Final Author comments in reply to two anonymous referees on :

“Bulk microphysical properties of semi-transparent cirrus from AIRS: a six year global climatology and statistical analysis in synergy with geometrical profiling data from CloudSat-CALIPSO”

by A. Guignard et al.

First of all we want to thank both referees for their very thoughtful reviews as well as their language and style corrections. We have included the suggestions in the manuscript which has lead to a reformulation of a large part of the manuscript. We hope that it is now easier to read. We have also slightly changed the title, as suggested, and included a flow chart of the retrieval method and revised the other figures for more clarity.

Reply to specific comments:

Referee #1

We have removed Figure 3, Figure 9 and Figure 13 and split Figure 4 into two figures for more clarity. In addition we have included a new Figure 1 which presents the retrieval scheme.

However, we decided to keep the part of the De parameterization in this article, because this part gives an example how the data may be used for testing a parameterization over the whole globe. We foresee a GCM study, but also in addition with the development of other parameterizations for comparison.

Section 2.2

When ‘cirrus emissivities’ are being discussed, are the authors using ‘emissivity ratios’ as described in Pavolonis (2010), or a different approach? This is a bit unclear.

We first determine cirrus spectral emissivities, in a similar way as in Eq 2 in (Pavolonis, 2010); Eq. 1 in our article, with the cloud pressure retrieved by using the CO2 channels (and a chi2 method) and atmospheric transmissions obtained from the TIGR data base (for the atmospheric profiles most similar to the ones retrieved by AIRS). However, for the retrieval of De and IWP we do not build emissivity ratios, but we use directly the six cirrus spectral emissivities to compare them to the simulated ones.

First paragraph rewritten as:

In the following we describe the methodology used to retrieve the De and IWP of semi-transparent cirrus (see also Figure 1). The method is based on cirrus spectral emissivity differences in the range 8 – 12 µm. Cirrus emissivities are determined as in Eq. 1, by using the measured, clear sky and cloudy spectral radiances. The latter are computed using the retrieved cloud pressure. They are then compared to simulated cirrus emissivities which depend on De and IWP. Therefore, cirrus emissivities have been simulated using single scattering properties (SSPs) of column-like or aggregate-like ice crystals. ….

Section 2.2.2

What AIRS channel numbers are being used? What are their noise characteristics? Have they been reliable over the entire AIRS mission? Are they in windows, on weak absorption lines, etc.?

First paragraph of section 2.2.2 rewritten as:
For the retrieval of De and IWP we have selected two channels in the range around 9 mm, two channels around the slope between 10 and 11 mum, and the average of two channels around 12 µm (indicated in black in Figure 3). The selected channels in the 8-12 µm range are those with the weakest absorption lines and smallest noise (by studying the simulated AIRS brightness temperatures of the TIGR dataset). Some channels could not be used, because they were not operational over the whole period (channels 518, 585 and 963), and some channels provide redundant information, so that by using more channels we obtained very similar results. This is in agreement with studies by L'Ecuyer et al. (2006) and Kahn et al. (2008)), which have shown that the retrieval does not improve by adding additional spectral information when the most sensitive channels are already being used. Once the physical cloud properties (pcld and εcld) are determined by the weighted c2 method (see Sect. 2.1 and Figure 1), cirrus spectral emissivities at 8.87, 9.12, 10.41, 10.70, 12.02 and 12.33 mm (corresponding to AIRS channels 1244, 1185, 903, 835, 557, 502) are determined for high clouds according to Eq. 1. ….

It is not clear how p_cld is obtained if none of the CO2-slicing channels are used in this retrieval. Are these derived separately (i.e., previous Stubenrauch et al. work), and then used as inputs to this approach?
Indeed, this was not clear in the previous version of our article. The cloud property retrieval has been published in Stubenrauch et al. 2010, but it is shortly presented in 2.1. The rewritten parts in section 2.2 as well as the retrieval flow chart in Figure 1 should clarify the retrieval method of microphysical properties. One needs the retrieved cloud pressure for the retrieval, as well as cirrus identification.

