Prediction of cirrus clouds in GCMs

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ABSTRACT

Specific features that distinguish high altitude cirrus from warm and mixed phase clouds are reviewed, along with observational evidence in support of these features. Implications for statistical cloud schemes based on probability distributions of total water are highlighted. A prognostic cloud scheme for non-convective cirrus formed by homogeneous freezing of supercooled aerosols is developed, predicting relative humidity fields and ice cloud properties in good agreement with observations. Uncertainties and future extensions of the cloud scheme are summarised.

1 Introduction

A central assumption common to virtually all cloud schemes is that cloud particles form as soon as saturated conditions are surpassed. Likewise, cloud particles are not allowed to exist in subsaturated conditions. These are fairly good approximations for low-level tropospheric clouds that form by activation of cloud condensation nuclei into cloud droplets close to water saturation. Hence, statistical schemes that are based on probability density functions (PDFs) of total water allow the cloud fraction and cloud water content to be diagnosed, once the moments of the underlying PDFs are known (Figure 1a).

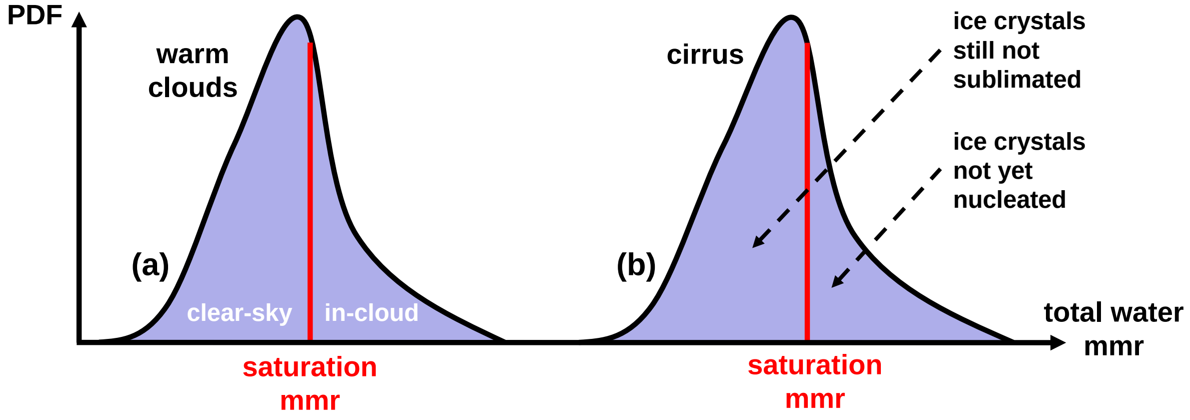

Figure 1: Schematic illustrating a single PDF for total water mass mixing ratio (mmr). For warm and mixed phase clouds (a), the saturation mmr line unambiguously separates clear-sky and cloudy regions. On the contrary, a single PDF is not sufficient to describe cirrus (pure ice) clouds (b). It is not known at which values of the mmr the cirrus cloud boundary is located, and it is unclear how nucleation and sublimation of ice crystals could possibly be treated.

Up to date, cirrus clouds–pure ice clouds that exist below about 235 K–are treated similar to other cloud types, despite the fact that cirrus usually form and develop in non-equilibrium conditions (Figure 1b). During the workshop, we have presented a novel prognostic cloud scheme that is able to track often long-lived, large-scale cirrus in GCMs properly (Kärcher and Burkhardt, 2007). The most important feature of this fully analytic scheme is its consistency between subgrid-scale microphysical processes that lead to the nucleation and sublimation of ice crystals and macrophysical processes that determine the evolution of horizontal cloud fraction and ice water content on the grid scale. Our key arguments and findings are summarised below.

2 Cirrus cloud specific features

Three specific features distinguish cirrus from other cloud types:

- high ice supersaturation (> 0.5) is required to nucleate ice homogeneously in liquid aerosol particles;
- rapid mesoscale temperature fluctuations create cooling rates (~ 10 K/h) that drive the nucleation of ice;
- long saturation relaxation times ($5 - 120$ min) cause the existence of ice in non-equilibrium conditions.

