Aerosol particles and their seasonal variability

Are aerosol particles important for seasonal prediction?

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Acknowledgments: Anna Lewinschal, Hamish Struthers
Outline

• Aerosol particles in the atmosphere.
• Aerosol direct and indirect effects.
• Aerosol particles, circulation and precipitation:
  – the weakening of the South Asian summer monsoon.
  – changes in extra-tropical stationary wave patterns.
• Aerosol particles and the large-scale surface temperature distribution.
• Conclusions, questions, discussion...
What is an aerosol?

“An aerosol is a suspension of small solid and/or liquid particles in a gas (air)”
Typical atmospheric aerosol components

- Sea salt
- Dust
- Sulfate
- Ammonia
- Nitrate
- Organic carbon
- Soot (or BC)
- Water
- ...

Stockholm University
TOA radiative forcing year 2000 vs. 1750

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF values (W m²)</th>
<th>Spatial scale</th>
<th>LOSU</th>
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</thead>
<tbody>
<tr>
<td><strong>Long-lived greenhouse gases</strong></td>
<td></td>
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<tr>
<td>CO₂</td>
<td>1.66 [1.49 to 1.83]</td>
<td>Global</td>
<td>High</td>
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<tr>
<td>N₂O</td>
<td>0.48 [0.43 to 0.53]</td>
<td>Global</td>
<td>High</td>
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<tr>
<td>CH₄</td>
<td>0.16 [0.14 to 0.18]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>0.34 [0.31 to 0.37]</td>
<td>Global</td>
<td>High</td>
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<tr>
<td><strong>Ozone</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Stratospheric</td>
<td>-0.05 [-0.15 to 0.05]</td>
<td>Continental</td>
<td>Med</td>
</tr>
<tr>
<td>Tropospheric</td>
<td>0.35 [0.25 to 0.65]</td>
<td>Continental</td>
<td>Med</td>
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<tr>
<td><strong>Stratospheric water</strong></td>
<td></td>
<td></td>
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<tr>
<td>vapour from CH₄</td>
<td>0.07 [0.02 to 0.12]</td>
<td>Global</td>
<td>Low</td>
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<tr>
<td><strong>Surface albedo</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Land use</td>
<td></td>
<td>Local to</td>
<td>Med</td>
</tr>
<tr>
<td>Black carbon on snow</td>
<td>-0.2 [-0.4 to 0.0]</td>
<td>continental</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Total aerosol</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct effect</td>
<td>-0.5 [-0.8 to -0.1]</td>
<td>Continental</td>
<td>Med - Low</td>
</tr>
<tr>
<td>Cloud albedo effect</td>
<td>-0.7 [-1.8 to -0.3]</td>
<td>Continental</td>
<td>Low</td>
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<tr>
<td><strong>Linear contrails</strong></td>
<td></td>
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<td></td>
<td>0.01 [0.003 to 0.05]</td>
<td>Continental</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Solar irradiance</strong></td>
<td>0.12 [0.06 to 0.30]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Total net anthropogenic</strong></td>
<td>1.6 [0.6 to 2.4]</td>
<td>Global</td>
<td>Low</td>
</tr>
</tbody>
</table>

IPCC, 2007
Trends in anthropogenic aerosol particle and precursor emissions [Tg yr$^{-1}$]

Lamarque et al. (2010)
January-March, 2001

August-October, 2001

IPCC, 2007, based on MODIS data
Measured aerosol particle size and number concentration

Riipinen et al. (2007)
Example of state-of-the-art aerosol module in an ESM

CAM-Oslo aerosol module, Seland et al. (2008)
How good are state-of-the-art aerosol modules in global models?

Shindell et al. (2012)
What is the cause of uncertainty?

**Aerosols**
(mass, number, size composition)

- Wet deposition
- Transport
- Secondary aerosol formation
- Natural aerosol emissions
- ...

**Meteorology/Climate**
(wind, temperature, cloudiness, precipitation)

- Number of CCN/IN
- Aerosol composition and mixing state
Aerosol direct and indirect effects

Aerosol direct effect

Aerosol indirect effects

\[ \text{aerosols as cloud condensation nuclei (CCN) or ice nuclei (IN)} \]

Aerosol 1st indirect effect

Aerosol 2nd indirect effect
Aerosol direct and indirect effects

Aerosol direct effect

Aerosol 1st indirect effect

Aerosol 2nd indirect effect

Changes in the radiative balance

How big impact?
Aerosol direct and indirect effects

Aerosol direct effect  Aerosol 1st indirect effect  Aerosol 2nd indirect effect

Changes in the radiative balance

Changes in large-scale circulation
Aerosol effects on atm. circulation and precipitation

- Anthropogenic aerosols may have weakened the South Asian summer monsoon. (e.g. Ramanathan et al., 2005; Chung and Ramanathan, 2006; Wang et al., 2009; Bollasina et al., 2011; Ganguly et al., 2012).

- Anthropogenic aerosols may affect the Walker circulation and associated precipitation patterns. (Bollasina et al., 2011; Rotstayn et al., 2012; Lewinschal et al., in prep.)

- Anthropogenic aerosols affect tropical precipitation (directly and indirectly) which induces changes in extra-tropical wave patterns. (Rodwell and Jung, 2008; Ming et al., 2011; Lewinschal et al., 2012).