What is the 'De-IWP couple'?
De-IWP couple was an expression employed to say that we retrieved the effective diameter and the ice water path at the same time.

Rewritten at end of section 2.2.2 as:

We choose for each crystal habit De and IWP for which the six simulated cirrus spectral emissivities are the most similar to the retrieved one, Eq. 3, …

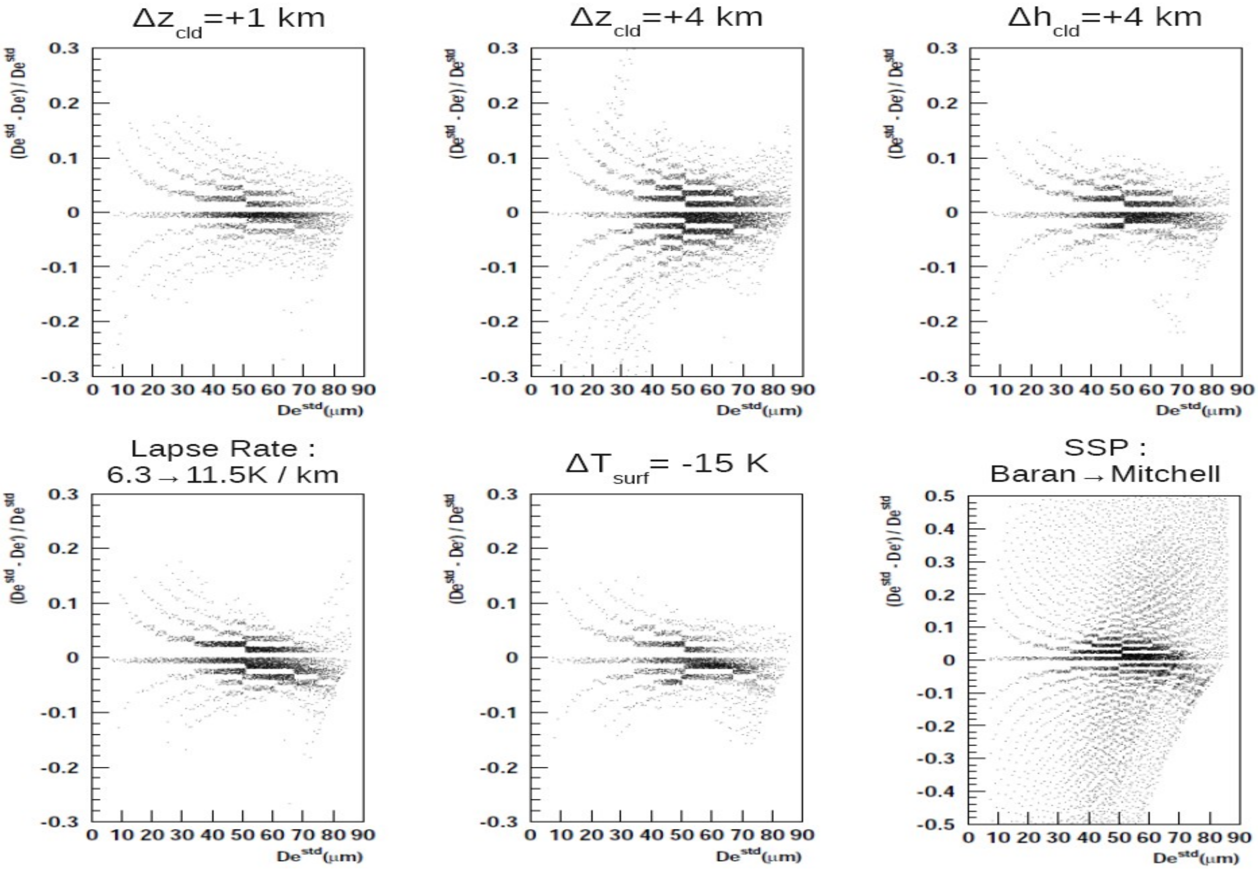
Section 3.1

The small changes in the retrieved parameters when the input variables are adjusted (e.g., Table 1) seem low to me. Are these consistent with Posselt at al. (2008), Kahn et al. (2008), Yue et al. (2007), etc. and so forth? Are these bias or random values?

