Cirrus clouds and ice supersaturated regions in global climate models

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Different indirect aerosol effects

- **Cloud albedo effect (Twomey or first indirect effect):**
  More aerosols → more and smaller cloud droplets per given liquid water path → more reflection of solar radiation (Twomey, 1959)

- **Cloud lifetime effect (Albrecht or second indirect effect):**
  More smaller cloud droplets collide less efficiently → less drizzle → longer cloud lifetime → more reflection of solar radiation (Albrecht, 1989)

- **Aerosol effect on cirrus clouds:** Same shortwave effects as for water clouds but also impacts on longwave radiation
Annual mean cirrus cloud amount

Joos et al. (2008)
Trend in cirrus cloudiness?

Minnis et al. (2004)
**Trend in cirrus cloudiness?**

**Motivation**

Cirrus formation in GCMs
Het. freezing
New studies
Conclusions

**Cirrus in ECHAM5**

**Trend in cirrus cloudiness?**

![Graph showing trends in cirrus cloudiness over different regions](image)

**Fig. 3.** Annual variation of CC over (a) five land regions [WASIA, WEUR, LOR, ERA, and United States (USA)] and (b) ocean regions (NA, NP, and OOR).

Minnis et al. (2004)

→ better understanding of cirrus clouds is needed
Homogeneous freezing of supercooled aerosols

- freezing rates are well-established; field data support lab results
- important ice formation mechanism in the UT (and LS)
- role of heterogeneous processes unclear

First step in the development of a physically-based parameterization of cirrus formation.
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Tompkins et al. (2007)
**Governing equations**

\[
\frac{dS_i}{dt} = a_1 S_i w - (a_2 + a_3 S_i) R_i \tag{1}
\]

\[
R_i = \frac{\rho_i}{m_w} \int_{-\infty}^{t} dt_0 \hat{n}_i(t_0) 4\pi r_i^2(t_0, t) \frac{dr_i}{dt}(t_0, t) \tag{2}
\]

\[
\hat{n}_i = \int_{r_s}^{\infty} dr_0 \frac{4\pi}{3} r_0^3 J \frac{dn}{dr_0}, \quad n_i = \int_{r_s}^{\infty} dr_0 \frac{dn}{dr_0} \tag{3}
\]

\[
\frac{dr_i}{dt} = \frac{b_1 (S_i - 1)}{1 + b_2 r_i} \tag{4}
\]

**Solution strategy**
- choose suitable ansatz for nucleation pulse
- evaluate (1) at the time where $S_i$ reaches a peak

**Two distinct timescales**

\[
\tau_f = \left[ c \left| \frac{\partial \ln(J)}{\partial T} \right| \frac{dT}{dt} \right]^{-1} \quad \tau_g = \left[ \frac{b_1 (S_{cr} - 1)/r_0}{1 + b_2 r_0} \right]^{-1}
\]

freezing ($\propto 1/w$) \quad \text{initial growth} ($\propto 1/n_{sat}$)
Governing equations

Solution character

\[ \tau_f \gg \tau_g : \text{fast growth (high } T, \text{ low } w, \text{ small } r_0) \text{ – the system loses memory about initial conditions} \]

\[ \tau_f \ll \tau_g : \text{slow growth (low } T, \text{ high } w, \text{ large } r_0) \text{ – vapor depletion controlled by frz haze distribution} \]
Homogeneous freezing including size effects

**Figure:** Parcel model results (symbols); parameterization (lines)

Kärcher and Lohmann (2002)
Homogeneous freezing in climate models

- Abandon the saturation adjustment scheme and allow supersaturation with respect to ice
- Solve the depositional growth equation:

\[ Q_{dep} = 4\pi CA_T f_{Re} (S_i - 1) N_i \]  \hspace{1cm} (1)

where \( A_T \) = thermodynamic term, \( C \) = capacitance, \( f_{Re} \) = ventilation factor

\[ N_i^{HOM} \propto w^{3/2} N_{si}^{-1/2} (T) \]  \hspace{1cm} (2)

and \( w = \bar{w} + 0.7\sqrt{TKE} \)
Validation of vertical velocity

NH data: 26.2 cm/s
ECMWF (synoptic): 1.3 cm/s
ECHAM (large-scale): 0.9 cm/s
ECHAM: 7.8 cm/s

Kärcher and Ström (2003)
Validation of supersaturation

Tompkins et al. (2007)
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Liu et al. (2007)
Heterogeneous vs. homogeneous freezing

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Cziczo et al. (2004)
Homogeneous vs. heterogeneous freezing

Figure: Grey line: homogeneous freezing; black lines: competition heterogeneous vs. homogeneous freezing

Kärcher et al. (2006)
Evidence of crystalline ammonium sulfate as ice nucleus?

