

# A microphysics guide to cirrus clouds – Part 1: Cirrus types

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## Abstract

The microphysical and radiative properties of cirrus clouds continue to be beyond understanding and thus still represent one of the largest uncertainties in the prediction of the Earth's climate (IPCC, 2013). Our study aims to provide a guide to cirrus microphysics, which is compiled from an extensive set of model simulations, covering the broad range of atmospheric conditions for cirrus formation and evolution. The model results are portrayed in the same parameter space as field measurements, i.e. in the Ice Water Content-Temperature (IWC-T) parameter space. We validate this cirrus analysis approach by evaluating cirrus data sets from seventeen aircraft campaigns, conducted in the last fifteen years, spending about 94 h in cirrus over Europe, Australia, Brazil as well as Southern and Northern America. Altogether, the approach of this study is to track cirrus IWC development with temperature by means of model simulations, compare with observations and then assign, to a certain degree, cirrus microphysics to the observations. Indeed, the field observations show characteristics expected from the simulated cirrus guide. For example, high/low IWCs are found together with high/low ice crystal concentrations  $N_{ice}$ .

An important finding from our study is the classification of two types of cirrus with differing formation mechanisms and microphysical properties: the first cirrus type is rather thin with lower IWCs and forms directly as ice (in-situ origin cirrus). The second type consists predominantly of thick cirrus originating from mixed phase clouds (i.e. via freezing of liquid droplets – liquid origin cirrus), which are completely glaciated while lifting to the cirrus formation temperature region ( $< 235$  K). In the European field campaigns, in-situ origin cirrus occur frequently at slow updrafts in low and high pressure systems, but also in conjunction with faster updrafts. Also, liquid origin cirrus mostly related to warm conveyor belts are found. In the US and tropical campaigns, thick liquid origin cirrus which are formed in large convective systems are detected more frequently.

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# 1 Introduction

The appearance of high altitude cirrus clouds, consisting of pure ice crystals in a cold environment where liquid water no longer exists<sup>1</sup>, is not only intriguing but also a research topic for the past hundred years. The impact of cirrus on climate has been studied since the early 1970s. Cox (1971), for example, questioned whether the presence of cirrus clouds tends to warm or cool the Earth's surface and came to the conclusion that tropical cirrus may have a significant warming tendency while mid-latitude cirrus produce a cooling effect. This is consistent with our understanding today, however, the question of the net global effect of cirrus clouds is still not answered definitively. The latest IPCC report (Boucher et al., 2013) states that together, clouds and aerosols continue to contribute the largest uncertainty to estimates and interpretations of the Earth's changing energy budget and that particularly the fundamental details of the microphysical processes of ice clouds are still poorly understood.

A major reason for this continuing uncertainty is the difficulty of measuring the respective key parameters with the required accuracy on fast-flying jet aircraft at high altitudes, as well as from ground-based and space-borne remote sensing platforms. Another problem is that aircraft measurements cannot capture the evolution of the cirrus cloud properties with time, but provide only snapshots of cirrus properties at the thermodynamic conditions encountered. In most cases, the measurements are shown along the flight tracks where they were obtained or as a function of altitude or temperature. Because of this sampling strategy, it is difficult to study cirrus processes from formation to dissipation based on in-situ observations. Instead, statistically-based approaches appear more promising.

The most common parameters that are measured in cirrus clouds – besides the meteorological variables – are ice water content (IWC), number and size of ice crystals ( $N_{\text{ice}}$  and radius  $R_{\text{ice}}$  or diameter  $D_{\text{ice}}$ ), their shapes and relative humidity (with

<sup>1</sup>This is below about 235 K (−38 °C); large ice crystals falling out of cirrus clouds can be observed at higher temperatures as “fall streaks”.

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respect to ice,  $RH_{ice}$ ). Sometimes the number and properties of ice nucleating particles (IN) and vertical velocity are also measured. Unfortunately, the measurements of ice crystal number and size as well as  $RH_{ice}$  have suffered from instrument issues over the last decades (see e.g. Peter et al., 2006; McFarquhar et al., 2011; Korolev et al., 2011, 2013; Krämer et al., 2013) so that interpretations of earlier observations should be made cautiously. Moreover, it is difficult to draw conclusions about the history of ice nucleation and the evolution of microphysical properties from these observations. Nevertheless, there are numerous aircraft and satellite-based observations, as well as modeling studies contributing to the field of cirrus research (e.g. Heymsfield and Iaquinta, 2000; McFarquhar et al., 2000; Sassen and Benson, 2001; Comstock et al., 2002; Heymsfield et al., 2002b, a; Kärcher and Lohmann, 2002; DeMott et al., 2003; Kärcher and Lohmann, 2003; Cziczo et al., 2004; Archuleta et al., 2005; Möhler et al., 2006; Sassen et al., 2008; Gettelman et al., 2010; Hoose and Moehler, 2012; Cziczo et al., 2013)<sup>2</sup>.

To help understand the appearance, properties and microphysical processes of cirrus clouds, our study aims to provide a guide to cirrus microphysics in a parameter space easily accessible by field measurements, i.e. in the IWC-Temperature (IWC-T) portrayal. The reason for this choice is that bulk IWC is a very robust parameter under different aspects: IWC is not as sensitive to atmospheric variations as ice crystal numbers. In addition, the measurement of bulk IWC is less complicated than ice crystal measurements and, finally, this study expands our previous work based on IWC observations (Schiller et al., 2008; Krämer et al., 2009; Luebke et al., 2013, note also the large IWC database presented by Heymsfield et al., 2013). Our new approach is to track cirrus IWC development with temperature by means of model simulations, com-

<sup>2</sup>Out of the nearly thousand cirrus studies since 2000, we provide a list here – created using the Web of Science – containing the 10 most cited and the highly cited studies and also 5 most or highly cited ice nucleation and global modeling studies; references contained already in this paper are not considered.

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pare with observations and then assign cirrus microphysics and formation mechanisms to the observations.

The first pillar of this work is the comprehensive measurements from the multiple field campaigns we have conducted in the last fifteen years with reliable instrumentation where instrument issues are minimized (see Sect. 2). Second, a “Cirrus Guide” is compiled from an extensive set of model simulations (see Sects. 3 and 4), covering the broad range of atmospheric conditions for cirrus formation and evolution. The model results are then portrayed in the IWC-T parameter space and validated by evaluating the data sets from the field campaigns. From the representation of simulated cirrus, we can then assign, to a certain degree, cirrus microphysics, history and the formation mechanism to specific combinations of IWC,  $N_{\text{ice}}$  and  $\text{RH}_{\text{ice}}$  inside and outside of cirrus as a function of temperature.

In Part 1 of the study, the field measurements as well as the Cirrus Guide simulations are described and the results with respect to cirrus microphysics and possible history are presented (see Sect. 5). Part 2 contains the assignment of the cirrus formation mechanisms to the observations.

## 2 Cirrus observations

Cirrus clouds were observed during 17 field campaigns performed between 1999 and 2014 over Europe, Africa, Seychelles, Brazil, Australia, USA and Costa Rica. A map of all 104 flights is shown in Fig. 1. The total time spent in cirrus clouds sums up to about 94 h. A summary of the campaigns, location, aircraft and the instrumentation on board the different aircraft is given in Table 1 and in the following sections. A variety of established instruments are used here, which are already well described in the literature. For brevity, here we give only that information necessary for this study and respective references for each instrument.

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## 2.1 Ice water content and humidity measurements

The ice water content (IWC) is derived during most campaigns from the measurements of  $\text{H}_2\text{O}_{\text{tot}}$ , which is the amount of total water (gas phase + evaporated ice crystals), and  $\text{H}_2\text{O}_{\text{gas}}$ , the gas phase water amount. IWC is then calculated by using the following Equation:

$$\text{IWC} = (\text{H}_2\text{O}_{\text{tot}} - \text{H}_2\text{O}_{\text{gas}})/E \quad (1)$$

where  $E$  is the enhanced volume out of which the ice crystals are sampled in comparison to the sampling volume of the gas phase. For more details see Schiller et al. (2008) and Luebke et al. (2013).  $\text{H}_2\text{O}_{\text{tot}}$  was measured by the total water instruments FISH and CLH (Table 1a and b),  $\text{H}_2\text{O}_{\text{gas}}$  with the gas phase water instruments FLASH, OJSTER, HWV, JLH, SEAL and SHARC (c–h in Table 1). For details about the instruments see the respective references in the table.

Since no total water measurements were available, IWC for COALESC, ML-CIRRUS and ACRIDICON-CHUVA is derived by integrating the ice crystal size distributions from NIXE-CAPS (see next section) using the mass-dimension ( $m$ – $D$ ) relation (see Luebke et al., 2015, modified  $m$ – $D$  relation of Mitchell et al., 2010):

$$m = a \cdot D^{(b)} \quad (2)$$

with

$$a = 0.082740, \quad b = 2.814 \quad \text{for } D < 240 \mu\text{m}$$

$$a = 0.001902, \quad b = 1.802 \quad \text{for } D > 240 \mu\text{m}.$$

The relative humidity with respect to ice ( $\text{RH}_{\text{ice}}$ ; shown in Part 2 of the study) is also derived from  $\text{H}_2\text{O}_{\text{gas}}$  using:

$$\text{RH}_{\text{ice}} = 100 \cdot \frac{\text{H}_2\text{O}_{\text{gas}}}{\text{H}_2\text{O}_{\text{sat, ice}}} \quad (3)$$

where  $H_2O_{\text{sat, ice}}$  is a function of temperature (Murphy and Koop, 2005). The accuracy of the water vapor instruments was debated during the last decade and thus a couple of studies were carried out to investigate their performance under laboratory and field conditions. The good agreement of the instruments deployed in the field campaigns investigated here is stated by the studies of Fahey et al. (2014); Rollins et al. (2014); Meyer et al. (2015). These studies provide further details of this group of instruments. Together with the respective uncertainties of the temperature measurements, the accuracy of the  $RH_{\text{ice}}$  observations here are between 10 and 20 %.

## 2.2 Ice crystal measurements

Ice crystal number ( $N_{\text{ice}}$ ) size distributions were measured during the different campaigns by the cloud spectrometers

FSSP-100/300	$D_{\text{ice}} = 3\text{--}30\ \mu\text{m}$
CAPS	$D_{\text{ice}} = 3\text{--}930\ \mu\text{m}$
NIXE-CAPS	$D_{\text{ice}} = 3\text{--}930\ \mu\text{m}$
2D-S	$D_{\text{ice}} = 15\text{--}1280\ \mu\text{m}$

$D_{\text{ice}}$  denotes the instruments size ranges used for this study, although the respective ranges might be larger (see Table 1 i–m and respective references). The upper size limits of the instruments differ. However, the largest contribution to the total ice crystal concentration comes from sizes between 3 and about  $30\ \mu\text{m}$ ; the concentrations of larger ice particles is in general about three orders of magnitude lower. Hence, the total ice number is covered by most instruments. The 2D-S with the lowest size at  $15\ \mu\text{m}$  does not record the smallest ice crystals, whose contribution to the total ice crystal number is highly variable and depends on cloud age: in the early stage of a cirrus most of the ice crystals are small, but grow to larger sizes when the cirrus develops.

