Extending a PDF cloud scheme in order to accommodate cirrus physics

Ulrike Burkhardt

Institute for Atmospheric Physics, DLR Oberpfaffenhofen,
82234 Weßling, Germany
ulrike.burkhardt@dlr.de

Abstract

Formation and microphysical properties of cirrus clouds are very different to those of liquid clouds but still cirrus physics is often not or only partly taken into account in large scale models. Incomplete knowledge of the processes involved in ice crystal nucleation prohibits a more complete description of ice cloud physics. Nevertheless those processes are crucial for a correct description of microphysical and optical properties of cirrus clouds. This article discusses the consistent parameterization of cirrus physics and its challenges in large scale models.

1. Introduction

The physics of ice clouds is known since several years but still climate models or numerical weather prediction models represent those physics only extremely simplified or not at all. This is problematic, since it is known that the realistic representation of cirrus is vital for e.g. radiation (Liou 1986), the upper tropospheric water budget and the water vapour input into the stratosphere (Holton and Gettelman 2001) and the glaciation of low level clouds through falling ice crystals (Herzegh and Hobbs 1980).

Ice clouds form at high supersaturation relative to ice and can persist in air that is at least ice saturated. Accordingly, high frequencies of ice supersaturation have been observed (Gierens et al., 1999) with clear sky ice supersaturation limited by the homogeneous freezing threshold (Jensen et al., 2001). Satellite data confirm the existence of spatially extended areas of ice supersaturation (Gettelman et al. 2006; Lamquin et al., 2012). The frequency of ice supersaturation is largest in the upper troposphere and at high latitudes. Cirrus form locally at high ice supersaturation and drive humidity towards saturation. The fact that cirrus clouds form at high ice supersaturations and persist at saturation means that cirrus coverage cannot simply be derived from relative humidity. An air volume that is first cooling, surpassing the ice nucleation threshold at high ice supersaturation in a fraction of the volume, and subsequently warming, will form a cirrus cloud which will not dissipate as long as the cirrus remains at least saturated. Therefore the coverage describes a hysteresis with evolving relative humidity (fig. 1). That means that, contrary to the coverage due to liquid water clouds, ice cloud coverage cannot be diagnosed (Kärcher and Burkhardt, 2008).

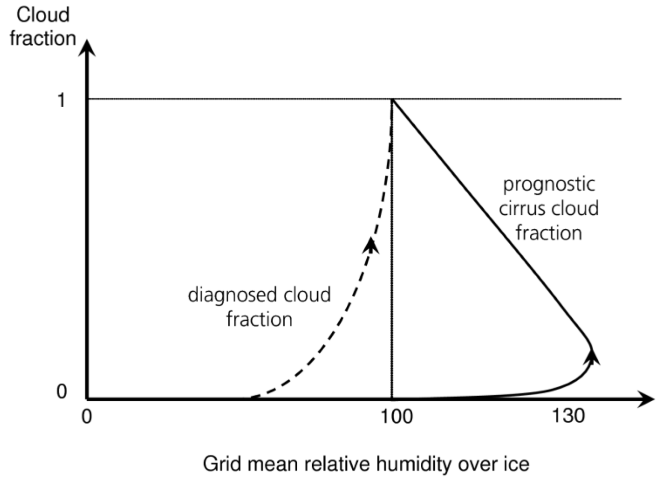

Figure 1: Hysteresis of cirrus coverage with relative humidity. Diagnostic cloud coverage (dashed curve) assuming a top hat PDF of subgrid scale variability and saturation within clouds. Evolution of cirrus coverage in a continuously cooling air parcel (solid curve). Cirrus forms locally at high ice supersaturation. Diagnostic cloud schemes cannot be reconciled with non-equilibrium ice-physics (from Burkhardt and Sölch, 2012).

