Extending a PDF cloud scheme to accommodate cirrus physics

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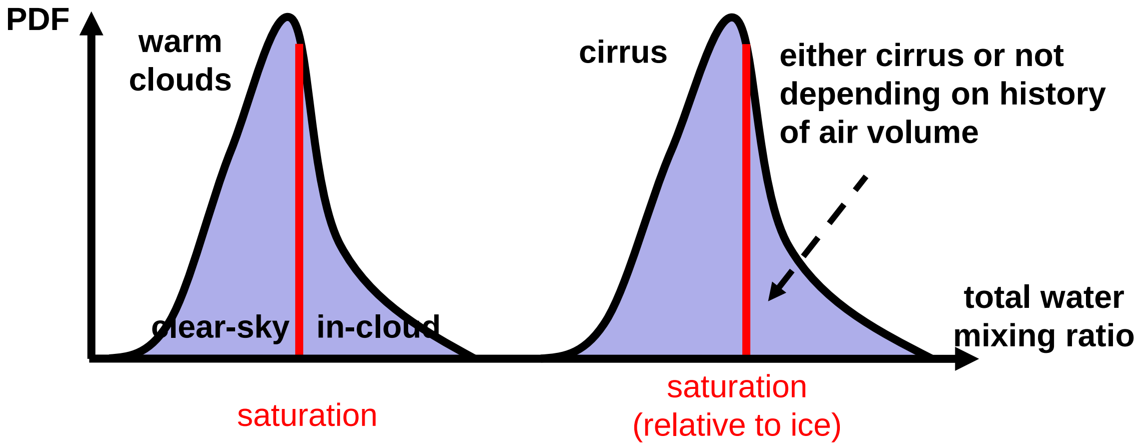
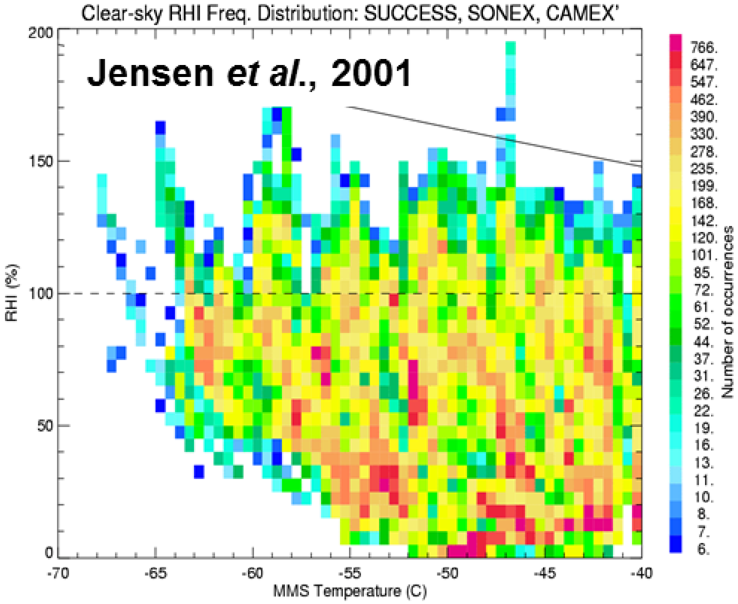
Ice clouds and ice supersaturation

Ice clouds form at high ice supersaturation and persist at ice saturation.

Ice cloud coverage cannot be inferred from relative humidity.

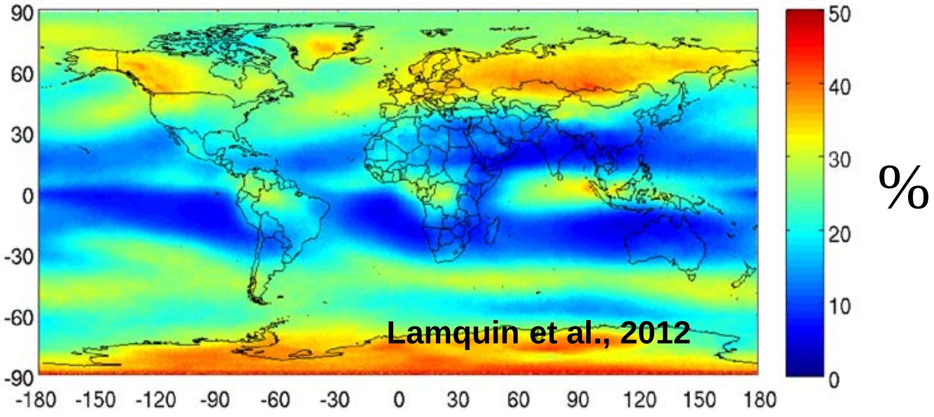


RHi clear sky



Ice supersaturations below the homogeneous freezing threshold are common in observations.

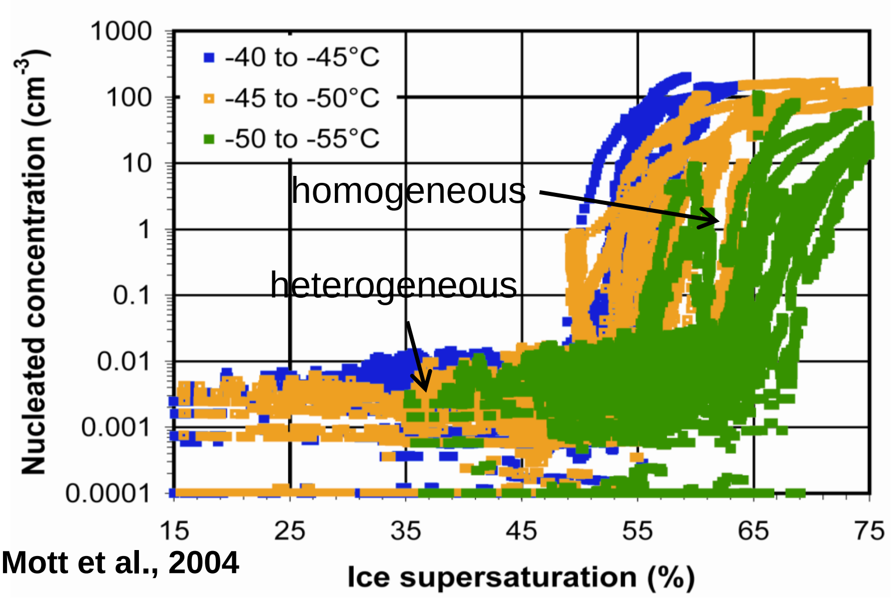
AIRS 200-300 hPa supersaturation frequency



