Competition of different nucleation mechanisms at the formation of cirrus clouds

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Introduction

- Cirrus clouds are important for radiative budget (net warming possible)
- Competition of different nucleation mechanisms (homogeneous vs. heterogeneous)
- Supersaturation inside cirrus clouds (also at warmer temperatures)

Model description

Basis: Multiscale non-hydrostatic, anelastic model EULAG (Smolarkiewicz and Margolin, 1997)

Recently developed bulk ice microphysics scheme for the low temperature range ($T < -38°\mathrm{C}$) including:

- Nucleation (homogeneous/heterogeneous)
- Deposition growth/evaporation
- Sedimentation

Arbitrary many classes of ice, discriminated by their formation mechanism.

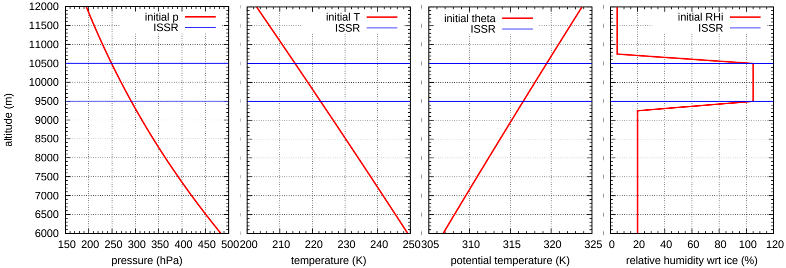
Consistent double moment scheme (ice crystal number and mass concentration) with additional background aerosol (explicit impact on nucleation).

Spichtinger and Gierens, 2008

Setup (2D)

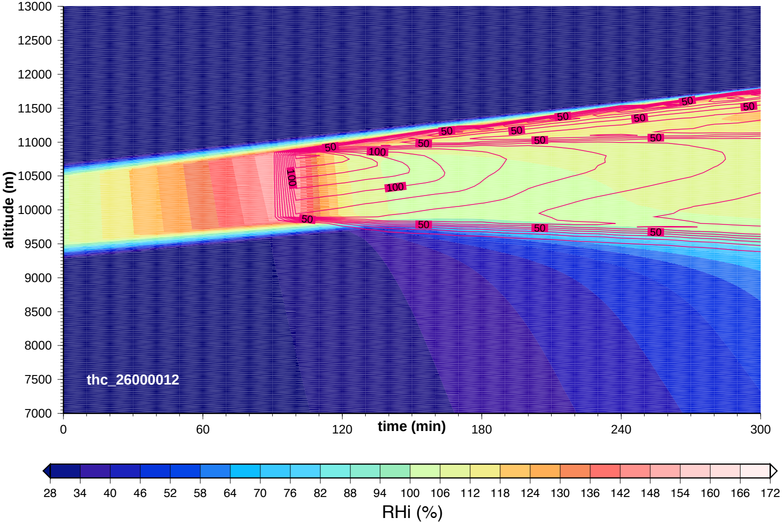
Two classes of ice (homogeneous freezing acc. to Koop et al., 2000, heterogeneous nucleation with threshold $RHi = 130\%$)

Constant uplift with $w = 0.06\,\mathrm{m\,s^{-1}}$, initial profiles:

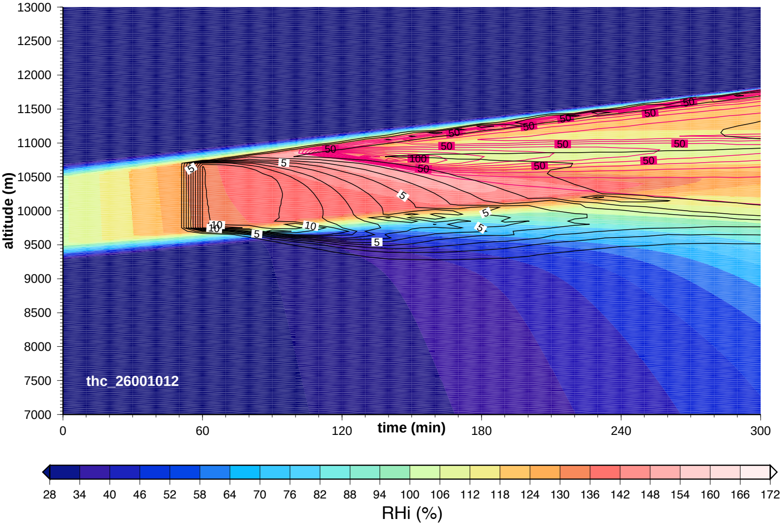


Following pictures: lines indicate ice crystal number density. Purple: homogeneous freezing, black: heterogeneous nucleation

