Cirrus clouds and ice supersaturated regions in global climate models

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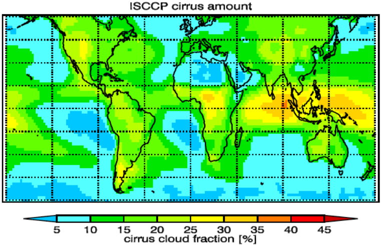
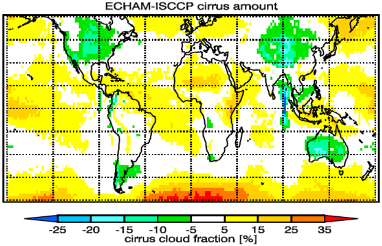
Different indirect aerosol effects

- 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

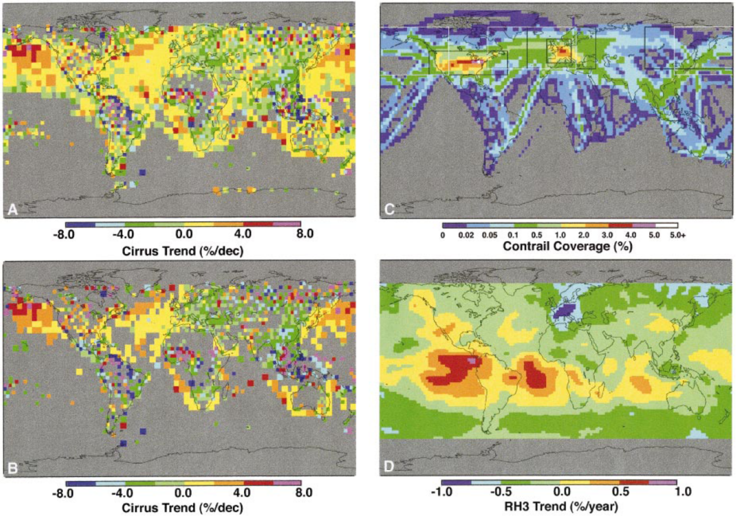
Annual mean cirrus cloud amount





Joos et al. (2008)

Trend in cirrus cloudiness?



Minnis et al. (2004)

Trend in cirrus cloudiness?

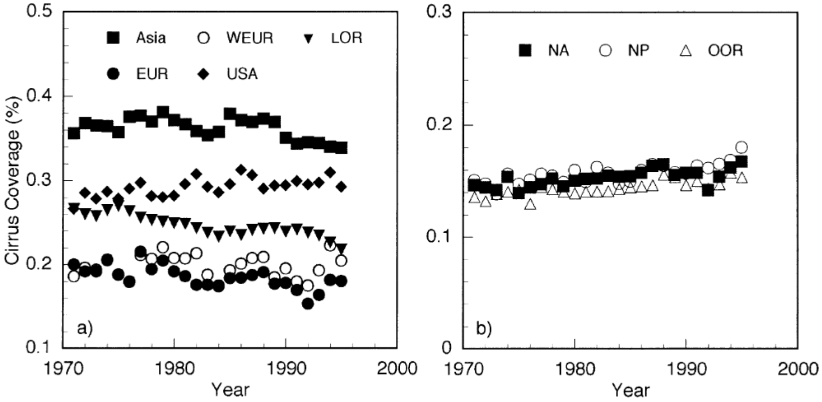
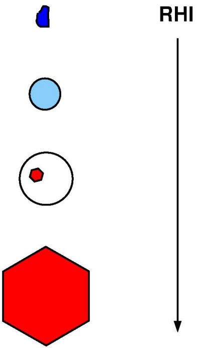


FIG. 3. Annual variation of CC over (a) five land regions [WASIA, WEUR, LOR, ERA, and United States (USA)] and (b) ocean regions (NA, NP, and OOR).

Minnis et al. (2004)

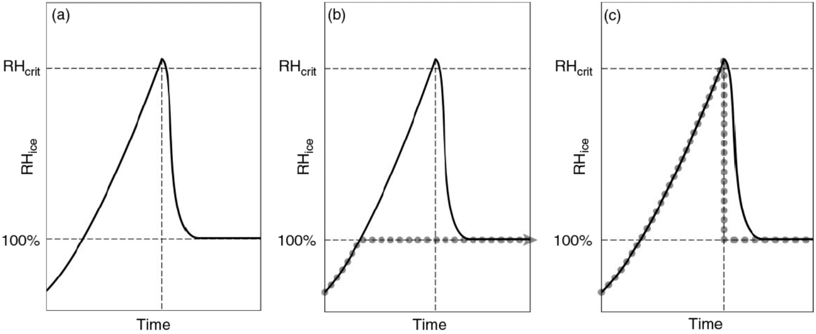
→ better understanding of cirrus clouds is needed

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.



