“Global hydrological cycle impacts: Are they larger than those of greenhouse gases?”

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With contributions from:

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Beate Liepert (Columbia University, New York)
Outline of my talk

• Aerosol impacts on the hydrological cycle by affecting the surface energy budget
• Aerosol impacts on the hydrological cycle via changes in riming rate (accretion of snow flakes with cloud droplets)
• Aerosol impacts on the hydrological cycle via changes in ice nucleation
• Conclusions
Climate model simulations

- ECHAM4-T31-L19 [Roeckner et al., 1996]
- Mixed layer ocean, thermodynamic sea-ice model
- Aerosol and sulfur chemistry model-bulk approach [Feichter et al., 1996; Lohmann et al., 1999]

3 pairs of simulations: Each pair consists of a simulation
for present-day conditions (1985)
and
for pre-industrial conditions (1860)
Each simulations is run for 50 years after a 25 year spin-up

1. Varying GHG concentrations (simulation GHG)
2. Varying aerosol emissions (simulation AP)
3. Varying both GHG and aerosol emissions (simulation GHG+AP)
Indirect effects of aerosols on the hydrological cycle?

- **CCN**
- **Oxidation, Nucleation**
- **SO$_2$, NO$_x$, Organics, Soot**
- **Water cloud**

Aerosol washout by precipitation

- More aerosols
- More and smaller cloud droplets
- Less rain production
- Clouds last longer
- Sunlight ↓
- Evaporation ↓
- Precipitation ↓

Industry

Biomass burning

Automobiles

Soil dust saltation
Can aerosols spin down the water cycle in a warmer and moister world? [Liepert et al., GRL, 2004]

Climate model simulations (atmosphere+ocean) for the present-day climate (1985) and a pre-industrial climate (1860) allowing both greenhouse gas and aerosol concentrations to increase
Can aerosols spin down the water cycle in a warmer and moister world? [Liepert et al., GRL, 2004]
Can aerosols spin down the water cycle in a warmer and moister world? [Courtesy: Hans Feichter]
Can aerosols spin down the water cycle in a warmer and moister world? [Liepert et al., GRL, 2004]

**Figure 3.** Simulated changes in (a) evaporation (colors) and net surface solar radiation (contours) and (b) precipitation (colors) and net surface solar radiation (contours).
Can aerosols spin down the water cycle in a warmer and moister world? [Liepert et al., GRL, 2004]

<table>
<thead>
<tr>
<th>Change</th>
<th>Land</th>
<th>Ocean</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ Cloud cover %</td>
<td>+0.0</td>
<td>+0.0</td>
<td>+0.0</td>
</tr>
<tr>
<td>Δ Cloud optical depth</td>
<td>+0.02</td>
<td>+0.03</td>
<td>+0.02</td>
</tr>
<tr>
<td>Δ Liquid water path g/m²</td>
<td>+13</td>
<td>+10</td>
<td>+11</td>
</tr>
<tr>
<td>Δ Ice water path g/m²</td>
<td>+0.07</td>
<td>-0.09</td>
<td>-0.05</td>
</tr>
</tbody>
</table>

Δ Aerosol optical depth
-0.07
+0.02
+0.03

Δ Column water vapour g/m²
+980
+1200
+1130

Δ Precipitation mm/d
-0.05 (-0.06N -0.04S)
-0.02 (-0.07N +0.01S)
-0.03

Δ Evaporation mm/d
-0.03 (-0.04N -0.01S)
-0.03 (-0.06N -0.01S)
-0.03

Δ Solar heating
-5.2 -3.2 -3.8 W/m²

Δ Infrared heating
-2.0 -1.8 -1.9 W/m²

Δ Sensible heating
-1.5 -0.8 -1.0 W/m²

Δ Latent heating
-0.9 -0.8 -0.8 W/m²

Δ T_surface K
+0.6 +0.5 +0.5
Change in net solar surface radiation [W/m²]

GHG&AP: $\Delta F = -3.8 \text{ W/m}^2$

AP: $\Delta F = -2.9 \text{ W/m}^2$

GHG: $\Delta F = -1.0 \text{ W/m}^2$

($GHG+AP: \Delta F = -3.9 \text{ W/m}^2$)
Change in net terrestrial surface radiation [W/m²]

GHG+AP: $\Delta F = -1.8$ W/m²
AP: $\Delta F = +0.4$ W/m²
GHG: $\Delta F = -2.2$ W/m²

