Aerosols in the IPCC Reports
TAR vs AR4

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The big picture

- We’ve come a long way with understanding the RF of aerosols,

AND

- We have a long way to go!
IPCC TAR (2001)

Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750

Global mean radiative forcing (Wm$^{-2}$)

- Greenhouse gases
  - Halocarbons
  - N$_2$O
  - CH$_4$
  - CO$_2$
- Tropospheric ozone
- Stratospheric ozone

Aerosols + clouds
- Black carbon from fossil fuel burning
- Mineral Dust
- Aviation Contrails Cirrus
- Organic carbon from fossil fuel burning
- Biomass burning
- Aerosol indirect effect
- Land use (albedo only)

The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present, the vertical line only indicates the range in best estimates with no likelihood.

LEVEL OF SCIENTIFIC UNDERSTANDING
- High
- Medium
- Low
- Very low
IPCC AR4 (2007)

- Total aerosol direct & indirect effect

Radiative Forcing (W m⁻²)

- Total net anthropogenic

RF Terms
- Long-lived greenhouse gases
  - CO₂
  - N₂O
  - CH₄
  - Halocarbons
- Ozone
  - Stratospheric
  - Tropospheric
- Stratospheric water vapour from CH₄
- Surface albedo
- Land use
- Black carbon on snow
- Total Aerosol
  - Direct effect
  - Cloud albedo effect
- Linear contrails
- Solar irradiance

RF values (W m⁻²) and Spatial scale

- CO₂: 1.66 [1.49 to 1.83] Global High
- N₂O: 0.48 [0.43 to 0.53] Global High
- CH₄: 0.16 [0.14 to 0.18] Global High
- Halocarbons: 0.34 [0.31 to 0.37] Global High
- Stratospheric: -0.05 [-0.15 to 0.05] Continental to Global Med
- Tropospheric: 0.35 [0.25 to 0.65] Continental to Global Med
- Stratospheric water vapour from CH₄: 0.07 [0.02 to 0.12] Global Low
- Surface albedo: -0.2 [-0.4 to 0.0] Local to continental Med - Low
- Land use: 0.1 [0.0 to 0.2] Local to continental Med - Low
- Black carbon on snow: -0.5 [-0.9 to -0.1] Continental to Global Med - Low
- Total Aerosol: -0.7 [-1.8 to -0.3] Continental to Global Med - Low
- Linear contrails: 0.01 [0.003 to 0.03] Continental Low
- Solar irradiance: 0.12 [0.06 to 0.30] Global Low
- Total net anthropogenic: 1.6 [0.6 to 2.4]
What are aerosols?
Tiny solid particles (usually a mixture of the types below, plus water)

<table>
<thead>
<tr>
<th>Type</th>
<th>Min. Size</th>
<th>% Anthrop.</th>
<th>Key Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfate</td>
<td>0.01 um</td>
<td>75%</td>
<td>fossil fuel combustion</td>
</tr>
<tr>
<td>Organic Carbon</td>
<td>0.01 um</td>
<td>75% ?</td>
<td>industry</td>
</tr>
<tr>
<td>Black Carbon</td>
<td>0.01 um</td>
<td>90%</td>
<td>fossil fuel combustion</td>
</tr>
<tr>
<td>Nitrate</td>
<td>0.01 um</td>
<td>75% ?</td>
<td>fossil fuel combustion</td>
</tr>
<tr>
<td>Dust</td>
<td>1 um</td>
<td>40%</td>
<td>deserts</td>
</tr>
<tr>
<td>Sea Salt</td>
<td>1 um</td>
<td>0%</td>
<td>oceans</td>
</tr>
</tbody>
</table>

Human-influenced

Nucleation mode
- typical size: ~1 um
- unactivated haze

Accumulation mode
- typical size: ~10 um
- cloud drops

Drizzle mode
- typical size: ~100 um
- drizzle

If Kohler curve is overcome, coagulation occurs.
Why are aerosols important?

Aerosols & Climate:
Global cooling effect, but spatially variable forcings may affect global circulation (e.g. regional warming or cooling)

Direct effect:
- Albedo

Indirect effect:
1st indirect effect: Albedo
2nd indirect effect: Cloud lifetime
Semidirect effect: Stability

Addressed in AR4
Why are aerosols important?

