Prediction of Cirrus Clouds in GCMs

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with contributions from

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Stratiform cirrus clouds

Three specific features distinguish cirrus ($T < 235$ K) from other cloud types:

- high clear-sky supersaturation ($S > 1.5$) is required to nucleate ice from supercooled aerosols (homogeneous freezing);
- rapid mesoscale temperature fluctuations create cooling rates that drive the nucleation of ice in cirrus;
- long supersaturation relaxation time scales cause the existence of ice in super- and subsaturated conditions.

Compelling observational evidence in support of these features.

Basic ingredients of a novel cirrus scheme for GCMs.

Recent advances in GCMs

ECMWF IFS:

Ice supersaturation consistent with prognostic cloud fraction (Tiedtke, 1993), but still using moisture adjustment and bulk-mass microphysics (Tompkins *et al*., 2006).

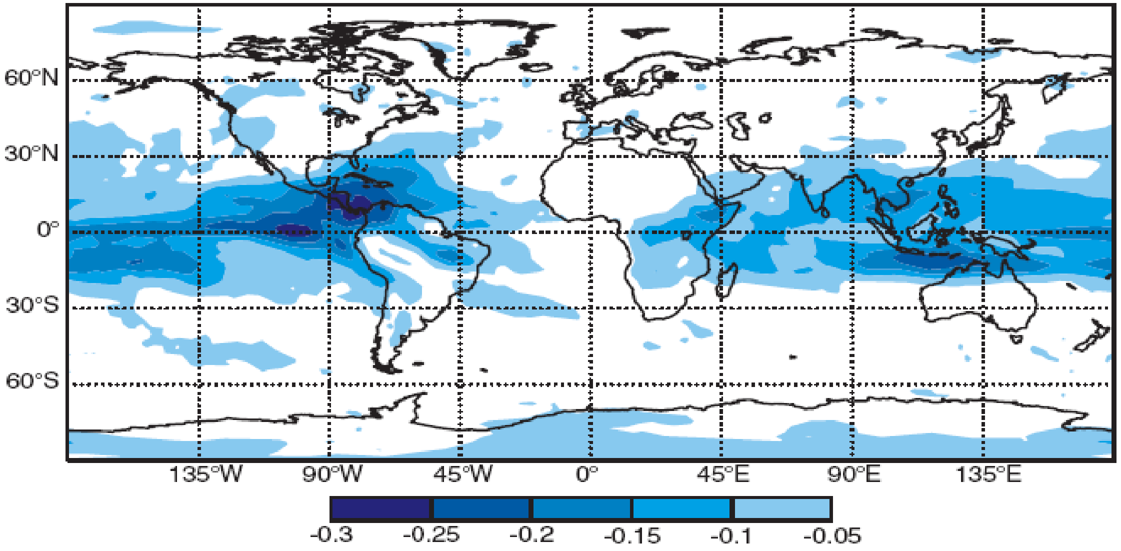


Figure 1 Difference in high cloud cover (pressure < 450 hPa approximately) between experiments using the new supersaturation scheme and the control, respectively, based on7-member ensemble mean 12-month averages.

Associated changes in RF are relevant.

Recent advances in GCMs, cont'd

ECHAM GCM:

Sophisticated microphysics with homogeneous freezing and water vapour diffusion (Lohmann and Kärcher, 2002), but using an inconsistent diagnostic cloud fraction (Sundqvist *et al*., 1989).

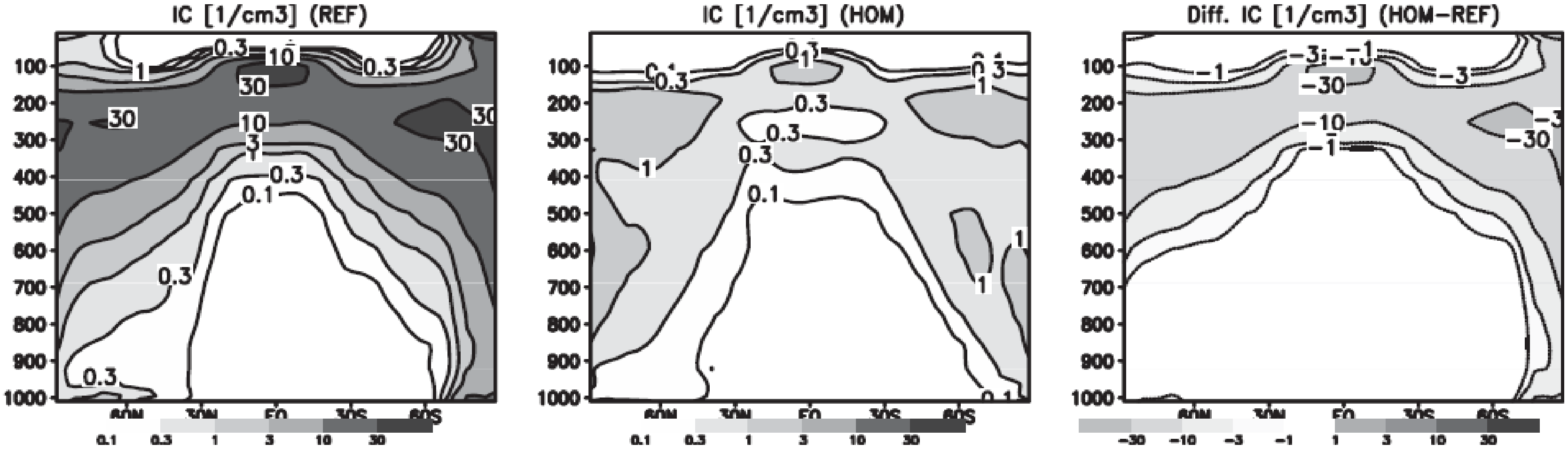
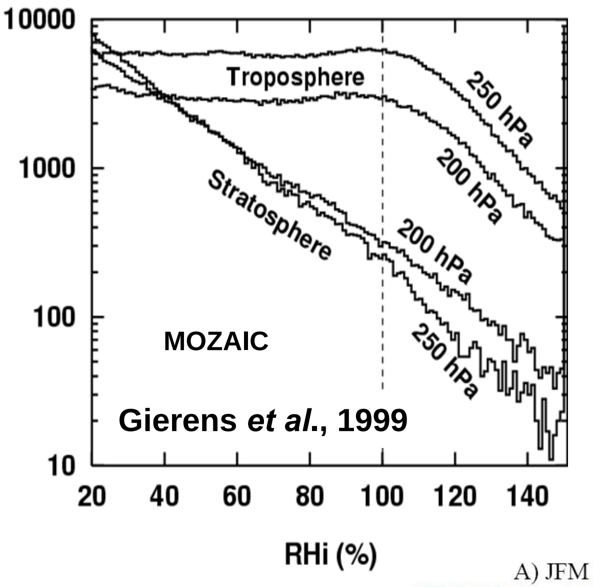


Figure 5. Annual zonal mean latitude versus pressure cross sections of ice water content (mg m^{-3}) and ice crystal number concentrations (cm^{-3}) for the simulations REF, HOM, and the difference HOM − REF.