(GHG+AP: $\Delta F = -1.8$ W/m²)
Change in sensible heat flux [W/m$^2$]

GHG+AP: $\Delta F = -1.0$ W/m$^2$
AP: $\Delta F = -0.1$ W/m$^2$
GHG: $\Delta F = -0.5$ W/m$^2$

($GHG+AP: \Delta F = -0.6$ W/m$^2$)
Change in sens. heat and wind speed

Annual Mean Change in 10 m Wind Speed

GHG+AP

GHG
Change in sensible heat and temp. gradient
Change in latent heat flux [W/m²]

GHG&AP: \(\Delta F = -0.8\) W/m²
AP: \(\Delta F = -3.2\) W/m²
GHG: \(\Delta F = 1.8\) W/m²

\((GHG+AP: \Delta F = -1.4\) W/m²\)
Change in precipitation [mm/d]

GHG&AP: \( \Delta P = -0.03 \) mm/d

AP: \( \Delta P = -0.11 \) mm/d

GHG: \( \Delta P = +0.06 \) mm/d

\((GHG+AP): \Delta P = -0.05 \) mm/d\)
Hydrodynamic sensitivity

Differences between global annual mean present-day and pre-industrial aerosol levels:

<table>
<thead>
<tr>
<th></th>
<th>GHG&amp;AP</th>
<th>GHG</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-m temperature [K]</td>
<td>0.6</td>
<td>1.3</td>
<td>-0.9</td>
</tr>
<tr>
<td>Precipitation [%]</td>
<td>-1.1</td>
<td>2.3</td>
<td>-3.5</td>
</tr>
<tr>
<td><em>Hydrological sensitivity [%/K]</em></td>
<td>-1.9</td>
<td>1.7</td>
<td>3.9</td>
</tr>
</tbody>
</table>
Conclusions thus far:

• In coupled atmosphere-mixed layer ocean climate simulations with increases in greenhouse gases and aerosols, solar radiation at the Earth’s surface is reduced due to the increased aerosol and cloud optical thickness caused by anthropogenic aerosols.

• The reduced solar radiation at the surface is compensated by reduced fluxes of sensible and latent heat in agreement with the observations by Roderick and Farquhar (2002).

• → Precipitation has to decrease (evaporation=precipitation in the global mean)

• → The global water cycle could be slower in a future warmer and moister climate.
Indirect Effects of Aerosols on the Snowfall Rate?

- CCN
- Oxidation, Nucleation
- SO$_2$, NO$_x$, Organics, Soot
- Soil dust saltation

Sources:
- Industry
- Biomass burning
- Automobiles

Effect:
- Water cloud
- Snowing cloud
Observations in orographic midlatitude clouds show an inverse relationship of sulfate and cloud droplets with snowfall rate [Borys et al. 2000]

**Graphs**

- **Graph (a)**: Snowfall Rate (mm hr⁻¹) vs. CAE Sulfate Concentration (µg/m³)
  - Slope: -0.26±0.08
  - Intercept: 0.34±0.05
  - N: 50
  - R²: 0.19

- **Graph (c)**: CAE Sulfate Concentration (µg/m³) vs. Snowfall Rate (mm hr⁻¹)
  - Slope: -0.115±0.053
  - Intercept: 0.21±0.05
  - N: 14
  - R²: 0.28

**Conditions**

- **All cases**
- **LWC > 0.2 g m⁻³**
Climate model simulations set-up

- Three 10 year-simulations (horizontal resolution: 3.75°*3.75°)
- **CTL**: constant riming efficiency (Esw=0.1)
- **ESWpl**: size dependent Esw assuming planar crystals
  [Mitchell, 1990]
- **ESWagg**: size dependent Esw assuming aggregates
  [Lew et al., 1986]
Implications of using a size-dependent accretion efficiency for the anthropogenic aerosol effect: Changes between pre-industrial and present-day times:

CTL, ESWpl, ESWagg

Aerosol optical depth
Cloud droplet radius [μm]
Liquid water path [g/m²]
Riming rate [mg m⁻² s⁻¹]
Snow and total precip [mm/d]
Shortwave radiation TOA (top of atmosphere) and surface [W/m²]
Ice water path [g/m²]
Surface temperature [K]
Change in temperature (K) and ice water content (mg/kg) due to anthropogenic aerosols
How big is the effect of a reduced collection efficiency for snowflakes with water drops globally?