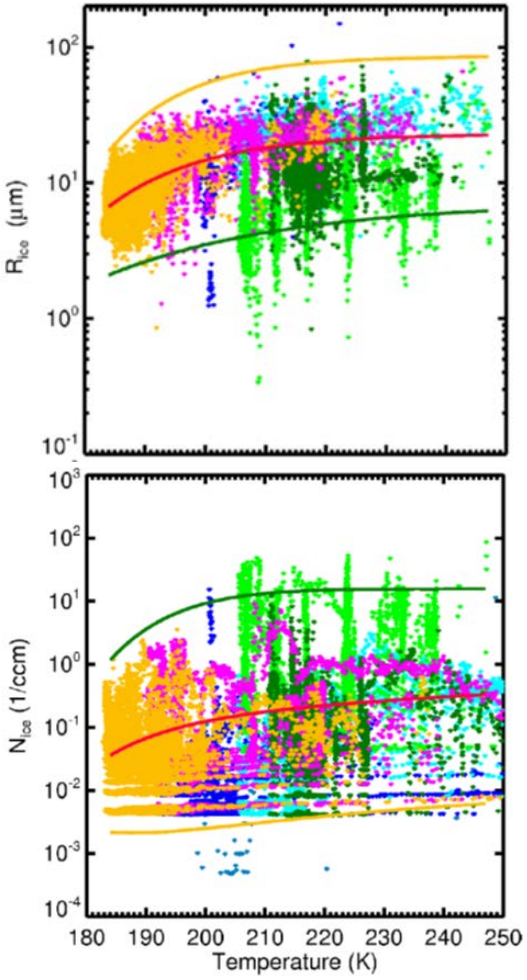
High frequencies of ice supersaturation observed globally.

Ice crystals and their radiative effect

Ice nucleates at high ice super-saturation heterogeneously (> 10%) but mostly homogeneously (~50%)



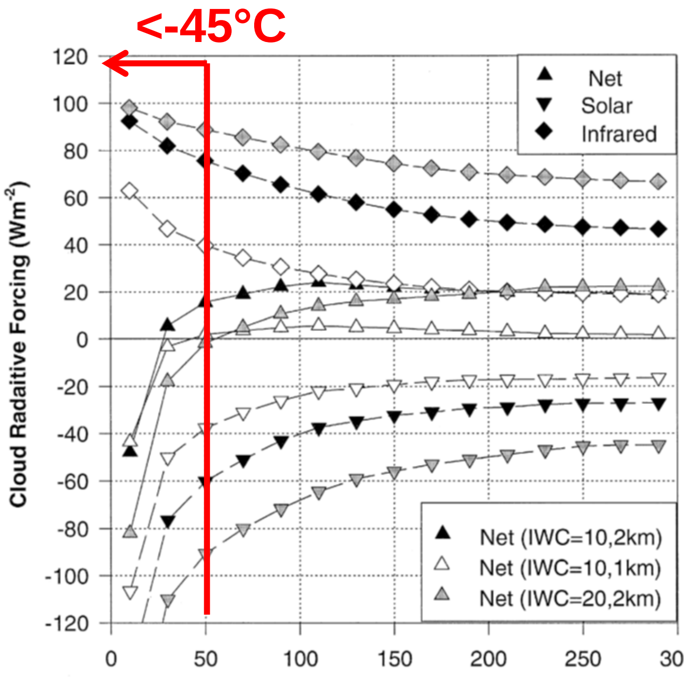
DeMott et al., 2004



Krämer et al., 2009

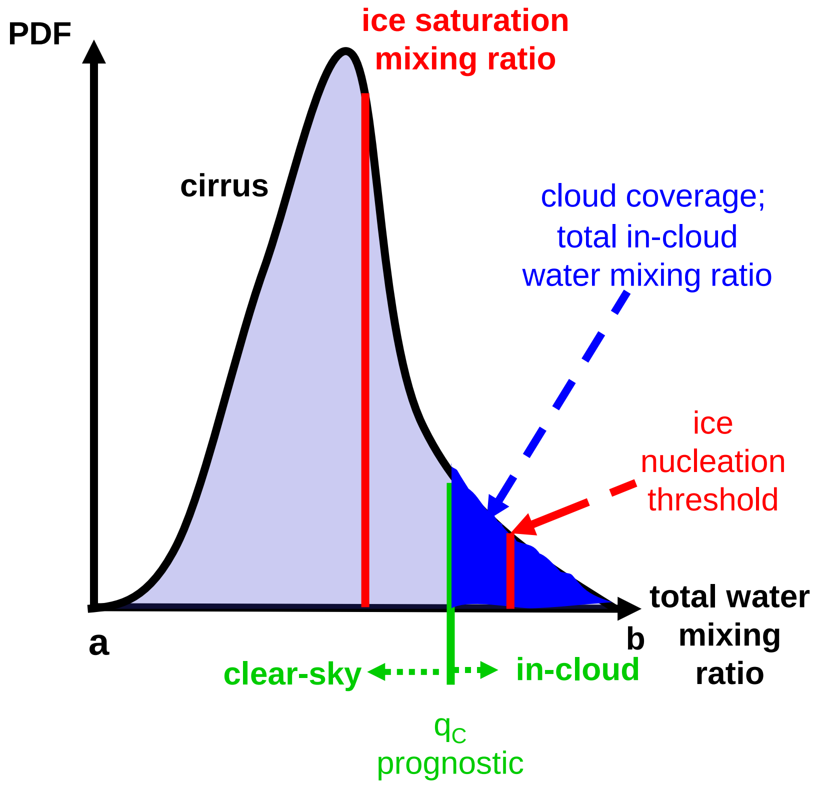
Ice crystal number concentrations and radii vary at fixed temperature by a few orders of magnitude.

Cloud radiative forcing strongly dependent on ice crystal sizes.



