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Atmospheric Measurement Techniques Discussions

Interactive comment on "Impacts of cloud heterogeneities on cirrus optical properties retrieved from spatial thermal infrared radiometry" *by* T. Fauchez et al.

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First of all, we would like to thank the reviewer for his helpful comments and suggestions. The paper has been modified following these recommendations. We hope that the paper is now more easily readable and understandable thanks to the suggestions of reviewer 3. We also thanks the reviewer for his English correction. In addition, the help of an English native contributed to improve the English.

The paper presents a modelling study of the effect of cloud heterogeneity on

retrieval of cirrus cloud optical properties from space-based thermal measurements. This is achieved by comparing full 3-D radiative transfer simulations with 1-D results. The paper highlights the importance of 3D heterogeneity effects. The paper is at places difficult to read and follow. There are also a few points that need clarification and explanation. Below are suggestions for improvements.

Specific remarks

- **Page 8777, Title: Maybe replace "spatial" with "space-based".**
  Done

- **Page 8778, lines 23-25: The last sentence in the abstract is hard to understand. Please clarify and rewrite.**
  This sentence was not clear indeed. We rewrote it (Page 2, line 22-24):
  "Cloud horizontal heterogeneity effects are larger than the IIR retrieval uncertainty if the standard deviation of the optical thickness, inside the observation pixel, is greater than 1."

- **Page 8780, lines 19-20: This paper discuss the IR part of the spectrum. Thus, please give the IR optical depth as well.**
  That is an error, optical thickness is defined at 12 μm.

- **Page 8781, line 17: Please describe how the effective diameter is defined for the various ice particle shapes.** We added that the effective diameter is defined for the aggregate crystal shape (Page 4, line 98):

"for aggregates crystal shape of the Yang et al., (2005) model"
And we added the mathematical formula of Deff.

- **Page 8782, line 19: A mono-disperse ice particle size distribution is used. Please discuss how realistic this assumption is and quantify the magnitude of this assumption by comparing with realistic size distributions.**
We used a mono-disperse ice particle size distribution for two reasons.
First of all, and the most important reason, is that in this paper, we modelled IIR observations and retrievals. The IIR retrieval algorithm uses the Yang et al., 2005 ice crystal model with a mono-disperse size distribution (see Garnier et al., 2013). Thus to be the closest as possible to the IIR retrieval and to not introduce another bias we follow this assumption. In addition, Dubuisson et al. (2008) have shown that although the IIR measurements allow us to obtain the ice crystal effective diameter and the cloud optical thickness, the sensitivity to the ice crystal shape is weak and that there is no sensitivity to the size distribution. We add this paragraph (page 5, lines 131-133):

"Note that Dubuisson et al., (2008) have shown that for the IIR thermal infrared channels, the sensitivity to the ice crystal shape is weak and that on the size distribution is nil. "

- **Page 8782, line 23: A Henyey-Greenstein phase function is used as that is what is provided by Yang et al. (2001). It was argued by Yang et al. (2001) that in the IR the asymmetry factor was sufficient and the full phase function was not needed, but no calculations were shown to support this statement. Later Baum et al. (2005a, 2005b) have provided full phase functions for various ice particle shapes. Please discuss, justify and quantify the error/uncertainty associated with the use of the Henyey-Greenstein phase function for highly irregular ice particles when**

calculating radiances.
Complementary to the study of Yang et al., (2001), Baran et al., (2001) built an analytic phase function based on the Henyey-Greenstein approximation and thus possesses the advantage to be only calculated from the asymmetry factor g. This phase function was based on laboratory measurements of Volkovitskiy and al., (1980) as well as airborne and satellite measurements. Baran et al., (2001) shown that, although they used the Henyey-Greenstein approximation, the phase function possesses a very good coherence with phase functions obtained from in situ measurements or from remote detection. For the IIR, the phase functions of the three particles used in the retrieval algorithm (Garnier et al., (2012, 2013)) are relatively smooth in the thermal infrared with a small forward peak (asymmetry factor G below 0.9). They are thus reasonably approximated by the Henyey-Greenstein phase function (Yang et al., (2001), Baran et al., (2001)). As we modelled IIR observations, we used also the same approximation that should not significantly impact the quantification of heterogeneity effects.
To clarify this we added this paragraph (page 5, lines 133-138):
"The IIR retrieval algorithm uses three ice crystal shapes (Garnier et al., (2012,2013)), namely a solid column aggregate and plate. The phase functions of these particles are relatively smooth in the thermal infrared with a small forward peak (asymmetry factor g usually below 0.9) and can be approximated by the Henyey Greenstein phase function. While this assumption is certainly problematic for irregular crystal shapes as shown by Baum et al., (2005a, 2005b), we use the Henyey-Greenstein phase function to remain consistent with the official IIR retrieval algorithm (Garnier et al., (2012,2013)). For these cirrus cases, the optical properties are constant over the entire cloud."