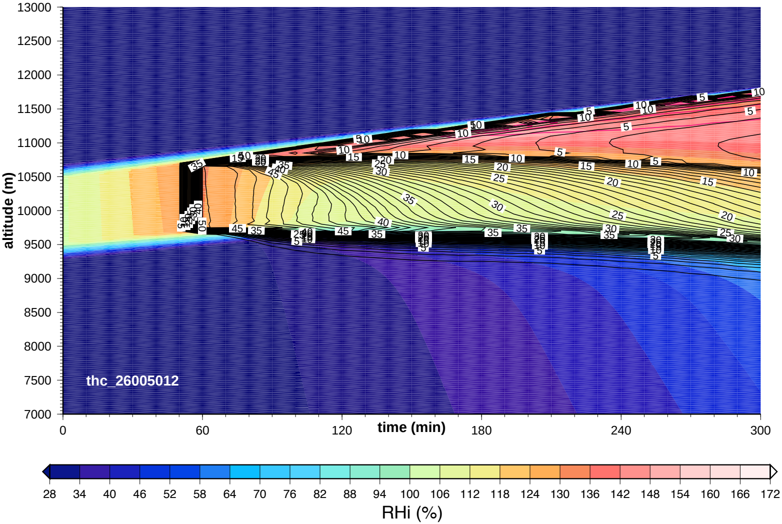
Reference simulation



Changing IN concentrations: $N = 10\mathrm{L}^{-1}$



Changing IN concentrations: $N = 50\mathrm{L}^{-1}$



Interpretation

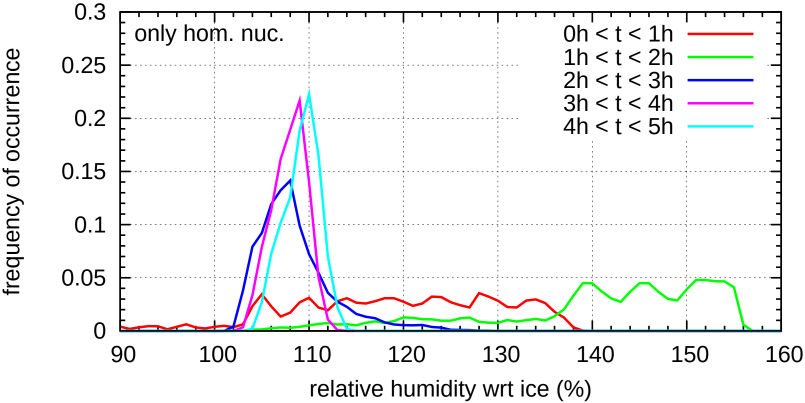
Three regimes:

- Few heterogeneous IN: Only few heterogeneous IN (up to about 10 L^{-1}): Homogeneous nucleation occurs over the whole depth of the cloud
- Medium number of IN (about 10 L^{-1}): Heterogeneous nucleation disturbs subsequent homogeneous nucleation; ice supersaturation inside the cirrus cloud possible.
- Large number of IN (20 L^{-1} and more): The cloud is completely dominated by heterogeneously formed ice.

RHi statistics

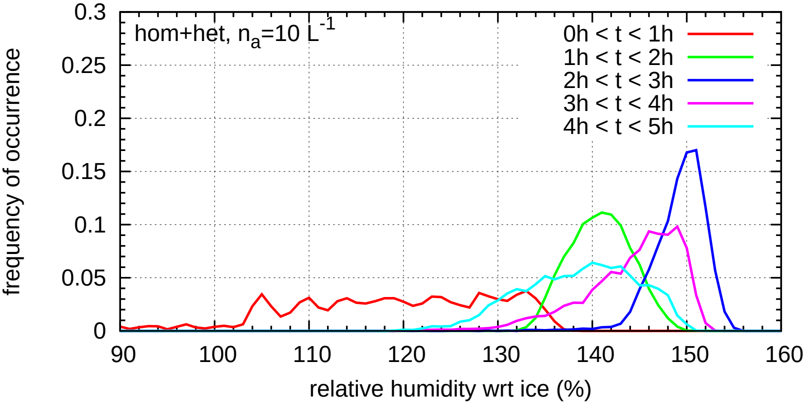
Time evolution of relative humidity for different amount of IN

$N = 0\mathrm{L}^{-1}$



RHi statistics

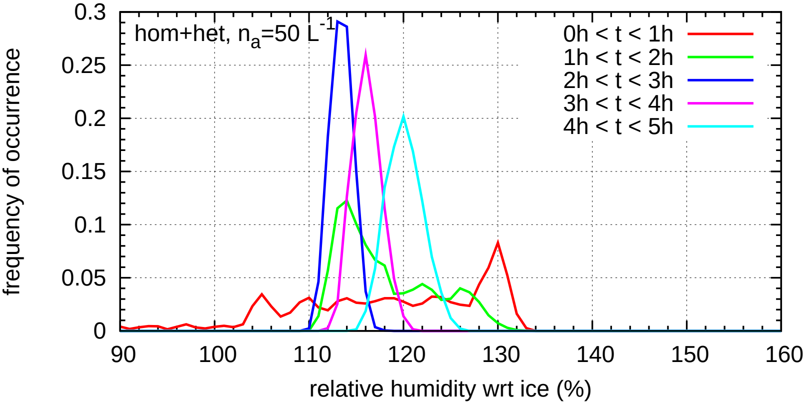
Time evolution of relative humidity for different amount of IN
$N = 10\mathrm{L}^{-1}$



RHi statistics

Time evolution of relative humidity for different amount of IN

$N = 50\mathrm{L}^{-1}$



Summary

- Competition of different nucleation mechanisms lead to modification of homogeneous freezing events
- Identification of three regimes
- Temperature variations have additional impact
- Supersaturation inside cirrus clouds possible only due to competition