The sensitivity study provides average biases and noise (the latter has been added now in Table 1). This was not clear in our earlier manuscript. For each sensitivity study we have replaced the standard LUTs against the corresponding new LUTs and performed a retrieval over two years of global AIRS data. We have then selected cases of optically thin clirrus and optically thicker cirrus and compared for them the new results with the standard ones, separately when De standard was small and when De standard was large.
Last paragraph in section 3, before 3.1 rewritten as:

To study the impact of changes in these assumptions, we have created for each change discussed in sections 3.1 and 3.2 new look-up tables. These have been used instead of the standard look-up tables, and average biases are determined by comparing standard retrieval results over the whole globe with these new results, separately for optically thin cirrus and optically thicker cirrus (emissivities 0.3 - 0.4 and 0.7 - 0.8), each with two examples of De (15 µm and 60 µm). The scatter between new and old results provides the noise.

The following figures present scatter plots of the De bias as function of De standard, for all cases of cirrus emissivity between 0.2 and 0.85, using 2 years of global AIRS data.



The outcome of our study is that on average biases are small (in general less than 5%), with a noise of the same amount. Only when comparing SSPs between aggregated columns and aggregated plates, the noise increases slightly to about 10%. The small biases and noise can be probably linked to the fact that De, which is the average De of an assumed size distribution, is retrieved over AIRS footprints at a spatial resolution of about 13.5 km and to the fact that we use six AIRS channels (see also comparison with TOVS). However, the bias of individual retrievals may be larger, especially for small De, as can be seen in the figure above.

It is difficult to compare our average biases and noise to the studies mentioned above, because they study only small regions and time periods or their studies are based on simulations. They also use different channels and also less channels.

Posselt et al use only 2 channels at 11 and 13 micron. Considering the imaginary index of refraction presented in Fig 1 of Pavolonis (2010), one recognizes that these channels should be less sensitive to De than the channels we use (between 9 and 12 micron). Therefore, the uncertainties could be larger than in our case.

Yue et al present uncertainties for cirrus with cloud optical depth of about 0.1, using simulations which do not include multiple scattering (which is ok for such thin cirrus. However, we only retrieve bulk microphysical properties for cirrus with a (vis) optical depth between 0.4 and 3.8 (corresponding to cirrus emissivity 0.2 – 0.85), because we have shown that for cirrus with smaller optical depth the retrievals are too much influenced by atmospheric noise compared to the lower sensitivity (Fig. 4 and Rädel et al. 2003).

The study of Kahn et al. (2008).is a simulation study to test the most sensitive channels for the retrieval of the different cloud properties It reveals that the IWP information comes mostly from channels around 12 micron, whereas De information comes from the whole spectral domain between 9 and 12 micron (with exception of the 03 absorption band).

Discussion on horizontal heterogeneity: De only changes by 10% in the presence of horizontal inhomogeneities? Did the authors show this in the paper?

As mentioned above, the retrieval is performed using measurements averaged over 13.5 km, and we perform again a sensitivity study using the data.

We have rewritten the last two paragraphs in 3.1 as

To evaluate the effect of partial coverage, we have an indication of heterogeneity at the spatial resolution of about 45 km x 45 km (AMSU footprint) by first distinguishing overcast scenes (all AIRS footprints cloudy) from partly cloudy scenes. For overcast scenes we distinguish scenes with cirrus only from those mixed with other cloud types (see Section 2.1). We assume that heterogeneous scenes have a higher probability for an AIRS footprint to be only partially covered by an ice cloud. The retrieval is therefore applied to overcast cirrus scenes. When including heterogeneous overcast scenes (which add 12% to the statistics of AMSU footprints that are entirely covered by cirrus), the retrieved De is on average only 3% smaller.