Tompkins et al. (2007)

Governing equations

$$\frac{dS_i}{dt} = a_1 S_i w - (a_2 + a_3 S_i) R_i \qquad (1)$$

$$R_i = \frac{\rho_i}{m_w} \int_{-\infty}^{t} dt_0\, \dot{n}_i(t_0)\, 4\pi r_i^2(t_0,t)\, \frac{dr_i}{dt}(t_0,t) \qquad (2)$$

$$\dot{n}_i = \int_{r_s}^{\infty} dr_0 \frac{4\pi}{3} r_0^3 J \frac{dn}{dr_0}, \quad n_i = \int_{r_s}^{\infty} dr_0 \frac{dn}{dr_0} \qquad (3)$$

$$\frac{dr_i}{dt} = \frac{b_1 (S_i - 1)}{1 + b_2 r_i} \qquad (4)$$

Solution strategy

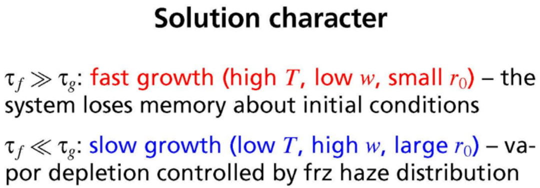
- choose suitable ansatz for nucleation pulse
- evaluate (1) at the time where S_i reaches a peak

Two distinct timescales

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

freezing ($\propto 1/w$) initial growth ($\propto 1/n_{\mathrm{sat}}$)

Governing equations



Solution character

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

$\tau_f \ll \tau_g$: slow growth (low T, high w, large r_0) – vapor depletion controlled by frz haze distribution

Homogeneous freezing including size effects

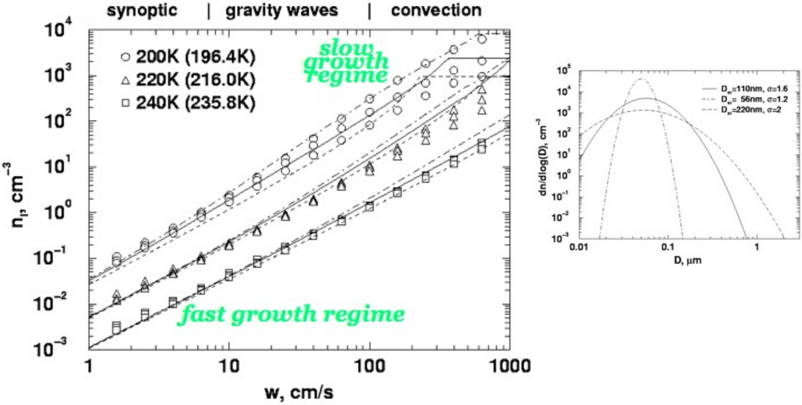


Figure: Parcel model results (symbols); parameterization (lines)

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:

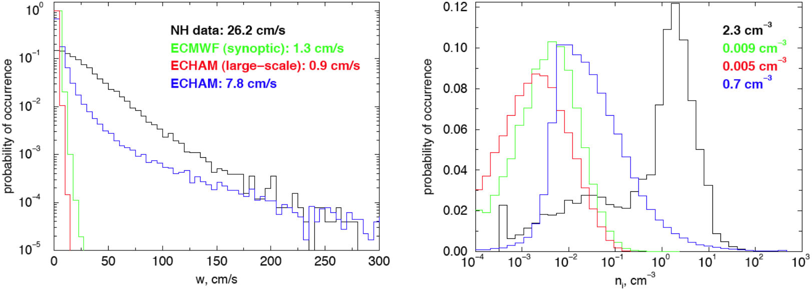
$$Q_{dep} = 4\pi C A_T f_{Re} (S_i - 1) N_i \tag{1}$$