Global Influence of Dust Mineralogy on Heterogeneous Ice Nucleation

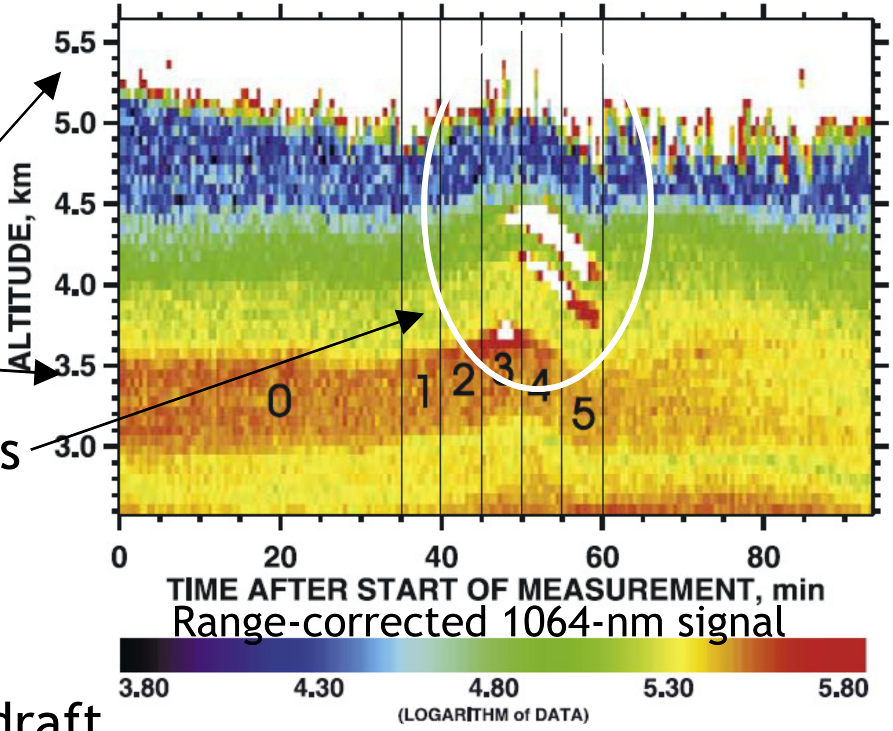
Corinna Hoose, Ulrike Lohmann and Rebekka Erdin
Institute for Atmospheric and Climate Science
ETH Zurich, Switzerland

Ina Tegen, Leibniz Institute for Tropospheric
Research, Leipzig, Germany

Observations: dust glaciates clouds

dust layers (green/red)

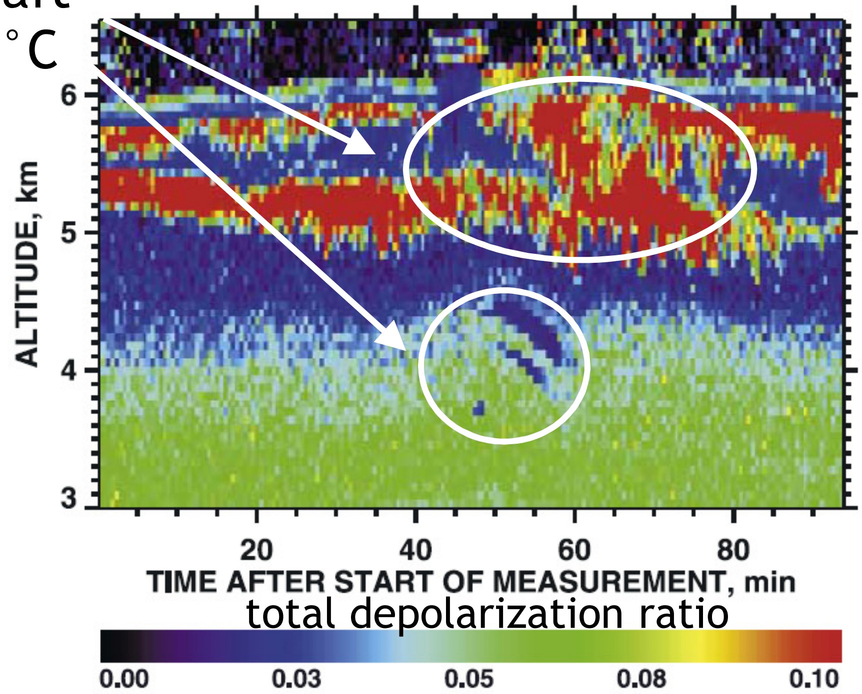
gravitity-wave induced clouds



Range-corrected 1064-nm signal

ice formation in downdraft

supercooled liquid at -9 to -16°C



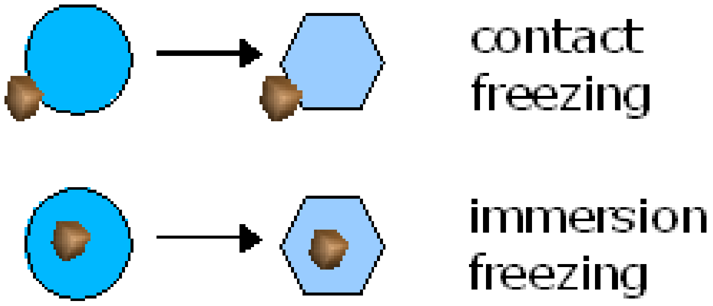
total depolarization ratio

Ansmann et al., JGR 2005

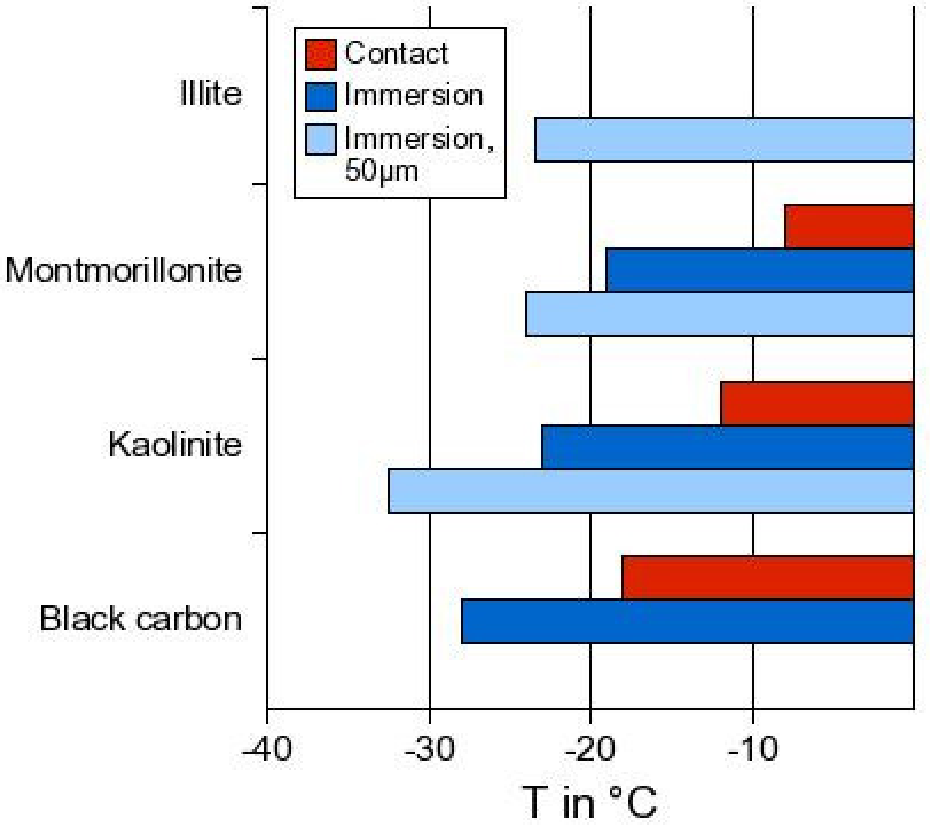
- why do some clouds glaciate and others don’t?
- what is the role of dust properties?
- how can we model that?