However, analyzing partially cloud covered AMSU footprints (with AIRS footprints not surrounded by other cloudy footprints), De is on average 10% smaller than in the case of a fully covered AIRS footprint. On the other hand, the population of cirrus within partially cloud covered AMSU footprints is, on a global scale, 10 times smaller than the population of overcast cirrus. A partially covered AIRS footprint leads to an overestimation of De, slightly smaller than for the TOVS retrieval (Radel et al. (2003)) . This is partly due to the better spatial resolution of the AIRS retrieval (13 km instead of 100 km for TOVS).

For the referee we include the following figures which show the normalized frequency distributions of De for the 3 cases:

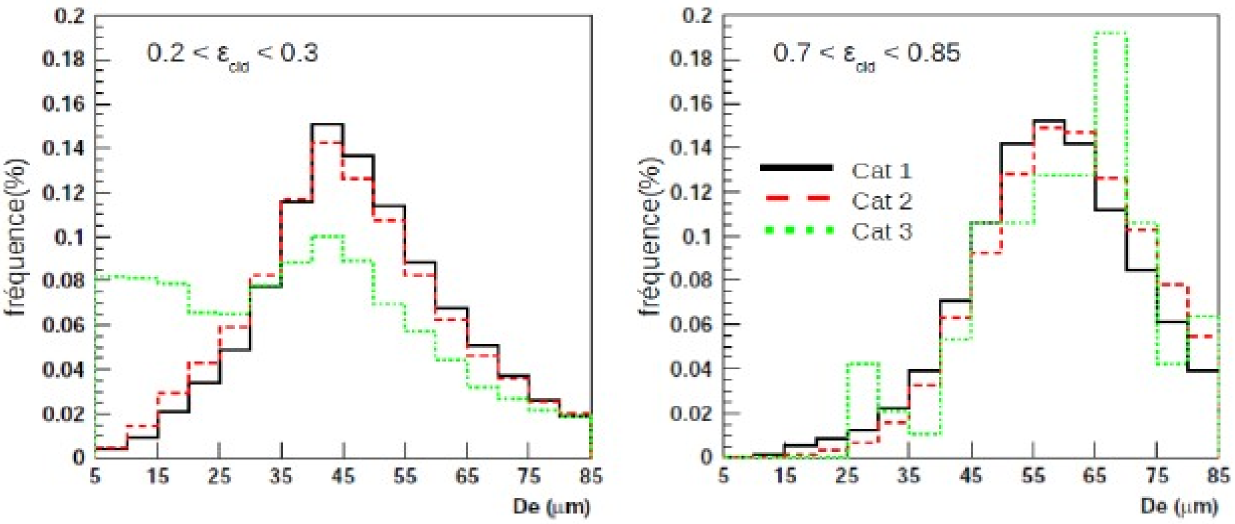
-Category 1: Golfballs fully covered by cirrus (9 AIRS footprints of type cirrus)

-Category 2: Golfballs totally cloudy but in which at least 4 AIRS spots contain a cloud type other than a cirrus

-Category 3: partly cloudy Golfballs with less than 4 cloudy AIRS footprints

The effective diameters determined for the homogeneous AIRS footprints (category 1) are taken as the standard case. The diameters estimated for heterogeneous spots (category 2) are underestimated by about 2% in the case of thin cirrus (epsilon = 0.3) and overestimated by about 4% in the case of thick cirrus (epsilon = 0.75).

These heterogeneous spots are twice more abundant than the homogeneous spots while the differences in size diameter are very low (~ 1%). For AIRS partially cloudy footprints (Category 3) however, the effective diameter of the thinnest cirrus is underestimated by about 20%. These cases still represent less than 10% of cirrus detected.