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

$$N_i^{HOM} \propto w^{3/2} N_{si}^{-1/2}(T) \tag{2}$$

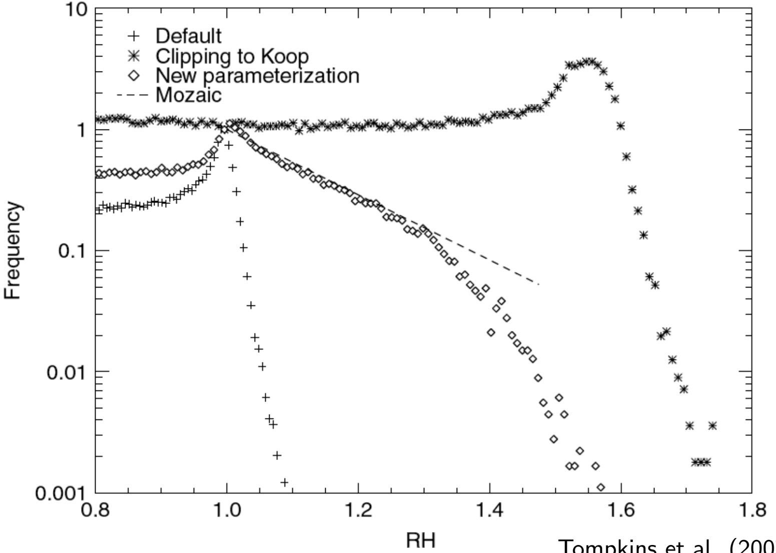
and $w = \bar{w} + 0.7\sqrt{TKE}$

Validation of vertical velocity



Kärcher and Ström (2003)

Validation of supersaturation



Tompkins et al. (2007)

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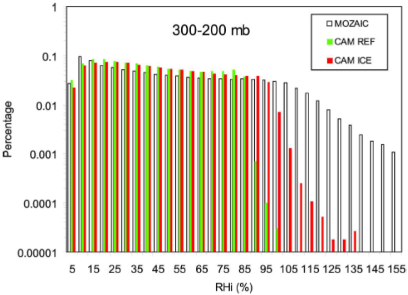
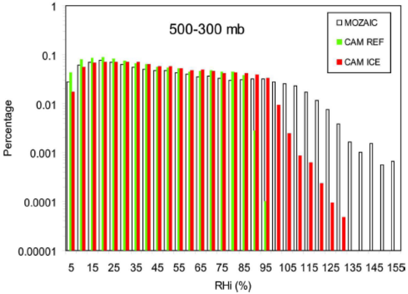
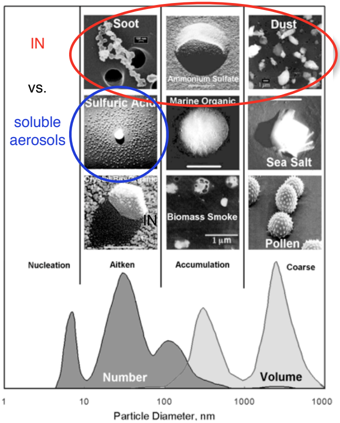




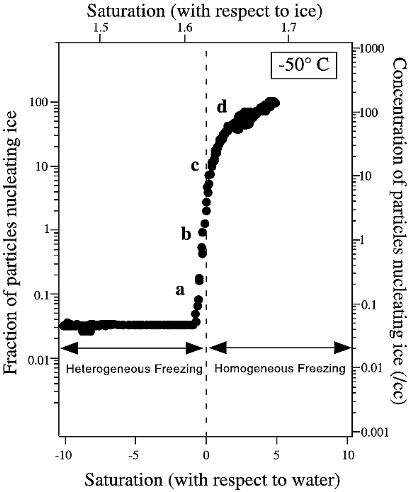
Liu et al. (2007)

Heterogeneous vs. homogeneous freezing


IN

vs.

soluble aerosols



Cziczo et al. (2004)