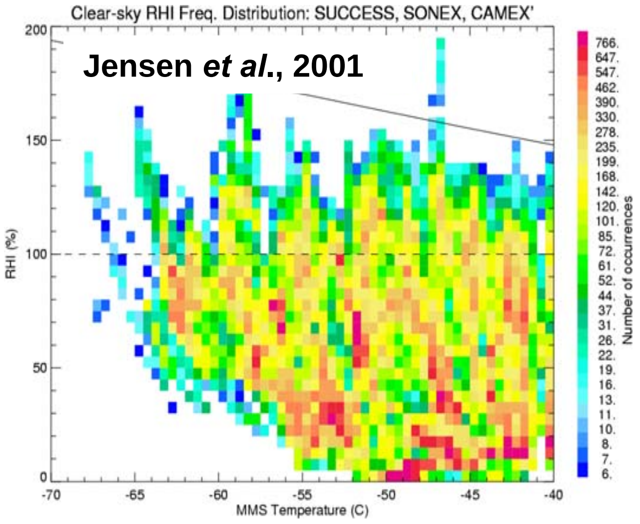
Missing link between cloud fraction and microphysics.

Upper tropospheric ice supersaturation

- Plethora of *in-situ*, lidar, radar, and satellite data demonstrate the occurrence of clear-sky *S* > 1
- Highest *S* occur within synoptic cold pools due to rapid adiabatic cooling and are consistent with homogeneous freezing

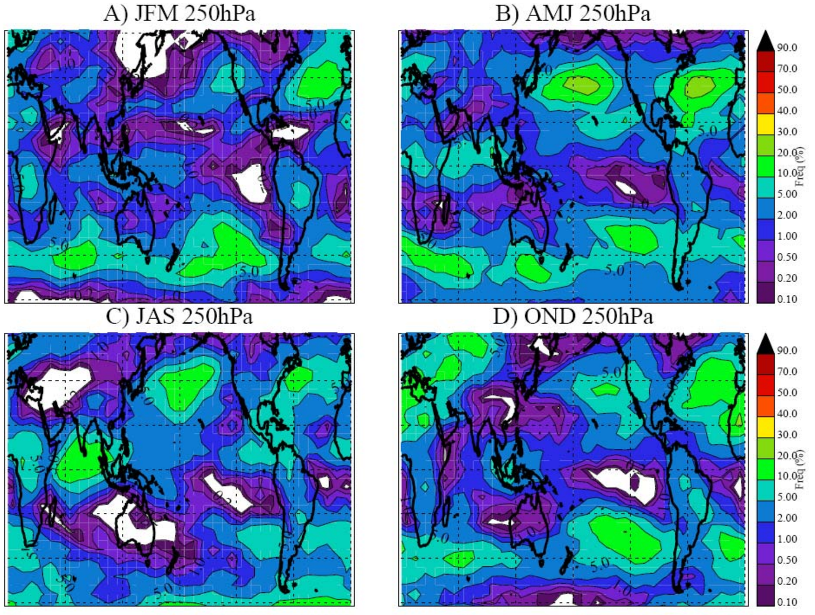


Gierens *et al.*, 1999



Jensen ***et al.***, 2001

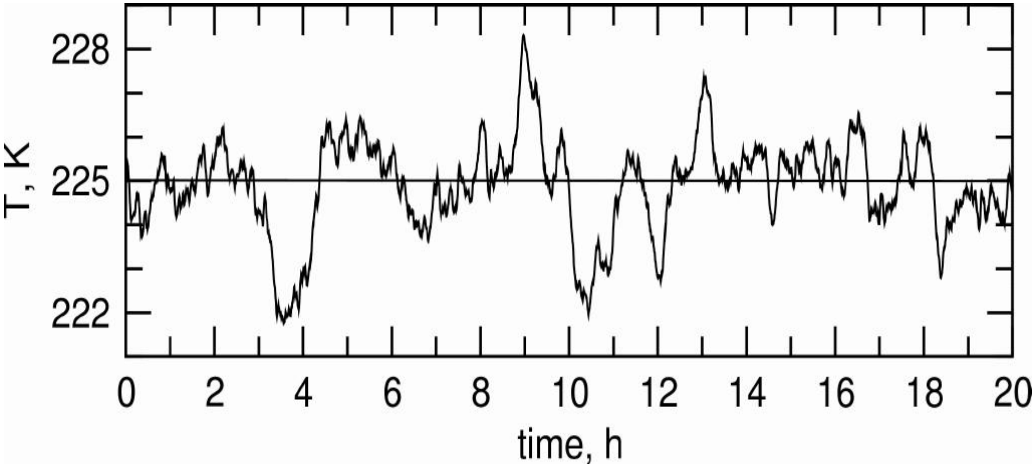
- Homogeneous freezing apparently occurred in most instances
- Low levels of heterogeneous ice nuclei (or lack thereof)
- Uncertainty issues remain, especially with supersaturation inferred from satellite data