Climate Cooling

Direct effect

Indirect effect

Acid Rain (sulfates)

Health Effects

Reduced Visibility

\[
\text{SO}_2(g) + \text{O}_2 \rightarrow \text{SO}_3(g) + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4
\]
Aerosol Growth

0.2 to 2 um diameters scatter the most light per unit mass

Hydration (dotted line) has higher SSA but less per unit aerosol mass

IPCC, 2001
Improvements TAR→ AR4

“We’ve come a long way….”

• Satellites
  – New generation sensors
  – Adv. retrieval - fine mode fraction, effective particle radius
  – Better algorithms
  – Measuring size dist, composition, scattering, absorption
  – Longer continuous running satellite obs to compare models to
  – Plus, new dedicated aerosol instruments
    • POLDER
      – 0.44-0.91 um spectral channels
      – Several viewing angles
      – Measures polarization of rad., $\tau_{aer}$, $A$, over oceans
      – Measures $\tau_{aer}$ over land
    • MISR
      – New aerosol type distinction algorithms
      – Mutiple viewing capability for brighter surfaces
      – Radiance signature measured using 9 viewing geometries; 2 radiances
Improvements TAR→ AR4

“We’ve come a long way….”

- Surface observations
  - More of them - near global retrieval now
    - 150 AERONET sites (surface sunphotometer)
    - 11 MPLNET sites (LIDAR network)
    - 15 EARLINET sites (European LIDAR network)
    - 12 ADNET sites (Asian LIDAR network)

Compared to satellite obs with improved consistency since TAR
Improvements TAR→AR4

“We’ve come a long way….”

**Modeling**
- Higher resolution (better than 2° x 2°; 20 vertical levels)
- Incorporation of more chemical species
- Increased number of runs
  - 16 groups in AEROCOM initiative
- Better (but still variable) consistency in $\tau_{aer}$ across models
  - Global $\tau_{aer}$ ranges from 0.11 to 0.14
  - But regional temporal distributions have larger variation
- More comparisons to (and agreement with) obs

*Direct effect uncertainty reduced by a factor of 2*
Remaining Issues
“…and we have a long way to go”

• Satellite + surface obs
  – Significant discrepancies still exist - RF variability reflects this
  – Challenges distinguishing Anthropogenic/Natural aerosols

• Modeling compared to obs
  – Modelled $\tau_{aer}$ 2-4 times lower than observations
  – Aerosol distributions, compositions, size uncertainty

• All models share some misleading limitations
  – Parameterizations
  – Similar emissions databases

• Clouds!
  – Algorithms for obs
  – Indirect effects for models
RF Calculations

• Mean values
  – TOA
  – Global-mean quantity integrated over 24 hours
  – Includes the effects of clouds
  – AEROCOM & other studies included

• Standard deviations
  – Model results statistics included
  – For AEROCOM results, emissions uncertainty is added to the error
Sulfate Direct RF

<table>
<thead>
<tr>
<th>Study</th>
<th>Direct RF (Wm⁻²)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg</td>
<td>Std Dev</td>
<td></td>
</tr>
<tr>
<td>TAR</td>
<td>-0.40</td>
<td></td>
<td>UF = 2</td>
</tr>
<tr>
<td>Non-AEROCOM</td>
<td>-0.46 ± 0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AEROCOM</td>
<td>-0.35 ± 0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AR4</td>
<td>-0.40 ± 0.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

“We’ve come a long way…."

- High confidence in optical parameters
  \( \omega_o = 1 \) (but minor absorption in near-IR)
  \( f_{RH} \) well understood
  Sig. contribution to accum. mode mass, \( \tau_{aer} \) and RF
  Average hasn’t changed; error reduced

“…and we have a long way to go”

- Internal/External mixtures are common, not well understood, and cause changes in optical properties
Black Carbon Direct RF

<table>
<thead>
<tr>
<th>Study</th>
<th>Direct RF (Wm⁻²)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg</td>
<td>Std Dev</td>
</tr>
<tr>
<td>TAR</td>
<td>+0.20</td>
<td>UF = 2</td>
</tr>
<tr>
<td>Non-AEROCOM</td>
<td>+0.13</td>
<td>± 0.03</td>
</tr>
<tr>
<td>AEROCOM</td>
<td>+0.22</td>
<td>± 0.11</td>
</tr>
<tr>
<td>AR4</td>
<td>+0.20</td>
<td>± 0.10</td>
</tr>
</tbody>
</table>