The quality of cloud spectrometer measurements is – as with humidity – under ongoing discussion. In particular, a boost of smaller ice crystals appearing through shatter-



ing of large crystals at the instrument tips was discovered as a source of error in many older observations (see e.g. Krämer et al., 2013, and references therein).

Out of the instruments used here, FSSP-100/300 and CAS during MidCix 2004 (part of the CAPS = CAS + CIP<sup>3</sup>) might be affected by shattering, since at that time the particles interarrival times could be recorded only with CIP, but not with CAS. To eliminate shattering artifacts, the data set from the CAPS instrument is carefully re-processed for this study by adjusting the size distributions in the overlap range of the two instruments to each other. This was necessary for this campaign since very large cloud particles, up to the CAPS upper size limit 930  $\mu\text{m}$ , were often present. However, it cannot be ruled out that some shattering influence is still present in the MidCix ice crystal data set, especially since there is an offset in the  $N_{\text{ice}}$  measurements in comparison to the other campaigns, which might represent either stronger ice nucleation in faster updrafts or shattering. Nevertheless, taking this offset into account, the MidCix data are a valuable contribution when looking at relative changes of ice crystal concentrations.

A contamination of the measurements from FSSP-100/300 by shattered ice crystals was discussed by Krämer et al. (2009), who stated that a significant effect from shattering is not expected at low temperatures where the ice crystals are smaller, but only at temperatures where the occurrence of larger ice crystals increases. From the analysis of the full data set of this study together with the cirrus simulations we can now conclude that during the campaigns where the FSSP-100/300 were deployed, the ice crystals were not as large as during MidCix or MACPEX, and the ice crystal numbers do not exceed the possible atmospheric range as during those WB-57 campaigns where ice crystal shattering became obvious (e.g. CRYSTAL FACE). Hence, though shattering cannot completely be ruled out, the ice crystal numbers appear to be dominated by natural ice production processes. Thus, we believe that the ice crystal number

<sup>3</sup>Two instruments are integrated in the CAPS (Cloud and Aerosol Particle Spectrometer): (1) CAS (Cloud and Aerosol Spectrometer: 0.6–50  $\mu\text{m}$ ) and (2) CIP (Cloud Imaging Probe, CIP:15–930  $\mu\text{m}$ ), (Baumgardner et al., 2001).

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data set from the Geophysica/Learjet – campaigns is suitable for the study presented here.

2D-S (MACPEX 2011) is a new generation cloud instrument, which is equipped with tips and software to minimize shattering effects. However, it starts to record ice crystals at larger sizes than the other instruments (15  $\mu\text{m}$  in comparison to 3  $\mu\text{m}$ , see above; note that technically it starts recording at 5  $\mu\text{m}$ , but it is recommended not to use the bin between 5–15  $\mu\text{m}$ ) and thus the total ice crystal number is lower. Nevertheless, as for the MidCix CAPS data, taking this offset into account, the MACPEX data provide a valuable contribution when looking at relative changes of ice crystal concentrations.

The CIP (part of CAPS used for TC-4) as well as NIXE-CAPS (ML-CIRRUS 2014) are also new generation cloud instruments so there are no restrictions for these data sets. NIXE-CAPS is a further development of the CAPS instrument, the new features and data evaluation procedure are described in Meyer (2012) and Luebke et al. (2015). One improvement realized for NIXE-CAPS is a modification of the particle inlet of the CAS probe – which is part of NIXE-CAPS – to minimize shattering. The wall of the inlet entrance is now “knife edged”, greatly reducing the area susceptible for ice crystal shattering. Comparisons to particle size and concentration measurements using other instruments such as SMPS, APS, VIPS, SID-3, 2D-S, CPD, made at the cloud chamber AIDA and on aircraft yield good agreement between the probes (Meyer, 2012).

### 2.3 Field measurements of IWC and $N_{\text{ice}}$

The total IWC database from all campaigns shown in Table 1 and Fig. 1 is presented in Fig. 2 as a function of temperature (left panel: mixing ratio, right panel: concentration). Altogether, about 94 h of flight time was spent in cirrus clouds, thus considerably extending the IWC climatologies of Schiller et al. (2008) (27 h) and Luebke et al. (2013) (38 h). Nevertheless, the median and core IWC – functions derived by Schiller et al. (2008) and confirmed by Luebke et al. (2013) are also valid for the new, extended IWC climatology.

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In Fig. 3 the IWC measured during the individual field campaigns are shown. The color code is the ice crystal number  $N_{\text{ice}}$ . The time of the simultaneous measurements of IWC and  $N_{\text{ice}}$  is indicated in the panels and sums up to 85.7 h for all campaigns, a little lesser than the 94 h quoted earlier because of the lesser overall sampling time of  $N_{\text{ice}}$ . In the lower left panel, the part of the IWC climatology of Schiller et al. (2008) where IWC and  $N_{\text{ice}}$  ice particle measurements were performed simultaneously is shown. Simultaneous IWC and  $N_{\text{ice}}$  measurements from TC-4 and MidCix are part of the climatology of Luebke et al. (2013) and are here shown in the right column. Recent studies are MACPEX, COALESC, AIRTOSS-ICE, ML-CIRRUS and ACRIDICON-CHUVA. The quite different ranges of IWC and the distribution of  $N_{\text{ice}}$  within these ranges will be discussed by comparing the measurements with a simulated cirrus climatology (Cirrus Guide, Sects. 5.1 and 5.2) in Sect. 5.3.

### 3 Cirrus simulations

A simulated cirrus climatology (the Cirrus Guide) is compiled by means of the detailed microphysical box model MAID (Model for aerosol and ice dynamics, Bunz et al., 2008; Rolf et al., 2012), which can be operated along idealized or realistic atmospheric air parcel trajectories.

#### 3.1 MAID

MAID simulates ice clouds that form directly from the gas phase in the temperature range below about 235 K. The ice nucleation processes implemented in MAID are heterogeneous freezing after Kärcher et al. (2006) and homogeneous freezing after Koop et al. (2000). The heterogeneously freezing ice nuclei (IN) can vary in concentration as well as freezing threshold ( $\text{RH}_{\text{ice}}$ , see Fig. 4):  $\text{RH}_{\text{ice}}^{\text{MD}}$  represents very efficient IN with a low freezing threshold (MD: mineral dust), while  $\text{RH}_{\text{ice}}^{\text{CS}}$  (CS: coated soot) are quite inefficient IN having a high freezing threshold (Gensch et al., 2008). The homogeneously



freezing aerosol particles are assumed to be supercooled binary solution particles with a number of  $300\text{ cm}^{-3}$  and a mode size of 200 nm. The threshold for homogeneous ice nucleation is higher than that of heterogeneous freezing (see Fig. 4, middle). Thus, in the case where both IN and supercooled solution particles are present, heterogeneous freezing occurs first.

Once the ice particles have formed, they grow by diffusional growth in separate size bins (Lagrangian ice particle tracking). When the temperature becomes warmer and the air parcel subsaturates, the ice crystals sublime and return their water vapor to the air parcel.

Ice crystal sedimentation is treated in MAID following the sedimentation scheme of Spichtinger and Gierens (2009), which uses ice mass and number-weighted terminal velocities (after Heymsfield and Iaquinta, 2000) to simulate sedimentation of ice crystals. The ice flux through the model box is defined by the “sedimentation factor” (sedi-f) and represents the ratio of the flux through the top divided by the flux through the bottom. sedi-f = 0 means there is no flux from above into the model box and all ice particles will fall out through the bottom (cloud top), sedi-f = 1 represents the cloud bottom where the flux from above is equal to the downward flux from the bottom, which simulates a no sedimentation scenario.

### 3.2 Cirrus scenarios

In one MAID Cirrus Guide scenario the cirrus temperature space is scanned in 10 K steps between 190–230 K (see Fig. 4, left). For each of the five temperatures, simulations with constant vertical velocities of 0.01, 0.1, 0.5, 1.0,  $3.0\text{ ms}^{-1}$  are performed, which are initialized with a water amount of 90 % RH<sub>ice</sub> (*T*). This sums up to twenty five simulations. Further, as at 190 and 200 K the vertical velocity of  $0.001\text{ ms}^{-1}$  is added to enclose the range of large scale upward motions at the cold temperatures in the Tropical Transition Layer (TTL). Altogether, one scenario contains 27 simulations. They represent the formation and evolution of cirrus clouds during air parcel ascent, covering the atmospheric range from slow frontal large scale updrafts up to fast lifting

in jetstreams or convection. The sublimation phase of the clouds is not considered in the simulations. Also, ice crystals sedimenting into subsaturated air as e.g. fall streaks are not included in the simulations.

For the complete MAID Cirrus Guide, 36 scenarios (972 model runs) were performed altogether, each varying in the initial and boundary conditions. First of all, pure homogeneous freezing (HOM) or heterogeneous followed by homogeneous freezing (HET + HOM) is allowed to occur. Second, the temperature course of the trajectory can be chosen to be a constant updraft or the updraft can be superimposed with temperature fluctuations. Further, the IN number and freezing threshold and the sedimentation parameter are prescribed for each scenario (see Fig. 4, right).

For the constant updrafts, two HOM scenarios with varying sedi-f (0.9 and 0.5: moderate and strong ice particle sedimentation) are performed, while for HET + HOM 16 scenarios are realized for each combination of: four possible IN numbers (0.001, 0.01, 0.1,  $1.0\text{ cm}^{-3}$ : very low to very high), two different freezing thresholds (MD, CS) and two sedimentation parameters (sedi-f = 0.9, 0.5). That means that each constant updraft scenario is simulated 18 times under different conditions, summing up to a total of 486 model runs. The scenarios are abbreviated as follows: the 16 HET + HOM scenarios are  $\text{HET + HOM}_{\text{sedi-f}}^{\text{IN-MD/CS}}$ , the two pure homogeneous freezing scenarios:  $\text{HOM}_{\text{sedi-f}}$ .

Finally, the 18 scenarios are repeated by superimposing temperature fluctuations on the constant vertical velocities. The fluctuations are superimposed with five different frequencies ( $2 \times 10^{-4}$ ,  $8 \times 10^{-4}$ ,  $2 \times 10^{-3}$ ,  $4 \times 10^{-3}$ ,  $8 \times 10^{-3}$  Hz) to cover those fluctuations significant for cirrus formation and to reproduce the typical turbulence spectrum found in the atmosphere. The amplitudes are statistically distributed, whereas the maximum amplitudes increases with height and range from 0.3 K for the slowest constant vertical velocity to 4 K for the fastest constant vertical velocity. The frequency spectra and the resulting power spectral density (PSD) are in accordance with Kienast-Sjögren et al. (2015) and also with in-situ measurements of temperature fluctuations during several aircraft campaigns (e.g. MACPEX, see Jensen et al., 2013b).