Zhang et al., 1999

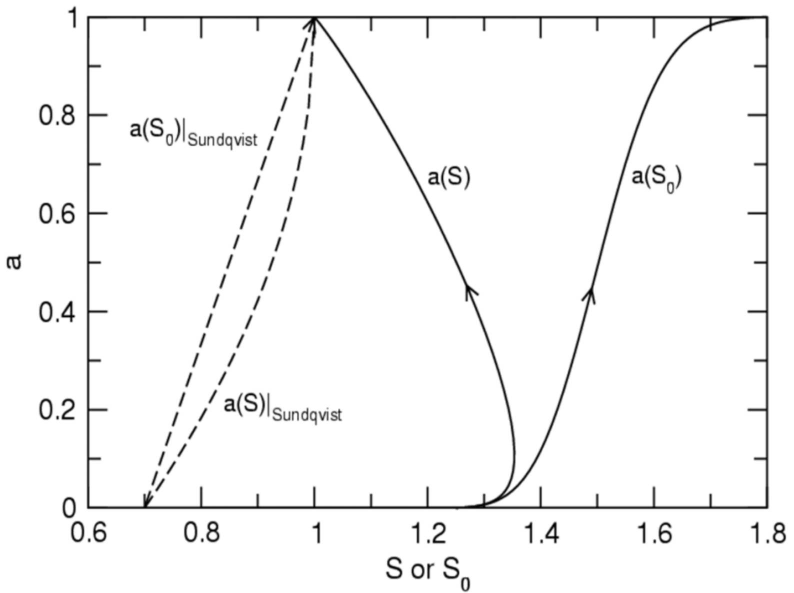
PDF scheme for cirrus



Key controlling factor of non equilibrium ice cloud coverage is history of relative humidity and its subgrid scale variability.

Total water variability described by PDF - PDF moments can change due to dynamical and microphysical processes.

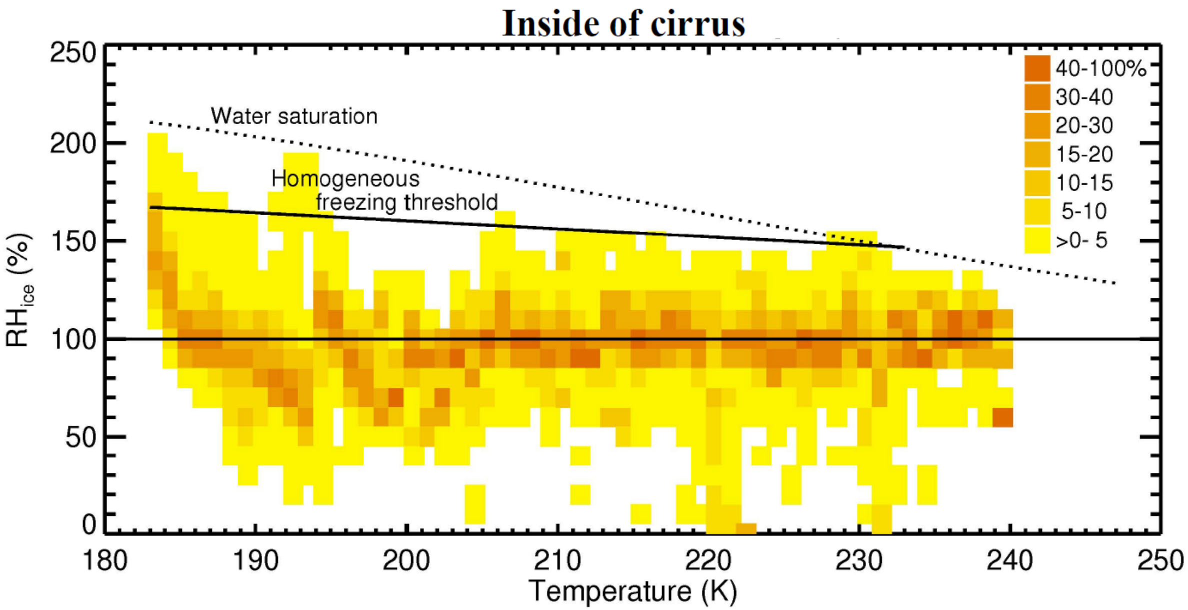
Prognostic variable can be introduced in PDF cloud scheme allowing estimation of ice cloud coverage and ice water content.



S_o - clear sky saturation ratio   S - grid mean saturation ratio

Kärcher and Burkhardt, 2008

Diffusional growth versus saturation adjustment



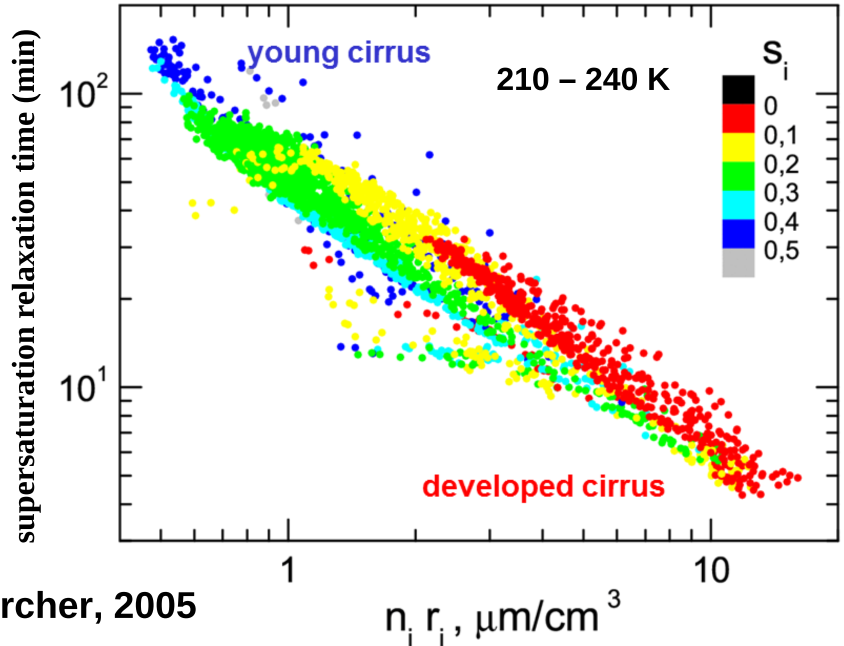
Krämer et al., 2009

Parameterizing diffusional growth of ice crystals instead of saturation adjustment requires additional prognostic variable.