AIRS

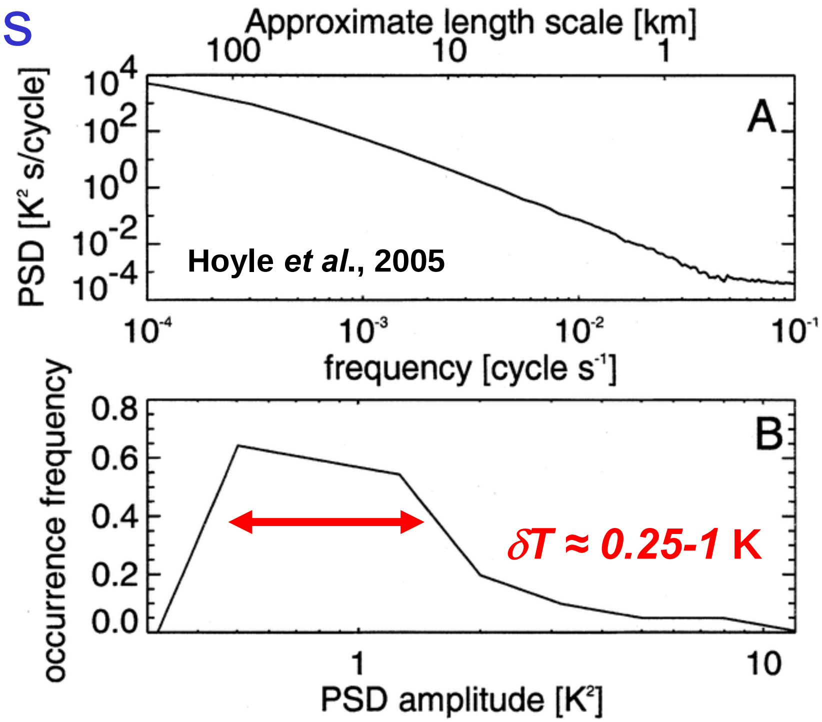
Gettelman *et al.*, 2006

Mesoscale temperature fluctuations



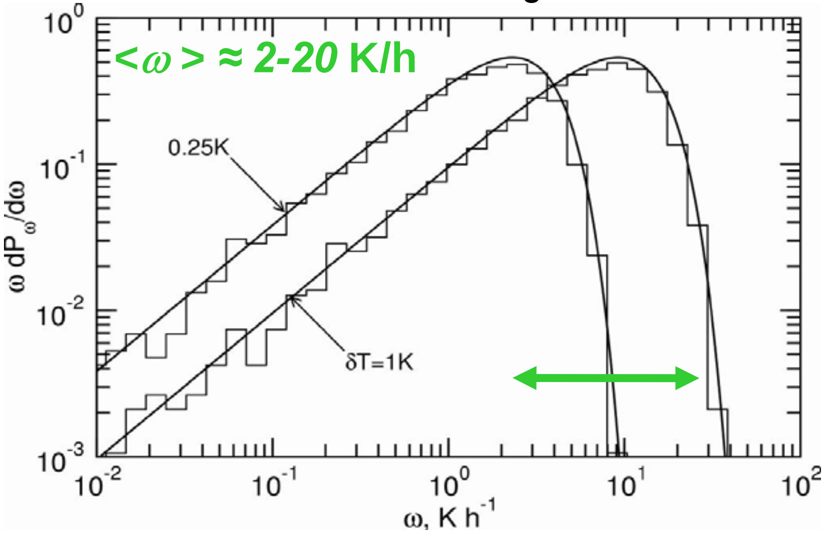
- Ever-present background of mesoscale variability (Gary, 2006; Bacmeister *et al*., 1996; Naström and Gage, 1985)
- Originate from gravity waves, vary with altitude, location, season, topography
- Unresolved in most global models:

  Length scales *10-100* km
  Time scales *10-20* min

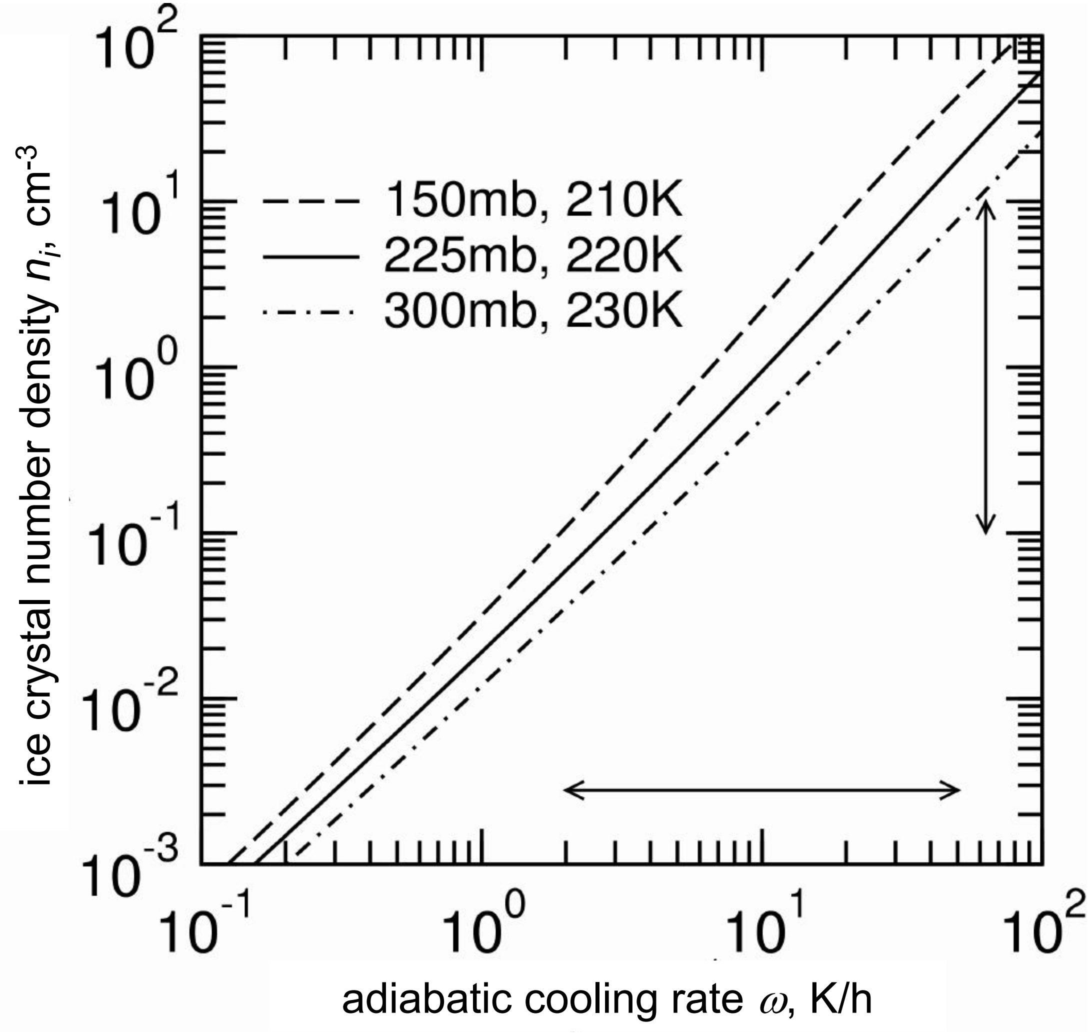

Hoyle *et al.*, 2005

$\delta T \approx$ 0.25-1 K

Distribution of cooling rates ω


$<\omega> \approx$ 2-20 K/h

Homogeneous freezing of supercooled aerosols



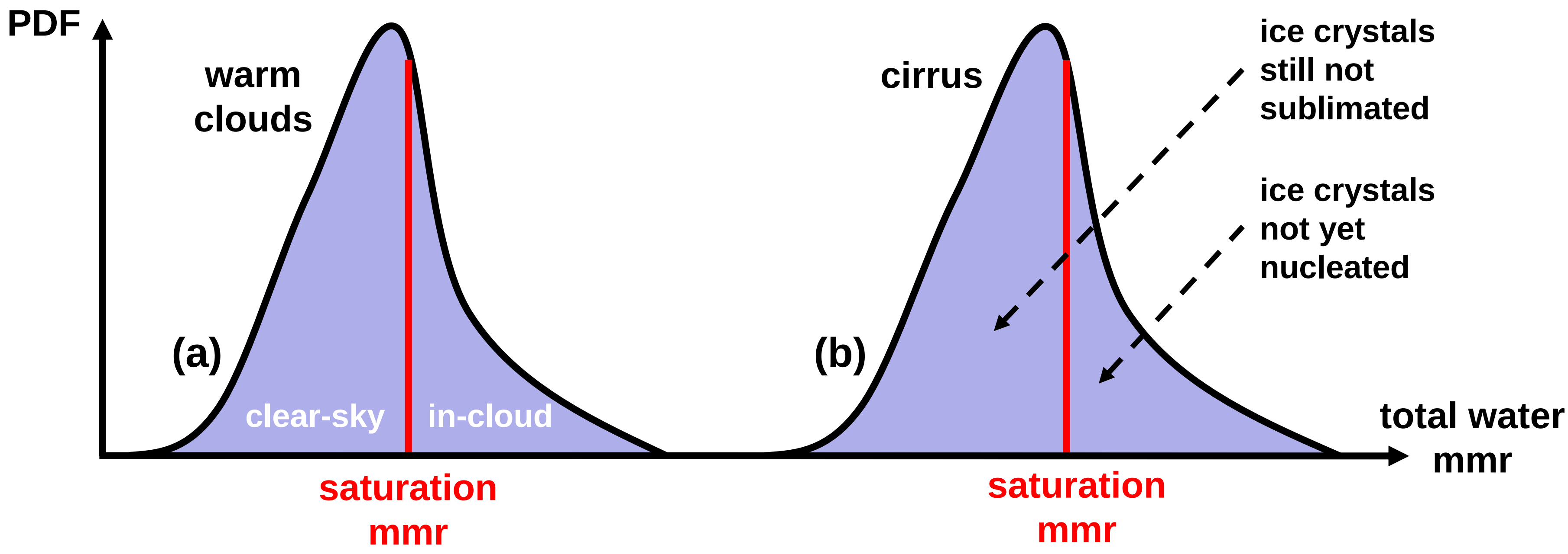
- Parametrization available (Kärcher and Lohmann, 2002)
- Cooling rate is key controlling factor for homogeneous frz
- Nucleation source term for prognostic ice number and mass
- Exploratory studies in the ECHAM-GCM

$$\delta T \rightarrow \langle\omega\rangle \rightarrow n_i$$

currently predicted *via* TKE in GCMs

Implication for statistical (PDF-based) schemes

One single PDF of total water mmr *q* is not sufficient to describe cirrus clouds:



At which *q* is the cirrus cloud boundary located in the PDF ?

How is ice nucleation and sublimation treated in such a framework ?

Cirrus cloud scheme

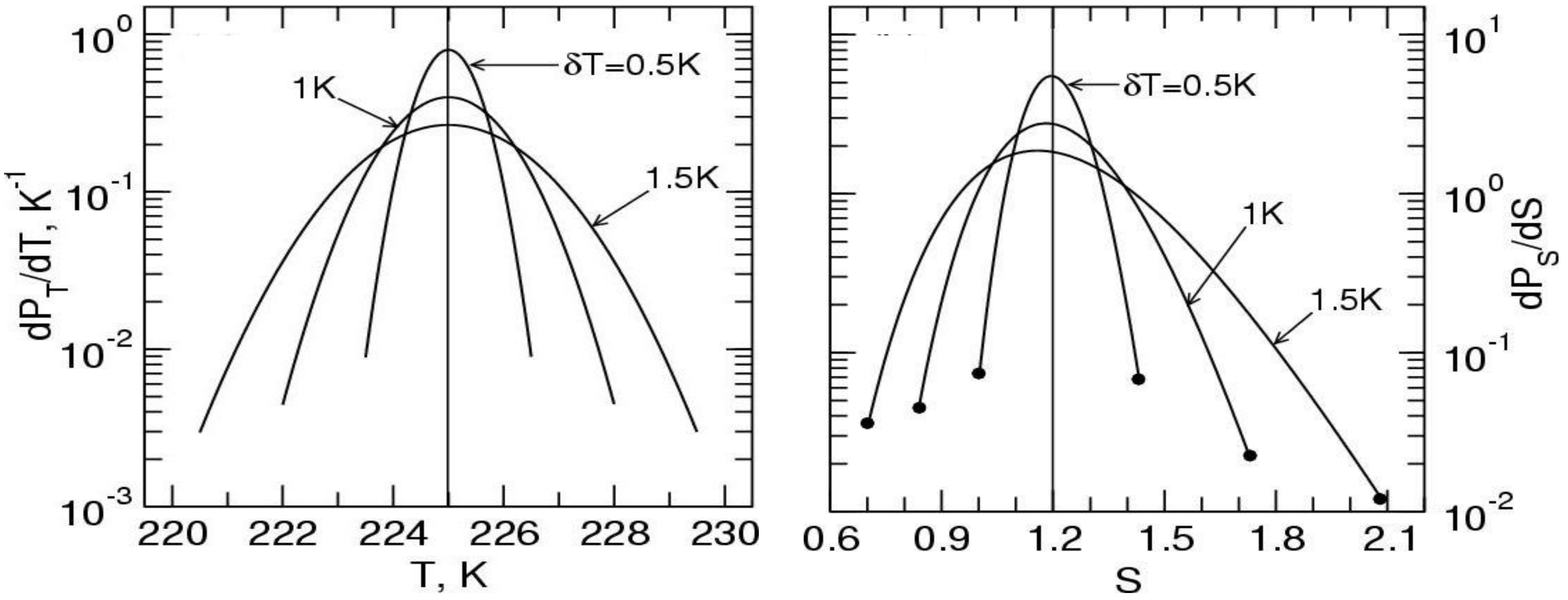
Separate PDFs for clear-sky and in-cloud total water to allow for time evolution of cloud fraction—presented next