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We would also like to mention that the computer time needed for the complete MAID Cirrus Guide sums up to several weeks where multiple PCs are operated simultaneously. The reason is the exact partitioning of the water vapor between gas and solid phase using the different water vapor partial pressures.

## 4 Cirrus Guide: microphysical properties

### 4.1 A selected cirrus scenario

As an example, Fig. 5 shows the Cirrus Guide scenario HET + HOM $_{\text{sedi}-0.9}^{0.01-\text{MD}}$ , which we consider as the “middle case” with assumed mean IN conditions of  $0.01 \text{ cm}^{-3}$ , MD, and a moderate sedimentation of  $\text{sedi-f} = 0.9^4$ . In the 2nd panel (from top to bottom) IWC is plotted vs. temperature in the same way as the observations shown in Fig. 2. The 3rd/top panels show the respective ice crystal numbers/mean mass radii together with minimum, middle and maximum  $N_{\text{ice}}/R_{\text{ice}}$  lines derived by Krämer et al. (2009) from observations<sup>5</sup>. The  $\text{RH}_{\text{ice}}$  development of the scenarios is shown in the bottom panel, together with the saturation line and the homogeneous freezing threshold. The simulations run from right to left in the figure (indicated by the arrow), starting at the highest temperature and cool further with the respective vertical velocity. The simulation time with temperature is indicated in the legend (in  $\text{min K}^{-1}$ ).

The first impression from Fig. 5 is that the simulated IWC climatology is well within the bounds of the observations (see Fig. 3).  $\text{RH}_{\text{ice}}$  ranges between saturation and the homogeneous freezing threshold as expected (subsaturation is not expected here

<sup>4</sup>Here and in the rest of our study we present the results of our simulations with constant updraft (“nofluct”), since the cirrus evolution can be seen more clearly in these scenarios. In Sect. 4.3 it is shown that the general cirrus patterns are well represented by the “nofluct” simulations.

<sup>5</sup>The mean mass radius  $R_{\text{ice}} = \text{IWC}/N_{\text{ice}}$  is used for the representation of the model results, because it is comparable to the established cloud effective radius  $R_{\text{eff}}$ .

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since the simulations represent the cooling phase of the cirrus and evaporation was not considered). However,  $N_{ice}$  exceeds the range of observations for fast updrafts and falls below for slow updrafts. For all scenarios (including those not shown here),  $N_{ice}$  does not change in fast updrafts but varies more in slow updrafts.

A reason that the high  $N_{ice}$  are above the maximum line of the observations is that the fast updrafts producing thick cirrus clouds with many ice crystals have a lifetime on the order of only minutes. They may live longer in multiple repeated cycles, such as in case where they are formed in stationary waves like leewave cirrus downstream of mountains. Nevertheless they are small scale phenomena and thus there is a low probability that they will be sampled by aircraft, unless deliberately targeted, and might not be present in the in-situ data sets. In the TTL, where gravity waves caused by convection from below might produce a larger number of ice crystals, the ice nucleation is stalled since the waves are so short that the updraft is reversed before all ice crystals are produced (see also Spichtinger and Krämer, 2013; Dinh et al., 2015).

$N_{ice}$  below the minimum line do exist, the minimum line derived by Krämer et al. (2009) represents the lower detection limit of the older instruments (FSSP with time resolution of 2 s). These lines are under revision based on more observations with advanced cloud probes.

The second important message from Fig. 5, representative for all scenarios of the Cirrus Guide, is that the simulations can generally be grouped by vertical velocities: red, purple and turquoise (fast updraft) on the one hand, and blue, green and gray (slow updraft) on the other hand. The first group of scenarios achieve high IWCs, high  $N_{ice}$  and rapidly decreasing  $RH_{ice}$  after ice nucleation, while the second group is characterized by low IWC and  $N_{ice}$  but higher  $RH_{ice}$ . A more detailed look into cirrus microphysics in the temperature parameter space is given in the next section.

## 4.2 Cirrus microphysics along selected trajectories

To provide a better understanding and a clearer view of cirrus microphysics in the temperature parameter space, some trajectories of cirrus formation and development

are selected from Fig. 5 and are shown in Fig. 6. Since the cloud processes are much more dependent on updraft than on temperature, we discuss two trajectories at slower updrafts (green line:  $1 \text{ cm s}^{-1}$  at 230 K and blue line:  $10 \text{ cm s}^{-1}$  at 220 K), three at higher (turquoise, purple and red:  $0.5, 1, 3 \text{ ms}^{-1}$  at 210 K) and one at a very low vertical velocity representative of the large scale ascent in the TTL ( $0.01 \text{ cm s}^{-1}$  at 190 K). The trajectory time proceeds from higher to lower temperatures, as marked by the black arrow. Note here that the times of the scenarios greatly differ: to cool the air by 1 K, 170/17/0.6 min are needed by the green/blue/red air parcels (low/middle/high updrafts). It should be kept in mind that the trajectories apply to the ice nucleation zone of cirrus clouds and not to regions that sedimenting ice crystals fall into. We discuss the two groups of scenarios – slow and fast updraft cirrus – mentioned in Sect. 4.1.

#### 4.2.1 Slow updraft cirrus

The green trajectory represents large-scale, very slow liftings associated with a large coverage of longer lived cirrus occurring e.g. in low or high pressure systems. Detailed inspection of the development of such cirrus, starting at the highest temperature at 90 %  $\text{RH}_{\text{ice}}$  (Fig. 6, bottom panel) show that when the temperature decreases,  $\text{RH}_{\text{ice}}$  starts to rise up to the heterogeneous freezing threshold. At this point, heterogeneously formed ice crystals (3rd panel) together with a low IWC (2nd panel) appear.  $\text{RH}_{\text{ice}}$  starts to decrease with decreasing temperature since the ice crystals grow by the uptake of water vapor. When the ice crystals reach a size large enough to fall out of the air parcel,  $N_{\text{ice}}$  and IWC strongly decreases again while  $\text{RH}_{\text{ice}}$  increases simultaneously due to the decrease in surfaces for water uptake. In this case, the cirrus completely vanishes and thus allowing  $\text{RH}_{\text{ice}}$  to steadily increase up to the homogeneous freezing threshold where a second, new ice nucleation event occurs. At the very low updraft speed and high cirrus temperature, the number of ice crystals produced by homogeneous freezing is slightly lower than the number of the heterogeneously formed ice particles of the previous cirrus event (note that in the “fluct” scenarios the homogeneously formed  $N_{\text{ice}}$  increase slightly due to the superimposed temperature fluctuations). In the remainder

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of this scenario, as long as the air parcel is cooled, a continuous cycle of ice crystal growth, sedimentation and new homogeneous ice formation proceeds, controlled by decreasing and increasing  $RH_{ice}$ . Notably, during this ongoing sedimentation–ice nucleation cycle  $RH_{ice}$  stays at a high level. As soon as the cooling is stopped,  $RH_{ice}$  will quickly relax to saturation (not shown here). The lifetime of this cirrus type – very low updraft, very low IWC and  $N_{ice}$  – is in the range of hours to days.

The blue lines also show large scale slow updrafts, but a little faster than the green case. The common updraft range of frontal systems is bounded between these two lines (compare blue and green lines at the different temperatures in Fig. 5). Here,  $RH_{ice}$  also rises until the heterogeneous freezing threshold is reached and the first ice crystals appear. However, no decrease of  $RH_{ice}$  caused by depletion of water vapor on the ice surface occurs, but rather the slope of the  $RH_{ice}$  increase weakens. This is because the updraft is now so large that the increase of  $RH_{ice}$  by cooling overcomes the water depletion by the ice crystals. Thus, the mean mass radius ( $R_{ice}$ ) of the ice crystals remains smaller than in the green case (see top panel) which is reflected in a weaker sedimentation and higher IWC in the further development of the cirrus. In addition the cirrus does not disappear, but instead a second, homogeneous ice nucleation event occurs – when the freezing threshold is reached – producing somewhat more ice crystals than in the green case due to the larger updraft. Now, the sedimentation–ice nucleation cycle with slightly changing IWC and  $N_{ice}$  and high in-cloud  $RH_{ice}$  runs as long as the cooling continues. The lifetime of the low updraft, low IWC and  $N_{ice}$  cirrus is in the range of several tens of minutes to hours.

#### 4.2.2 Fast updraft cirrus

The turquoise, purple and red trajectories illustrate cirrus formed in large updrafts caused e.g. by gravity waves or orographic waves. Those cirrus typically are of small scale and have a short lifetime of less than an hour. An example is mountain wave cirrus, which indeed can be observed over a longer period, however, such a seemingly longer living cirrus represents continuously formed short wave cirrus in standing

waves. Their development, starting again at the highest temperature at 90 %  $RH_{ice}$  in Fig. 6 (bottom panel), is comparable to the other scenarios – but much faster – for the first, heterogeneous freezing events. However, then  $RH_{ice}$  quickly increases up to the homogeneous freezing threshold and a strong outburst of homogeneously formed ice crystals appear, with more crystals formed the faster the updraft. Thus, the IWC reaches high values. However, the crystals remain small since the available water is distributed equally on the many ice particles. As a consequence, sedimentation is of minor importance in such cirrus and the in-cloud  $RH_{ice}$  quickly drops down to a dynamical equilibrium close to saturation.

### 4.2.3 TTL cirrus

Cirrus in the very cold tropical tropopause layer are special. They have very low ice crystal numbers found together with high  $RH_{ice}$  (Krämer et al., 2009; Jensen et al., 2013a), but spikes of high ice numbers embedded in saturation are also reported by Jensen et al. (2013a). Case studies of TTL cirrus observations are also analysed by Frey et al. (2011, 2014). Spichtinger and Krämer (2013) and recently Dinh et al. (2015) state that low  $N_{ice}$  in high supersaturation are mostly produced by homogeneous freezing in very slow large scale updrafts, superimposed by very short gravity waves. Due to the shortness of the waves, the ice nucleation process is stalled at the beginning when only a few ice crystals have formed. The IWC is accordingly low. In addition, Dinh et al. (2015) explain the high  $N_{ice}$  in saturation by small variations of water vapor which cause very high supersaturations during the ice nucleation process and thus many more ice crystals.

Though this cirrus formation mechanism is not included in our simulations, we attempt to form these cirrus by assuming heterogeneous-homogeneous freezing in very slow large scale updrafts (gray case; the IN number is only  $0.001 \text{ cm}^{-3}$  which is more typical for the TTL). The observations of low  $N_{ice}$  and IWC together with high  $RH_{ice}$  can be reproduced with these assumptions. The evolution of the cirrus is comparable to the green case: the first heterogeneously formed cirrus crystals sediment out and the next

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cirrus is formed purely homogeneously since all IN are already consumed. However, the spikes of high ice numbers embedded in saturation could not be explained with this model approach. Nevertheless, from the data set of Krämer et al. (2009) it seems that low  $N_{ice}$  are the favored state in TTL cirrus. A conclusion for the representation of TTL cirrus by global models – which in most cases overestimate TTL ice crystal numbers – could be that the approach used here might be an useful approximation.