High observed in cloud ice super- subsaturations particularly at low temperatures (aerosol effects in TTL?).

Simulation of arctic cirrostratus in slow uplift using a detailed 1D aerosol - cirrus model with Lagrangian ice crystal tracking.

At low ice particle number and size ice supersaturation within a cirrus cloud may exist for a long time.

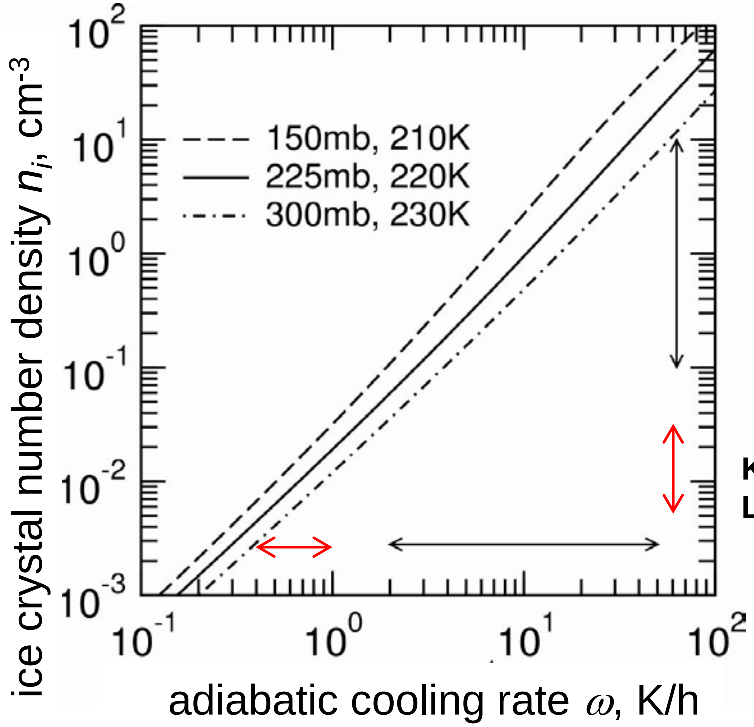


Kärcher, 2005

Ice nucleation

Relative humidity and cooling rate are key controlling factors for ice nucleation in cirrus clouds.

nucleation source term for ice crystal number

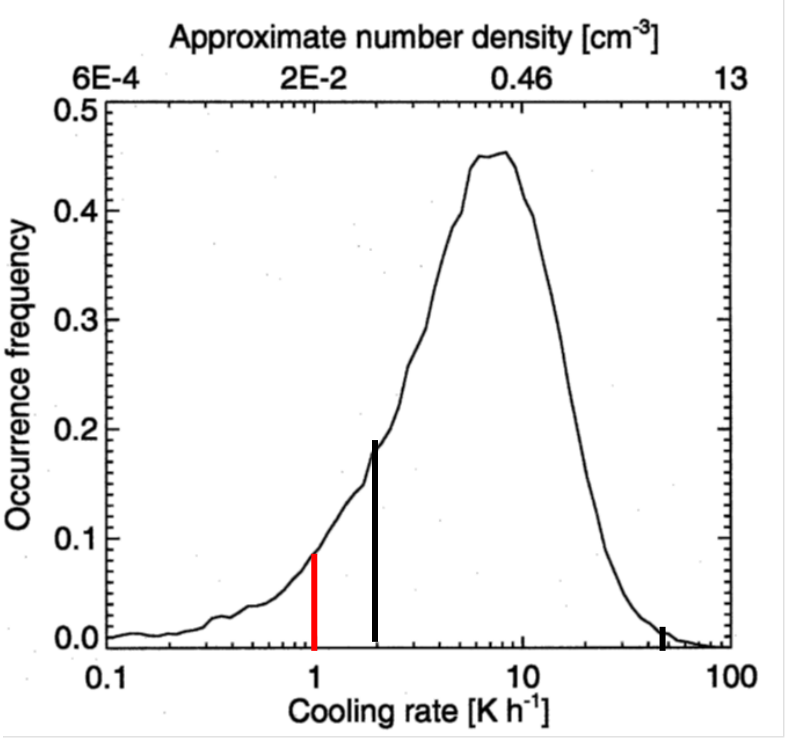


Kärcher and Lohmann, 2002

cooling rate from synoptic motion (< 1 K/h)

⇒ n much lower than observed

observed n range between 0.1 and 10 cm^{-3} => cooling rate from gravity waves + turbulence (2-50 K/h)

