed since 1860.” -- Stott, Tett, Mitchell, \textit{et al.}, Science, 2000
Simulations that include estimates of natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20th century.

Most model estimates that take into account both greenhouse gases and sulphate aerosols are consistent with observations over this period.
FORCING AND RESPONSE IN THE GISS MODEL (2005)

Model sensitivity = 2.7 K per CO\textsubscript{2} doubling; direct (incl BC) and indirect, -1.39 W m\textsuperscript{-2} (2003)

“Good fit of observed and modeled temperatures also could be attained with smaller forcing and larger climate sensitivity, or with the converse.” -- Hansen et al., Science, 2005.
UNCERTAINTY PRINCIPLES

Climate sensitivity $\lambda = \Delta T / F$

The fractional uncertainty in climate sensitivity $\lambda$ is evaluated from fractional uncertainties in temperature change $\Delta T$ and forcing $F$ as:

$$\frac{\delta \lambda}{\lambda} = \sqrt{\left(\frac{\delta \Delta T}{\Delta T}\right)^2 + \left(\frac{\delta F}{F}\right)^2}$$

A reasonable target uncertainty might be:

$$\frac{\delta \lambda}{\lambda} = 30\%, \text{ e.g., } \Delta T_{2\times\text{CO}_2} = (3 \pm 1) \text{ K}$$

This would require uncertainties in temperature anomaly and forcing:

$$\frac{\delta \Delta T}{\Delta T} \approx \frac{\delta F}{F} \approx 20\%.$$ 

This imposes **stringent requirements on accuracy of aerosol forcing!**
REQUIRED ACCURACY IN AEROSOL FORCING

Uncertainty in total forcing not to exceed 20%

GHG Forcing (well mixed gases + strat and trop O₃) = 2.6 W m⁻² ± 10%

Uncertainty in aerosol forcing must be reduced by at least a factor of 3 to meet requirements for determining climate sensitivity.
CONCLUSIONS

• Radiative forcing of climate change by anthropogenic aerosols is substantial in the context of other forcings of climate change over the industrial period.

  Global annual mean aerosol forcing of -1 to -3 W m\(^{-2}\) is plausible given present understanding.

• Uncertainty in radiative forcing of climate change by anthropogenic aerosols is the greatest source of uncertainty in forcing of climate change.

  This uncertainty precludes:
  - Evaluation of models of climate change.
  - Inference of climate sensitivity from temperature changes over the industrial period.
  - Informed policy making on greenhouse gases.

• Uncertainty in aerosol forcing must be reduced at least three-fold for uncertainty in climate sensitivity to be meaningfully reduced and bounded.
SOME CONCLUDING OBSERVATIONS

- GHG concentrations and forcing are increasing. GHGs persist in the atmosphere for decades to centuries.
- Aerosol forcing is comparable to greenhouse gas forcing but much more uncertain.
- Hence total forcing over the industrial period is highly uncertain.
- Hence the sensitivity of the climate system remains highly uncertain.
- Climate sensitivity will remain uncertain unless and until aerosol uncertainty is substantially decreased.
- Decisions must be made in an uncertain world. (Lack of controls on GHG emissions is also a decision).
RADIATIVE FORCING OF CLIMATE CHANGE
BY AEROSOLS

WHY THIS IS IMPORTANT
AND HOW WELL IT NEEDS TO BE KNOWN

Thank You