Differences between present-day and pre-industrial aerosol levels and percentage change from pre-industrial values in parenthesis:

<table>
<thead>
<tr>
<th></th>
<th>CTL</th>
<th>ESWpl</th>
<th>ESWagg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riming rate [mg/m²/s]</td>
<td>0.06 (4)</td>
<td>-0.09 (3)</td>
<td>-0.04 (1)</td>
</tr>
<tr>
<td>Snowfall rate [mm/d]</td>
<td>0.003 (2)</td>
<td>0.003 (2)</td>
<td>0.003 (2)</td>
</tr>
<tr>
<td>Total precip [mm/d]</td>
<td>-0.05 (2)</td>
<td>-0.05 (2)</td>
<td>-0.05 (2)</td>
</tr>
<tr>
<td>Surface temperature [K]</td>
<td>-0.028 (0.2)</td>
<td>-0.025 (0.2)</td>
<td>-0.023 (0.2)</td>
</tr>
<tr>
<td>Ice water path [g/m²]</td>
<td>0.18 (2)</td>
<td>0.20 (2)</td>
<td>0.16 (2)</td>
</tr>
</tbody>
</table>
Riming aerosol effect conclusions:

• Midlatitude data suggest that there is an effect of anthropogenic aerosols on the snowfall rate through inhibition of riming.

• Examination of this effect in global climate model simulations shows that the riming rate in stratiform clouds has indeed decreased due to the smaller cloud droplets in polluted clouds, but the snowfall rate has actually increased.

• This is caused by the pollution induced increase in aerosol and cloud optical thickness which reduces the solar radiation and causes a cooling that favors precipitation formation via the ice phase.
Pathways of the traditional warm indirect aerosol effect and the glaciation indirect aerosol effect [Lohmann, 2002]
Experimental design

• **Motivation:** Laboratory studies \cite{Gorbunov et al. 2001} show that hydrophilic soot is an effective contact ice nuclei.

• Pre-industrial simulations: No fossil fuel use and no biomass burning.

• Present-day simulations: All aerosol sources

• Conduct different pairs of 5 year simulations with ECHAM4 in T30 horizontal resolution (3.75° x 3.75°):
  – *BC0%*: Only dust acts as contact ice nuclei
  – *BC1% (BC10%)*: 1% (10%) of the hydrophilic soot (BC) acts as contact ice nuclei in addition to dust
Differences in cloud water (LWC) and cloud ice (IWC) [mg/kg] between present-day and pre-industrial times
Differences between present-day and pre-industrial times:

- BC0%
- BC1%
- BC10%
Global mean differences between present-day and pre-industrial aerosol levels

<table>
<thead>
<tr>
<th>Experiment</th>
<th>BC10%</th>
<th>BC1%</th>
<th>BC0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ Aerosol burden (Tg)</td>
<td>-1.1</td>
<td>-1.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Δ Liquid water path (g m⁻²)</td>
<td>-3.0</td>
<td>7.9</td>
<td>18.4</td>
</tr>
<tr>
<td>Δ Ice water path (g m⁻²)</td>
<td>0.5</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Δ Cloud cover (%)</td>
<td>-1.3</td>
<td>-0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Δ Precipitation (mm d⁻¹)</td>
<td>0.05</td>
<td>-0.02</td>
<td>-0.05</td>
</tr>
<tr>
<td>Δ $F_{SW}^{\text{TOA}}$ (W m⁻²)</td>
<td>+1.9</td>
<td>-1.0</td>
<td>-2.1</td>
</tr>
<tr>
<td>Δ $F_{LW}^{\text{TOA}}$ (W m⁻²)</td>
<td>-3.5</td>
<td>-0.5</td>
<td>+0.6</td>
</tr>
<tr>
<td>Δ $F_{\text{NET}}^{\text{TOA}}$ (W m⁻²)</td>
<td>-1.6</td>
<td>-1.5</td>
<td>-1.5</td>
</tr>
</tbody>
</table>
Main results from this study:

- Laboratory results showed that hydrophilic black carbon (soot) is a good ice nuclei.
- Simulations using the ECHAM4 climate model showed that the model is very sensitive to the amount of soot acting as ice nuclei.
- The glaciation indirect aerosol effect can at least partially offset the shortwave indirect aerosol effect on warm clouds and could have the opposite influence on precipitation.
Overall conclusions:

• Aerosol effects on the hydrological cycle can be as least as important as those on the radiation balance
• Probably the largest impacts on the hydrological cycle stem from changes in the surface energy budget
• This can have regional consequences, such as causing droughts in the Sahel or floods in China/India (➔ Surabi’s, Leon’s & Danny’s talk)
• Greenhouse gases and aerosol effect are not linear in terms of the hydrological sensitivity (➔ Jeff’s talk)
Annual mean change in 2 m temperature (K)

GHG+AP: $\Delta T = +0.6$ K

AP: $\Delta T = -0.9$ K

GHG: $\Delta T = 1.3$ K

(GHG+AP: $\Delta T = 0.4$ K)
Vertically integrated anthropogenic aerosol mass

**GHG&AP:**
\[ \Delta T = +0.6 \, \text{K} \]
\[ \Delta AOD = 0.053 \]

**AP:**
\[ \Delta T = -0.9 \, \text{K} \]
\[ \Delta AOD = 0.032 \]
### Increase in GHG concentrations

<table>
<thead>
<tr>
<th>Surface Budget</th>
</tr>
</thead>
</table>
| Δ S (down)     | < 0  
| Δ S (up)       | < 0  
| Δ S (net)      | < 0  
| Δ L (down)     | > 0  
| Δ L (up)       | > 0  
| Δ L (net)      | < 0  
| Δ SH           | < 0  
| Δ LH           | > 0  
| Δ T            | > 0  
| Δ P            | > 0  
| Δ P / Δ T      | > 0  

**Warming effect**

**Cooling effect**
## Increase in aerosol emissions

<table>
<thead>
<tr>
<th>Surface Budget</th>
<th>( \Delta S ) (down)</th>
<th>(&lt; 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta S ) (up)</td>
<td>(&lt; 0)</td>
</tr>
<tr>
<td></td>
<td>( \Delta S ) (net)</td>
<td>(&lt; 0)</td>
</tr>
<tr>
<td></td>
<td>( \Delta L ) (down)</td>
<td>(&lt; 0)</td>
</tr>
<tr>
<td></td>
<td>( \Delta L ) (up)</td>
<td>(&lt; 0)</td>
</tr>
<tr>
<td></td>
<td>( \Delta L ) (net)</td>
<td>(&gt; 0)</td>
</tr>
<tr>
<td></td>
<td>( \Delta SH )</td>
<td>(&lt; 0)</td>
</tr>
<tr>
<td></td>
<td>( \Delta LH )</td>
<td>(&lt; 0)</td>
</tr>
<tr>
<td></td>
<td>( \Delta T )</td>
<td>(&lt; 0)</td>
</tr>
<tr>
<td></td>
<td>( \Delta P )</td>
<td>(&lt; 0)</td>
</tr>
<tr>
<td></td>
<td>( \Delta P / \Delta T )</td>
<td>(&gt; 0)</td>
</tr>
</tbody>
</table>
### Increase in GHG and aerosol concentrations

<table>
<thead>
<tr>
<th>Surface Budget</th>
<th>Δ S (down)</th>
<th>&lt; 0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δ S (up)</td>
<td>&lt; 0</td>
</tr>
<tr>
<td></td>
<td>Δ S (net)</td>
<td>&lt; 0</td>
</tr>
<tr>
<td>Δ L (down)</td>
<td>&gt; 0</td>
<td></td>
</tr>
<tr>
<td>Δ L (up)</td>
<td>&gt; 0</td>
<td></td>
</tr>
<tr>
<td>Δ L (net)</td>
<td>&lt; 0</td>
<td></td>
</tr>
<tr>
<td>Δ SH</td>
<td>&lt; 0</td>
<td></td>
</tr>
<tr>
<td>Δ LH</td>
<td>&lt; 0 !!!</td>
<td></td>
</tr>
<tr>
<td>Δ T</td>
<td>&gt; 0</td>
<td></td>
</tr>
<tr>
<td>Δ P</td>
<td>&lt; 0 !!!</td>
<td></td>
</tr>
<tr>
<td>Δ P / Δ T</td>
<td>&lt; 0 !!!</td>
<td></td>
</tr>
</tbody>
</table>

- **Netto-Forcing > 0**

- Warming effect
- Cooling effect