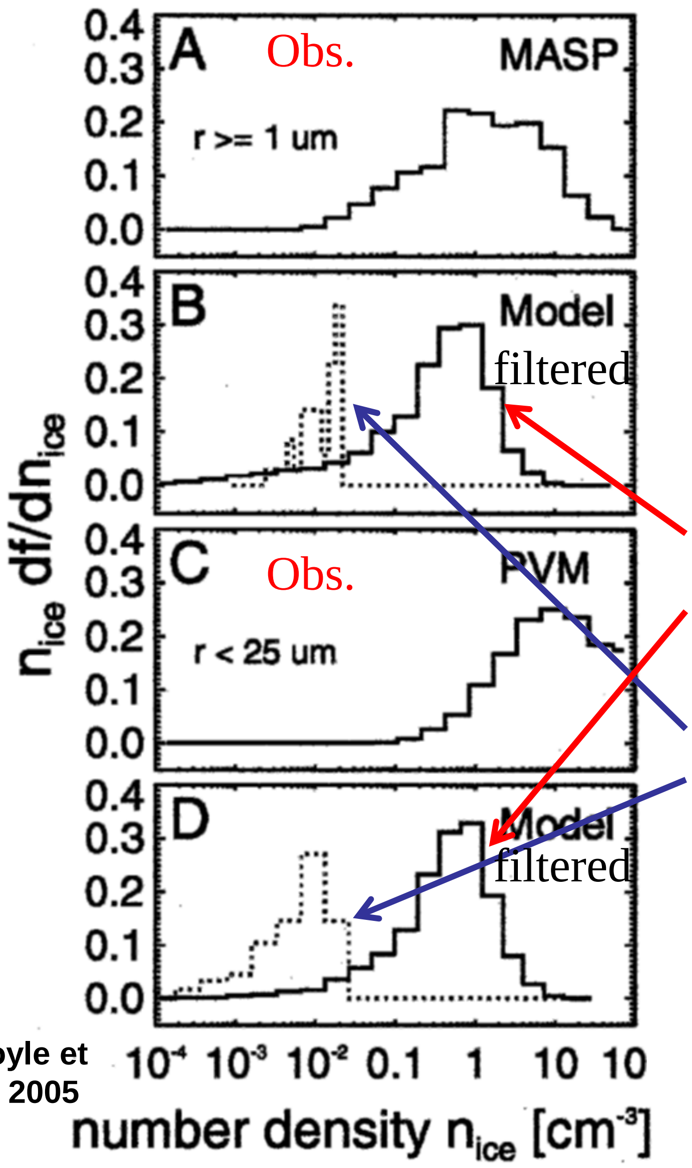


Hoyle et al. 2005

Mesoscale fluctuations of cooling rate crucial for nucleation and for ice cloud properties -> radiation.

Which fluctuations are important? – microphysics

Frequency of number density



ECMWF T511 trajectory + ΔT

ECMWF T511 trajectory

Hoyle et al. 2005

Cooling rate at the moment of ice nucleation

↓

Number of nucleation events per air volume

↓

Size of ice crystals at given humidity

↓

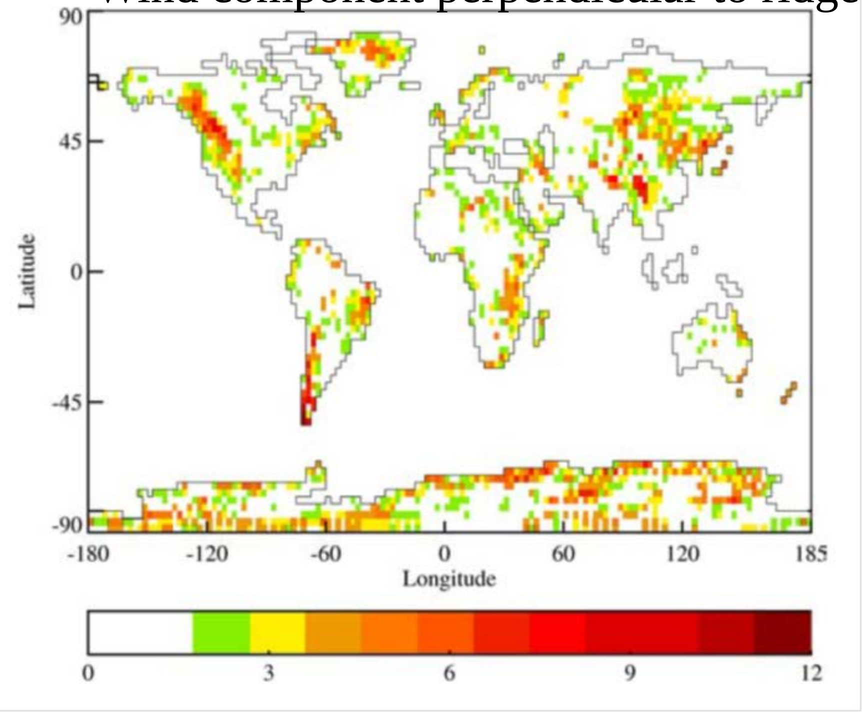
Radiative and microphysical properties of cirrus clouds

Small scale temperature variability important for crystal number density.

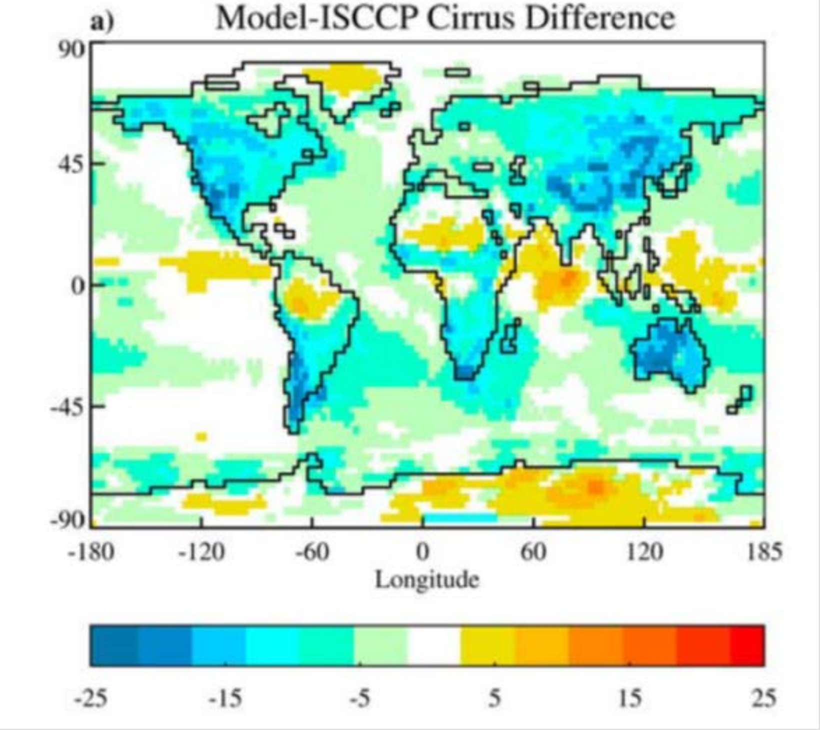
Despite increasing resolution of GCMs cooling rates will likely stay subgrid scale in the future.