“We’ve come a long way….”
- BC has complex chain structure; collapses as it ages; modifies optical properties
- Absorbs strongly across most wavelengths
- Average hasn’t changed; error reduced

“And we have a long way to go”
- Uncertainty in split between anthrop/natural
- Internal/External mixtures…
Organic Carbon Direct RF

<table>
<thead>
<tr>
<th>Study</th>
<th>Direct RF (Wm$^{-2}$)</th>
<th>Avg</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAR</td>
<td>-0.10</td>
<td></td>
<td>UF = 3</td>
</tr>
<tr>
<td>Non-AEROCOM - total</td>
<td>-0.24</td>
<td>± 0.08</td>
<td></td>
</tr>
<tr>
<td>Non-AEROCOM - FF only</td>
<td>-0.06</td>
<td>± 0.03</td>
<td></td>
</tr>
<tr>
<td>AEROCOM - total</td>
<td>-0.18</td>
<td>± 0.10</td>
<td></td>
</tr>
<tr>
<td>AEROCOM - FF only</td>
<td>-0.04</td>
<td>± 0.02</td>
<td></td>
</tr>
<tr>
<td>AR4</td>
<td>-0.10</td>
<td>± 0.10</td>
<td></td>
</tr>
</tbody>
</table>

“We’ve come a long way….”

• TAR had virtually a “wild guess”
• Improvements in understanding composition; internal/external mixing

“And we have a long way to go”

• Internal/External mixtures; optical properties…lots of room for improvement
Nitrate Direct RF

<table>
<thead>
<tr>
<th>Study</th>
<th>Direct RF (Wm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg</td>
</tr>
<tr>
<td>Van Dorland (1997)</td>
<td>-0.03</td>
</tr>
<tr>
<td>Jacobson (2001)</td>
<td>-0.16</td>
</tr>
<tr>
<td>Adams et al (2001)</td>
<td>-0.22</td>
</tr>
<tr>
<td>TAR</td>
<td>N/A</td>
</tr>
<tr>
<td>Martin et. Al (2004)</td>
<td>-0.06</td>
</tr>
<tr>
<td>Liao and Seinfeld (2005)</td>
<td>-0.16</td>
</tr>
<tr>
<td>AR4</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

“We’ve come a long way….”
- TAR had no confidence in an estimate
- Additional studies conducted; slightly better agreement

“…and we have a long way to go”
- Limited studies!
- Internal/External mixtures; optical properties…lots of room for improvement
Mineral Direct RF

<table>
<thead>
<tr>
<th>Study</th>
<th>Direct RF (Wm⁻²)</th>
<th>Avg</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAR</td>
<td>+0.4 to -0.6</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Liao et al (2004)</td>
<td>+0.1</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Reddy et. al (2005a)</td>
<td>-0.14</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Jacobsen (2001)</td>
<td>-0.13</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Myhre and Stordal (2001a)</td>
<td>-0.70</td>
<td>± 0.60</td>
<td></td>
</tr>
<tr>
<td>AEROCOM LSCE</td>
<td>-0.30</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>AR4</td>
<td>-0.10</td>
<td>± 0.10</td>
<td></td>
</tr>
</tbody>
</table>

“We’ve come a long way….”

• TAR had very little confidence - just a range
• Additional studies conducted; enough confidence to estimate an RF

“…and we have a long way to go”

• Limited studies! Large disagreement!
• Anthropogenic component; optical properties…lots of room for improvement
**Combined Species RF**

<table>
<thead>
<tr>
<th>Study</th>
<th>Direct RF (Wm(^{-2}))</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg</td>
<td>Std Dev</td>
<td></td>
</tr>
<tr>
<td>TAR</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Simulation (minus nit, dust)</td>
<td>-0.20</td>
<td>± 0.20</td>
<td></td>
</tr>
<tr>
<td>Estimated with nit, dust</td>
<td>-0.40</td>
<td>± 0.30</td>
<td></td>
</tr>
<tr>
<td>Bellouin et al (2005)</td>
<td>-0.80</td>
<td>± 0.10</td>
<td></td>
</tr>
<tr>
<td>Chung et al (2005)</td>
<td>-0.35</td>
<td>± 0.25</td>
<td></td>
</tr>
<tr>
<td>Yu et al (2006)</td>
<td>-0.50</td>
<td>± 0.33</td>
<td></td>
</tr>
<tr>
<td>AR4</td>
<td>-0.50</td>
<td>± 0.40</td>
<td></td>
</tr>
</tbody>
</table>

“We’ve come a long way….”