Section 3.2

What do the authors mean by 'uncertainty'?

The difference between both solutions in De was meant.

Last paragraph of section 3.2 rewritten as:

By using LUTs for both, pristine and aggregated columns, the retrieval also provides an estimation of the most probable ice crystal habit. For each retrieval we determine the first and second best fit (minimum Δ in Eq. 3) of De and IWP for each crystal habit, and then we choose the overall best fit . For most of the cases, the first and second best fits of De stem from the same ice crystal habit (96% and 87% for small and large particles, respectively). For these cases the difference between first and second best solution of the retrieved De is quite small (within 4 %). When both best fits do not present the same habit (4% and 13% for small and large particles, respectively), the difference in the retrieved De remains small (slightly larger for optically thin clouds). In this case, we choose the average of the two effective diameters, and the habit is set to uncertain.

Section 4

What is meant by a 'stable solution'? Unique? A single solution? A solution that converges well with low chi-squared values?

We apply the retrieval of bulk microphysical properties to all AIRS footprints supposed to be covered by ice clouds. Therefore, we select overcast AMSU footprints, containing high clouds (pcld < 440 hPa) with Tcld < 260 K..The weighted χ2 method provides pcld corresponding to a minimum c2 solution in cloud emissivity. The uncertainty in pcld (εcld) is estimated by the pcld (εcld) difference between the minimum and the second small χ2. The solutions are stable, when both uncertainties are small. We have changed this in the text.

The authors use 'cuts' many times, but it isn't entirely clear what is meant. 'Boundaries?'

Replaced in the whole manuscript by boundaries, range or intervals

What is the total % of AIRS FOVs being retrieved for this paper compared to the

total number?

Added to paragraph in section 4, before section 4.1:

Furthermore, we only consider AIRS footprints observed under a zenith viewing angle smaller than 30° (52% of AIRS fields of view), so that the integral product of IWP corresponds closest to the cloud vertical extent.

Section 4.1

It is not clear at all what the uncertainty in the habit type is near zero for the thickest clouds

Actually from the old figure 3 (which has been now removed and a similar figure has been cited (âdel et al. 2003), one could already conclude that the sensitivity of the retrieval is not anymore reliable at large and at small εcld. For ecld > 0.85 the spectral variability is too small and the method is also not sensitive anymore to the crystal habit.

We have rewritten section 4.1:

From Rädel et al. (2003) we know that the retrieval sensitivity of De decreases towards clouds with low and high emissivity. Figure 4 presents retrieved De and IWP as well as fraction of aggregate-like ice crystals and the uncertainty in habit as a function of AIRS cloud emissivity determined by the χ2w –method. Results are shown separately for three latitude bands and two seasons. Abrupt changes in behaviour indicate the range of cloud emissivity in which the bulk microphysical properties are well retrieved: the fraction of uncertain shape (Sect. 3.2) strongly increases in the midlatitudes for cloud emissvity smaller than 0.2 and drops to nearly 0 when εcld >0.85. The retrieved IWP strongly increases with εcld (and this similarly for all latitude bands and seasons) to reach a maximum at εcld around 0.85.
These behaviours indicate that the retrieval of bulk microphysical properties can be conducted for AIRS for εcld between 0.2 and 0.85, corresponding to semi-transparent cirrus. These boundaries are consistent with previous studies (R¨adel et al., 2003). The lower emissivity threshold for the TOVS retrieval was fixed at εcld =0.3, but the improvement of the spectral and spatial resolution of the AIRS instrument allows us to reduce this value to εcld = 0.2. Bulk microphysical properties of these semi-transparent cirrus correspond to an average over the whole cloud vertical extent (Radel et al., 2003).

Section 4.2

Is the habit-temperature dependence consistent with previous research, especially in situ aircraft data?