Heterogeneous Freezing

- Mixed-phase clouds (-38°C<T<0°C)
- In ECHAM5-HAM: only contact and immersion freezing, dust and black carbon

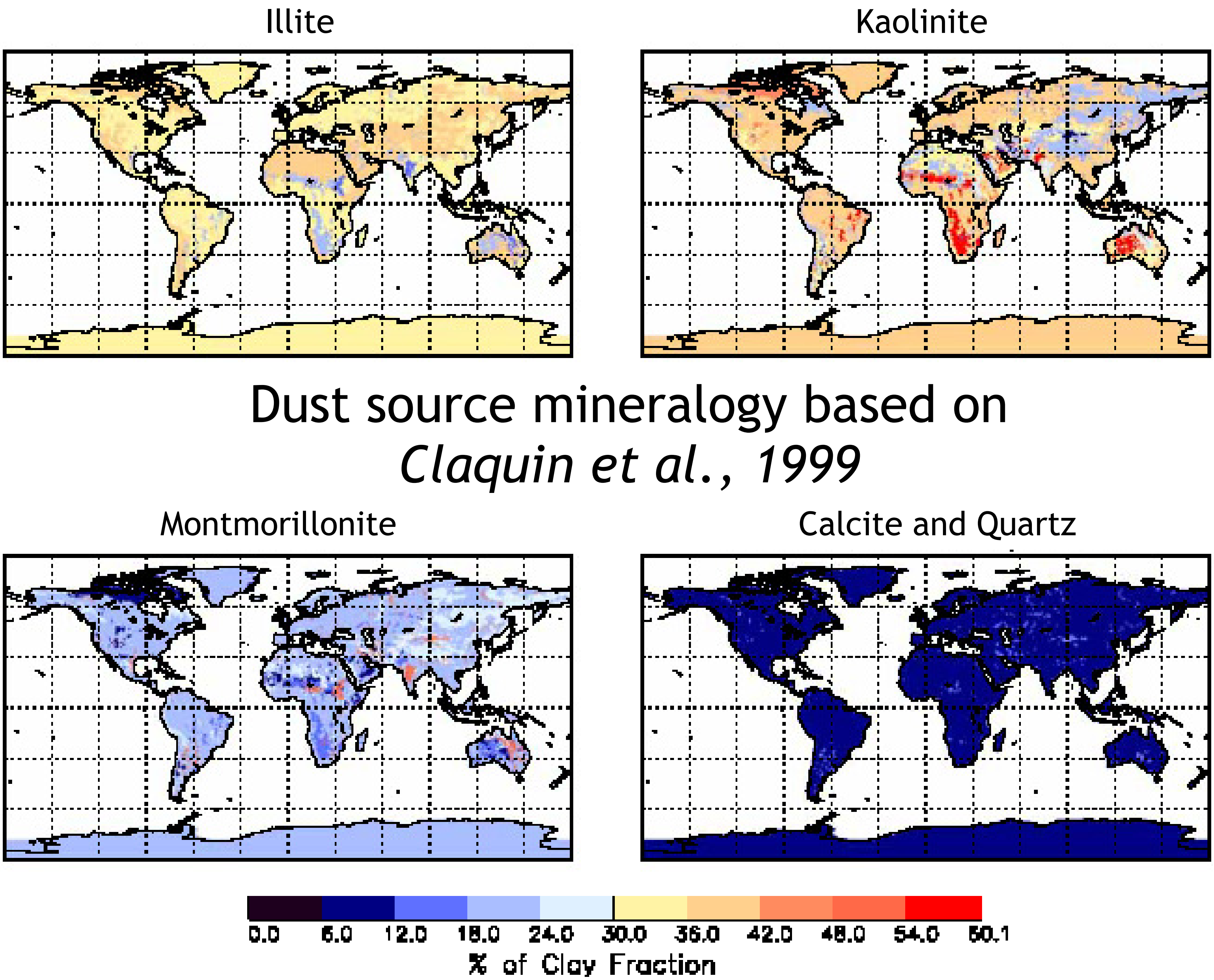


- IN efficiencies depend on material and drop volume

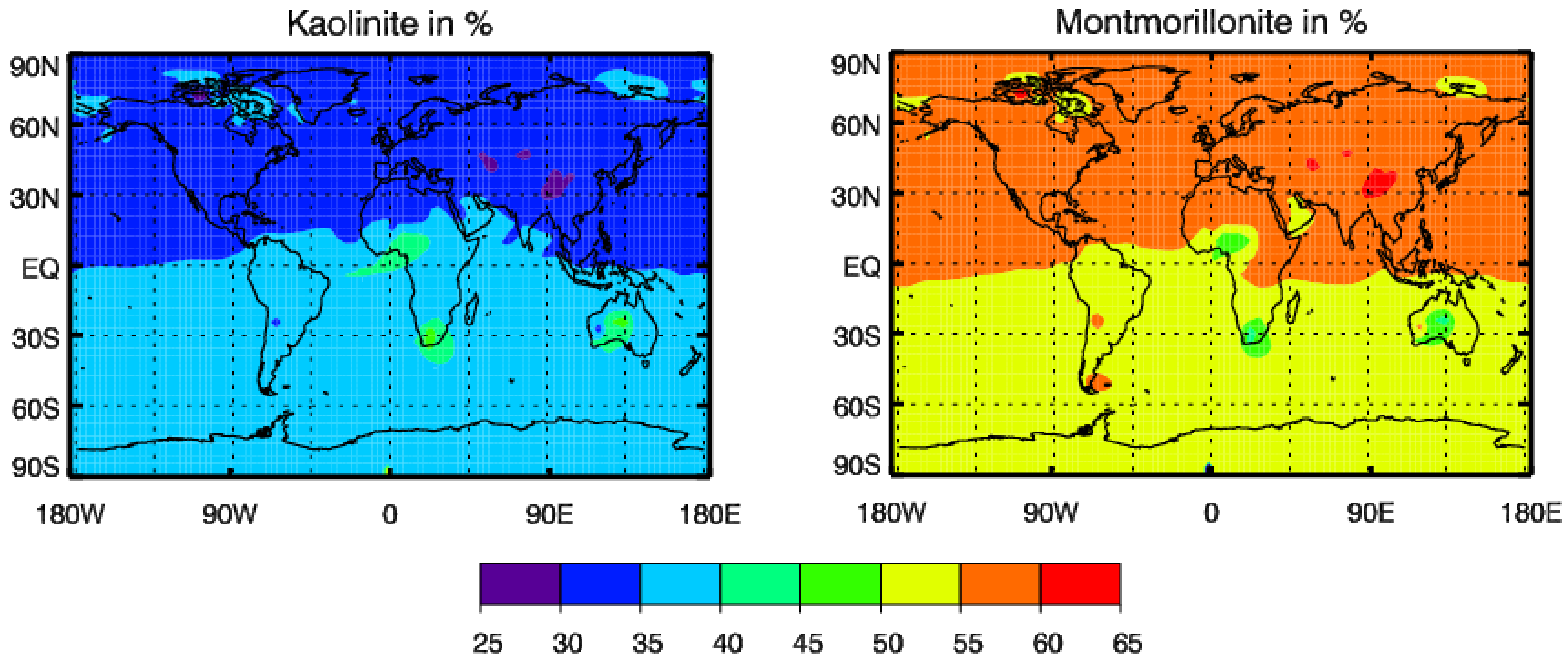