### 4.3 A cirrus scenario ensemble

A representative sampling of all 36 cirrus scenarios in the IWC-T parameter space is shown in Fig. 7. Each panel includes all 27 trajectories, covering the full cirrus temperature and vertical velocity range, as described in Sect. 3 (see Fig. 4). Eight scenarios are shown here: the top row represents simulations with efficient IN like mineral dust (MD, low freezing threshold) and the bottom row inefficient IN like coated soot (CS, high freezing threshold), while the columns show varying IN concentrations. For all scenarios shown here the sedimentation factor is assumed to be moderate ( $sedi-f = 0.9$ ).

It is obvious from Fig. 7 that the differences between the IN initial conditions (concentration and freezing threshold) do not greatly influence the general pattern of the IWC-T portrayal of cirrus. In other words, it means that the IWC is a quite stable parameter, particularly in comparison with the variability of  $N_{ice}$  and  $R_{ice}$  in dependence to the initial atmospheric conditions (see Sect. 5.3, Fig. 12).

In Fig. 8, the scenario HET + HOM <sub>$sedi=0.9$</sub> <sup>0.01-MD</sup> (same as in Fig. 7: red box; see also Figs. 5 and 6) is shown three times. The left panel depicts the IWCs when temperature fluctuations are superimposed on the constant vertical velocities (“fluct” runs). It can be seen that the general IWC distribution is preserved, looking less structured, while the individual model runs are generally shorter in comparison to the “nofluct” cases (= constant updrafts). The IWC oscillations are parallel to the temperature course, reflecting growing and shrinking ice crystals with increasing and decreasing temperature. The shorter lifetimes can be explained by the fact that the temperature fluctuations contain warming phases so that the cirrus clouds simply evaporate. From the middle panel

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(“nofluct” scenario, color coded by time from blue to red) it can be seen that the parts of the simulations that have disappeared in the “fluct” scenario are cirrus older than about 18 h (reddish colours). Since the general pattern of IWC evolution is more clear in the “nofluct” simulations, we prefer to show those in this study, though the scenarios with temperature fluctuations better reflect atmospheric conditions.

Next, in the right panel of Fig. 8 the scenario “nofluct” is shown again, but with enhanced sedimentation ( $\text{sedi-f} = 0.5$ ). Here, a decrease of IWCs can be seen at warmer temperatures, where the ice crystals are large and preferentially fall out. However, from comparison of the Cirrus Guide scenarios with the meteorological situations found in the observations (see Sect. 5.3), we can conclude that the observations are better represented by the simulations with moderate sedimentation ( $\text{sedi-f} = 0.9$ ).

## 5 Cirrus Guide: cloud types

First of all, we remind the reader that the ice clouds represented in the Cirrus Guide are “in-situ origin cirrus”. This means that this type of ice clouds is formed “in-situ” in the temperature range below about 235 K directly from the gas phase. The reason for being so specific will become obvious in the following subsections.

### 5.1 In-situ origin cirrus in slow and fast updrafts

From the previous sections we conclude that two types are not only found in selected trajectories (Sect. 4.2), but are a general feature of mid-latitude in-situ origin cirrus (205–235 K, Sect. 4.3).

#### 5.1.1 Slow updraft cirrus

The first type is characterized by slow updrafts, producing low-middle IWCs which consist of low-middle  $N_{\text{ice}}$  with middle-to large  $R_{\text{ice}}$  (see black solid and dotted lines in Fig. 5). Sedimentation plays a crucial role by controlling the development of micro-

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physical properties and the in-cloud supersaturation: in the HET part of the “slow updraft cirrus”,  $RH_{ice}$  lies between the heterogeneous and homogeneous freezing threshold, while in the later HET + HOM part  $RH_{ice}$  remains slightly below the homogeneous freezing threshold. The formation mechanism of this cirrus type starts with HET freezing that is followed by a second, HOM ice nucleation event (since all IN are already consumed) if the cooling phase is long enough and temperature fluctuations do not cause a HOM freezing event earlier. Thus, the slow updraft cirrus have a possibility to remain as purely HET formed ice clouds. On the other hand, purely HOM formed cirrus also only appear in the long lasting, slow updraft cirrus: they evolve after the earlier HET cirrus have disappeared by sedimentation. The frequency of occurrence of these cirrus is unknown.

### 5.1.2 Fast updraft cirrus

The second type are “fast updraft cirrus” with high ice crystal numbers and IWCs. Sedimentation does not play a great role in this cirrus type and thus the in-cloud  $RH_{ice}$  quickly reduces to saturation. The formation mechanism of this cirrus type is also HET + HOM, but it is dominated by HOM ice formation.

## 5.2 Cirrus microphysics in the IWC-T parameter space

We can conclude that cirrus microphysics is visible in the IWC-T parameter space up to a certain degree, i.e. depicting measurements of IWC vs. temperature gives an impression of the nature of observed cirrus without the need of more detailed microphysical measurements. This is summarized in the sketch shown in Fig. 9, where we plotted some of the MAID scenarios together with the median, core and maximum IWC-lines to guide the eye.

IWCs below the median line mostly stem from slow updraft cirrus in low or high pressure systems. They consist of few, but large ice crystals which are – due to the increasing amount of available water vapor – larger the warmer the cirrus is. The first



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part of these cirrus is determined by HET freezing. However, if the cloud life time is long enough, HOM freezing will start as well. Due to the slow updrafts, the number of ice crystals produced by HOM freezing is on the same order of magnitude as the HET nucleated ice crystals and thus also have low IWCs. We emphasize here that in slow updraft regions the difference in microphysics between homogeneous and heterogeneous freezing is small. In this cirrus type, sedimentation plays an important role, controlling the microphysical properties and might produce fallstreaks, which causes some vertical redistribution of water.

High IWCs above the median line are mostly produced by fast updraft cirrus caused by atmospheric waves. The cirrus is only briefly at low IWC during the HET phase since the HOM freezing quickly pushes the IWC above the median line. With their large number of small, non-sedimenting ice crystals, these cirrus are microphysically very different from the slow updraft cirrus.

An impression of the radiative properties in terms of extinction of the two cirrus types is given in the lower right panel of Fig. 12, where the ice crystal number  $N_{\text{ice}}$  is shown vs. the corresponding mean mass radius  $R_{\text{ice}}$  for all temperatures. The IWCs are plotted as black isolines. The top panel shows the same, but with color code IWC, in the left panel the color code is vertical velocity. The extinction of all simulated cirrus is calculated from the empirical relationship between IWC and extinction provided by Gayet et al. (2004). Those cirrus with a low number of large crystals (slow updraft, low IWC, see top and left panel) have a small extinction, i.e. they are optically thin, while the cirrus with the many small ice crystals (fast updraft, large IWC, see top and left panel) have larger extinctions and are optically thicker.

The majority of cirrus clouds in the atmosphere are of the first “slow updraft” type, i.e. they appear on a larger scale and have a longer lifetime, while the second “fast updraft” type occurs less frequently since the fast updrafts are limited in space and time.

## 5.3 Comparison of simulations and observations

In this section, we compare observed and simulated cirrus clouds to demonstrate that the simulated Cirrus Guide shown in Fig. 9 is confirmed by measurements and thus is indeed appropriate for an impression of the cirrus microphysics.

### 5.3.1 IWC-T parameter space

In Fig. 10 (upper left panel) the simulated Cirrus Guide is shown again, but color coded by the ice crystal number  $N_{\text{ice}}$ . It can be seen that in the simulations few ice crystals are present below the median IWC line (light blue), while more and more (darker blue)  $N_{\text{ice}}$  appear with increasing IWC. As described in Sect. 3.2, the simulations in the Cirrus Guide represent the formation and evolution of cirrus as long as the air parcels are cooled. Subsaturated environments with shrinking ice crystals or fallstreaks are not included. Thus, there is the possibility that a part of the small IWCs in the observations are not comparable to the Cirrus Guide.

From all of our measurements, we have compiled a data set that compares best to the Cirrus Guide (Fig. 11). For that purpose, we used only measurements where  $\text{RH}_{\text{ice}} > 95\%$ . Also, only those campaigns where ice crystals with diameters larger than  $3\text{ }\mu\text{m}$  were measured and minimized ice crystal shattering effects are guaranteed were considered (Geophysica – TTL flights, COALESC, AIRTOSS-ICE, ML-CIRRUS; ACRIDICON 2014 fits these requirements but is not considered since it is nearly entirely driven by strong convection). Comparing Fig. 10 (upper left panel, simulations) with Fig. 11 (observations) yields in general the same  $N_{\text{ice}}$  pattern in the simulations and the measurements. This means that the simulations are able to represent the increasing ice crystal number with increasing IWC seen in the measurements. Some dots in darker blue colors are visible in the observations, particularly at higher IWC. They can be traced back to situations with higher vertical velocities and thus represent the rare fast updraft cirrus discussed above.



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Looking back now at the full data sets of the individual campaigns (Fig. 3), it can be seen that the decreasing  $N_{\text{ice}}$  with decreasing IWC is visible in all field campaigns, even when the measurements are under suspicion of shattering effects. This suggests that in the respective data sets shown here, the amount of small artifacts of shattered ice crystals is not large enough to overlay the microphysical cirrus properties. Thus, we look now in more detail at the different field experiments.

We start with the AIRTOSS-ICE campaign (Fig. 3, left column, top panel). Here, one can see that very low  $N_{\text{ice}}$  concentrations were observed. The measurements were performed in August and September 2013 above the German North Sea (for geographical regions see Fig. 1) under Indian summer conditions, which implies that very low vertical updrafts associated with high pressure systems prevailed during the flights.

The IWC climatology from the Geophysica/Learjet measurements between 1999 and 2006, which covers a large geographical range, is shown in Fig. 3 (left column, second panel from top). Measurements in the TTL ( $T < 200$  K) are contained here, with very low  $N_{\text{ice}}$  detected at low IWCs – probably formed in very slow updrafts – but also higher  $N_{\text{ice}}$  together with high IWCs formed at higher updrafts. These two types of cirrus are also observed during the Global Hawk ATTREX mission in the TTL (Jensen et al., 2013a). Additionally, very high  $N_{\text{ice}}$  (dark blue points) can be seen above the median IWC line in the measurements at temperatures larger than about 205 K. Closer inspection of the meteorological situation shows that these measurements were performed downstream of the Norwegian mountains at very high vertical velocities and can be interpreted as leewave cirrus. High  $N_{\text{ice}}$  below the median IWC line in this temperature range might be a result of ice crystal shattering.

Calmer meteorological conditions prevailed during COALESC (left column, second panel from bottom) in spring 2011 over the Southern part of the UK. This is visible in the quite smooth color gradient, only disturbed by a dark blue patch at higher IWC between 210 and 215 K. These high ice crystal numbers represent very fresh contrails,

which were chased during one flight. The grouping of the points in a small temperature range reflect the cruising altitude of passenger aircraft.