A plethora of *in-situ*, lidar, radar, and satellite observations demonstrate the frequent occurrence of clear-sky ice supersaturations in the upper troposphere. The most obvious manifestation of ice supersaturation are aircraft-induced contrails that often persist prior to natural cirrus formation and develop into extended contrail cirrus cloud decks. The highest relative humidities occur within synoptic cold pools or in wave clouds due to adiabatic cooling, and are consistent with homogeneous freezing. The fact that homogeneous freezing is frequently observed implies that the upper tropospheric concentrations of heterogeneous ice nuclei (IN) are low ($< 10 - 100$ per litre of air). In such conditions, IN may nucleate ice at significantly lower supersaturations than liquid particles, but do not prevent homogeneous freezing from occurring.

The homogeneous freezing process appears to be well understood and has been confirmed in numerous laboratory and field studies. We have developed a parametrization scheme that provides the number and mass concentrations of ice crystals formed by this nucleation mode as a function of relative humidity, cooling rate, temperature, and aerosol parameters. This scheme includes the prediction of ice supersaturation on the grid scale. It has been implemented into the ECHAM GCM and tested in several exploratory studies with gratifying results. Fields of upper tropospheric relative humidity and ice water content improved significantly in this way, and global distributions of ice crystal concentrations could be simulated for the first time.

Aircraft *in-situ* observations in the tropical and extra-tropical upper troposphere and lower stratosphere have demonstrated that even away from direct convective or lee wave influence and turbulence triggered by jet stream instabilities, an ever-present background of mesoscale temperature fluctuations (MTF) exists, with characteristic temperature amplitudes $\delta T \simeq 0.25 - 1$ K (standard deviation). MTF originate from gravity waves and vary with altitude, location, season, and underlying topopgraphy. MTF occur on horizontal length scales $1 - 100$ km and buoyancy time scales $\sim 10 - 20$ min and are not resolved in even the most advanced global models.

The total number of ice crystals formed in a homogeneous freezing event is a strong function of the cooling rate $\omega = |dT/dt|$. It has been shown that mesoscale variability in ω is the most important factor controlling cirrus formation, leading to the observed high concentrations of cirrus ice crystals (~ 1 per cm^3 of air) embedded in broad distributions. It is key to provide accurate mesoscale cooling rates to drive the freezing parametrization in a GCM. Currently, these are obtained by tuning a subgrid-scale vertical wind component that originates from the turbulent kinetic energy of the flow. We plan to use δT directly parametrized from MTF observations to calculate background ω in future applications.

3 Recent progress in representing cirrus clouds

In the ECMWF IFS (cycle 31r1), a simple method to represent ice supersaturation before cirrus formation *via* homogeneous freezing has been implemented into the operational Tiedtke scheme (Tompkins et al., 2007). This step has led to an improvement of the relative humidity fields at the tropopause, and to corresponding increases of the net incoming solar and outgoing longwave radiation of ~ 2 W/m^2 that almost cancel each other globally. However, the Tiedtke scheme still relies on bulk-mass microphysics with a temperature-dependent water/ice phase partitioning and uses hard moisture adjustment after cirrus formation.

A different approach has been taken in the ECHAM GCM, cf. Section 2. An improved microphysics package is currently being implemented (Hendricks et al., 2007) that parametrizes homogeneous freezing in competition with heterogeneous ice nucleation (Kärcher et al., 2006). This allows more interactions between dynamics and aerosols during cirrus formation to be studied on a global scale, so there are surprises still in store. However, the diagnostic Sundqvist cloud cover in use in ECHAM cannot deal with the supersaturation now allowed in cirrus conditions, as it predicts an overcast grid box already at saturation. This inconsistency can only be overcome with the introduction of a proper prognostic cloud scheme as outlined next.