Median freezing temperatures for different IN from lab experiments. Drop radii 250-350 µm. Adapted from *Diehl et al. (2006)* and *Hoffer (1961)*.

Dust source mineralogy based on *Claquin et al., 1999*



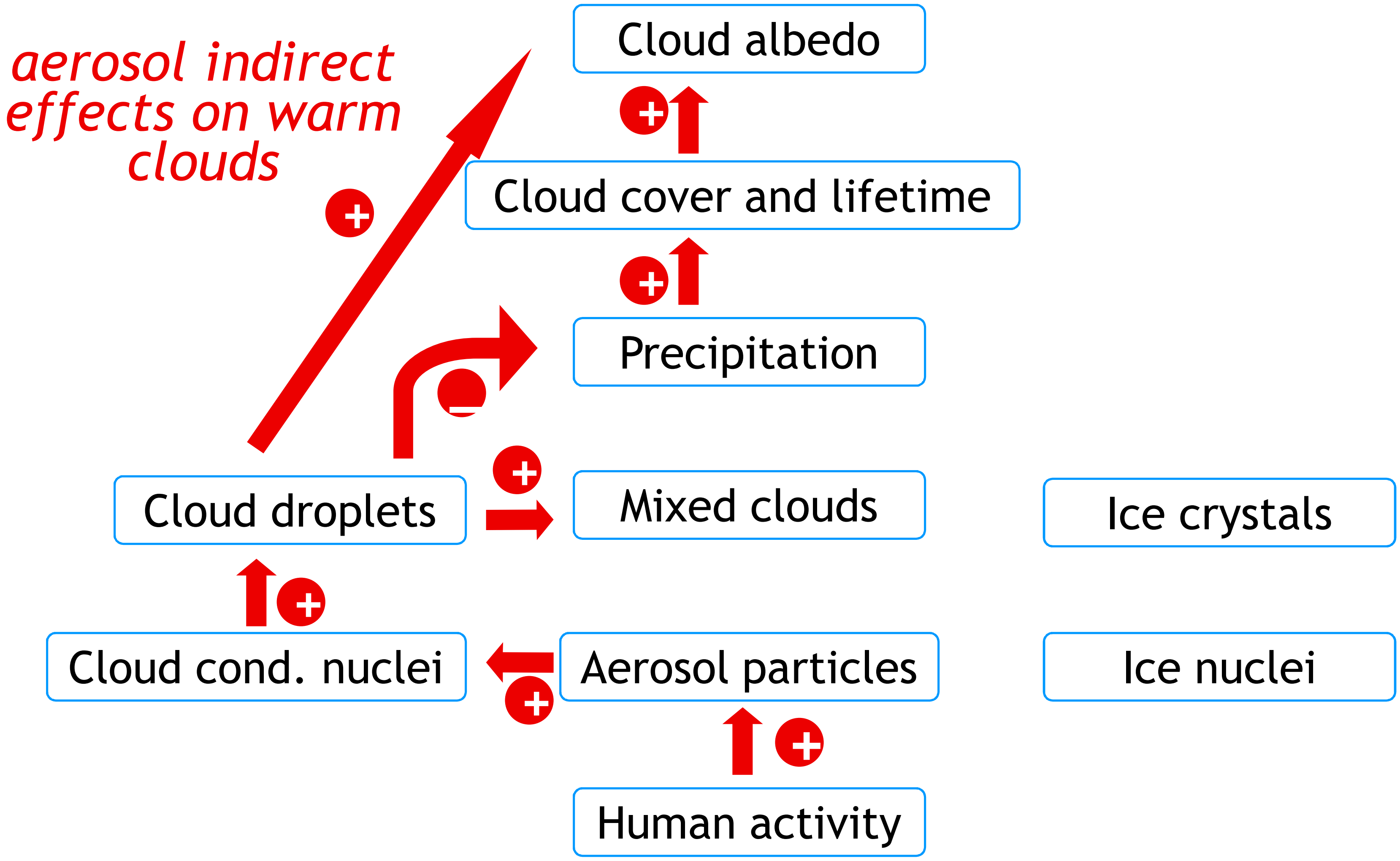
Simulated mineralogical composition in the surface layer (annual mean)