Which fluctuations are important? – orographic forcing

Wind component perpendicular to ridge



Dean et al 2005



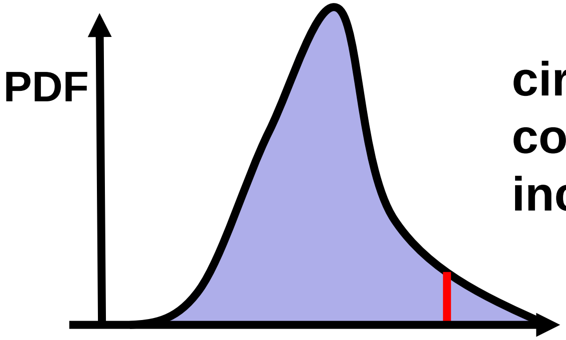
Representation of cirrus can be significantly improved by simulating cirrus triggered by orographic gravity waves (Dean et al 2007; Joos et al 2008)

Cirrus bias in other areas remains – temperature fluctuations significant also in areas not directly influenced by orography (Gary 2006)

Coupling ice microphysics and cirrus coverage

Coverage

fractional coverage dependent on PDF of q_{tot} (and T, ..)



cirrus coverage increases

Newly formed cirrus coverage

Nucleation

dependent on mean RH_i, mean T, cooling rate

If ∂T/∂t indicates warming

→no formation of new crystals dN=0

⇒ Change in cirrus coverage forced to be zero

or

=> crystal number density decreasing

If coverage does not know about cooling rates (that are the main control for N) and nucleation does not know about spatial variability of q_{tot} then coverage and 2-moment microphysics not consistent.