ML-CIRRUS (Fig. 3, left column, bottom panel) took place in spring 2014 over Europe. Here, low and high pressure systems, some jet stream cirrus as well as contrails and aviation induced cirrus were probed. Nevertheless, the pattern of  $N_{ice}$  increasing with IWC is also visible here. As during COALESC, a block of higher  $N_{ice}$  at higher IWC around 210 K is found, though  $N_{ice}$  is a little lower here. They represent older contrails and aviation induced cirrus which were omnipresent in the cirrus probed over Central Europe.

Next, we discuss the two campaigns over the US continent, MACPEX (2011) and MidCix (2006), TC-4 (2007) over Costa Rica and ACRIDICON-CHUVA (2014) over Brazil (Fig. 3, right column). Again, the general pattern of  $N_{ice}$  increasing with IWC can clearly be seen in the measurements, though TC-4 is in general on the lower IWC side in comparison to MidCix and MACPEX and especially ACRIDICON-CHUVA, which reaches very high IWCs. The meteorological situations for MidCix and MACPEX, which took place in the same region (Southern US continent), were mostly determined by mesoscale convective systems with high updrafts, while ACRIDICON-CHUVA represents smaller scale tropical deep convection.

What is surprising for ML-CIRRUS, MidCix and MACPEX and particularly ACRIDICON-CHUVA are the many data points at very high IWCs: high IWCs should appear from fast updrafts, which are discussed as small scale features that do not appear frequently (see Sect. 5.1). To further investigate this, we have plotted the simulated Cirrus Guide again, now color coded by the the mean mass size  $R_{ice}$  of the ice crystals in Fig. 10, upper right panel. It is seen that  $R_{ice}$  is largest (dark green) at low IWCs and high temperatures. For comparison the same plot type is shown for MidCix in the panel below (for consistency the MidCix IWC colored by  $N_{ice}$  is shown in the left panel). Conversely to the simulations, the largest ice crystals appear at the highest IWCs in the MidCix observations. Seemingly, these frequently appearing cirrus with high IWCs and large ice crystals are not present in the simulations of in-situ origin

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cirrus. They represent a different type of ice clouds originating in liquid droplets, which will be further discussed in Sect. 5.4.

### 5.3.2 $N_{\text{ice}}-R_{\text{ice}}$ -IWC parameter space

For the ML-CIRRUS (2014) campaign, it was possible to extract the in-situ origin cirrus from the observations by analyzing the cloud history along backward trajectories (for more detail see Luebke et al., 2015; Rolf et al., 2015). Hence, this data set is particularly suitable for comparison with the MAID simulations. For that purpose, we show a different type of plot (introduced already in Sect. 5.2), including the information of IWC,  $N_{\text{ice}}$  and  $R_{\text{ice}}$  all at once. In Fig. 12 the ice crystal number  $N_{\text{ice}}$  is plotted as function of  $R_{\text{ice}}$ . In the upper row, the color code is IWC and the black lines are isolines of constant IWC. The upper left panel shows the observations during ML-CIRRUS (2014) and in the right panel the Cirrus Guide simulations of all “fluct” scenarios (including temperature fluctuations, see Sect. 3) are shown. For a better interpretation, the same plot is shown in the lower left panel of the Figure, now color coded by vertical velocity in the same colors used in previous figures. In the lower right panel the color code is extinction (see Sect. 5.2).

Inspection of the Cirrus Guide vertical velocity plot (Fig. 12, lower left) shows that high updrafts (red dots) can produce ice crystals smaller than  $10\mu\text{m}$  (mass mean radius) with concentrations between  $5\text{--}500\text{cm}^{-3}$ . With decreasing updraft,  $N_{\text{ice}}$  decreases to values down to  $10^{-4}\text{cm}^{-3}$  while  $R_{\text{ice}}$  grows to maximum sizes of  $100\mu\text{m}$ . Note that  $R_{\text{ice}}$  is also an indicator for cirrus age, the larger the mass mean size, the older the cloud. Comparing with the IWC plot (upper right) it can be seen that lower vertical velocities are related to lower IWCs with fewer, larger ice crystals and higher updrafts with higher IWC and more, smaller ice crystals (as also shown in Sect. 5.2).

From a comparison of the observations (upper left) with the simulations (upper right), it is evident that the observed cirrus are located well within the bounds of the simulations. The range of values covered by the observations is smaller because they represent mid-latitude cirrus clouds with temperatures between about 205–235 K and mostly

slow updrafts, while the simulations represent the full cirrus climatology including colder temperatures and higher vertical velocities. The observed concentrations of small ice crystals  $5\text{--}20\text{ cm}^{-3}$  are mostly related to the contrails noted already in the previous section. Also, some meteorological situations with higher updrafts were probed during the campaign, leading to observations with a maximum  $N_{\text{ice}}$  of  $5\text{ cm}^{-3}$ . The maximum sizes of the observed cirrus particles are smaller than in the simulations, which points to a shorter cirrus lifetime in the atmosphere than in the simulations. Also, some thicker cirrus (red points between the IWC isolines  $200\text{--}300\text{ ppmv}$ ) are detected during ML-Cirrus. However, given the wide range of different parameters influencing the cirrus formation and evolution, the good agreement between observations and simulations demonstrates that with the help of the Cirrus Guide an interpretation of cirrus observations is possible in greater depth.

## 5.4 Liquid origin cirrus

In the last paragraph of Sect. 5.3.1 it is mentioned that high IWCs above the median IWC together with large ice crystals (Fig. 10) are not represented in the Cirrus Guide. Nevertheless, this type of cirrus is found in the observations, especially during MidCix, MACPEX and ACRIDICON-CHUVA, as well as in the other campaigns shown in Fig. 3 (except AIRTOSS-ICE). Here, a larger number of very high IWC are detected than was expected based on the MAID simulations. From further analysis, relating meteorological situations to cirrus types, it can be concluded that these high IWC cirrus stem from lower altitudes and are not produced by in-situ ice nucleation directly from the gas phase like in our simulations (for detail see Luebke et al., 2015). Instead, they are formed by heterogeneous freezing of liquid droplets at temperatures  $> 235\text{ K}$  or possibly as low as  $235\text{ K}$  by homogeneous drop freezing. The ice crystals were then lifted to the temperature range  $< 235\text{ K}$  and are therefore regarded as cirrus clouds. This can happen in regions with mesoscale convective activity (observed during MidCix and MACPEX), but also in warm conveyor belts (observed during ML-CIRRUS). In tropical



convective systems, which are observed in this study during ACRIDICON-CUVA, this cirrus type is known as “anvil cirrus” or “anvil outflow”.

Note that in addition to a high IWC, other indicators for cirrus originating from liquid drops are high  $N_{\text{ice}}$  together with the appearance of larger ice crystals (for more detail see Luebke et al., 2015). The high ice crystal concentrations may stem from an originally larger frozen drop number, or from an additional freezing event that may happen on top of the preexisting ice in case the updraft is fast enough. The nucleation mechanism will probably be homogeneous freezing, since the IN are already consumed in the previous liquid cloud. The high supersaturation that is needed can be reached in fast updrafts, when the reduction of  $RH_{\text{ice}}$  by uptake of water on the ice surfaces is lesser than the  $RH_{\text{ice}}$  enhancement caused by the decreasing temperature.

Altogether, these thick liquid origin cirrus have microphysical, and thus optical, properties quite different from the in-situ cirrus formed directly via the gas phase. Further, they appear together with mixed-phase and often liquid clouds below. This is shown in detail for liquid origin clouds stemming from warm conveyor belts in comparison to in-situ cirrus observed during ML-CIRRUS by Luebke et al. (2015).

It is a surprising result from this study that these “liquid origin cirrus” seem to appear in the complete cirrus temperature range with a non-negligible frequency. As a consequence, for a complete understanding we recommend devoting further research to assessing their properties and including them in model studies.

## 6 Summary and conclusions

The goal of this study is to track cirrus IWC development with temperature by means of model simulations, compare the simulations with observations in the IWC-T parameter space and then assign, to a certain degree, cirrus microphysics to the observations.

To this end, an extensive set of model simulations, covering the broad range of atmospheric conditions for cirrus formation and evolution, is compiled, which we call the Cirrus Guide. Further, cirrus data sets from seventeen aircraft campaigns, conducted

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between 1999–2014, spending about 94 h in cirrus over Europe, Australia, Brazil as well as Southern and Northern America are evaluated.

We found good agreement between observations and simulations, demonstrating that the Cirrus Guide is applicable for the interpretation of observations. A summary of the findings with respect to cirrus microphysics is provided in a sketch of the IWC-T parameter space shown in Fig. 13.

1. Two different types of cirrus are characterized in our study. The first represents the “classical” cirrus (simulated in the Cirrus Guide), where the ice crystals form heterogeneously+homogeneously directly from the gas phase (“in-situ origin cirrus”, greenish color in Fig. 13). The second type consists of ice crystals formed by heterogeneous (or sometimes homogeneous) freezing of liquid drops farther below in the atmosphere which are uplifted into the cirrus temperature range (“liquid origin cirrus”, blueish color in Fig. 13). The liquid origin cirrus are not included in our simulations, but are identified from the observations. These two cirrus types in general can be distinguished by IWC, where in-situ cirrus are preferably thin with lower IWC, while liquid origin cirrus are mostly thick with higher IWC. In addition, the liquid origin cirrus seems to have larger ice crystals than the in-situ cirrus. The microphysical properties of the two cirrus types are further investigated by Luebke et al. (2015).
2. Within the in-situ cirrus, two classes are also identified. (1) The first are thin cirrus that appear in slow updraft situations (range up to about  $0.1 \text{ ms}^{-1}$ ). Their IWC is low and they consist of few, large ice crystals. Due to the slow updraft, their microphysical properties are only slightly dependent on the type of ice nucleation (heterogeneous or homogeneous). They appear in low or high pressure frontal systems and thus have a large geographic coverage and a long lifetime. (2) The second in-situ cirrus class are thick cirrus forming in fast updrafts triggered by atmospheric waves (i.e. leewave cirrus). They have high IWCs and many, small ice crystals. Their formation mechanism is dominated by homogeneous freezing,

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i.e. they are not sensitive to IN properties. The geographic coverage of fast updraft in-situ cirrus is low. In principle they have a short lifetime, unless they do not form continuously in standing waves as e.g. orographic cirrus downstream of mountains.

3. Analyzing the cirrus over the European and American continents, we found that over Europe in-situ and liquid origin cirrus in slow updrafts (warm conveyor belts, high pressure systems) are observed most frequently. Over the American continent, liquid origin cirrus in fast updrafts (mesoscale convective systems, tropical convection) were more abundant in the observations.

To conclusively draw a line from cirrus to the Earth's climate, we hypothesize here that on average the physically and optically thinner in-situ slow updraft cirrus cause a warming effect, while cooling might rather be induced by the thicker fast updraft in-situ and particularly liquid origin cirrus.

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**Table 1.** Overview of campaigns and instruments. IWC: ice water content,  $RH_{ice}$ : relative humidity over ice,  $N_{ice}$ : ice crystal number concentration.