Kaolinite in %

Montmorillonite in %

- North-south gradient
- „Montmorillonite“ (=illite+montmorillonite) is more abundant than kaolinite

Anthropogenic effect on warm clouds



aerosol indirect effects on warm clouds

Cloud albedo

Cloud cover and lifetime

Precipitation

Cloud droplets

Mixed clouds

Ice crystals

Cloud cond. nuclei

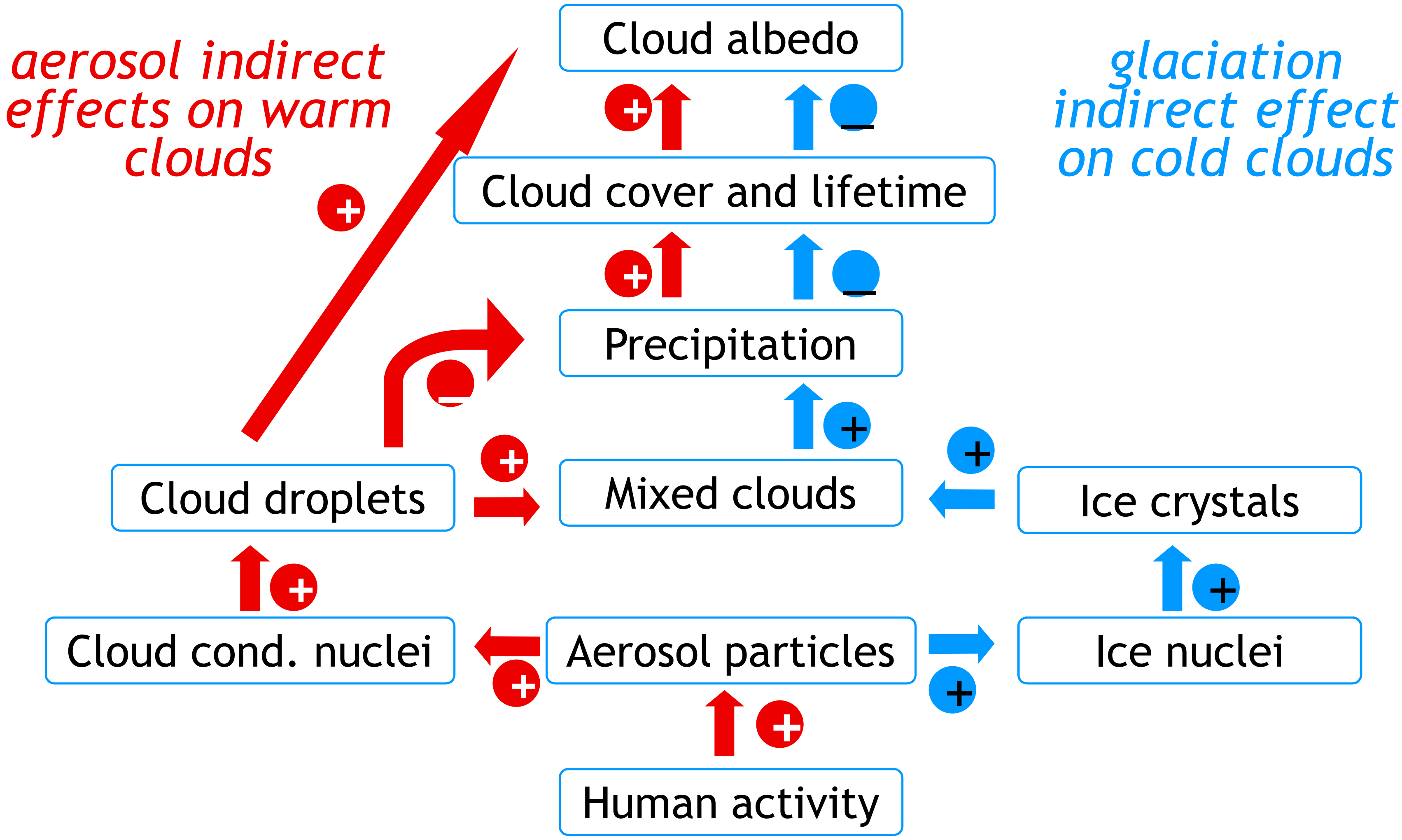
Aerosol particles

Ice nuclei

Human activity

Lohmann, GRL, 2002

Anthropogenic effect on freezing: the glaciation indirect effect



aerosol indirect effects on warm clouds