Homogeneous vs. heterogeneous freezing

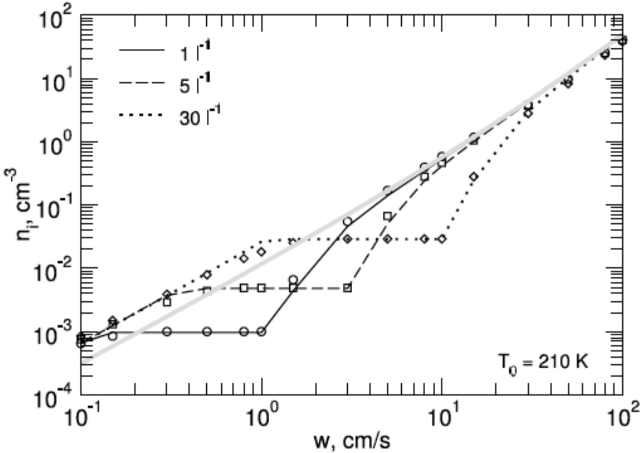
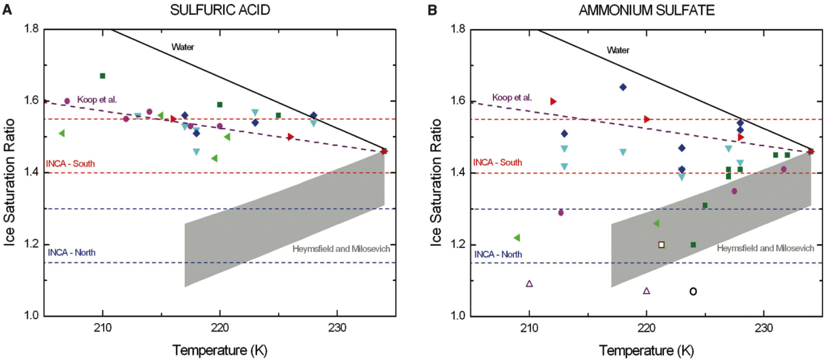


Figure: Grey line: homogeneous freezing; black lines: competition heterogeneous vs. homogeneous freezing

Kärcher et al. (2006)

Evidence of crystalline ammonium sulfate as ice nucleus?



Abbatt et al. (2006)

Effects on radiation

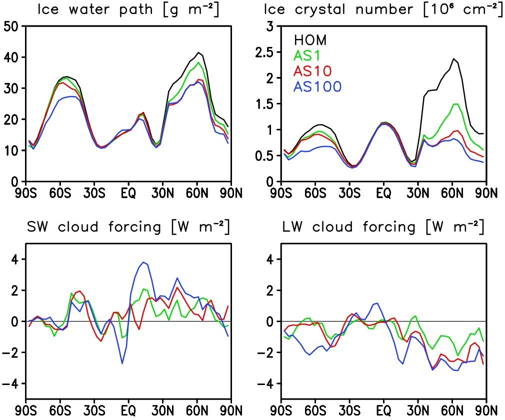


Figure: Annual zonal mean ice water path and ice crystal number for simulations HOM, AS1, AS10, AS100. Differences of the short- and longwave cloud forcing vs. HOM: AS1, AS10, AS100

Abbatt et al. (2006)

Model set-up in the ECHAM5 studies

- T42 horizontal resolution ($\sim 2.8^\circ \times 2.8^\circ$), 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} = number of immersed dust nuclei (Hoose et al., 2008)
  - ECHAM5-homhet: heterogeneous freezing for $N_{IN} > 1\ \mathrm{l}^{-1}$, homogeneous freezing otherwise
  - ECHAM5-alpha: As ECHAM5-hom, but with α reduced to 0.006 (Magee et al., 2006)

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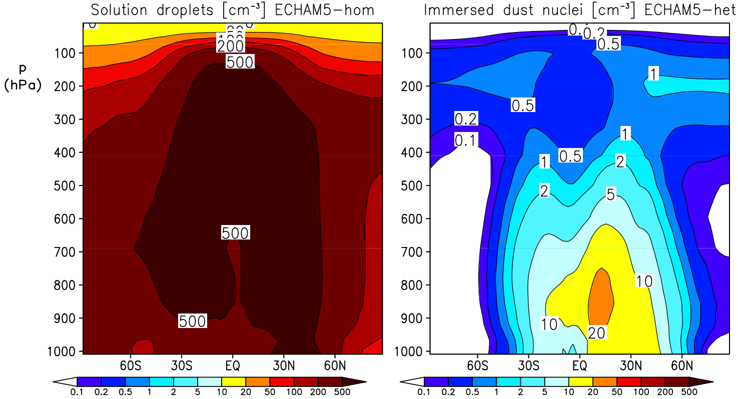
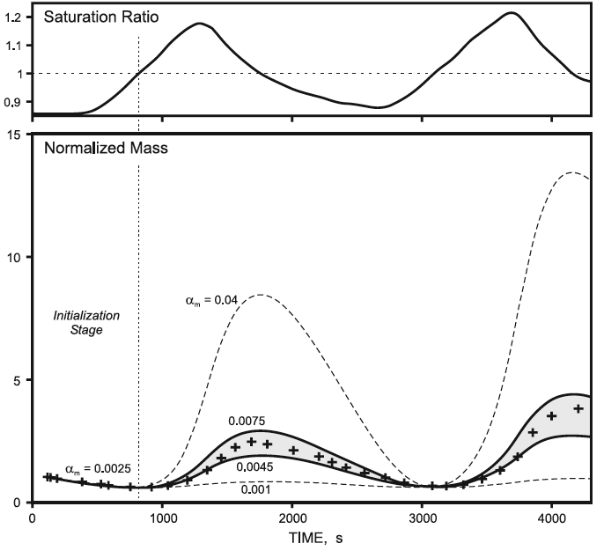
Solution droplets versus immersed dust nuclei