Aircraft	Locations	IWC	$RH_{ice}$	$N_{ice}$
Geophysica	Seychelles <sup>1</sup> , Europe <sup>2</sup> , Brazil <sup>3</sup> , Australia <sup>4</sup> , Africa <sup>5</sup>	FISH <sup>a</sup>	FLASH <sup>c</sup>	FSSP-100 <sup>i</sup>
Learjet	Europe <sup>6</sup>	FISH <sup>a</sup>	OJSTER <sup>d</sup> , SEAL <sup>e</sup>	FSSP-300 <sup>j</sup>
WB-57	USA <sup>7</sup> , Costa Rica <sup>8</sup>	CLH <sup>b</sup>	HWV <sup>f</sup> , JLH <sup>g</sup>	CAPS <sup>k</sup> , 2-DS <sup>l</sup>
BAe-146	UK <sup>9</sup>	NIXE-CAPS <sup>m</sup>	–	NIXE-CAPS <sup>m</sup>
HALO	Europe <sup>10</sup> , Brazil <sup>11</sup>	NIXE-CAPS <sup>m</sup>	SHARC <sup>h</sup>	NIXE-CAPS <sup>m</sup>

The campaigns under 1–6 are described by Schiller et al. (2008); Krämer et al. (2009) and Finger et al. (2015), 7–8 by Luebke et al. (2013); Jensen et al. (2013b), 9 Jones et al. (2012), 10 Voigt (2015), 11 Wendisch et al. (2015).

<sup>1</sup> APE-THESEO 1999.

<sup>2</sup> ENVISAT 2002, EUPLEX 2003, ENVISAT 2003.

<sup>3</sup> TROCINOX 2005.

<sup>4</sup> SCOUT-O<sub>3</sub> 2005.

<sup>5</sup> AMMA 2006.

<sup>6</sup> CIRRUS 2003, CIRRUS 2004, CIRRUS 2006, AIRTOSS-ICE 2013.

<sup>7</sup> MidCix 2004, MACPEX 2011.

<sup>8</sup> TC-4 2007.

<sup>9</sup> COALESC 2011.

<sup>10</sup> ML-CIRRUS 2014.

<sup>11</sup> ACRIDICON-CHUVA 2014.

<sup>a</sup> Lyman- $\alpha$  fluorescence hygrometer (Schiller et al., 2008; Krämer et al., 2009; Meyer et al., 2015).

<sup>b</sup> Tunable diode laser hygrometer (Luebke et al., 2013).

<sup>c</sup> Lyman- $\alpha$  fluorescence hygrometer (Krämer et al., 2009).

<sup>d</sup> Tunable diode laser hygrometer (Krämer et al., 2009).

<sup>e</sup> Tunable diode laser hygrometer (Buchholz et al., 2013).

<sup>f</sup> Lyman- $\alpha$  fluorescence hygrometer (Rollins et al., 2014).

<sup>g</sup> Tunable diode laser hygrometer (May, 1998).

<sup>h</sup> Tunable diode laser hygrometer (Meyer et al., 2015).

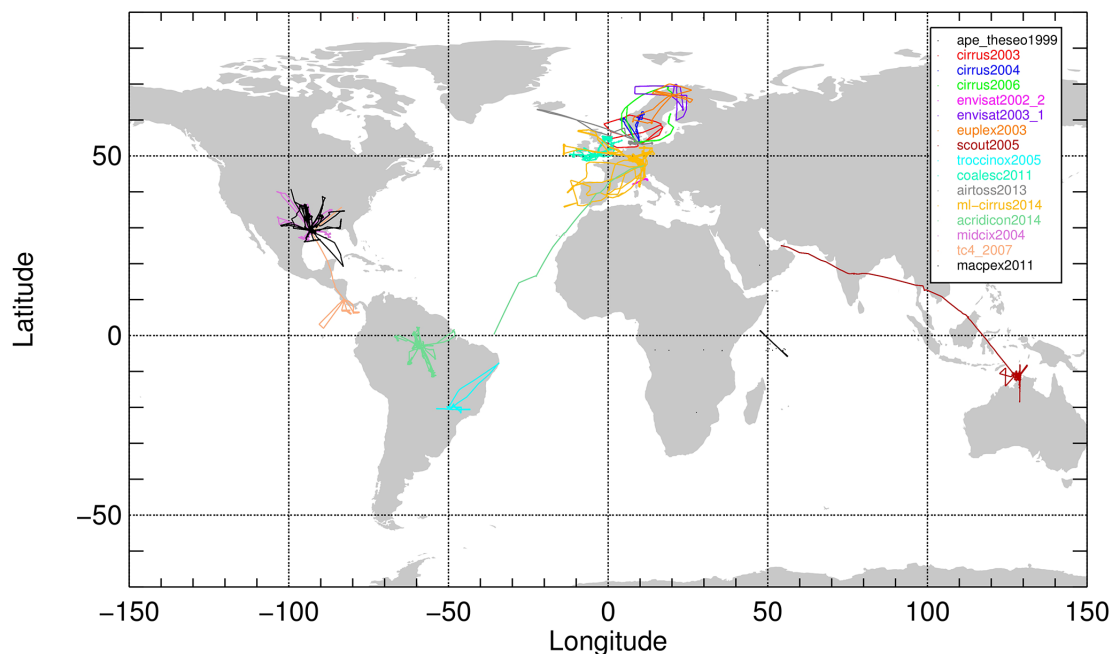
<sup>i</sup> Light scattering cloud probe (Krämer et al., 2009).

<sup>j</sup> Light scattering cloud probe (Krämer et al., 2009).

<sup>k</sup> Light scattering and optical imaging cloud probe (Baumgardner et al., 2001).

<sup>l</sup> optical imaging cloud probe (Lawson et al., 2006).

<sup>m</sup> Light scattering and optical imaging cloud probe (Meyer, 2012; Luebke et al., 2015).



10 campaigns	Geophysica/Learjet: 8.4h	28 flights	1999-2006, see Table 1
COALESC	BAe-146: 9.9h	16 flights	2011 February - March, UK
AIRTOSS-ICE	Learjet: 1.1h	9 flights	2013 August, Northern Germany
ML-CIRRUS	HALO: 17.9h	17 flights	2014 March-April, Southern Germany
ACRIDICON	HALO: 12.0h	16 flights	2014 September-October, Brazil
MidCix	WB-57 11.4h	7 flights,	2004 April-May, Southern USA
TC-4	WB-57 12.5h	5 flights	2007 July-August, Costa Rica
MACPEX	WB-57 19.7h	14 flights	2011 April, Southern USA

**Figure 1.** Aircraft flight paths during the campaigns listed above. Total number of flights: 104, total time of IWC measurements: 93.6 h.

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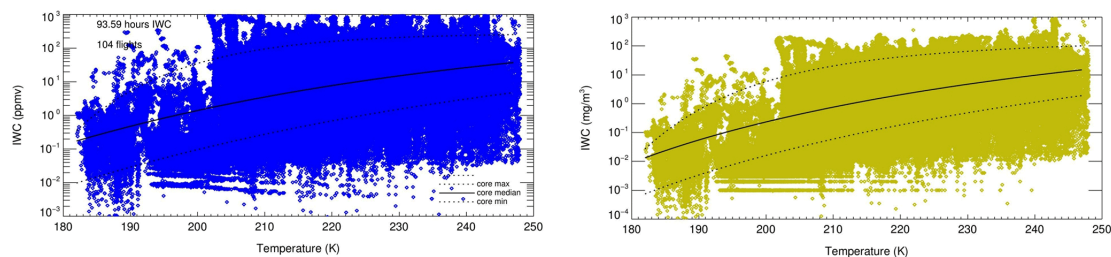
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**Figure 2.** Observations of IWC vs. temperature during the flights shown in Fig. 1 (left: mixing ratio, right: concentration). Lines: median IWC (solid) and upper and lower bound of core IWC band (dotted) from observations of Schiller et al. (2008); Luebke et al. (2013). Total flight distance in clouds was about 67.390 km  $\approx$  336.960 data points (all data are sampled at 1 Hz).

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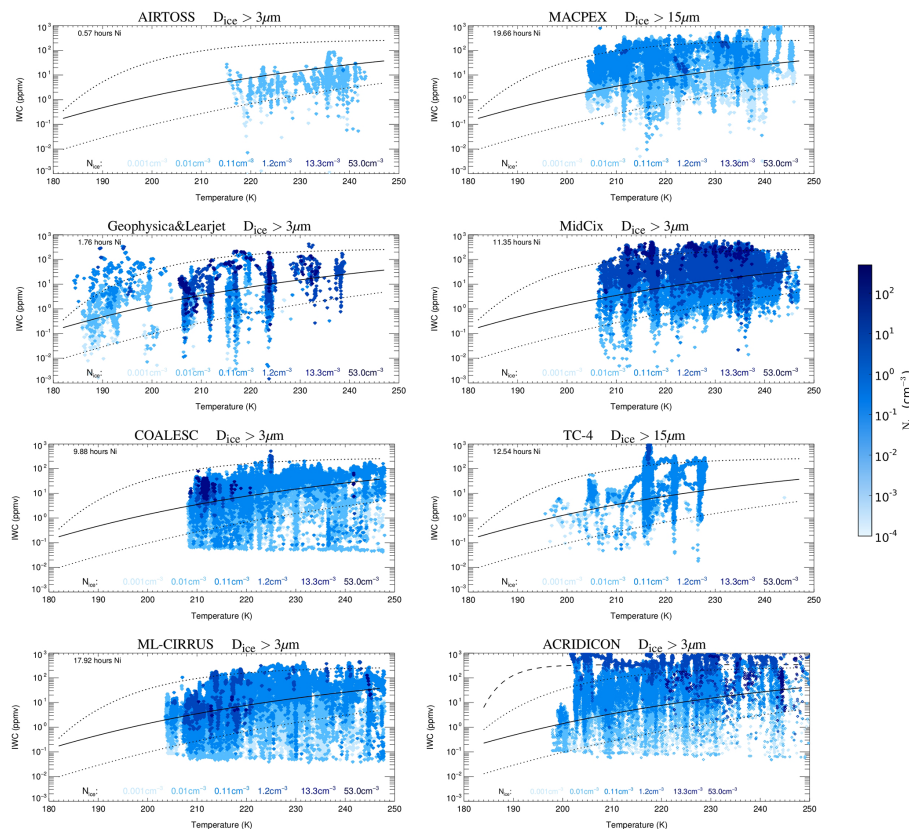
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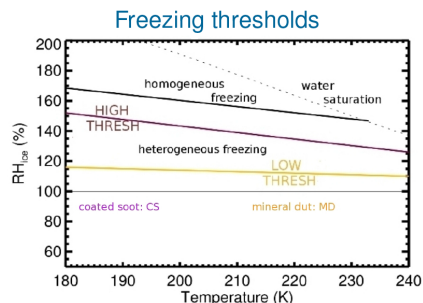


**Figure 3.** Observations of IWC vs. temperature, color coded by  $N_{ice}$  (= total number of ice crystals  $> D_{ice}$ ). Left column: European field campaigns, right column: US/Brazil field campaigns. Total simultaneous IWC- $N_{ice}$  measurements 85.7 h. Solid line: median IWC, dotted lines: upper and lower bound of the core IWC band (from observations of Schiller et al., 2008; Luebke et al., 2013). For instrumentation and campaigns see Table 1 and Fig. 1.