Variables

- q_v grid-mean water vapour mmr
- q_i grid-mean ice water mmr
- c_i grid-mean ice crystal number mr (from nucleation parametrization)
- $q^c{}_v$ in-cloud water vapour mmr (from diffusional growth equation)
- $q^e{}_v$ clear-sky water vapour mmr (diagnosed from $q_v = a\, q^c{}_v + (1-a)\, q^e{}_v$)
- a cirrus cloud fraction

Clear-sky PDF

- Map Gaussian PDF of mesoscale temperature variability into PDF of *S*

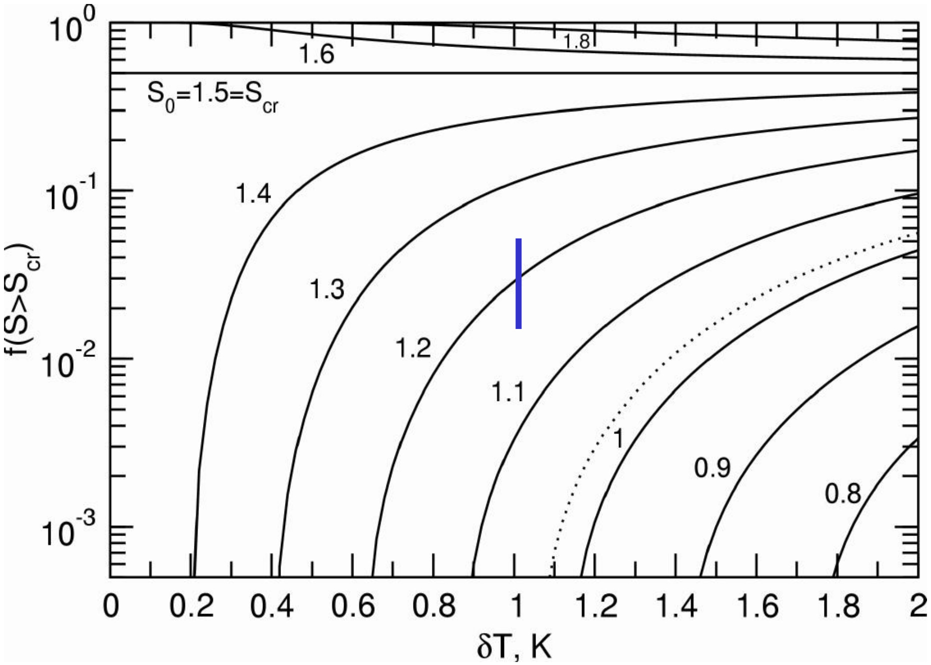


$$\frac{dP_S}{dS} = \frac{1}{\mathcal{N}_S} \frac{1/(\sigma_S\sqrt{2\pi})}{S\,\ln^2(S/\alpha)} \exp\left\{ -\beta_S \left[\frac{1}{\ln(S/\alpha)} - \frac{1}{\ln(S_0/\alpha)} \right]^2 \right\}$$

- Essentially neglects mesoscale water vapour variability (increases PDF variance) and adiabatic H_2O partial pressure corrections (decreases variance)

Clear-sky PDF, cont'd

- Portion of dP_S/dS above nucleation threshold S_{cr} determines Δa and Δq_i



$$\Delta a = (1-a)\int_{S_{cr}}^{S_{max}} \frac{dP_S}{dS}\,dS$$

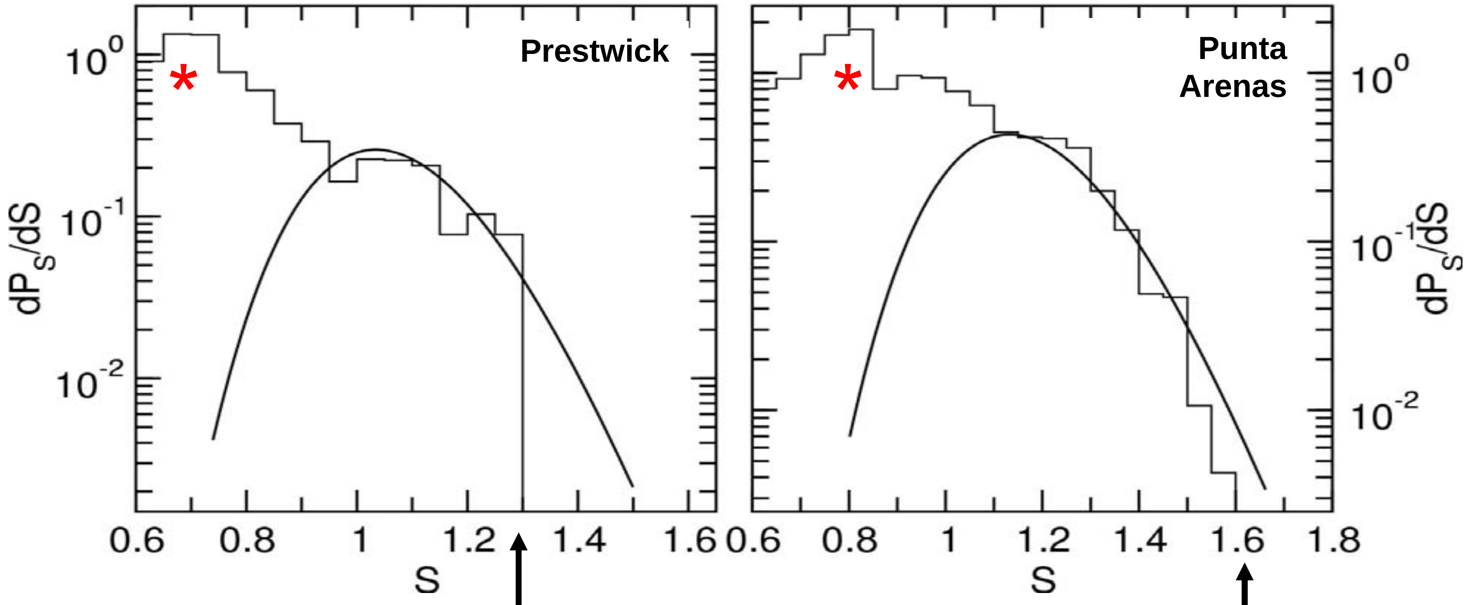
$$= (1-a)\ f(S > S_{cr})$$

homogeneous
freezing threshold (> *1.5*)

- Homogeneous freezing commences at grid-scale *S ~ 1.2* for δT ~ *1* K
- Subsaturated conditions need unrealistically high δT > *1.5* K to push distribution above S_{cr}
- H_2O mass Δq_i deposited on ice during nucleation and initial growth follows from freezing parametrization (≤ S_{cr}) and from PDF (> S_{cr})