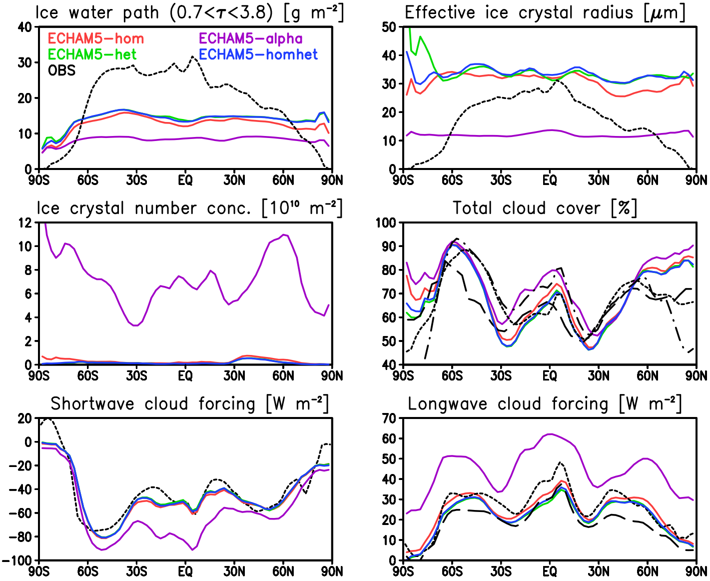


Importance of α

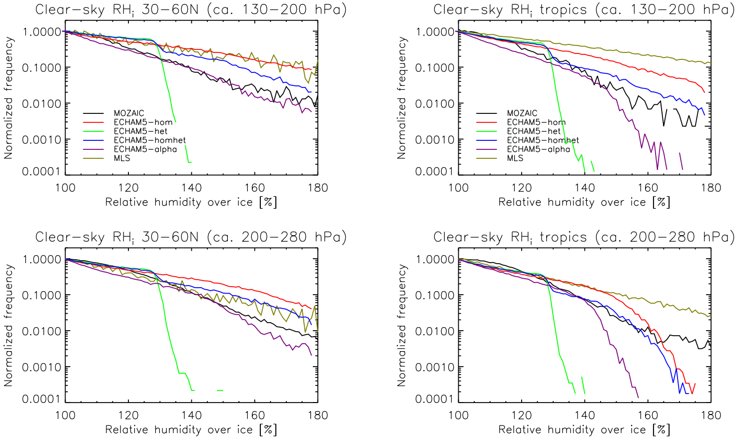


Magee et al. (2006)

Zonal mean results



Frequency distribution of ice supersaturation in NH midlatitudes and tropics



Observations from MOZAIC and MLS

Supersaturated regions

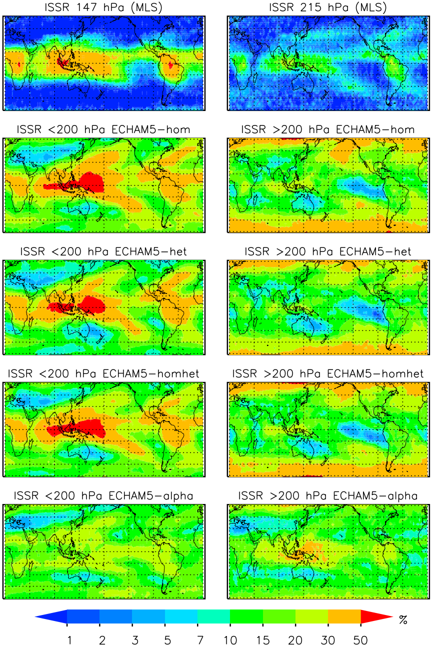


Table: Global annual mean ice water path (IWP), vertically integrated ice crystal number (N_i), total cloud cover (CC) and shortwave (SCF) and longwave (LCF) cloud forcing at the top-of-the-atmosphere.

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

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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 α to 0.006 enhances the ice crystal number by a factor of 25. Comparisons with observations suggest that such a low value of α 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.