Actually, in the temperature range 200 – 230 K in which the influence of water droplets should not influence our retrieval (which assumes only ice crystals in the cloud), we do not recognize a strong dependence on temperature, except in NH midlatitudes in winter, where there is a slightly larger occurrence of columns at lower Tcld. Ice crystal habit seems to depend slightly more on εcld, with increasing occurrence of aggregated crystals with increasing εcld.
Aircraft data often explore a profile of ice crystal habits within the same cloud; they have found that smaller particles are near the top of the cloud, whereas one finds more aggregates near the bottom of the cloud. With our retrieval we determine bulk microphysical properties, averaged over the whole cirrus, and Tcld corresponds to the temperature of the cloud, we do not perform a retrieval of a profile. For this reason, relationships with T are difficult to compare.

How do the authors deduce that ice-only clouds exist for T_cld < 230 K?

By exploring the relationship of the different retrieved bulk microphysical properties with Tcld, we recognized a change in behaviour around 230 K. Since our retrieval method assumes clouds that consist of ice crystals, we interpret the change in behaviour as an influence of cloud droplets on the retrieval.

Again we were not clear in the text; we have rewritten parts of section 4.2:

The change in behaviour of De and IWP around 230 K as well as the increase of the rate of column-like ice crystals (with SSPs more similar to spheres than to aggregate-like ice crystals) demonstrate that clouds with Tcld between 230 and 260 K seem to include a substantial part of water droplets which influence the retrieval. Thus pure ice clouds preferably occur when Tcld < 230 K. This is in agreement with previous studies (Yang et al., 2002; Hu et al., 2009; Riedi et al., 2010; Martins et al., 2011). Cloud temperature does not much affect the crystal habit in pure ice clouds, which is consistent with the fact that the aspect ratio of small particles is a weak function of temperature (Korolev and Isaac, 2003).

Section 5.1

Discussion on the seasonal cycle

This section has been rewritten and the Figures have been restructured.

what are the 'middle range values'? Is the 'dominating' shape the one that is in the majority, or the one with the largest %?

Rewritten:

The ice crystal habit is defined as dominating, when the habit appears more often than 40% over the period, else it is set to mixed habit.

Is there a possible retrieval issue with the surface that was not accounted for?

The maps present dominating habit; this is in effect more often attached to columns over continents, but this can also be explained that over continents the IWP is slightly lower on average. From Table 4 we deduce that aggregates are present in about 40 % of the cases over continents.

However, we have conducted a sensitivity analysis by changing the surface emissivity (like in section 3). In our simulations we considered a surface emissivity of 1, constant between 8 and 12 microns. We changed these values by considering the spectral surface emissivityies determined over the Sahara in Péquignot et al., 2006. These emissivities represent an extreme case, because they are significantly lower and have a large spectral variability between 8 and 12 microns. The average bias on De appears to be low (10%) while the habit of the crystals did not change.

Section 5.3

The authors need to be specific about the channel selection. There are dozens, if not more, AIRS channels that fall within the HIRS spectral response function.

We have added the channels in the text as well as a clarification of the three results which we are comparing:

In addition, we have included results (in red) from an AIRS retrieval we have performed by using only two channels (channels 557 and 1244) similar to those in TOVS and using the same single scattering properties in the simulation (Mitchell et al. (1996)) as for the TOVS retrieval

Referee #2

Section 2.1

It would be helpful if some more details of the χ2 method could be provided here, since its application seems to be one of the essential operations in the retrieval.

We have included a flow chart of the retrieval (Figure 1) and also rewritten parts of sections 2.1 and of 2.2. The retrieval has been evaluated using CALIPSO (Stubenrauch et al. 2010); some results have been summarized in the last paragraph of section 2.1.