Ice crystals nucleate either heterogeneously at a few 10% ice supersaturation or homogeneously at about 50% ice supersaturation (Koop, 2004). Heterogeneous ice nucleation leads to ice crystal concentrations of below 0.01-0.1 cm-3 due to the limited supply of heterogeneous ice nuclei in the air (DeMott et al., 2004). Homogeneous ice nucleation can lead to much higher concentrations. This means that heterogeneous ice nucleation has the potential to modify natural clouds depending on the local ice nuclei concentration and the dynamical forcing driving the increase in relative humidity that leads to cloud formation. At high dynamical cooling rates homogeneous ice nucleation is likely to be the main nucleation process. Ice crystal number concentrations depend strongly on the dynamical forcing causing temperature fluctuations. At low cooling rates ice crystals can more effectively limit peak ice supersaturations and therefore fewer ice crystals are formed than when cooling rates are high (Jensen and Toon, 1994; Kärcher and Lohmann, 2002). This can cause a significant change in cirrus cloud microphysics. At high cooling rates a few ice crystals cannot limit the increase in relative humidity efficiently so that they cannot prevent homogeneous nucleation by reducing relative humidity (DeMott et al., 2003). In situ observations confirm the large variability of ice crystal number concentrations and ice crystal radii (Kärcher and Ström, 2003; Krämer et al., 2009). Ice crystal radii and their variability are important due their influence on microphysical processes and on the cloud radiative forcing. Below crystal mean sizes of 50 µm cloud radiative forcing is strongly dependent on the size (Zhang et al., 1999). These small sizes are very common at low temperatures e.g. below -45°C (Gayet et al., 2006).

2. Cirrus modelling

Using a PDF cloud scheme coverage and liquid water content of warm clouds can be diagnosed from the PDF of subgrid scale variability of e.g. total water and is calculated from the part of the PDF that lies above the saturation value (Tompkins, 2002). In order to resolve the hysteresis behaviour of cirrus coverage it is necessary to introduce a prognostic variable for cirrus coverage. The additional prognostic variable may be also used to calculate the ice water content of cirrus when assuming in cloud saturation. The fraction of the PDF of subgrid scale variability that lies above the nucleation threshold will form a cirrus cloud (figure 2). Once cirrus is formed the cirrus covered fraction of the PDF may drop below the nucleation threshold without any change in the cirrus coverage or the associated ice water content as long as the area covered by cirrus is ice saturated. A further increase in the total water mixing ratio in the cloud free fraction of the PDF may lead to an increase in cirrus coverage and ice water content if the ice nucleation threshold is exceeded in the cloud free area. Ice cloud coverage and ice water content are therefore dependent on the history of relative humidity and its subgrid scale variability

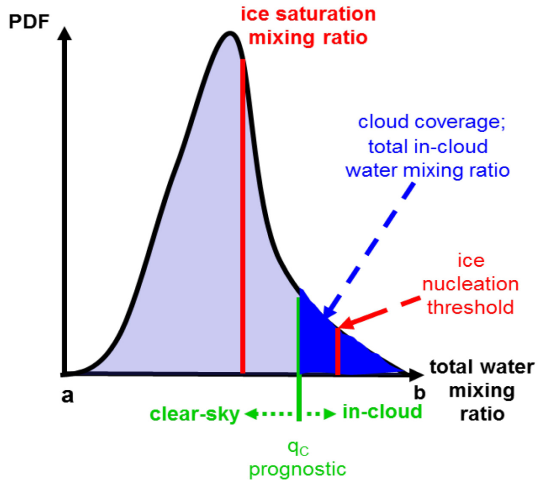

Figure 2: PDF of total water variability. Usually the whole area above saturation is diagnosed to be cloud covered. In order to introduce cirrus physics a new prognostic variable has to be introduced that carries the memory of the relative humidity development of the air parcels.