- **Page 8782, line 24: It is stated that the "optical properties are constant over the entire clouds". Presumably this does not include the optical**

depth? Please clarify what is meant by "optical properties".
That was not clear indeed. We changed this by (page 5, lines 138-139):
"only one crystal is used over the entire cloud"

- **Page 8783, line 4-16: 3DMCPOL is a Monte Carlo code. As such all the quantities calculated by the code has a statistical uncertainty which depends on the number of photons traced and the atmospheric conditions. Please give the number of photons traced and the statistical uncertainty in the calculated quantities. The statistical uncertainty in the calculated quantities should be compared with the noise-equivalent temperature of the IIR-instrument and should be smaller than that.**

  We are agree and we add a paragraph concerning our statistical uncertainty. Between 5 billion and 10 billion of photons were used in the simulations. All radiative transfer simulations were performed with a statistical error below or equal to 0.5 K to be below to the IIR accuracy which is about 1 K. This paper is focuses on the retrieval, the same cirrus were simulated and presented in Fauchez et al., 2014 with comparisons between heterogeneity effects, statistical errors, IIR accuracy in Figures 8 and 10. We add this paragraph (page 5, lines 158-162):

  "Note that the statistical errors of these simulations are below 0.5 K, which less than the IIR accuracy of about 1 K. Comparisons between 3DMCPOL statistical uncertainty, IIR accuracy and heterogeneity effects can be found in Fauchez et al., 2014 (Figures 8 and 10) for the same cloud scenes. This statistical accuracy is reached by simulating between between 5 billion and 10 billion of photons for each case."

- **Page 8786, line 1: Please specify what the "optical and microphysical properties" are.**
  Optical properties concern effective diameters, extinction coefficients, single scattering albedo and asymmetry factor. Microphysical properties concern the IWC. We added this description to this sentence (page 7, lines 224-226):
  "... different cloud optical properties (i.e. optical thickness, effective diameters, extinction coefficients, single scattering albedo and asymmetry factor) and microphysical (IWC) properties, cirrus top altitude and geometrical thickness."

- **Pages 8786, lines 7-8: The symbols $\varepsilon 3 - Deff$ and $\varepsilon 1 - Deff$ are at best very confusing. It is presumed that the eff-label here refers to ε and that the Deff at nothing to do with the effective radius? What not use for example ε_{eff}^{3D} and ε_{eff}^{1D}? Why not used τ_{eff}^{3D} and τ_{eff}^{3D}? If these are adopted the sentence in lines 14-15 needs to be changed. In any case the above mentioned symbols should be simplified to avoid confusion.**
  We changed this as you suggested.

- **Page 8786, lines 15-16: τ_{1km} is defined here, but it not used anywhere in the error definitions above. May this sentence be omitted?**
  No this parameter is not used anymore in this version of the paper. We deleted it, thank you very much.

- **Page 8787, line 2: On the previous page it is stated that "BT3D1km is larger than BT1D1km". This then implies that the PPA bias is smaller than 1. On line 2 it is stated that "The PPA is greater ..." Please clarify these two statements. Also it is not the PPA that is greater, it is the PPA bias. Hence change "The PPA" to "The PPA bias".** This need to be clarify indeed. We used the PPA bias as an absolute value, we added after (page 8, line 227):

"The PPA bias ($|BT3D_{1km} - BT1D_{1km}|$ is greater".
We changed also PPA to PPA bias

- **Page 8789, line 4: "too large" compared to what?**
That was not clear, we changed the sentence as (page 10, lines 311-314):

"As ΔMI = MI3D - MI1D are negatives, the impact of cloud heterogeneities lead to an underestimation of the microphysical indices. This underestimation leads then to an overestimation of the retrieved effective diameters (as smaller is the microphysical indices, larger is the effective diameter)."

- **Page 8789, line 15: Please replace "PPA." with "PPA bias."** Done

Page 8804, Fig. 1:
- Different texts are used for x-labels in plots c) and d). Please make them similar.
- X-axis and Y-axis are not very informative choices for axes-labelling. Choose something else, for examples x-direction (or east) and y-direction (or north?)?
- Indicate in plots a) and c) for which y-value the vertical cross sections in plots b) and d) are made.
Thank you for these suggestions. We changed X axis and Y axis by X direction and Y direction respectively and we plot red lines on plots (a) and (c) corresponding to the cross section of plots (b) and (d) respectively.