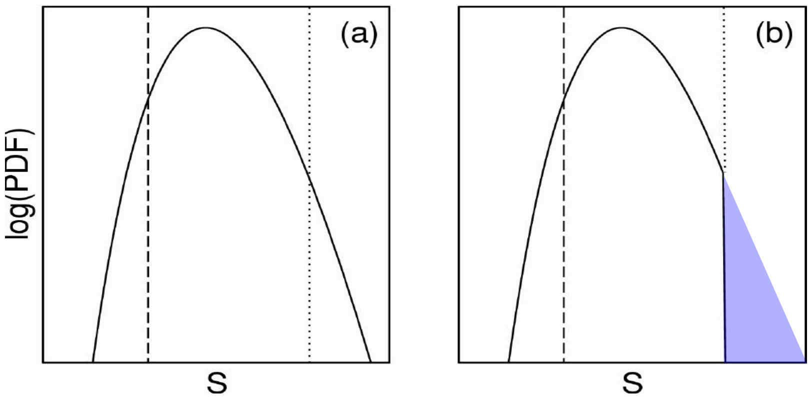

Figure 2: Schematic illustrating cirrus formation, shown is the clear-sky PDF. Its tail whose mean is above ice saturation (dashed line) is pushed above the homogeneous freezing threshold (dotted line) by cooling or transport of moisture (a). This clear-sky state is difficult to observe in the atmosphere, because freezing moves the coloured portion (b) to the in-cloud PDF within seconds to minutes, creating new cloudy area.

4 Outline of the cirrus cloud scheme

The features discussed in Section 2 constitute the basic ingredients for our cirrus cloud scheme. As it is not possible to track the time evolution of cirrus cloud fraction with one PDF of total water alone (recall Figure 1), the use of two PDFs for clear-sky and in-cloud total water provides a clue. The six variables of our scheme are:

- grid mean water vapour mmr, ice water mmr, and ice crystal number mr;
- clear-sky water vapour mmr; in-cloud water vapour mmr;
- horizontal cirrus cloud fraction.

While the clear-sky water vapour mmr is diagnosed, all other variables are obtained from solving corresponding prognostic equations. In particular, the in-cloud water vapour mmr follows from a diffusional growth equation and the local increases of ice crystal number and mass during cirrus formation are obtained from the homogeneous freezing parametrization. The saturation adjustment usually employed in GCMs is abandoned.

We map the Gaussian PDFs of background mesoscale temperature variability into PDFs of clear-sky ice saturation ratio S. The shape of the resulting PDF (Figure 2a) as well as its moments are then determined by the mean clear-sky ice saturation ratio and δT. The simplification of only accouting for MTF in computing clear-sky PDFs neglects variability of water vapour (increasing the PDF variance) and adiabatic water vapour partial pressure (p_v) corrections (decreasing the variance).

Figure 2b sketches how the cloud cover increase Δa is obtained from the clear-sky PDF, whose shape is in good agreement with *in-situ* data. The coloured region is proportional to Δa. We find that cirrus formation *via* homogeneous freezing commences at grid mean values $S \simeq 1.2$ for $\delta T \simeq 1\,\mathrm{K}$, and that unrealistically high δT values are needed to trigger homogeneous freezing when the mean state is subsaturated.

A recent analysis of observed fluctuations δp_v and temperature along major aircraft flight routes shows that in high relative humidity conditions on a T42 scale, $\delta p_v / p_v \simeq 10\%$ (Gierens et al., 2006), with possible implications for the prediction of cirrus cloud fraction a. The temperature fluctuations inferred from this data source are in reasonable agreement with those noted above.

To assess the impact of mesoscale water vapour variability in our cloud scheme, we added both the adiabatic corrections and assumed water fluctuations to the PDF and evaluated the relative change in cloud fraction increase in supersaturated conditions. We found that values $\delta p_v / p_v > 3-8\%$ suffice to significantly enhance Δa relative to the PDF obtained from pure temperature variability. Hence, this issue warrants further study.