In most cloud schemes it is assumed that air within cirrus clouds is saturated. Whether this assumption is realistic or not depends on the temperature of the cirrus cloud and the time step of the model. Over a large temperature range (temperature above 200 K) the by far most common in-cloud relative humidity is the saturation value. Higher or lower relative humidities may indicate very young cirrus with a low ice crystal number concentration that has not yet decreased relative humidity towards saturation and cirrus that are in the process of dissipation with large ice crystals taking a long time to sublimate. At temperatures below about 190°C the probability of in-cloud supersaturation is increased and below about 185°C in-cloud supersaturation seems to be more common than saturation (Krämer et al., 2009). One explanation may be that aerosols undergo a phase transition into a glassy state (Murray et al., 2010). In-cloud ice supersaturation may also be found in cirrus clouds due to low ice crystal number concentration. The supersaturation relaxation time scale in cirrus with low ice crystal number concentrations can be much larger than a model time step. Treating such cirrus with saturation adjustment would mean that subsequent nucleation events could not increase the ice crystal number concentration of the cirrus and therefore the optical properties may be changed. Resolving in cloud ice supersaturation is a requirement for simulating effects of aerosols on cirrus clouds. Efficient ice nuclei lead to heterogeneous ice crystal nucleation at lower ice supersaturations than the homogeneous freezing threshold but due to their often limited number concentration may not reduce ice supersaturation efficiently in order to prevent subsequent nucleation events. Simulating the competition between heterogeneous and homogeneous nucleation may be important for the realistic representation of cirrus optical properties and relies on the resolution of in-cloud ice supersaturation.

3. Two-moment microphysics

Ice nucleation in cirrus clouds is mainly controlled by the relative humidity and the local adiabatic cooling rate (Kärcher and Lohmann, 2002). The small scale cooling rates responsible for the nucleation events are much larger than the cooling rates connected with synoptic variability. The latter would create crystal number concentrations that are a few orders of magnitude smaller than expected from observations (Kärcher and Ström, 2003; Hoyle et al., 2005). Observational crystal number concentrations may be overestimating real number concentrations due to the fact that observations are often affected by shattering (Field, 2006, Korolev et al., 2011). Nevertheless, the large discrepancy between predicted and observed crystal concentrations means that the local cooling rates must be dominated by variability due to gravity waves and turbulence and, judging from the observed ice crystal number concentrations, must be of the order 2 - 50 K/h. Associated temperature fluctuations have been found to be widespread in the atmosphere (Hoyle et al., 2005, Gary, 2006). The total ice crystal number concentration is an important property of cirrus clouds since it determines the effective ice crystal size and therefore the radiative properties of the clouds and the microphysics. The dynamical forcing responsible for the high ice crystal number concentrations is not resolved by the ECMWF model at T511 resolution (Hoyle et al., 2005). Using the meteorological fields on trajectories and calculating ice crystal number concentrations, measurements could not be reproduced. When the meteorological variability on trajectories was complemented with unresolved variability such as the one found in observations, the modelled and observed number concentrations were much closer. Despite increasing resolution of GCMs cooling rates will likely stay subgrid scale in the future. The subgrid cooling rates are connected with turbulence and gravity waves that may result e.g. from convection, orography or decaying Rossby waves. This means that the cooling rates and therefore the cirrus properties are dependent on the location (closeness to orography), circulation regimes and synoptic situations. One particular kind of cirrus clouds that are commonly not resolved very well by GCMs are the cirrus forced by orographic gravity waves. It has been shown that these orographic cirrus can be better represented by coupling the cirrus forcing to the orographic gravity wave scheme (Dean et al., 2007; Joos et al., 2008). Nevertheless, even away from orography cirrus clouds are typically not well simulated by GCMs. These are connected with non-orographic gravity waves. From LES simulations we know that large variations in crystal number concentrations and mean size are possible on the cirrus cloud scale due to the variability of the dynamical forcing given by cloud induced turbulence (Sölch and Kärcher, 2011). This leads to large variations in microphysical rates such as aggregation events which in turn lead to the efficient removal of ice crystals within fall streaks. Those cloud scale variations in the microphysical rates impact the development of the whole cloud.