Abbatt et al. (2006)
Effects on radiation

**Figure:** Annual zonal mean ice water path and ice crystal number for simulations HOM, AS1, AS10, AS100. Differences of the short- and longwave cloud forcing vs. HOM: AS1, AS10, AS100  

Abbatt et al. (2006)
Model set-up in the ECHAM5 studies

- T42 horizontal resolution (∼ 2.8° x 2.8°), 19 vertical levels
- 5 year-simulations after a 3-months spin-up
- Different simulations:
  - ECHAM5-hom: Reference simulation with ECHAM5 employing only homogeneous freezing and using $\alpha = 0.5$ for deposition and sublimation
  - ECHAM5-het: As ECHAM5-hom, but with heterogeneous immersion freezing instead of homogeneous freezing. $N_{IN} = \text{number of immersed dust nuclei}$ (Hoose et al., 2008)
  - ECHAM5-homhet: heterogeneous freezing for $N_{IN} > 1 \text{ l}^{-1}$, homogeneous freezing otherwise
  - ECHAM5-alpha: As ECHAM5-hom, but with $\alpha$ reduced to 0.006 (Magee et al., 2006)
Solution droplets versus immersed dust nuclei

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Solution droplets \( [\text{cm}^{-3}] \) ECHAM5–hom

Immersed dust nuclei \( [\text{cm}^{-3}] \) ECHAM5–het

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Importance of $\alpha$

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Cirrus in ECHAM5

Magee et al. (2006)
Zonal mean results

- Ice water path ($0.7 < \tau < 3.8$) [g m$^{-2}$]
- Effective ice crystal radius [$\mu$m]
- Ice crystal number conc. [$10^{10}$ m$^{-2}$]
- Total cloud cover [%]
- Shortwave cloud forcing [W m$^{-2}$]
- Longwave cloud forcing [W m$^{-2}$]

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Frequency distribution of ice supersaturation in NH midlatitudes and tropics

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Observations from MOZAIC and MLS
Supersaturated regions

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ISSR 147 hPa (MLS)
ISSR 215 hPa (MLS)

ISSR <200 hPa ECHAM5–hom
ISSR >200 hPa ECHAM5–hom

ISSR <200 hPa ECHAM5–het
ISSR >200 hPa ECHAM5–het

ISSR <200 hPa ECHAM5–homhet
ISSR >200 hPa ECHAM5–homhet

ISSR <200 hPa ECHAM5–alpha
ISSR >200 hPa ECHAM5–alpha

1 2 3 5 7 10 15 20 30 50 %
Table: Global annual mean ice water path (IWP), vertically integrated ice crystal number ($N_i$), total cloud cover (CC) and shortwave (SCF) and longwave (LCF) cloud forcing at the top-of-the-atmosphere.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>ECH5-hom</th>
<th>ECH5-het</th>
<th>ECH5-homhet</th>
<th>ECH5-alpha</th>
<th>OBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>IWP, g m$^{-2}$</td>
<td>13.8</td>
<td>14.9</td>
<td>14.8</td>
<td>8.6</td>
<td>25.2</td>
</tr>
<tr>
<td>$N_i$, 10$^{10}$ m$^{-2}$</td>
<td>0.28</td>
<td>0.17</td>
<td>0.18</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>TCC, %</td>
<td>66.0</td>
<td>64.1</td>
<td>64.3</td>
<td>71.2</td>
<td>62-67</td>
</tr>
<tr>
<td>SCF, W m$^{-2}$</td>
<td>-52.2</td>
<td>-50.7</td>
<td>-51.1</td>
<td>-68.4</td>
<td>-47 to -50</td>
</tr>
<tr>
<td>LCF, W m$^{-2}$</td>
<td>27.1</td>
<td>24.5</td>
<td>25.0</td>
<td>47.4</td>
<td>22-30</td>
</tr>
</tbody>
</table>
Conclusions

▶ Introducing a cirrus scheme (i.e. abandoning saturation adjustment schemes) into GCMs reproduces the observed frequency of ice supersaturation in different GCMs

▶ Anthropogenic ice nuclei (soot, crystalline ammonium sulfate, maybe organics) could lead to an inverse cloud albedo effect in cirrus clouds

▶ Decreasing the mass accommodation coefficient $\alpha$ to 0.006 enhances the ice crystal number by a factor of 25. Comparisons with observations suggest that such a low value of $\alpha$ is not appropriate for a GCM.

▶ There is some support for some limited heterogeneous freezing, possibly due to immersed mineral dust particles, in addition to a pronounced homogeneous freezing pathway.