Aerosol Effects on Cirrus Clouds

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Aerosol Effects on Mixed-phase and Cirrus Clouds

Fig. 1. Schematic diagram of the effect of ice nuclei from various possible aerosol sources on midlevel precipitating clouds and cirrus ice clouds. The likely but uncertain change in the magnitude of the general cooling impact (blue arrows) of midlevel clouds and warming impact (red arrows) of high cirrus clouds in response to increases in the relative number concentrations of IN is indicated (see text for further description).

DeMott et al. (2010)
Cirrus (Ice) Ice Nucleation

Multiple mechanisms for ice formation can be active.

**Ice Crystal Population**

**Homogeneous Freezing**
Mainly depends on $RH_i$ and $T$

**Wet aerosol particles**

**Heterogeneous Freezing**
(Immersion, deposition, …)
Also depends on the material and surface area

$+ \text{ Insoluble Material ("Ice Nuclei")}$

http://www.alanbauer.com
Motivation

- Ice nucleation mechanisms in cirrus (ice) are uncertain
  - Heterogeneous vs homogeneous nucleation balance
  - Role of different types of aerosols as heterogeneous ice nuclei (IN) is uncertain: dust, black carbon (BC-soot), ‘glassy’ aerosol, biological aerosol

- Aerosol effects on cirrus clouds are not well quantified.

- The goal of our study is to investigate the impact of ice nucleation on cirrus clouds.
Two-moment prognostic cloud microphysics for liquid and ice (Morrison and Gettelman 2008)

Modal aerosol module for aerosol microphysics (Liu et al. 2012)

Ice nucleation in cirrus clouds \((T<-37^\circ C)\) (Liu and Penner 2005)
- Homogeneous freezing on sulfate in competition with
- Heterogeneous nucleation on dust aerosol

Ice nucleation in mixed-phase clouds \((T>-37^\circ C)\) (Liu et al. 2007)
- Meyers et al. (1992) for deposition/condensation nucleation
- Bigg (1953) for immersion freezing of cloud droplets
- Young (1974) for contact freezing of cloud droplets by dust aerosol

Ice supersaturation, explicit vapor deposition and ice sedimentation
**Liu and Penner (2005):** consider the competition between homogeneous (HOM) and heterogeneous (HET) immersion nucleation (hereafter LP). Heterogeneous nucleation based on classical nucleation theory (CNT).

**Barahona and Nenes (2008a,b; 2009):** develop a framework that can use different IN nucleation spectra for HET, and consider the competition of HOM and HET (hereafter BN). IN spectra:

- Classical nucleation theory (Pruppacher and Klett 1997)
- CFDC measurement (Phillips et al. 2008)
Ice Mass vs. CloudSat

A) CAM IWC+SNOW (mg/m3)

B) CloudSat (color) & MLS (contour) IWC

C) CAM IWC+SNOW (mg/m3) 232hPa

D) CloudSat Ann IWC (mg/m3) 225hpa

Gettelman et al. 2010
Ice Number and Size vs. Krämer Data
Gettelman, Liu et al. (2012)

A) T v. Ice Concentration, (300-80 hPa, -60 to 75 lat)

B) T v. Ice Radius, (300-80 hPa, -60 to 75 lat)
Impacts of Heterogeneous IN Spectrum

Barahona and Nenes (2008a,b; 2009)

1. Philips et al. (2008): CFDC measurements

\[
N_{\text{het}}(s_i) = N_{\text{dust}} \left[ 1 - \exp \left( -\frac{2}{3} H_{\text{dust}}(s_i, T) \frac{N_{\text{het, PDG07}}}{7.92 \times 10^4} \right) \right] + N_{\text{soot}} \left[ 1 - \exp \left( -\frac{1}{3} H_{\text{soot}}(s_i, T) \frac{N_{\text{het, PDG07}}}{1.04 \times 10^6} \right) \right]
\]

Turn off soot

1. Classical nucleation theory (CNT)

\[
N_{\text{het}}(s_i) = 0.05 \left[ \min \left( \frac{s_i}{0.2} N_{\text{dust}} e^{-0.0011 k_{\text{hom}}(0.2-s_i)}, N_{\text{dust}} \right) + \min \left( \frac{s_i}{0.3} N_{\text{soot}} e^{-0.039 k_{\text{hom}}(0.3-s_i)}, N_{\text{soot}} \right) \right]
\]