- TAR had no confidence in an overall estimate
- Extensive validation/constraint conducted between models and observations since then
- Nonlinear interactions between species makes an educated overall effect more reliable than adding each species individually

“…and we have a long way to go”

- Still a lot of disagreement/uncertainty
### Aerosol Anthropogenic Direct RFs

<table>
<thead>
<tr>
<th>Type</th>
<th>TAR (Wm(^{-2})) Avg</th>
<th>U.F.**</th>
<th>AR4 (Wm(^{-2})) Avg</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>-0.40</td>
<td>2</td>
<td>-0.40</td>
<td>± 0.20</td>
</tr>
<tr>
<td>Black Carbon</td>
<td>+0.20</td>
<td>2</td>
<td>+0.20</td>
<td>± 0.10</td>
</tr>
<tr>
<td>Organic Carbon</td>
<td>-0.10</td>
<td>3</td>
<td>-0.10</td>
<td>± 0.10</td>
</tr>
<tr>
<td>Nitrate</td>
<td>N/A</td>
<td>N/A</td>
<td>-0.10</td>
<td>± 0.10</td>
</tr>
<tr>
<td>Mineral Dust</td>
<td>+0.4 to -0.6</td>
<td>N/A</td>
<td>-0.10</td>
<td>± 0.20</td>
</tr>
<tr>
<td>Biomass Burning*</td>
<td>-0.2</td>
<td>3</td>
<td>+0.00</td>
<td>± 0.10</td>
</tr>
<tr>
<td>Combined</td>
<td>N/A</td>
<td>N/A</td>
<td>-0.50</td>
<td>± 0.40</td>
</tr>
</tbody>
</table>

AR4 RFs remain similar to TAR…with a narrower range (except biomass burning)

*Produces OC, BC, nitrate, sulfate….separate category due to unlikelihood of regulating components from this emissions source

**Uncertainty Factor – too many unknowns for a std dev; range is approximately x times the average
### Aerosol Anthropogenic Indirect RFs

<table>
<thead>
<tr>
<th>Study</th>
<th>Indirect RF (Wm(^{-2}))</th>
<th>Avg</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAR</td>
<td>N/A</td>
<td>0 to -2</td>
<td></td>
</tr>
<tr>
<td>AR4 – All 16 models</td>
<td>-1.09</td>
<td>± 0.47</td>
<td></td>
</tr>
<tr>
<td>AR4 – 8 most confident models*</td>
<td>-0.90</td>
<td>± 0.43</td>
<td></td>
</tr>
<tr>
<td>POLDER</td>
<td>-0.85</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>AVHRR</td>
<td>-0.64</td>
<td>± 0.16</td>
<td></td>
</tr>
<tr>
<td>AR4</td>
<td>-0.90</td>
<td>± 0.43</td>
<td></td>
</tr>
</tbody>
</table>

*Models w/ higher resolution and incorporating numerous chemical species

"We’ve come a long way…"
- TAR had no confidence in an overall estimate; just a wide range
- Extensive validation/constraint conducted between models and observations since then

"…and we have a long way to go"
- Still a lot of disagreement/uncertainty
- *ONLY 1\(^{st}\) indirect effect taken into account (cloud albedo effect)
IPCC TAR (2001)

Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750

Global mean radiative forcing (Wm^-2)

Warming

- Greenhouse gases
- Halocarbons
- N_2O
- CH_4
- CO_2
- Tropospheric ozone

Cooling

- Stratospheric ozone

The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.

LEVEL OF SCIENTIFIC UNDERSTANDING

- High
- Medium
- Medium
- Low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low

No total aerosol RF
No indirect effect
Total aerosol direct & indirect effect
Aerosol Summary - AR4 vs TAR

“We’ve come a long way….”

- Aerosol total direct RF and indirect effect calculated
- “LOSU” increased from low/very low to medium/low
- Good news – averages haven’t changed much
- Increased aerosol confidence level contributed to confidence in anthropogenic cause of earth’s increasing surface T
  - TAR - “Likely” (66%)
  - AR4 - “Very Likely” (90%)

“…and we have a long way to go”

- Clouds!
  - Algorithms for obs
  - Indirect effects for models
- Aerosol spatial distributions, compositions, size distributions
- Better understand model parameterizations
- Improve observations