- **Page 8805, Fig. 2: The plots would benefit from inclusion of near-vertical lines indicating the optical thickness of the ice clouds. For an example of**

such a plot, albeit for volcanic clouds, see Fig. 2 of Wen and Rose (1994).
Arches are usually represented without optical thickness axes. To avoid the overloading of the figures we prefer to not add vertical optical thickness lines. In addition, Fig 3. shows how optical thickness are retrieved from arches.

- **Page 8806, Fig. 3, lines 5-6 in caption: The sentence starting with "Heterogeneity effects" is not clear. Maybe rather write: "Using the PPA gives an overestimate of Deff compared to a 3D retrieval."?**
We changed this in the caption of the Fig. 3, lines 5-6:
"Using the PPA leads to overestimate the effective diameter and to underestimate the optical thickness respectively compared to a 3D retrieval."

- **Page 8807, Fig. 4, lines 5-6 in caption: No reference is given for the Jensen inequality, nor is it discussed in the text. May this sentence be omitted?**
We rewrite this sentence which was unclear as:
"The mathematical formulation of the PPA is expressed by the Jensen inequality:"

- **Page 8809 and 8811, Figs. 6 and 8: R-values are given in the plots. The R-values are not discussed in the text nor the captions and may be omitted.**
Thank you for this remark we added a description of R in both caption (Figs 6 and 8):
Fig 6:
"R represents the correlation coefficient between ΔMI and $\sigma_{\tau_{1km}}$."
Fig 8:
"R represents the correlation coefficient between $\Delta\varepsilon_{eff}$ ((a), (b) and (c) and $\sigma_{\tau_{1km}}$ and between $\Delta\tau_{eff}$ ((d), (e) and (f)) and $\sigma_{\tau_{1km}}$."

Technical remarks

Generally the language throughout the manuscript would benefit from a careful read by a native English speaker. At least consider the following:
For this new version, the text was reviewed by an English native speaker.

- **Page 8778, line 22-23: Please consider replacing "are much higher" with "are larger".**
  Also suggested by reviewer 1, we replace "are much higher" by "greater

- **Page 8778, line 24: Please consider using uncertainty instead of incertitude.**
  Also suggested by reviewer 1, done

- **Page 8779, lines 10-11: Please consider using "space mission" instead of "spatial mission".**
  Also suggested by reviewer 1, we replace "space mission" by "space-based mission"

- **Page 8780, line 25: Please replace "in the same time" with "simultaneously".**
  Done

- **Page 8781, line 8: Please change "generated" to "generate".**
  Done

- **Page 8784, line 9: It is not clear what is meant here. Please rewrite this sentence.**
  It was not clear indeed. We rewrite the sentence as (page 6, lines 179-181):
  "Dubuisson et al. (2008) also show that the retrieval accuracy of the ice crystal effective diameter is between 10% *and* 25% *and of about* 10% *for the optical thickness."*

- **Page 8786, lines 7-13: Replace "on the" with "the" in four places.**
  We replaced "on the" by "for"

- **Page 8787, line 6: Replace "The Fig. 3" with "Fig. 3".**
  Done

- **Page 8787, line 8: Replace "an homogeneous" with "a homogeneous".**
  Done

- **Page 8787, line 20: Replace "no linear" with "non-linear".**
  Also suggested by reviewer 1, done

- **Page 8788, line 4: Replace "weaker" with "smaller".**
  Also suggested by reviewer 1, done

- **Page 8788, line 12: Replace "Garnier et al. (2012) shown" with "Garnier et al. (2012) have shown".**
  Done

- **Page 8788, line 17: Replace "superior to" with "larger than".**
  Done

- **Page 8790, line 10: Replace "than cirrus" with "as cirrus".**
  Also suggested by reviewer 1, done

- **Page 8790, line 14: Replace "very close" with "similar".**
  Done

- **Page 8790, line 23: Replace "the PPA" with "the PPA bias".**
  Done

- **Page 8791, line 27: What is meant by "in relative".**
  "Relative" no correctly used, we removed it.

- **Page 8794, line 4: Please replace "discussed on the" with "discussed the".**
  Done

- **Page 8794, line 6: Please replace "have been focused" with "have focused".**
  Done

- **Page 8801, line 7 in caption of Table 1: Please replace "define" with "defined".**

Done

- **Page 8815, Fig. 12, line 2 in caption: Please change "assymetry" to "asymmetry".**
  Done

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