Maximum freezing ratio

Sensitivity to Heterogeneous Nucleation

Classical nucleation theory

Phillips et al. (2008)
Effect of maximum freezing ratio limit (CNT scheme)

5% (Barahana and Nenes, 2009)

100% (Liu & Penner; Hoose et al. 2010)
**Global Annual Means (Present-Day Climate)**

<table>
<thead>
<tr>
<th></th>
<th>SWCF</th>
<th>LWCF</th>
<th>CLDHGH</th>
<th>CLDTOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN_Phillips</td>
<td>-56.2</td>
<td>31.9</td>
<td>42.7</td>
<td>66.6</td>
</tr>
<tr>
<td>BN_CNT_5%</td>
<td>-56.5</td>
<td>31.7</td>
<td>42.3</td>
<td>66.4</td>
</tr>
<tr>
<td>BN_CNT_10%</td>
<td>-56.2</td>
<td>31.4</td>
<td>42.3</td>
<td>66.3</td>
</tr>
<tr>
<td>BN_CNT_100%</td>
<td>-55.7</td>
<td>30.8</td>
<td>43.3</td>
<td>66.9</td>
</tr>
</tbody>
</table>

\[ \Delta \text{(SWCF)} = +0.8 \text{ W/m}^2, \Delta \text{(LWCF)} = -0.9 \text{ W/m}^2 \]

20 x IN ➔

\[ \Delta \text{(SWCF)} = +0.8 \text{ W/m}^2, \Delta \text{(LWCF)} = -0.9 \text{ W/m}^2 \]
Impacts of Black Carbon

Adding a small (0.1%) amount of BC to LP (classical nucleation theory) shifts balance of nucleation towards more heterogeneous nucleation, ice number increases for cirrus, but mass gets slightly smaller.

Literature: BC efficiency values should be 0.1% or less…

Classical nucleation theory very sensitive to how much BC…

![Graphs showing impact of 0.1% BC on homogeneous and heterogeneous nucleation with and without BC addition.](graph.png)
Impacts of Black Carbon

With 2% BC

No BC

With 0.1% BC
# Global Annual Means (Present-Day Climate)

<table>
<thead>
<tr>
<th></th>
<th>SWCF</th>
<th>LWCF</th>
<th>IWP</th>
<th>INC150</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LP</strong></td>
<td>-51.8</td>
<td>24.0</td>
<td>17.7</td>
<td>111</td>
</tr>
<tr>
<td><strong>LP_BC_0.1%</strong></td>
<td>-51.5</td>
<td>23.6</td>
<td>17.5</td>
<td>102</td>
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<tr>
<td><strong>LP_BC_2%</strong></td>
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<td>31.5</td>
<td>22.3</td>
<td>184</td>
</tr>
<tr>
<td><strong>LP_BC_100%</strong></td>
<td>-78.3</td>
<td>51.8</td>
<td>33.9</td>
<td>2180</td>
</tr>
</tbody>
</table>

### 0.1% BC
- $\Delta$ (SWCF) = +0.3 W/m², $\Delta$ (LWCF) = -0.4 W/m²

### 2% BC
- $\Delta$ (SWCF) = -6.0 W/m², $\Delta$ (LWCF) = +7.5 W/m²
Aerosol Indirect Effects on Cirrus
Gettelman, Liu et al. (2012)

- Perform RFP experiments (PD and PI) with IPCC emissions
- Climatological SST & sea ice and same GHG
- Diagnostics of ice AIE in two different ways: (1) Fixed ice nucleation in cirrus

AIE (liquid + ice) = -1.36 W/m²

AIE (liquid) = -1.58 W/m² (no aerosol effect on ice clouds by fixing ice nuclei number in cirrus as a function of temperature)
Perform RFP experiments changing emissions
Climatological SST & sea ice and same GHG
Diagnostics of ice AIE in two different ways: (2) Fixed droplet number

AIE (ice) = 0.31 W/m² (CAM5)
AIE (ice) = 0.19 W/m² (BN)
Intercomparison of Aerosol Effects on Cirrus Clouds under AEROCOM

- Invite GCMs with capability of aerosol-cirrus cloud interactions to participate; also satellite and in situ data analysis
- Submit GCM simulations (PD & PI):
  - Homogeneous nucleation only
  - Homogeneous and heterogeneous combined
  - Fixed ice nucleation in cirrus clouds
- Analysis of variables:
  - \( w \), \( \text{Ni} \), \( \text{Reff} \), IWP, cloud cover, \( \text{Qv} \), cloud forcing

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