## Single scenario

- Temperature range  
190 - 230 K  
in 10 K steps
- $H_2O_{init}(T)$ :  
90%  $RH_{ice}$
- Vertical velocities:  
0.0001, 0.01, 0.1,  
0.5, 1.0, 3.0 m/s

➤ each scenario  
contains  
27 model runs



## Scenarios

- HOM
- HET+HOM :  
- Ice nuclei (IN):  
0.001, 0.01, 0.1, 1.0  $cm^{-3}$   
- High/low freezing thresholds
- sedimentation parameter  
 $f = 0.9 / 0.5$
- temperature fluctuations  
fluct / nofluct

➤ 18 nofluct , 18 fluct scenarios  
→ Cirrus Guide:  
972 model runs

**Middle:** Freezing thresholds of heterogenous and homogeneous ice nucleation:

Heterogeneous freezing thresholds (Gensch et al., 2008):

$$RH_{ice}^{MD} = 134. - 0.1 \cdot T \quad (MD: \text{mineral dust, } T: \text{temperature in K}), \quad RH_{ice}^{CS} = 230. - 0.433 \cdot T \quad (CS: \text{coated soot}).$$

Schematic homogeneous freezing threshold after (Koop et al., 2000) - in reality there are small variations in the threshold in dependence of the aerosol particle size and cooling rate.

**Left:** Description of a single scenario.

5 temperatures x 5 updrafts (190, 200, 210, 220, 230 K) X (0.01, 0.1, 0.5, 1.0, 3.0 m/s)

2 temperatures x 1 updrafts (190, 200) X 0.001m/s = 27 scenarios.

**Right:** Description of the various scenarios.

2 scenarios HOM: 2 sedimentation parameters  $sedi-f = 0.9/0.5$ .

16 scenarios HET+HOM: 4 IN concentrations (0.001, 0.01, 0.1, 1.0  $cm^{-3}$ ), 2 freezing thresholds (MD/CS),

2 sedimentation parameters  $sedi-f = 0.9/0.5$ .

Total: 18 scenarios with constant updrafts (nofluct)

+ 18 scenarios with temperature fluctuations superimposed to the (fluct) constant cooling

= 36 scenarios.

972 model runs are performed for the complete MAID Cirrus Guide.

Scenario abbreviations:

$HOM|_{sedi-f}$  and  $HET+HOM|_{sedi-f}^{IN-MD/CS}$ , with HOM: homogeneous freezing, HET: heterogeneous freezing, HET+HOM: ice nucleation starts HET and possibly a subsequent HOM event occurs.

For more detail see text.

**Figure 4.** Description of the MAID Cirrus Guide scenarios.

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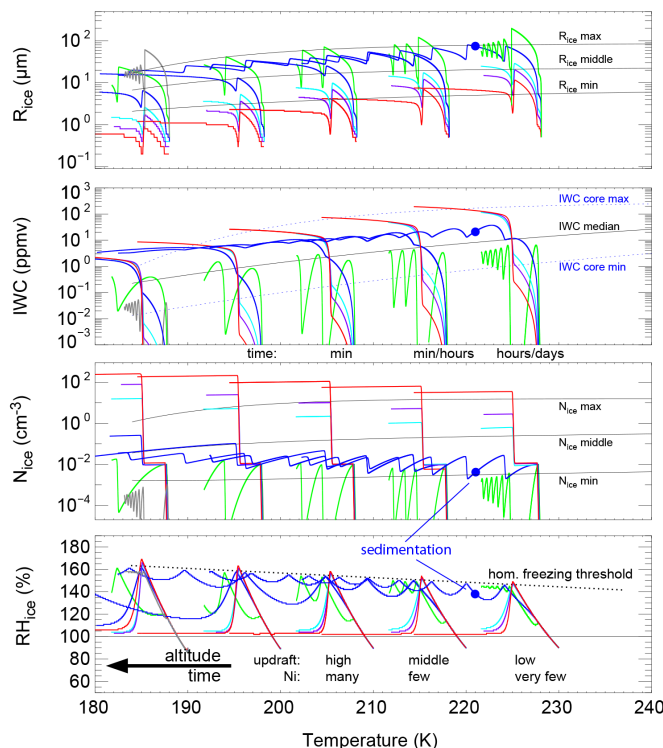
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sedi 0.9,  $IN=0.01\text{ cm}^{-3}$ , MD  
 3.0 m/sec  $\approx 0.6\text{ min/K}$   
 1.0 m/sec  $\approx 1.7\text{ min/K}$   
 0.5 m/sec  $\approx 3.4\text{ min/K}$   
 0.1 m/sec  $\approx 17\text{ min/K}$   
 0.01 m/sec  $\approx 170\text{ min/K}$

sedi 0.9,  $IN=0.001\text{ cm}^{-3}$ , MD  
 0.0001 m/sec  $\approx 28\text{ h/K}$



**Figure 5.** Cirrus scenario HET+HOM<sub>sedi=0.9</sub><sup>0.01-MD</sup>: simulated evolution of cirrus clouds at different temperatures and varying vertical velocities (see legend). The simulations propagate from right to left, the time of the simulations is indicated in the legend (in  $\text{min K}^{-1}$ ). Top panel:  $R_{ice}$  (lines: min, middle, max  $R_{ice}$  from Krämer et al. (2009)), 2nd panel: IWC (solid line: median IWC, dotted lines: upper and lower bound of the core IWC band from observations of Schiller et al. (2008); Luebke et al. (2013)), 3rd panel:  $N_{ice}$  (lines: min, middle, max  $N_{ice}$  from Krämer et al. (2009)), bottom panel:  $RH_{ice}$ .

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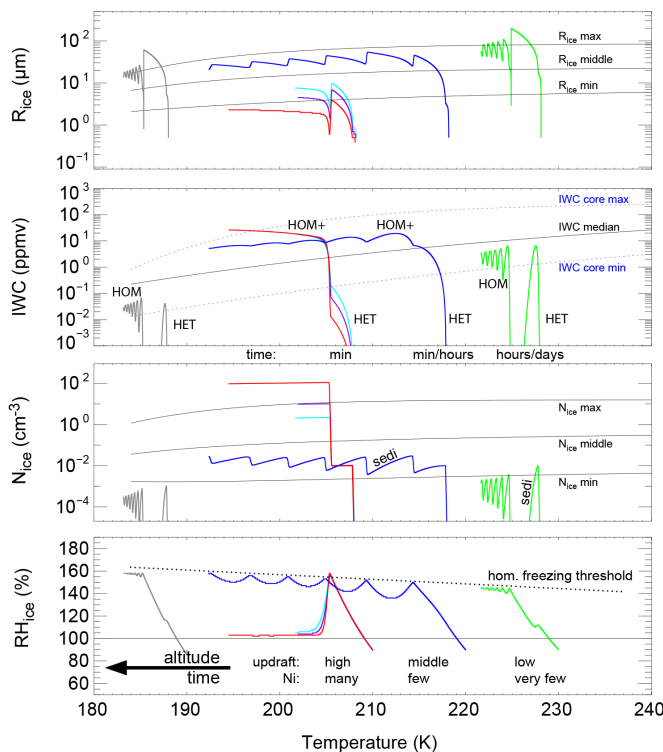
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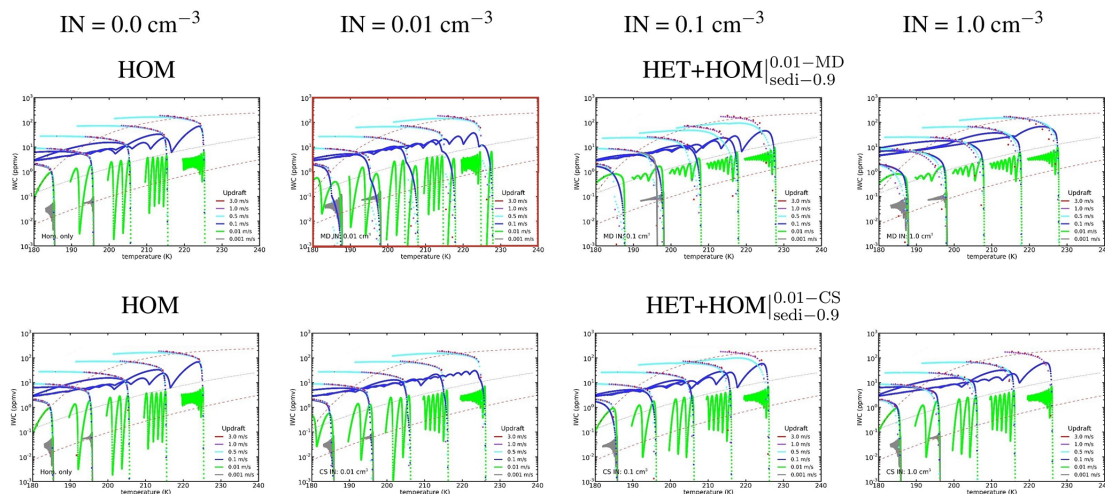




sedi 0.9, IN=0.01 cm<sup>-3</sup>, MD  
 3.0 m/sec ≈ 0.6 min/K  
 1.0 m/sec ≈ 1.7 min/K  
 0.5 m/sec ≈ 3.4 min/K  
 0.1 m/sec ≈ 17 min/K  
 0.01 m/sec ≈ 170 min/K  
  
 sedi 0.9, IN=0.001 cm<sup>-3</sup>, MD  
 0.0001 m/sec ≈ 28 h/K



**Figure 6.** Same as Fig. 5, but only some selected trajectories are shown.



**Figure 7.** Cirrus scenarios in the IWC-Temperature parameter space for varying initial conditions, color coded by vertical velocities (color code see legend). Columns (from left to right): scenarios HOM ( $IN = 0.0 \text{ cm}^{-3}$ ) and HET + HOM ( $IN = 0.01, 0.1, 1.0 \text{ cm}^{-3}$ ); top/bottom panels – freezing threshold MD/CS, sedi-f = 0.9 for all scenarios. Note that the IWC of the different vertical velocities is only weakly dependent on the different initial conditions. Solid line: median IWC, dotted lines: upper and lower bound of the core IWC band from observations of Schiller et al. (2008); Luebke et al. (2013).