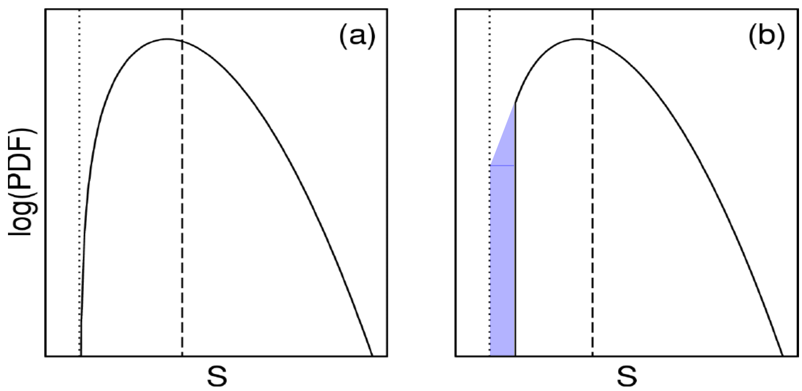

Figure 3: Schematic illustrating cirrus decay, shown is the in-cloud PDF. Contrary to Figure 2, S is now the total (gas plus ice phase) saturation ratio. When ice crystals sublimate depending on the gas saturation ratio, ice water is transferred to the gas phase at the lowest possible total saturation ratio where cirrus can exist (dotted line). This reduces the cloud cover by narrowing the phase space in the PDF available for cloud (coloured portion). Dashed line indicates ice saturation.

We employ a similar strategy to predict cloud decay by means of the in-cloud PDF. Figure 3a shows such a distribution of total water schematically. The analytic form of the distribution was guided by aircraft observations. Unimodality seems to capture the salient features of the non-convective cirrus water distributions, but there are not enough data sources available to finally conclude on this point. Typically, the ice water content amounts to only few tens of percent of the total in-cloud water. MTF are not explicitly accounted for, because the presence of ice damps the resulting oscillations in relative humidity.

The most important property of the PDF, though, is the sharp cut-off at a minimum ice saturation ratio S_{min}, below which cirrus clouds cannot exist. According to observations and investigations of the survival times of ice crystals falling from cirrus into subsaturated air, this value is near 0.7. The distribution variance is proportional to the total water content (that is, the prognosed in-cloud water vapour mmr and the ice water mmr) reduced by S_{min}. Vapour is distributed from S_{min} to approximately the homogeneous freezing limit (dashed line). Ice crystals are distributed over the entire range of S-values in the PDF, but sublimate only at S_{min}.

Once the mean in-cloud water vapour mmr falls below saturation, ice crystals are forced to sublimate, increasing the relative humidity. At the same time, the loss of ice mass translates into a narrowing of the PDF right above S_{min} (coloured region in Figure 3b), from which the loss of cloud fraction Δa can be calculated. If few (1 per litre), large (100 μm) ice crystals sublimate, substantial subsaturations up to $1 - S_{min}$ can occur on the grid-scale in the presence of cirrus, while a does not fall below ~ 0.9. The situation reverses during the sublimation of many, small crystals (e.g., 100 per litre, 20 μm).

5 Outlook

The basic equations for the full cirrus cloud scheme follow consistently from integrals over the clear-sky and in-cloud distributions of S as introduced above. We point out that cirrus formation and evolution is allowed to respond realistically to changes in local cloud forcing conditions, because the PDF moments are determined by humidity variables and temperature fluctuations that are temporally and spatially variable.

A detailed derivation of the cirrus scheme with explicit solutions and a discussion of future avenues of research will soon be available (Kärcher and Burkhardt, 2007), along with a full list of references relevant to this brief workshop report. Future work will first concentrate on finding an appropriate statistical scheme for warm and mixed phase clouds, in which this cirrus scheme can be realised. Further research issues to be tackled include:

- global distribution of temperature fluctuations;
- water vapour fluctuations;
- heterogeneous ice nucleation;
- cirrus ice from different sources (e.g., convection, contrail cirrus);
- cloud-scale feedbacks between radiation and dynamics.

6 Conclusion

The inclusion of more processes and more prognostic variables provides a challenge to complex, large-scale models such as the IFS or ECHAM. The obvious benefit is that high, thin ice clouds can feed back on upper tropospheric humidity and radiation, with potentially important improvements of water vapour abundance at the entry to the tropical stratosphere (important for chemistry-climate interactions) and a potentially better representation of effective ice crystal radii and ice water paths (important for radiative forcing).

Future models will be able to investigate interactions with other types of ice clouds such as contrail cirrus using prognostic parametrizations for their cloud fraction (Burkhardt et al., 2007), and to study the impact on cirrus of natural and anthropogenic changes of vertical wind variability and aerosol composition (Haag and Kärcher, 2004) in a changing climate more realistically.

We hope that our proposed cirrus scheme–when combined with an appropriate host cloud scheme–provides the missing link between ice microphysics and cloud fraction and paves the way for a consistent, physically-based treatment of this radiatively and hydrologically important cloud type in the most advanced weather forecast and climate models.

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