Prediction of Cirrus Clouds in GCMs

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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 on 7-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
- 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
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
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 $S$

$$\frac{dP_s}{dS} = \frac{1}{N_s} \frac{1}{S \ln^2(S/\alpha)} \exp \left\{ -\beta_S \left[ \frac{1}{\ln(S/\alpha)} - \frac{1}{\ln(S_0/\alpha)} \right]^2 \right\}$$

- Essentially neglects mesoscale water vapour variability (increases PDF variance) and adiabatic $\text{H}_2\text{O}$ partial pressure corrections (decreases variance)
Clear-sky PDF, cont'd

- Portion of $dP_S/dS$ above nucleation threshold $S_{cr}$ determines $\Delta a$ and $\Delta q_i$

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

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

- Homogeneous freezing commences at grid-scale $S \sim 1.2$ for $\delta T \sim 1$ K
- Subsaturated conditions need unrealistically high $\delta T > 1.5$ K to push distribution above $S_{cr}$
- H$_2$O mass $\Delta q_i$ deposited on ice during nucleation and initial growth follows from freezing parametrization ($\leq S_{cr}$) 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 $<\omega> \sim 10$ K/h and $<n_i> \sim 1$ cm$^{-3}$

- Prestwick data show cut-off below homogeneous freezing threshold

- Dry modes * from observations taken in different air masses

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**Graphical Representation**

- Left: Prestwick data
  - Most likely induced by heterogeneous ice nucleation

- Right: Punta Arenas data
  - Homogeneous freezing

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*Note: Graphs show PDF distributions with cut-off points indicated.*
In-cloud PDF

- Guided by aircraft measurements of total water (INCA, stair steps), use observed total $S \sim 1.2$ to determine distribution width $\Delta_S$

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

- At and below $S_{\text{min}} \sim 0.7$, 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 $q_v^e$ and fluctuation std $\delta T$;
• in-cloud PDF moments are fcns of total water content $q_v^c + q_i/a$ 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).

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

Courtesy of Bob d'Entremont, AER
PDF for joint temperature and water vapour fluctuations (T42)

- 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 $S_0$. 

\[ S_0 = 0.7 \quad \delta p_v / p_{v0} = 0.19 \]

\[ S_0 = 1.3 \quad \delta p_v / p_{v0} = 0.1 \]
Impact of clear-sky mesoscale water vapour variability

- Add Gaussian random H$_2$O fluctuations and adiabatic corrections to pure MTF, evaluate relative change in predicted cloud fraction in freezing conditions.

- 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 $b$:

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

**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

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

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

- 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.