Clear-sky PDF, cont'd

- Comparison with aircraft data (INCA, stair steps) justifies approach: use $\delta T = 1$ K consistent with observed $\langle \omega \rangle \sim 10$ K/h and $\langle n_i \rangle \sim 1$ cm^{-3}



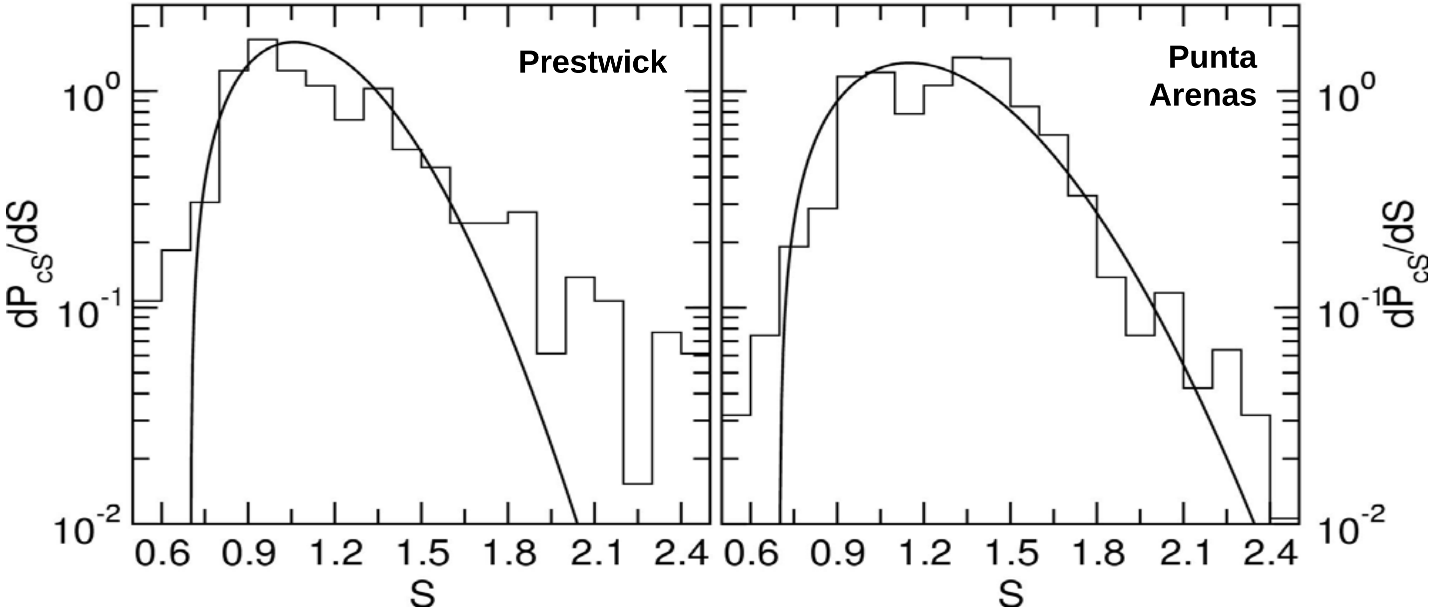
most likely induced
by heterogeneous
ice nucleation

homogeneous
freezing

- Prestwick data show cut-off below homogeneous freezing threshold
- Dry modes * from observations taken in different air masses

In-cloud PDF

- Guided by aircraft measurements of total water (INCA, stair steps), use observed total *S* ~ *1.2* to determine distribution width Δ_S



$$\frac{dP_{cS}}{dS} = \frac{S - S_{min}}{\Delta_S^2} \exp\left[-\frac{1}{2}\left(\frac{S - S_{min}}{\Delta_S}\right)^2\right]$$

- At and below S_{min} ~ *0.7*, ice crystals cannot exist (Hall and Pruppacher, 1976); Ström *et al*. (2003) outline measurement issues.

Cloud scheme

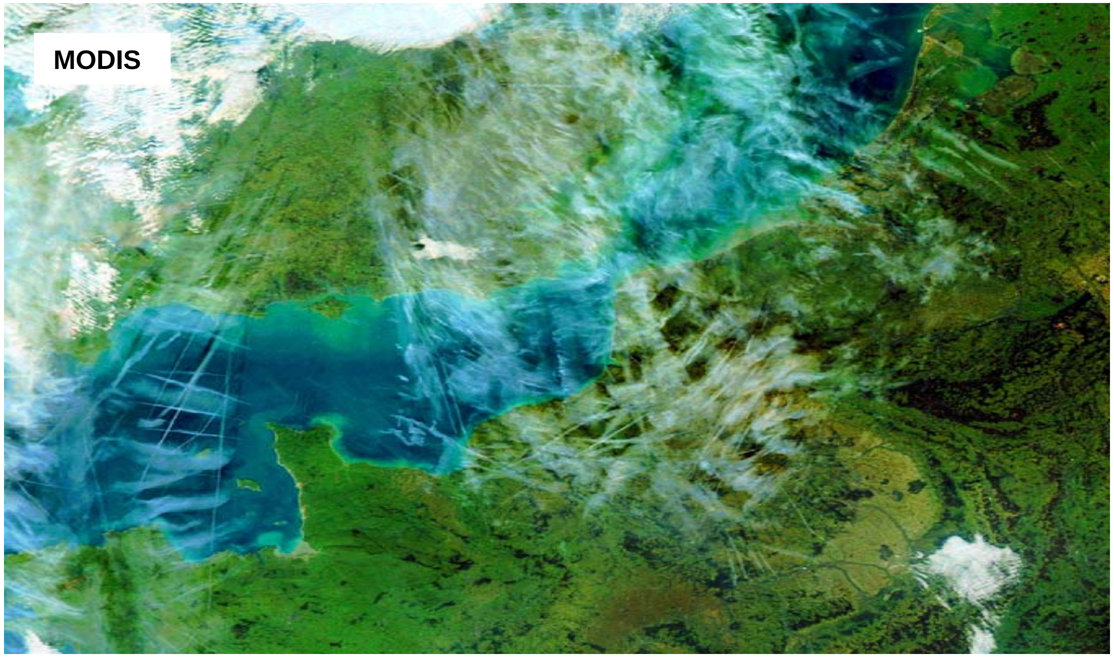
Basic equations for the full cirrus cloud scheme follow consistently from PDFs, supported by a vapour diffusion equation and the freezing parametrization.

Cirrus can respond to changes in local dynamical conditions:

- clear-sky PDF moments are fcns of q^e_v and fluctuation std δT;
- in-cloud PDF moments are fcns of total water content $q^c_v + q_i/a$ and S_{min}.