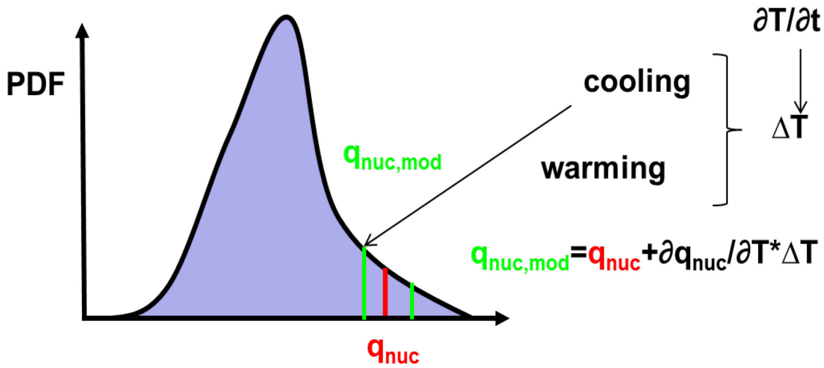

Figure 3: Modification of the cirrus coverage source term in order to formulate cirrus coverage and crystal number concentrations consistently. Assuming that the subgrid scale cooling rate fluctuations are independent of the subgrid scale variability of total water the nucleation threshold can be modified in accordance with the cooling rates.

Ice nucleation and number concentrations are largely controlled by subgrid scale gravity wave activity whereas models usually only resolve the dependency of cirrus coverage on relative humidity and its history. This poses a problem when introducing a microphysical two-moment scheme in a GCM since cloud coverage is parameterized without any knowledge about the subgrid cooling rate fluctuations which are key for parameterizing ice crystal number concentration so that the two variables can fluctuate independently of each other. Cloud coverage can increase when relative humidity increases but at the same time the cooling rate fluctuations may not support formation of new ice crystals. In case of pre-existing cirrus in the same grid box this would lead to a decrease in ice crystal number concentration and therefore changed cirrus cloud properties. Without pre-existing cirrus, cloud coverage would have to remain zero due to the absence of nucleated ice crystals.

In order to consistently treat cloud coverage and microphysics it is necessary that the nucleation parameterization takes into account the subgrid fluctuations of relative humidity. At the same time the fractional cloud coverage needs to be not only dependent on the PDF of subgrid scale variability of total water and maybe temperature but also on the subgrid fluctuations of cooling rates (fig. 3). This could be either achieved by basing the cloud parameterization on a multidimensional PDF including the subgrid variability of cooling rates or assuming that the cooling rate fluctuations are uncorrelated with the fluctuations of total water and/or temperature. In that case the cooling rate fluctuations may be simply used to modify the nucleation threshold (fig. 3) while the PDF describes only the subgrid variability of total water and/or temperature.

4. Interaction between cirrus and convection

Cirrus coverage and ice water content is large within the tropics and in the storm track areas (Waliser et al., 2009). In the tropics, cirrus result to a large extent from deep convection that reaches the upper troposphere and detrains there. The convective detrainment increases the total water content in the upper troposphere locally. Otherwise the upper troposphere is usually relatively dry and is moistened by the convective detrainment (Wright et al., 2009; Horvath and Soden, 2008). This means that convective detrainment is likely to cause a bimodal distribution of total water in the upper troposphere (fig. 4). This bimodal distribution cannot be resolved by those PDF schemes that are based on a unimodal distribution function. Convective detrainment of total water causes a change in the PDF which may or may not lead to a realistic change in cirrus coverage and properties. In the Tiedtke cloud scheme (Tiedtke, 1993) a change in cloud coverage is attributed to the convective detrainment

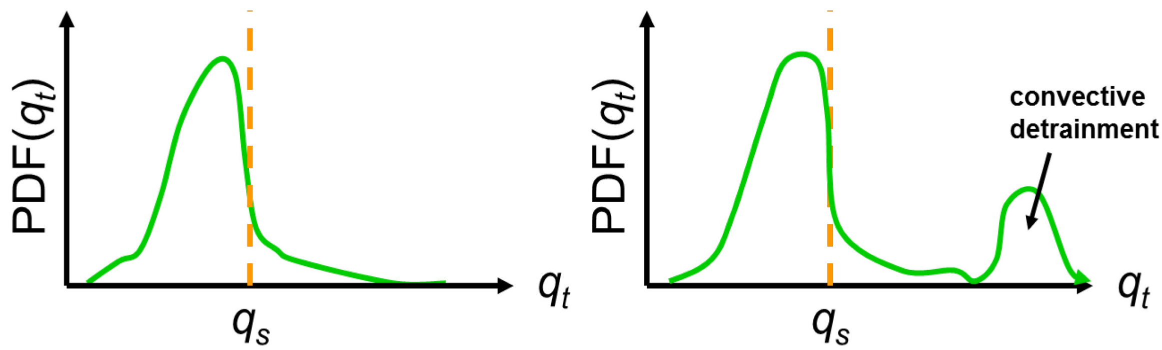

Figure 4: Total water PDF before and after convection. The bimodal distribution cannot be resolved by unimodal PDF schemes. This leads to problems deriving the coverage and water content of cirrus with convective origin.