The “proximity recognition” should be explained in more detail

Rewritten in section 2.1:

For the computation of Iclr and Icld we need spectral transmissivity profiles corresponding to the observed atmospheric profile as well as spectral surface emissivity. Spectral transmissivity profiles are taken from the Thermodynamic Initial Guess Retrieval (TIGR) dataset (Chédin et al. (1985), Chevallier et al. (1998). They have been computed for the AIRS channels by the Automatized Atmospheric Absorption Atlas (4A) radiative transfer model (Scott and Chédin (1981)) for about 2100 different atmospheric profiles. We compare the observed NASA L2 atmospheric temperature and water vapour profiles to those of the TIGR dataset and choose the spectral transmissivity profiles of the TIGR atmospheric profiles which are the most similar to the observed one, as described in (Stubenrauch et al. (2008)). ….

Section 2.2.1

Figure 1 reveals that for a specific emissivity and a certain IWP also a specific effective diameter occurs. How can De vary, with constant emissivity and IWP ?

De can vary because we consider a range of emissivity (+-0.05) around the value, now indicated in the figure legend.

Section 2.2.2

It should be explained in more detail how the De-IWP couple is derived

We have rewritten a large part of 2.2.2 :
…. Then the cirrus emissivities (ε_m) are compared to pre-calculated ones which have been stored in LUTs (ε_s) as function of De and IWP, separately for the two assumed ice crystal habits (column-like or aggregate-like) (see Section 2.2.1). We choose for each crystal habit De and IWP for which the six simulated cirrus spectral emissivities are the most similar to the retrieved ones, Eq. 3, where ($\sigma\varepsilon_s$) is the root mean square of the spectral variance of the simulated cirrus emissivities: ….

It should be explained how the minimization handles non-unique solutions for De-IWP (how is the optimal solution with smallest emissivity differences found?)

Last paragraph of section 3.2 rewritten as:

By using LUTs for both, pristine and aggregated columns, the retrieval also provides an estimation of the most probable ice crystal habit. For each retrieval we determine the first and second best fit (minimum Δ in Eq. 3) of De and IWP for each crystal habit, and then we choose the overall best fit . For most of the cases, the first and second best fits of De stem from the same ice crystal habit (96% and 87% for small and large particles, respectively). For these cases the difference between first and second best solution of the retrieved De is quite small (within 4 %). When both best fits do not present the same habit (4% and 13% for small and large particles, respectively), the difference in the retrieved De remains small (slightly larger for optically thin clouds). In this case, we choose the average of the two effective diameters and the habit is set to uncertain.

Section 2.3

Why do you only keep situations with overcast AMSU golfballs ?

We only use overcast golfballs to do the retrievals over more homogeneous scenes. These are about 90% of all cirrus scenes.

The section has been rewritten:
…We assume that heterogeneous scenes have a higher probability for an AIRS footprint to be only partially covered by an ice cloud. The retrieval is therefore applied to overcast cirrus scenes. When including heterogeneous overcast scenes (which add 12% to the statistics of AMSU footprints that are entirely covered by cirrus), the retrieved De is on average only 3% smaller. However, analyzing partially cloud covered AMSU footprints (with AIRS footprints not surrounded by other cloudy footprints), De is on average 10% smaller than in the case of a fully covered AIRS footprint. On the other hand, the population of cirrus within partially cloud covered AMSU footprints is, on a global scale, 10 times smaller than the population of overcast cirrus. A partially covered AIRS footprint leads to an overestimation of De, slightly smaller than for the TOVS retrieval (Radel et al. (2003)) This is partly due to the better spatial resolution of the AIRS retrieval (13 km instead of 100 km for TOVS).

Section 3

With T_s=300K and a lapse rate of 6.5K/km, a temperature T_cld of 235Kwould be obtained instead of 237K.