- Anthropogenic aerosols (especially BC?) may cause a widening of the NH tropical belt (Allen et al., 2012).
Precipitation trends over the South Asian monsoon region (Jun-Sep, 1950-1999)

Bollasina et al. (2011)
Precipitation trends over the South Asian monsoon region (Jun-Sep, 1950-1999)

Bollasina et al. (2011)
Aerosols and the weakening of the South Asian summer monsoon

Change explained by "thermodynamic scaling" argument

Bollasina et al. (2011)
Aerosols and the weakening of the South Asian summer monsoon

Surface Radiative Flux Perturbation (Jun-Sep)
Aerosols and the weakening of the South Asian summer monsoon

Change due to SH-NH temperature gradient

Bollasina et al. (2011)
Simulated (CAM-Oslo) monthly AOD variability over Asia (40-year simulation)
Aerosols and changes in extratropical stationary wave patterns.

- Aerosol particles, through their direct and indirect effects, have a potential of altering the location and strength of tropical precipitation (Chen and Ramaswamy, 1996; Ramaswamy and Chen, 1997; Chung et al., 2002; Rotstayn and Lohmann, 2002; Wang, 2004; Allen et al., 2012).

- Latent heat release in tropical deep convection is a major diabatic heat source in the atmosphere.

- Tropical heating is well known to excite waves propagating into the extra-tropics (Hoskins and Karoly, 1981; Simmons, 1982; Jin and Hoskins, 1995; Ting, 1996; Held et al., 2002).
Aerosols and changes in extra-tropical stationary wave patterns.

**Aerosols:**
Direct effect of sulfate, black carbon, organic carbon, dust and sea salt

Present-day (PD) = 2000
Pre-Industrial (PI) = 1850

Aerosol data from
Lamarque et al. (2010)

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Lewinschal et al. (2012)
Radiative forcing and temperature response: PD-PI, DJF

Lewinschal et al. (2012)
Radiative forcing and temperature response: PD-PI, DJF

Δ geopotential height @ 300 hPa [m]

Contour interval = 5m

2m temperature response [K]

Lewinschal et al. (2012)
Analysis using linear baroclinic model LUMA

**Convective precipitation [mm day⁻¹]**

![Map showing convective precipitation](image)

**Linear stream function @ 0.35 [m²s⁻¹]**

![Map showing linear stream function](image)

**Equation:***

\[ Y^* = -L^{-1}F \]

- \( Y^* \) = perturbed state
- \( L \) = linear operator
- \( F \) = Forcing

Contour interval = \( 10^4 \) m²s⁻¹

Lewinschel et al. (2012)
Change in geopotential height (EC-EARTH) vs. Change in linear stream function (LUMA)

EC-Earth

\[ \Delta \text{geopotential height @ 300 hPa [m]} \]

Contour interval = 5m

LUMA

\[ \Delta \text{Linear stream function @ 0.35 [m}^2\text{s}^{-1}] \]

Contour interval = \(10^4\) m^2s\(^{-1}\)

Lewinschal et al. (2012)
Aerosols and changes changes in extra-tropical stationary wave patterns.

- Aerosol forcing → tropical precipitation anomalies → Rossby waves → extra-tropical surface temperature change.

(Rodwell and Jung, 2008):

- A more realistic aerosol climatology introduced in IFS led to improved local medium-range forecast skill and reductions in seasonal-mean errors (wind, temperature) throughout the globe.
Aerosol effects on weather and climate

Aerosol direct effect

Aerosol 1st indirect effect

Aerosol 2nd indirect effect

Changes in the radiative balance

Changes in large-scale circulation
Aerosol effects on weather and climate

Aerosol direct effect  Aerosol 1st indirect effect  Aerosol 2nd indirect effect

Changes in the radiative balance

What is the local impact on $T_{sfc}$?
The aerosol direct effect
The aerosol direct effect
Radiative forcing and temperature response: PD-PI, DJF

Due to the model and/or that only direct aerosol effects are simulated?

Lewinschal et al. (2012)
Interactive Aerosol - Global Climate Model: CAM-Oslo

- CAM-Oslo is based on the NCAR-CAM3 general circulation model (Collins et al., 2006).
- In the current set-up, CAM-Oslo is coupled to a mixed-layer ocean.
- Five prognostic aerosol compounds are considered: Sulfate (SO$_4$), organic matter (POM), black carbon (BC), sea salt (SS) and mineral dust (DU), cf. Seland et al. (2008).
- Two gaseous aerosol precursors are also considered: dimethylsulfide (DMS), and sulfur dioxide (SO$_2$).
- 70 years of equilibrium climate simulations are conducted for the years 2000 and 1970. Last 40 years used for the analysis.
- Both aerosol direct and indirect (albedo and precipitation) effects are considered.
Trends in anthropogenic aerosol particle and precursor emissions [Tg yr\(^{-1}\)]

- SO\(_2\): -15%
- Black carbon: +42%
- Organic carbon: +32%

Lamarque et al. (2010)
Change in TOA SW RF and $T_{\text{surface}}$
2000-1970 Aero

Total Radiative Forcing
Global average: $-0.18 \text{ Wm}^{-2}$

$T_{\text{surface}}$ change
Global average: $-0.24 \text{ K}$
Change in $T_{sfc}$ 2000-1970 (CAM-Oslo)
Change in 300 hPa geopotential 2000-1970 (CAM-Oslo)

GHG

AERO

GHG + AERO

NCEP
Conclusions

• Aerosol particles display a high temporal and spatial variability, i.e. there is a possibility for fast, relatively localized, forcing and response.

• The amount (and type) of aerosol particles over Asia can affect the Indian monsoon, the Hadley circulation and the Walker circulation.

• Aerosol particles affect (directly and indirectly) tropical precipitation (location and intensity) and thereby also extratropical stationary waves and surface temperatures.

• In the extra-tropics, the direct relation between the change in SW radiative fluxes and the pattern of surface temperature change is small.

• Other links between aerosols and seasonal prediction: volcanoes, dust storm outbreaks....