but in a PDF cloud scheme the associated change in cloud attributed to the convective detrainment but in a PDF cloud scheme the associated change in cloud coverage is also dependent on the moments of the PDF before the convective mass flux. Those moments change due to the convective detrainment, but this does not necessarily lead to a realistic change in cloud coverage. If the cirrus cloud that originated from convective detrainment coexists with in situ formed ice clouds within the same grid box then the properties of both kinds of ice clouds will be changed at the next time step. The potentially larger ice crystals originating from the convective detrainment will increase the model estimate of ice crystal mean size in the pre-existing cirrus which again has implications for microphysical process rates, such as sedimentation, and ultimately the cirrus life time.

5. Contrail cirrus

Aviation induces cirrus clouds. Persistent contrails can form in air that is only slightly ice supersaturated. The warm and moist engine exhaust plume air mixes with the surrounding air and, if water saturation is exceeded within the plume, contrails form. That means that ice supersaturated air can cloud over with cirrus clouds without the relative humidity having reached a nucleation threshold. Contrails may also replace natural cirrus clouds in situations when relative humidity would have risen above a nucleation threshold if contrails would not have formed. In those situations contrails may still have an impact on the meteorological situation since the microphysical and optical properties of contrail cirrus are very different to those of natural cirrus due to the large number of very small ice crystals within young contrails (Gayet et al., 1996). Contrails often form in the same area as other contrails in so called contrail outbreaks (Duda et al., 2004). Those outbreaks are associated with particular synoptic situations, such as ahead of frontal systems (Kästner et al, 1999; DeGrande et al, 2000). Contrail cirrus significantly alters the cloud coverage and cloud properties and therefore has an impact on climate (Burkhardt and Kärcher, 2011). Within contrail outbreak regions contrails are likely to have a significant impact on the meteorological situation via altered radiative fluxes (Sassen, 1997) and changes in the upper tropospheric temperature and water budget. Particularly over the USA and Europe these outbreaks are relatively common.

6. Conclusions

A two-moment microphysical scheme for ice clouds would allow the simulation of the regime dependence and synoptic variability in ice crystal sizes and microphysics, which has an impact on the radiative transfer. In order to simulate crystal number concentrations within cirrus realistically it is necessary to represent the cooling rate fluctuations which are the major control for the nucleation source term. Cooling rate fluctuations due to gravity waves and turbulence which are controlling the ice crystal concentration are not well known and not or only partly resolved in models down to very high resolutions. Even inhomogeneities within single cirrus clouds seem to be connected with variability in the cooling rate. A two-moment microphysical scheme can be implemented consistently with coverage only if both the nucleation source term and the source term for cirrus coverage are formulated consistently. This means that the nucleation source term needs to consider the PDF of subgrid scale variability used in the derivation of cloud coverage and the cloud coverage source term needs to consider the cooling rate fluctuations. Convective outflow is likely to be problematic as soon as the model resolution is so coarse that dry upper tropospheric air or in situ formed cirrus are situated in the same grid box as cirrus fed by convective outflow. Depending on the cloud scheme this can lead to problems in the derivation of cirrus coverage and of the microphysical properties of the cirrus.

This problem will decrease with increasing model resolution. Contrail cirrus modify high cloudiness directly and indirectly by changing the upper tropospheric temperature and water budget. Within contrail outbreaks this may lead to a significant change in the meteorological state. One way of improving our understanding of cirrus processes and their representation in low resolution models is by learning from very high resolution modelling, an approach that may lead ultimately to a better representation of the dynamical cirrus forcing, the effect of microphysical processes on subgrid scale variability and the interaction of convection and cirrus clouds.

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