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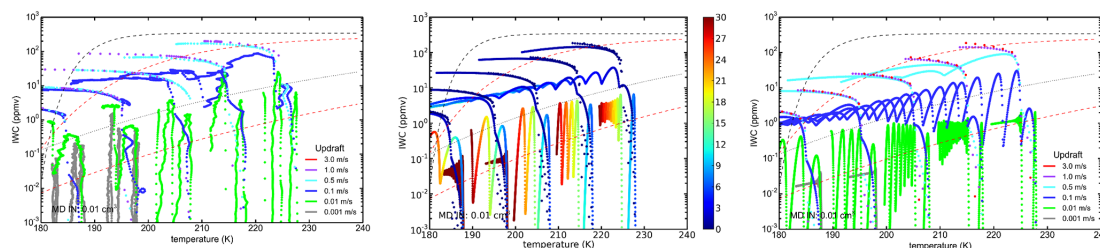
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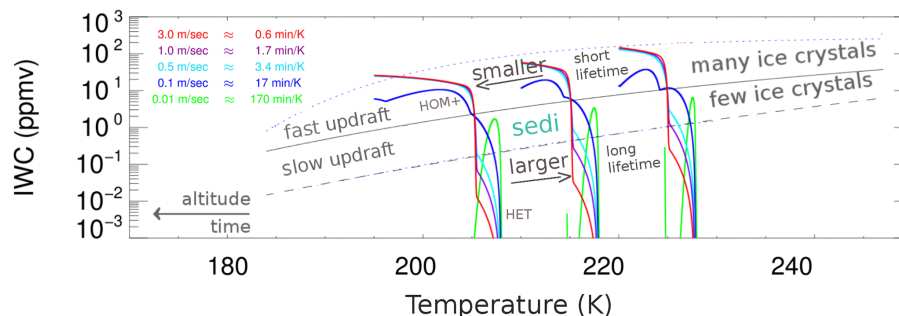
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**Figure 8.** Cirrus scenario HET + HOMI<sup>0.01-MD</sup><sub>sedi=0.9</sub>. Same as in Fig. 7 (red box) (and also Figs. 5 and 6), but: left: with superimposed temperature fluctuations, middle: color coded by time, right: with strong sedimentation (sedi = 0.5).



**Figure 9.** Sketch of the MAID in-situ Cirrus Guide: two classes of in-situ cirrus clouds are identified in the IWC-T parameter space. (1) IWCs below the median IWC line (Schiller et al., 2008; Luebke et al., 2013) mostly stem from **slow updraft cirrus**. They consist of few, but large ice crystals which are the larger the warmer the cirrus is. The first part of these cirrus is determined by HET freezing (indicated in the Figure). If the clouds life time is long enough, HOM freezing also starts. Due to the low updrafts, the number of ice crystals produced by HOM freezing does not greatly differ from the HET nucleated ice crystals. Thus, in slow updraft regions the difference in microphysics between HET and HOM formed cirrus is small. (2) High IWCs above the median IWC line are mostly produced by **fast updraft cirrus**. The time of the HET cirrus part at low IWC is short since the HOM freezing pushes the IWC quickly above the median line. With their large number of small, non-sedimenting ice crystals, these cirrus are microphysically very different from the slow updraft cirrus.

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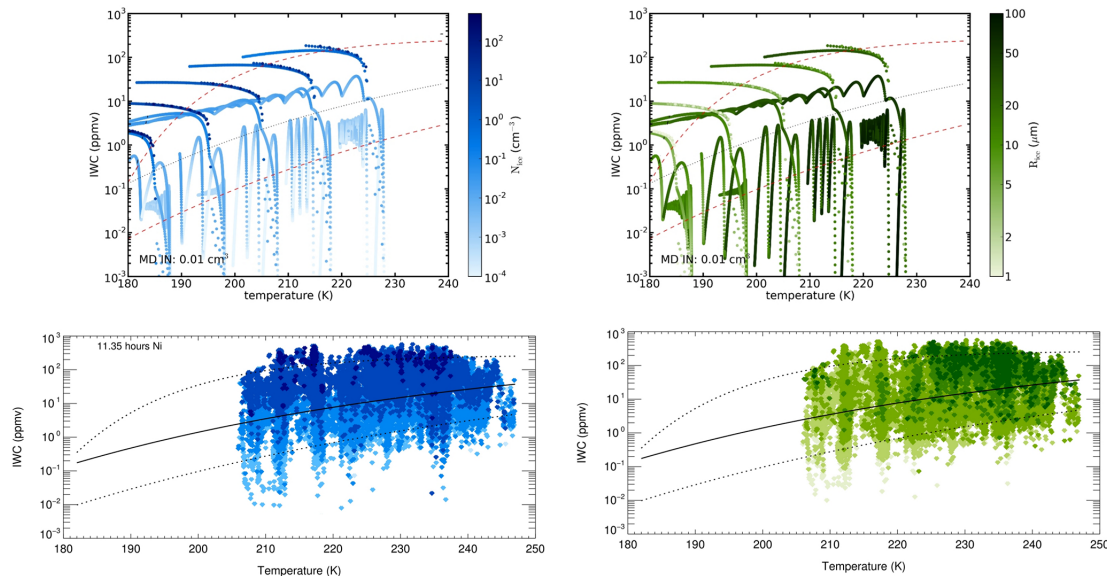
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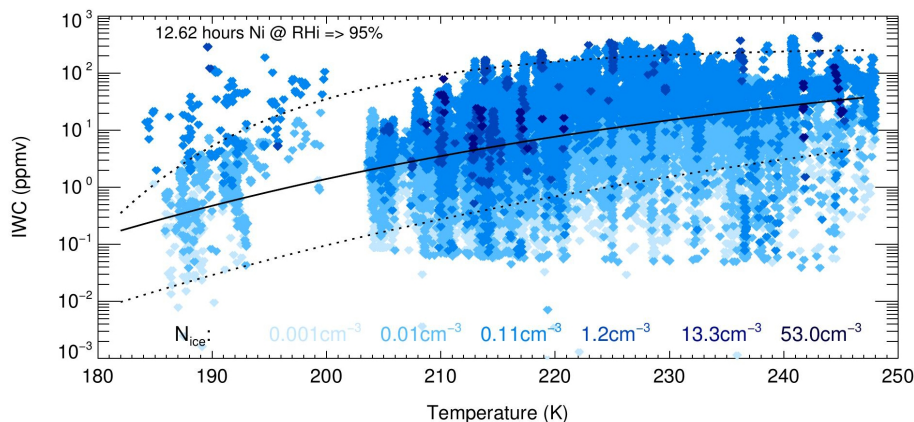
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**Figure 10.** IWC colored by  $N_{ice}$  (left) and  $R_{ice}$  (right); top panels: MAID scenario HET + HOM<sub>sed</sub><sup>0.01-MD</sup>, bottom panels: observations from MidCix.



**Figure 11.** IWC colored by  $N_{ice}$  for (1)  $RH_{ice} > 95\%$ , which compares best to Cirrus Guide, and (2) those campaigns with PSDs for ice crystals with  $D > 3\mu m$  and minimized ice crystal shattering effects (Geophysica – TTL flights, COALESC, AIRTOSS-ICE, ML-CIRRUS; ACRIDICON 2014 is not considered since it is nearly entirely driven by strong convection).

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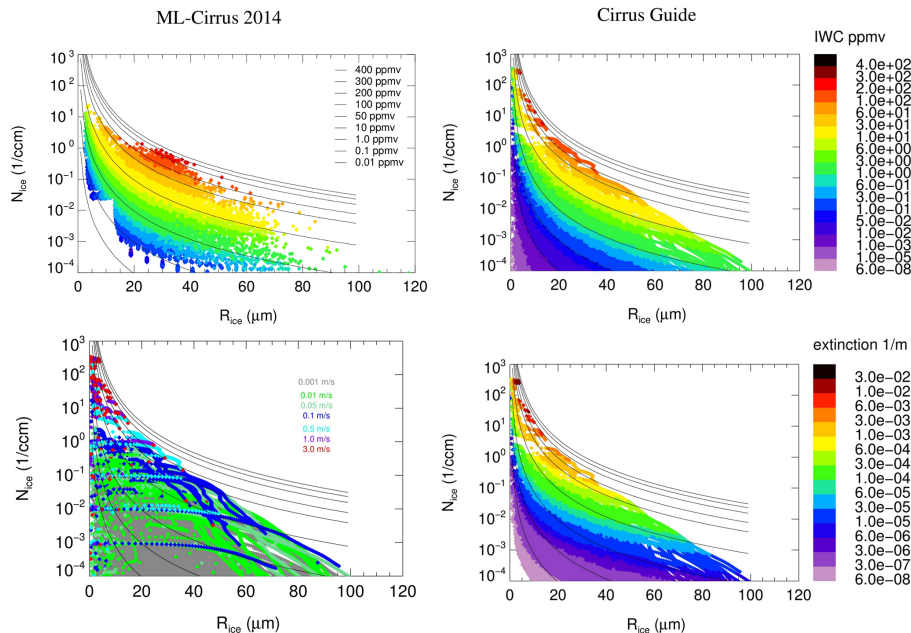
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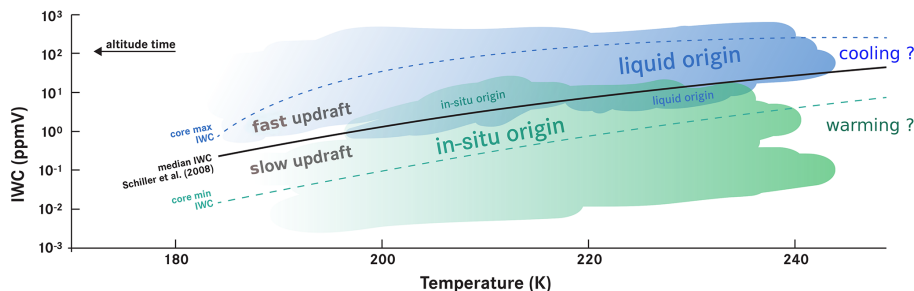
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**Figure 12.**  $N_{ice}$  vs.  $R_{ice}$ . Upper left panel: observations of in-situ cirrus during ML-CIRRUS 2014 – color code IWC, black lines are IWC isolines. The other panels show the simulated Cirrus Guide: upper right – color code IWC, lower left – color code vertical velocity, lower right – color code extinction. The simulations contain all scenarios including temperature fluctuations (“fluct”, see Sect. 3).

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**Figure 13.** Sketch of in-situ and liquid origin cirrus (large letters: high frequency of occurrence, larger ice crystals, stronger sedimentation, longer lifetimes; small letters: low frequency of occurrence, smaller ice crystals, lesser sedimentation, shorter lifetimes). **In-situ origin cirrus** (greenish color): ice crystals form heterogeneously+homogeneously directly from the gas phase. In-situ cirrus are preferably thin with lower IWC. They divide in two classes (see also Fig. 9): (1) thin cirrus forming in slow updrafts consisting of few, large ice crystals with a large geographic coverage and a long lifetime, (2) thicker cirrus forming in fast updrafts consisting of many, small ice crystals with a smaller geographic coverage. **Liquid origin cirrus** (blueish color): ice crystals stem from frozen liquid drops which are uplifted from farther below in the atmosphere into the cirrus temperature range. Liquid origin cirrus are mostly thick with higher IWC and have larger ice crystals than the in-situ cirrus (for more detail see Luebke et al., 2015). Their geographic coverage/lifetime depend on the meteorological situation: larger/longer in warm conveyor belts, smaller/shorter in convective systems.

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