Pertinent deficits in GCMs

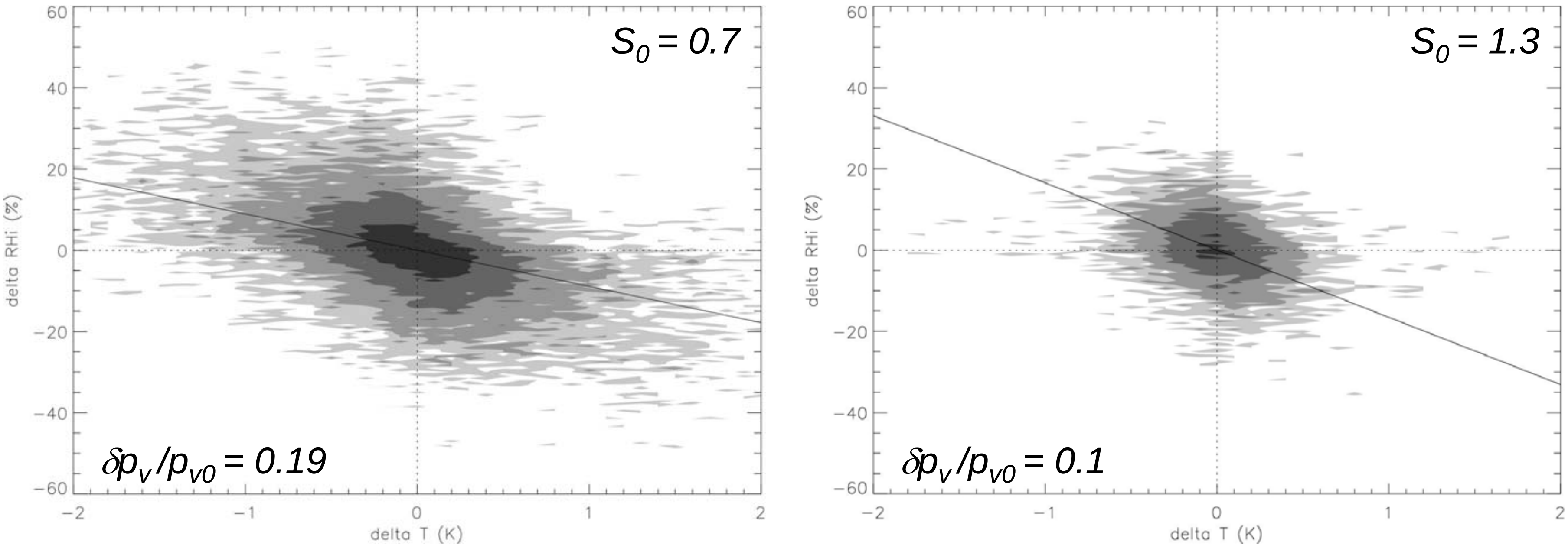
- Updraught speeds used for nucleation rely on poorly constrained model TKE.
- Missing cloud-scale feedbacks between radiation and dynamics.
- Role of heterogeneous ice nucleation.
- Subgrid-scale water vapour fluctuations enhance cloud fraction increase.
- Cirrus ice from different sources with different properties is not tracked separately (stratiform, convective, mixed-phase, contrail cirrus).



Courtesy of Bob d'Entremont, AER

Aircraft contrail cirrus alter the regional radiative balance and could make up a significant portion of high cloudiness in the future .....

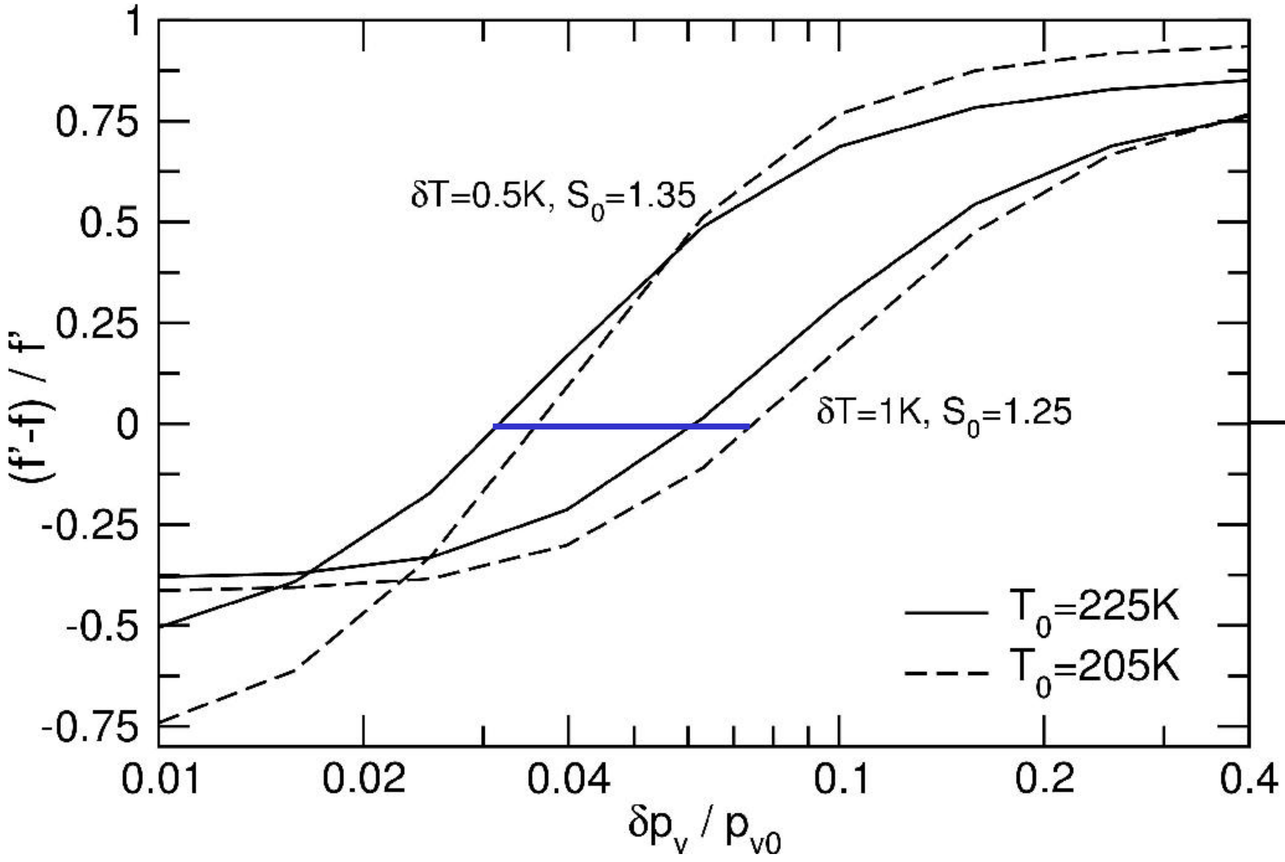
PDF for joint temperature and water vapour fluctuations (T42)



- New analysis based on 9 years of MOZAIC data (1995-2003).
- Data shown are for $T_0 = 220$ K and two different mean humidity states S_0.
- Mean temperature std $\delta T = 0.82$ K, averaged over all S_0.