Coupling ice microphysics and cirrus coverage

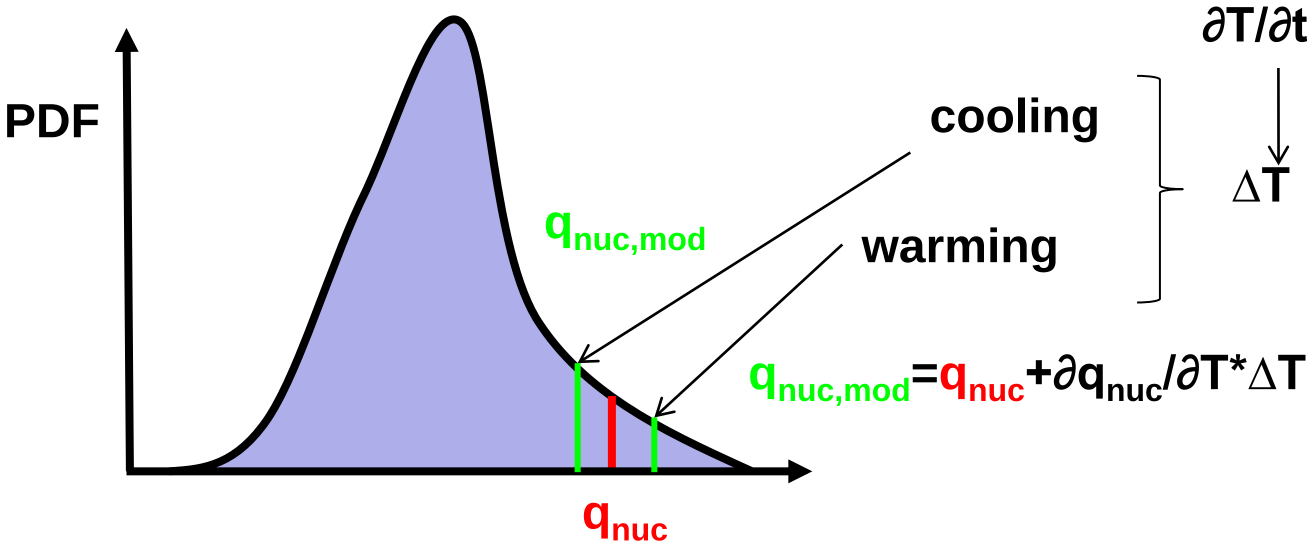
Coverage

prognostic coverage dependent on PDF of q_{tot} (and T) and cooling rate

Microphysics

nucleation dependent on PDF of q_{tot}, T, cooling rate

assumption: cooling rate uncorrelated with q_{tot} variability

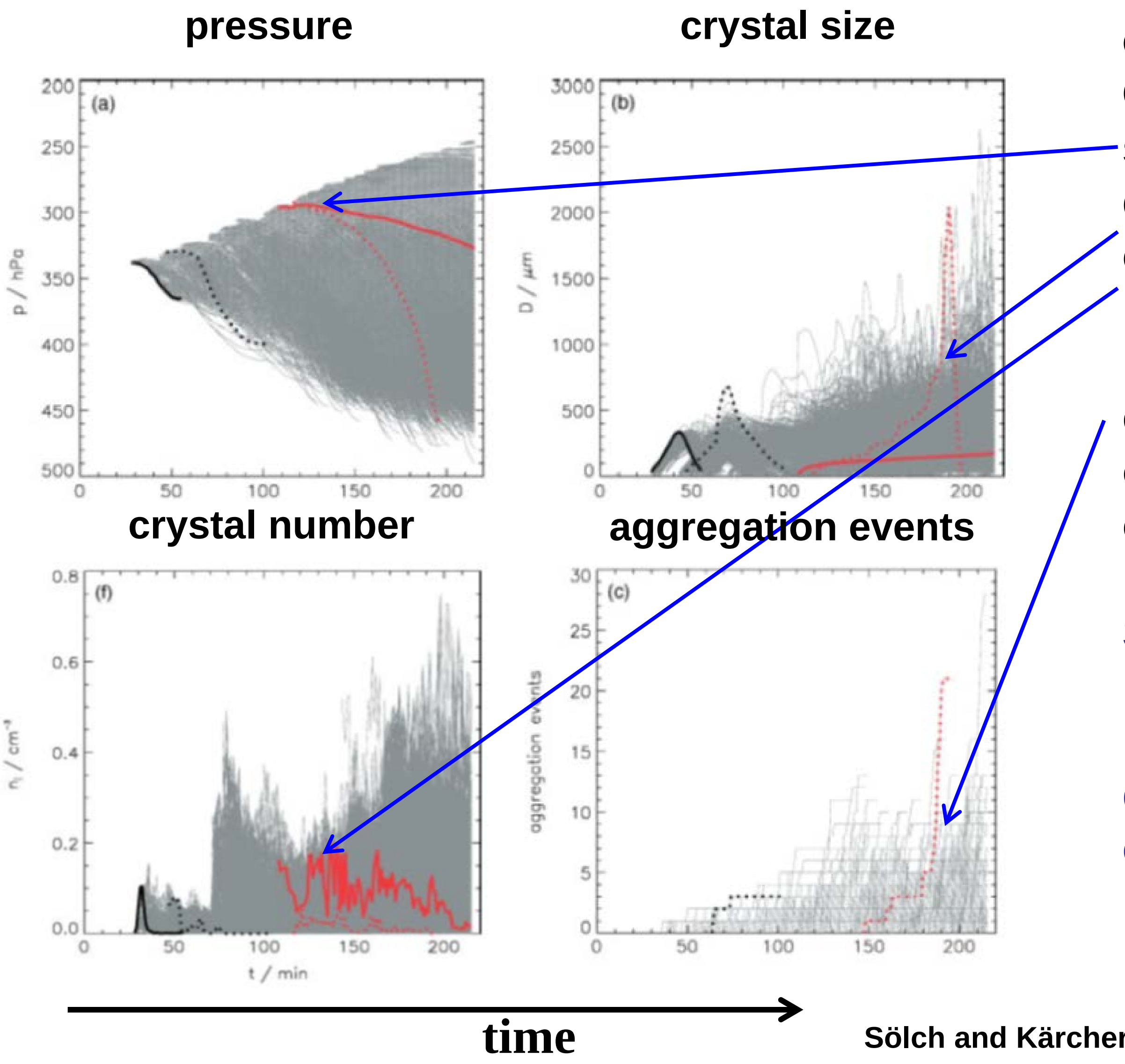


$q_{nuc,mod} = q_{nuc} + \partial q_{nuc}/\partial T * \Delta T$

Within area in which cirrus is formed, particles are nucleated depending on local q_{tot} and $\partial T/\partial t$

$q_{nuc,mod}$ threshold for nucleation and formation of coverage

Variability of fluctuations important at cloud scale



LES simulation of a cirrus cloud:
Cirrus ice particles in very similar locations have very different sizes and number concentrations after nucleation and experience no/many aggregation events leading to a removal of ice particles from the cloud in fall streaks.

Small scale cloud inhomogeneities affect microphysics and development of whole cloud.

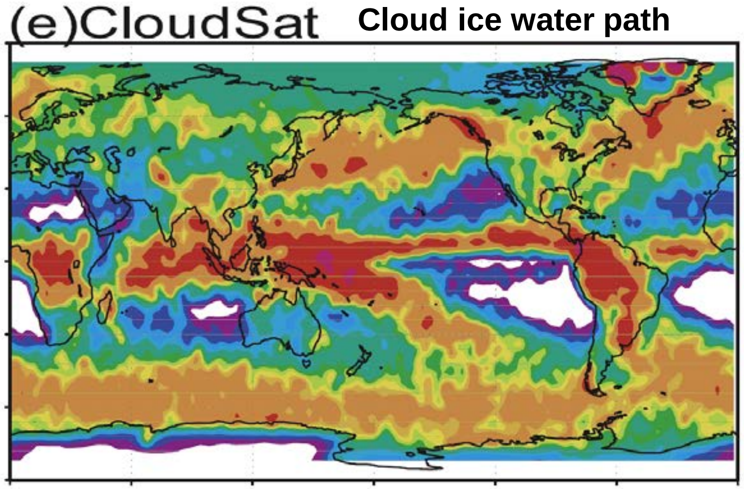
Sölch and Kärcher, 2011

Convection between large scale cirrus and convection

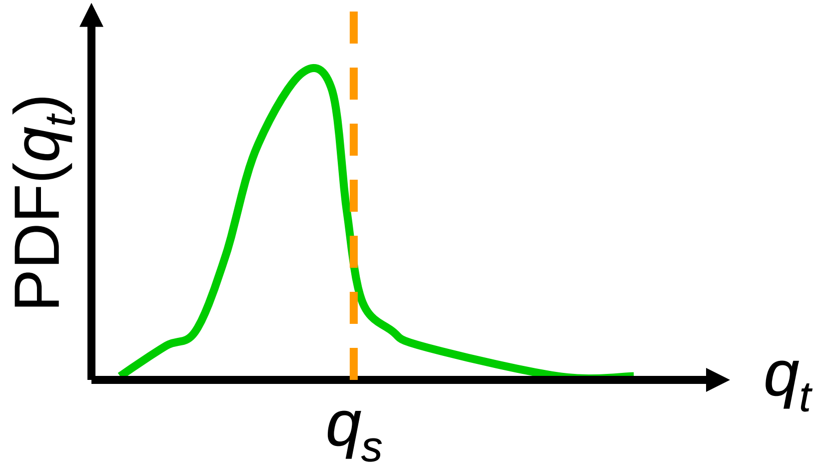
Convection can cause bimodality in total water distribution at cirrus levels. Bimodality cannot be resolved by unimodal PDF.

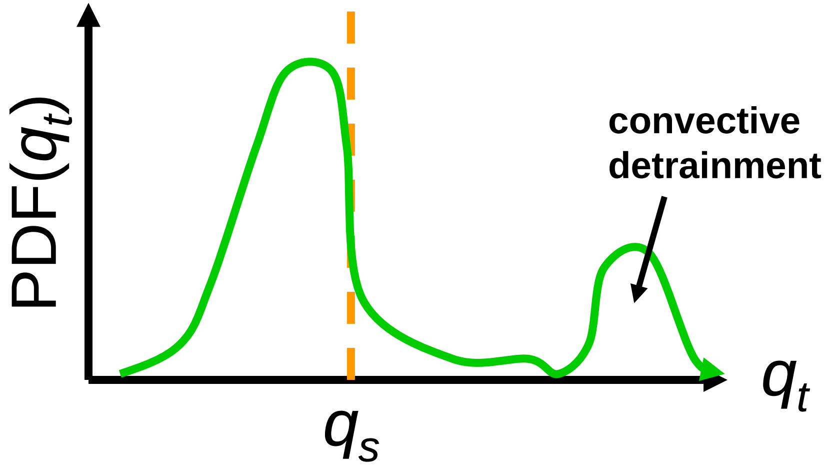
⇒ convective detrainment may not increase cirrus coverage (if $q_c<q_{nuc}$)

⇒ ice cloud properties averaged over all ice clouds.