glaciation indirect effect on cold clouds

Cloud albedo

Cloud cover and lifetime

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Aerosol particles

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Lohmann, GRL, 2002

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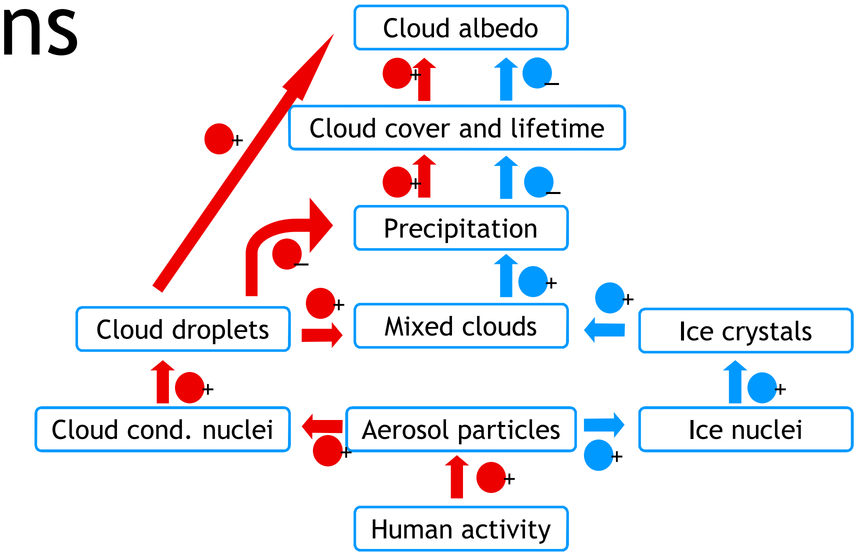
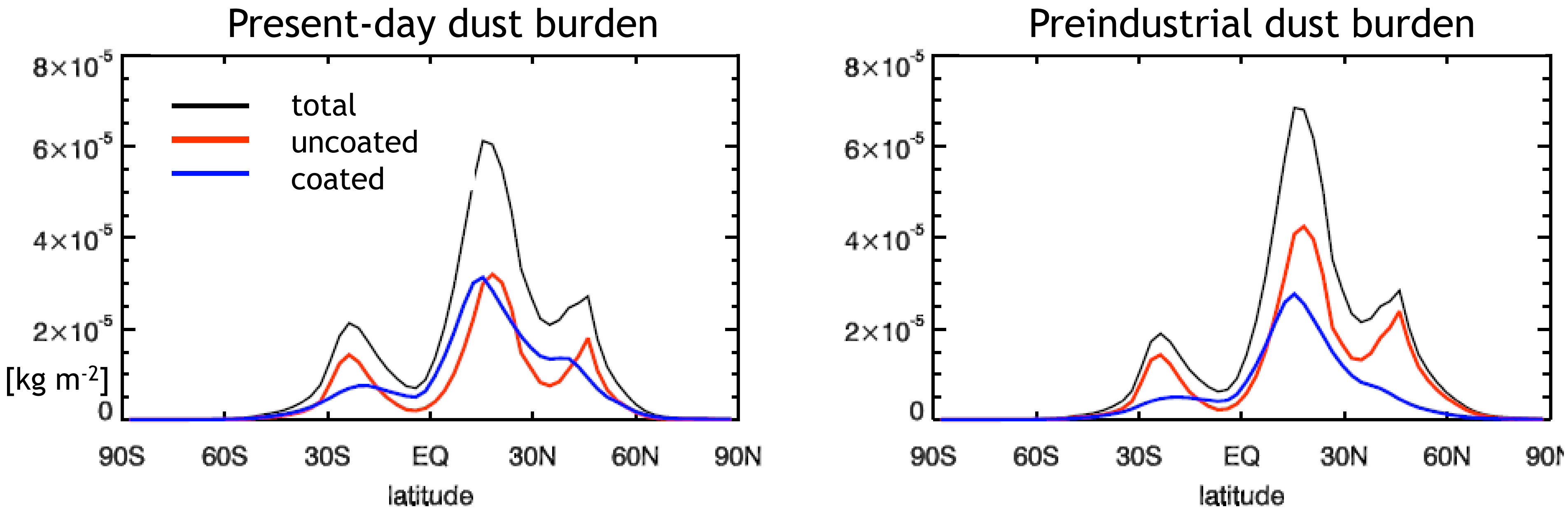
Anthropogenic effect on freezing: the glaciation indirect effect

- ECHAM5-HAM simulations for present-day and preindustrial climate
- anthropogenic IN: BC
- surprising result: glaciation indirect effect is very small