Impact of clear-sky mesoscale water vapour variability

- Add Gaussian random H_2O fluctuations *and* adiabatic corrections to pure MTF, evaluate relative change in predicted cloud fraction in freezing conditions.



H_2O variability

+

–

adiabatic changes

- Impact cannot be ignored for $\delta p_v / p_{v0} > 0.03 – 0.08$.

Prognostic contrail cirrus

Contrail formation, accumulation, spreading, mixing, competition for condensate, evaporation, precipitation, persistence and advection over large distances

- Moisture, cirrus ice, and contrail cirrus ice are distributed in clear-sky and cloudy regions.
- Processes affecting contrail cirrus fraction *b*:

$$\frac{\partial b}{\partial t} = \left(\frac{\partial b}{\partial t}\right)_{src} + \left(\frac{\partial b}{\partial t}\right)_{transp} + \left(\frac{\partial b}{\partial t}\right)_{spread} - \left(\frac{\partial b}{\partial t}\right)_{mix} - \left(\frac{\partial b}{\partial t}\right)_{pot} - \left(\frac{\partial b}{\partial t}\right)_{evap}$$

Source: Aircraft path lengths from AERO2K emission inventory, including diurnal variations

Transport: Horizontal and vertical advection, diffusion

Spreading: Extending contrail width by vertical shear of horizontal wind

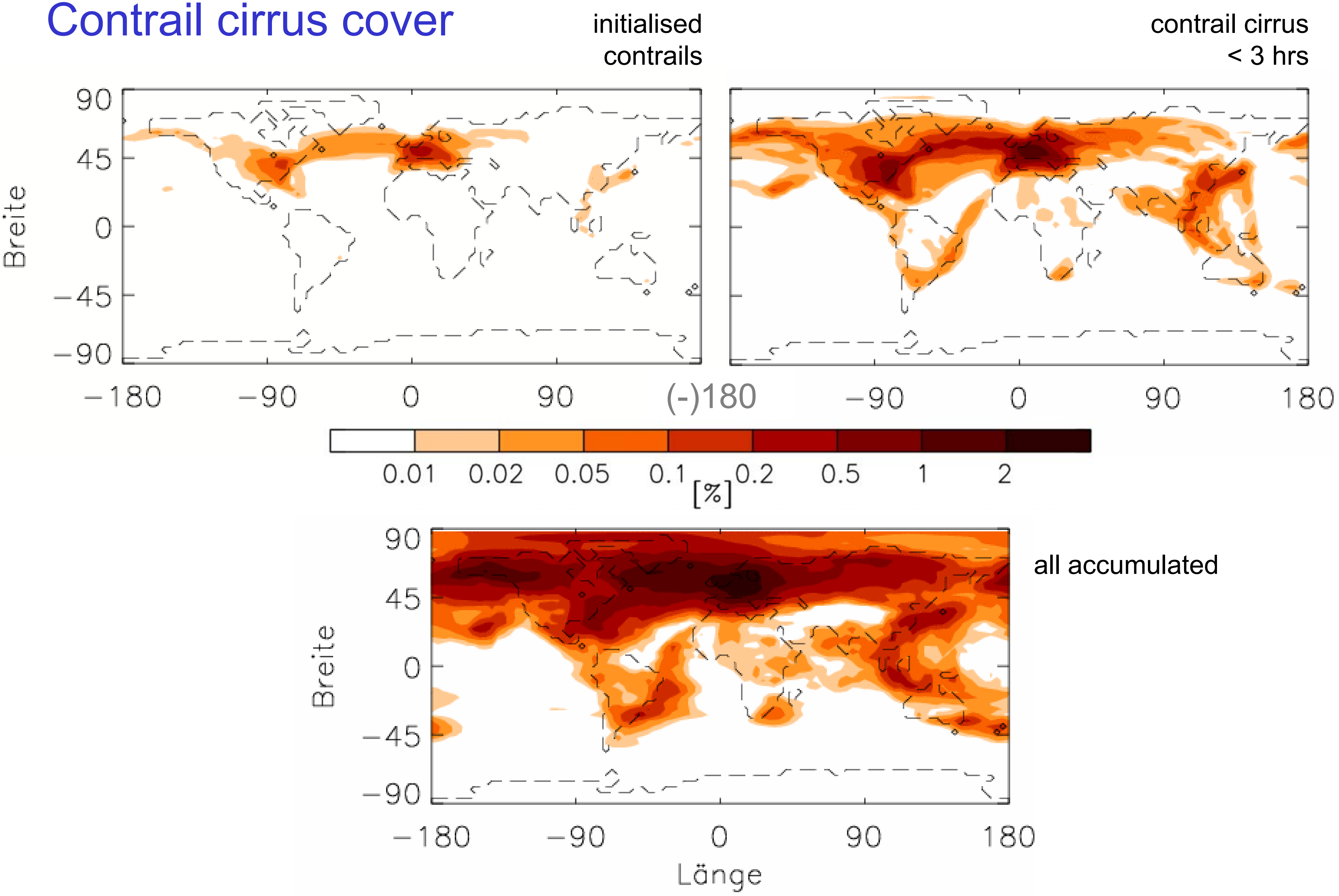
Mixing: Erosion *via* turbulent mixing with subsaturated air at contrail boundaries, affecting width only

Potential coverage: Restrict phase space for contrail cirrus existence by natural clouds and available ice supersaturated regions

Evaporation: Loss *via* sublimation of ice at the end of decay phase

- Contrail cirrus have different radiative properties and affect the evolution of natural cirrus

Contrail cirrus cover



initialised contrails

contrail cirrus < 3 hrs

all accumulated

Summary

Novel statistical cloud scheme for non-convective cirrus clouds formed by homogeneous freezing of supercooled aerosols.

Prognostic approach with separate clear-sky and in-cloud distributions of total water allows existence of thermodynamically metastable states.

Grid-scale sub- and supersaturation, and ice crystal number and size in good agreement with observations.

Main work ahead concerns realisation in an existing GCM cloud scheme, and future couplings with a full ice nucleation scheme and contrail cirrus.