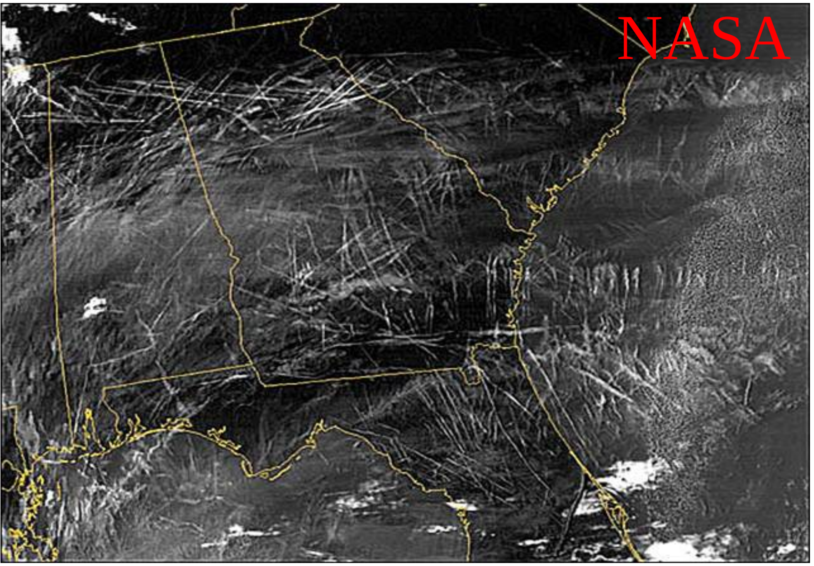
Waliser et al 2009





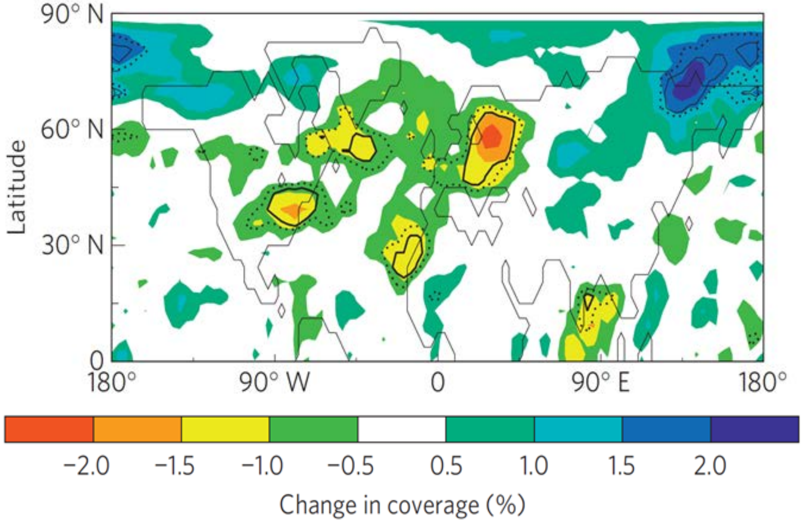
Convection changes microphysics of all ice clouds within a grid box.
=> implications for radiation and cirrus life times.

Contrail cirrus

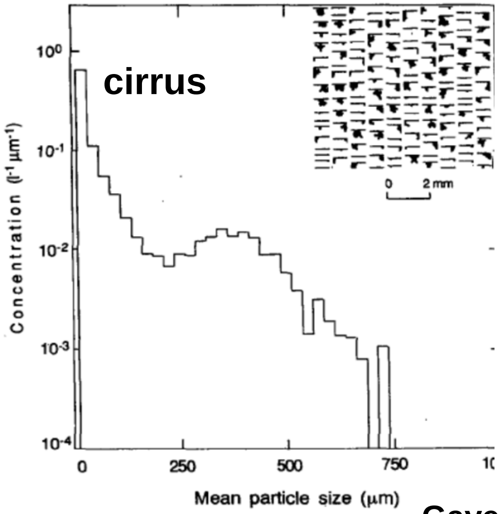


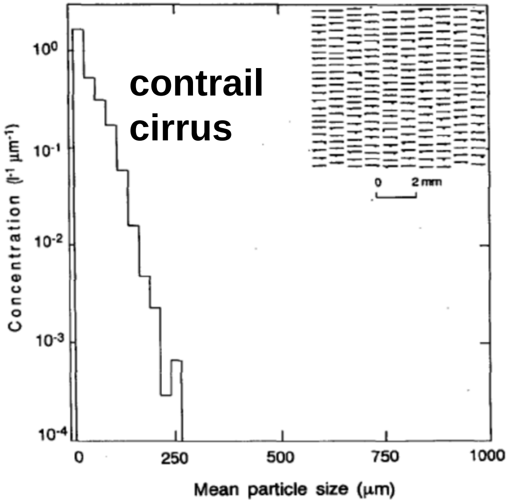
Contrail cirrus can increase cirrus coverage by several percent over the USA and Europe.

Contrails can replace natural cirrus or modify the natural cirrus due to changes in the temperature and humidity field.



Burkhardt and Kärcher, 2011





Gayet et al 1996

Contrails can replace natural cirrus and have very different optical properties

Conclusions

Two-moment microphysical scheme would allow simulation of regime dependence /synoptic variability in crystal sizes and microphysics, but cloud inhomogeneities still impact microphysics and radiation.

Cooling rate fluctuations due to gravity waves and turbulence controlling ice particle nucleation not well known and not (only partly) resolved in models down to very high resolutions.

Parameterizations of ice cloud cover and ice crystal number concentrations inconsistent as long as driven by independent forcings.

Convective outflow likely to change microphysics of preexisting cirrus clouds – probably resolution dependent

Contrail cirrus modify high cloudiness directly and indirectly by changing the upper tropospheric water budget.

HD(CP)^2 – use high resolution modelling in order to improve cloud parameterizations, study small scale cooling rates, coupling convectíon – cirrus, cloud overlap.