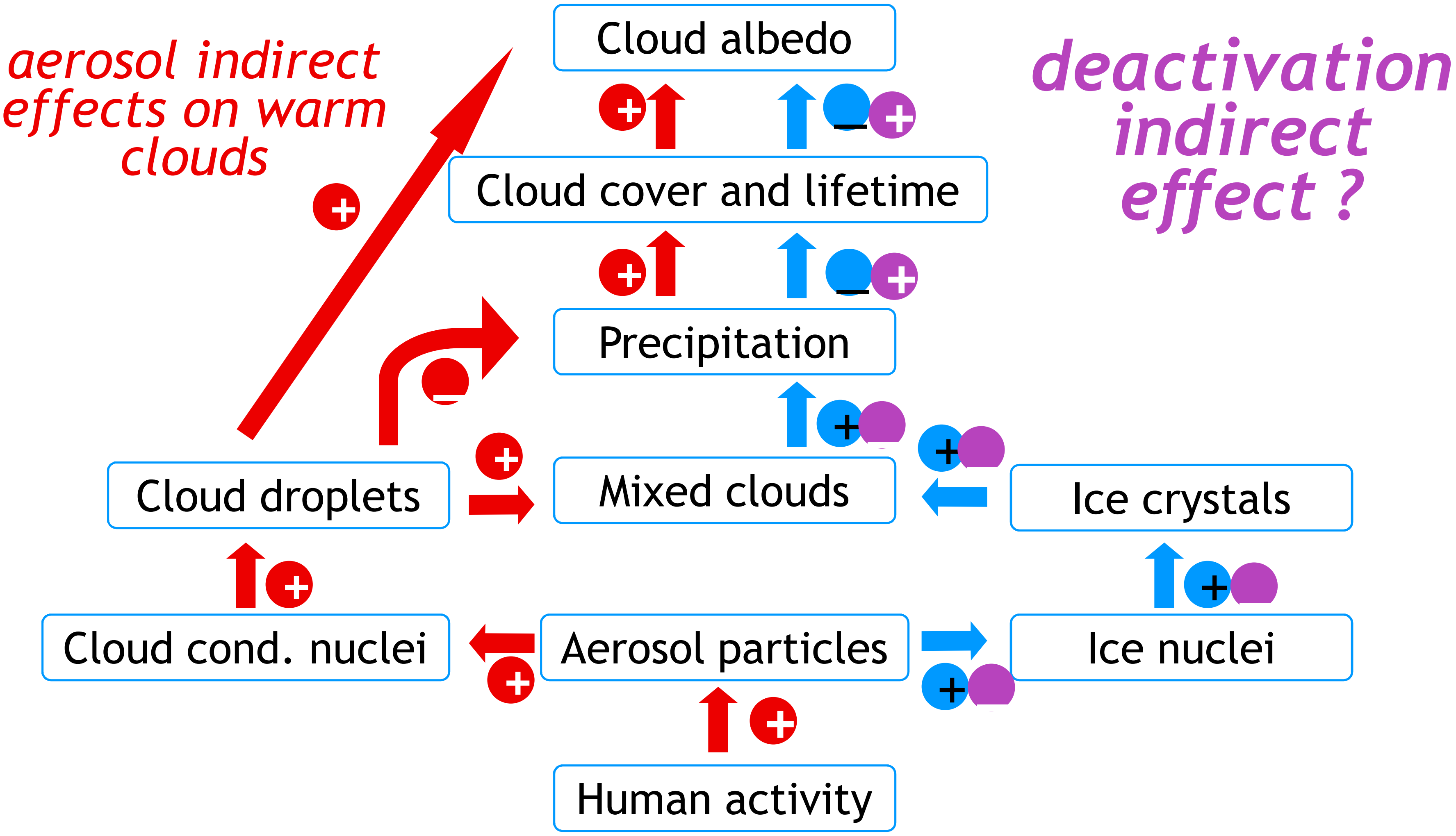
Simulation	MIX	MIX-noBC
ΔLWP in gm^{-2}	7.25±0.9	7.04±0.9
ΔF_{SW} in Wm^{-2}	-2.25±0.5	-2.13±0.4

Additional effect of anthropogenic aerosols: coating



- coating with sulfate -> dust acts as immersion nuclei rather than as contact nuclei
- -> freezing threshold at lower T
- -> kaolinite is quasi deactivated!

Anthropogenic effect on freezing: deactivation instead of glaciation?



aerosol indirect effects on warm clouds

deactivation indirect effect ?

Cloud albedo

Cloud cover and lifetime

Precipitation

Cloud droplets

Mixed clouds

Ice crystals

Cloud cond. nuclei

Aerosol particles

Ice nuclei

Human activity

Summary

- first global climate simulations with a 3D dust mineralogy to account for different freezing properties
- glaciation indirect effect is very small
- coating with sulfate leads to a shift from contact to immersion ice nuclei, possibly deactivation (depends on mineralogy)

Do anthropogenic aerosols increase or decrease global IN concentrations?

Thank you for your attention!

Model description – Deposition

For diffusion growth/evaporation we generally use the ansatz by Koenig (1971), which is modified using a correction derived from the numerical solution of the growth equation ($\alpha = 0.5$):

$$\frac{dm}{dt} \approx a \cdot m^b \cdot \left(1 - \exp\left(-(m/m_0)^\gamma\right)\right) \tag{1}$$

Using general moments of the mass distribution $f(m)$ (kth moment: $\mu_k[m] := \int f(m) m^k \, dm$) and the definition of the ice water content ($\mathrm{IWC} = \mu_1[m]$) we obtain:

$$\frac{d\mathrm{IWC}}{dt} \approx a \cdot \mu_b[m] \cdot \left(1 - \exp\left(-(\overline{m}/(m_0 \cdot \chi))^\gamma\right)\right) \tag{2}$$

with the mean mass $\overline{m} = \mu_1/\mu_0$ of the mass distribution and a correction factor $\chi \approx 20$

Model description – Sedimentation

Two different terminal velocities (mass weighted and number weighted, $v_{t,m}, v_{t,n}$):

$$\mathrm{IWC} \cdot v_{t,m} = \int_0^\infty f(m)\ m\ v_t(m)\ dm \tag{3}$$

$$N_i \cdot v_{t,n} = \int_0^\infty f(m)\ v_t(m)\ dm \tag{4}$$

We use mass–velocity relations by Heymsfield and Iaquinta (2000):

$$\frac{v_t}{v_0} = \alpha \cdot \left(\frac{m}{m_0}\right)^\beta, \quad v_0, m_0 \text{ unit velocity/mass} \tag{5}$$

and derive the following formulas for the terminal velocities:

$$v_{t,n} = v_0 \cdot \frac{\alpha}{m_0^\beta} \cdot \frac{\mu_\beta[m]}{\mu_0[m]} \tag{6}$$

$$v_{t,m} = v_0 \cdot \frac{\alpha}{m_0^\beta} \cdot \frac{\mu_{\beta+1}[m]}{\mu_1[m]} \tag{7}$$

Model description – Nucleation

Two different processes, both determined by the background aerosols, respectively:

- homogeneous nucleation: the number concentration of sulfuric acid is prescribed as background aerosol
  → size distribution of aqueous solution droplets which freeze homogeneously acc. to Koop et al. (2000), depending on water activity and temperature.
- heterogeneous nucleation: Background aerosol determines the maximal number of ice nuclei. After passing a threshold RHi_{het} all available aerosol particles act as ice nuclei and form ice crystals

in both cases: washout possible