Indeed, it has been corrected in the table and in the text

Section 3.2

A discussion of the differences between the results obtained for complex and pristine shapes shown in Table 1 is missing

done

Section 4

'Stable solutions' should be explained

We apply the retrieval of bulk microphysical properties to all AIRS footprints supposed to be covered by ice clouds. Therefore, we select overcast AMSU footprints, containing high clouds (pcld < 440 hPa) with Tcld < 260 K..The weighted χ2 method provides pcld corresponding to a minimum c2 solution in cloud emissivity. The uncertainty in pcld (εcld) is estimated by the pcld (εcld) difference between the minimum and the second small χ2.
The solutions are stable, when both uncertainties are small. We have changed this in the text.

The difference between emissivity and effective emissivity is not explained in the manuscript. The two terms are mixed up several times.

We have corrected this and added a short text at the end of section 2.1:
This means that neither cloud pressure (and deduced cloud temperature) nor cloud

emissivity correspond to the top of the cloud, but to a layer within the cloud (Stubenrauch et al. (2010)). For this reason, the cloud IR emissivity is often called ’effective emissivity’ (Pavolonis (2010)), but since the retrieved cloud height is also an ’effective’ or ’radiative’ cloud height, we omit these attributes in the following for a more fluid reading.

Section 4.1

Wrong atmospheric profile’ of which quantity ?

Rädel et al (2003) have shown that when the cirrus emissivity is smaller than 0.3, a wrong selection of the TIGR atmospheric transmission (for a TIGR atmospheric T and H2O profile similar to the retrieved one; see section 2.1) could lead to a bias in the TOVS De retrieval.

Discussion of Fig.6: Why is the sum of the different fractions smaller than one? Because the shape was not determined for all clouds? Should be explained.

Now Figure 5
Fraction of Aggregates+Columns+Uncertain habit=100%:
The sum of the fraction of aggregate-like ice crystals and of column-like crystals is not equal to 100% because for some cases, the habit is set to uncertain (Sect. 3.2).

Section 5.4

'De varies only 10 to 20 µm ...’. I do not understand this since the variation of De revealed by Figure 16 is larger.

This is the dependence with Tcld

Rewritten as :

For a fixed IWC De only varies by about 15 µm within the temperature range between 200 and 230 K (see also Figure 5), another sign that the dependence on IWP is better suited to parameterize De (Baran et al., 2009).

‘because IWP and temperature present a weak dependence...’. This explanation is not clear to me and should be discussed in more detail.

Changed to:

Compared to a parameterization developed for in situ measurements at a specific latitude band as for example by Boudala et al. (2002), it seems to be difficult to determine a global multivariate parameterization for De dependent on both IWP and temperature, because the latter are not independent as can be seen in Figure 5.

Include references (examples) for ‘Some GCMs use a parameterization

Done: Mc Farlane et al. 1992, Liou et al. 2008

Section 6

4A-OP was not yet explained. Only 4A was mentioned in section 2.2.1.

corrected

The caption should explain which quantities are shown in the table and the symbols and abbreviations used should be explained. The values for Delta z presented in the table are not consistent with figure 13.

In the table we report the vertical extent of the clouds, determined by the GEOPROF data, whereas in Figure 13 we have wrongly reported maps of the **‘apparent’** vertical extent of cirrus (determined by Caliop up an optical thickness of 5) and the proportion of cases of single layer cirrus. The determination of the vertical extension is detailed in the article: We have taken out Figure 13, because the information is included in the table and in Figure 13 (distributions of Δz)

Figure 10

With regard to the crystal shapes it is not clear what is shown in the figure.

Are these the most frequent shapes? It is not clear why in a specific region only one specific shape should occur

Now Figure 9
On this map we consider 3 habits: aggregates, columns and uncertain habit. Uncertain means that one can not distinguish between aggregate and column.
If uncertain habit represents more than 40% of the statistics, it is considered as the dominating habit. On the contrary, if one habit (aggregates or columns) is at least 10% more representative than the other habit, it is considered as the dominating habit. In the other cases, the dominating habit is set to mixed. We recognize in table 4 that the occurrence of cirrus with aggregates is around 40% over continental surfaces.