Answer to Referee #1's comments on manuscript: 'A variational approach for retrieving ice cloud properties from infrared measurements: application in the context of two IIR validation campaigns' by O. Sourdeval *et al.*

The authors are extremely thankful to the referee #1 for the thorough reading of our paper, and for the sound recommendations and criticisms that greatly helped us in improving the quality of the manuscript. Each of the referee's suggestions has been carefully taken into consideration in the revision process of the manuscript, and detailed responses are explicitly provided below.

We are particularly grateful to the referee for his efforts to bring to our attention a number of ambiguous words and sentences, along with several grammatical mistakes. Consequently, the points 7, 10, 12, 13, 14, 15, 16, 17, 19, 20, 21, 22, 24, 25, 27, 29, 30, 32, 34, 35, 36, 37, 42, 43, 45, 48, 49, 50, 51, 52, 54, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, and 67 have all been taken into account when correcting and clarifying the manuscript. In most cases, the suggestions proposed by the referee have been directly followed, and further details on these modifications thus do not appear necessary here. As advised by the referee, we have also used these suggestions as hints for correcting other non-listed grammatical mistakes or ambiguities that were present in the manuscript.

The authors would nevertheless like to provide a more detailed answer to the most important rearrangements suggested by the referee:

1. Abstract - Sentence beginning line 6, please re-write as the flow of the sentence is difficult to read.
The sentence has been replaced by 'The satellite constellation A-Train has for instance proven to be particularly helpful for the study of cirrus. More particularly, the Infrared Imaging Radiometer (IIR) carried onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite shows a great sensitivity to the radiative and microphysical properties of these clouds.'

2. The word 'algorithm' is used; you are not presenting a computational logical but rather a methodology so why not just say 'a novel methotology, ...'.
The authors agree with the referee on the misuse of the word 'algorithm' to present our new methodology for the retrieval of ice cloud properties. The words 'method', 'approach', or 'novel methodology' are thus now utilized through the entire revised manuscript.

3. The use of the words 'the effective size of their ice crystals...' The effective size is computed over a PSD so it is the effective size of the cirrus case rather than single ice crystals, which the former implies
The effective size such as it is utilized in our study (defined by Eq. 3 or 11) is indeed clearly computed over a PSD, and referring to it as 'the effective size of their ice crystals' is very ambiguous. This formulation has thus been rearranged (for instance by 'the ice crystal effective size') through the entire revised manuscript.

4. In the abstract you need to say that shattering could be the reason as to why the retrieved De is larger than in situ estimated De.
The possible reasons why the retrieved De is larger than in situ estimated De could indeed be the shattering effect, but also the position of the aircraft that flies at the top of the cirrus decks (as discussed in section 5 of the paper). We believe that such details may not be absolutely necessary in the abstract, in order to keep the latter brief and clear. However, the sentence referring to *in situ* estimates has been rewritten as: 'Comparisons with in situ observations and with operational products of IIR are also discussed and appear to be coherent with our results', in order to emphasize that a detailed discussion takes place in this paper when comparing our retrievals to in situ estimates (and IIR operational products).

5. The use of the word 'comfort' please replace this word as it conveys the wrong impression, in my opinion.
The word 'comfort' has often been used when referring to the fact that the authors seek to consolidate the results of a previous validation study by Sourdeval et al. [2012] of IIR measurements. We nevertheless agree on the ambiguity of this term, and it has consequently been replaced through the entire revised manuscript.

8. Can you put numbers to the statement '.. but their albedo-versus-greenhouse effect balance..' (do you mean effect or balance?), what is the uncertainty?
The sentence including this statement appears to be unclear, as our purpose was to indicate that the balance between the greenhouse and albedo effects related to ice clouds strongly depends on the properties of these clouds. This fact appears extremely important as it leads to the necessity of developing methods capable of retrieving these properties along with precise retrieval uncertainties. The entire sentence has thus been rearranged, and new references containing quantitative values have been added: 'Nevertheless, the radiative impact of clouds remains one of the largest source of uncertainties on climate models predictions [Forster et al., 2007]. The aforementioned large variability of cirrus cloud properties can indeed lead to difficulties for a precise quantification of the balance between their albedo and greenhouse effect (*e.g.* [Fusina et al., 2007, Zhang et al., 1999]).'

11. A number of instruments are mentioned - line 17 onwards, it would be useful to also include the wavelength range of each instrument.
The wavelength ranges have been added for CALIOP and IIR: 'Indeed, instruments such as the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) (measuring at 532 nm and 1024 nm) and the Infrared Imaging Radiometer (measuring in three narrow bands centered at 8.65, 10.66, and 12.05 μm) [...]'

28. Subsection 3.3.1 page 11, please include in this sub-section all assumptions such as plane-parallel and homogeneous layers, each of x thickness.
The assumptions related to the use of FASDOM have been included, and the first sentence of subsection 3.3.2 has been moved to subsection 3.3.2 for better clarity.

31. Subsection 3.3.3 page 11 line 4 can the thickness of the layer be quantified?
We refer here to the fact that the cloud layer appeared optically very thick. The radiometric measurements are effectuated over a land surface only during the leg of 18 October 2008. The presentation of this campaign day is useful in this paper as it shows retrievals of high optical

depth. Our hypothesis about keeping an oceanic surface for all the retrievals was motivated by the fact that Sourdeval et al. [2012] have shown that the brightness temperatures measured by CLIMAT-AV and IIR between 40.0 and 42.5 degrees of latitude appear to be as low as 240K, which indicates a strong extinction of the signal by the cloud in this area. This hypothesis is consolidated by the values of extinction optical thicknesses at 12 μm retrieved by our methodology in this area can reach 8. The authors would nevertheless prefer to avoid providing quantitative results of the retrievals at this point of the paper, and the addition of a reference to the study by Sourdeval et al. [2012] has thus been preferred in response to the referee's suggestion.

53. Page 25 line 3 satisfying - satisfactory. Please be quantitative. Are consistent with respect to what uncertainty?
We agree that this sentence is ambiguous, and have reorganized it for a better clarity: 'Fig. 6b shows that the effective diameters are again much less correlated than the optical thicknesses. Comparisons between IIR operational estimates and our restitutions of the effective diameter are nevertheless satisfactory when taking into account their respective uncertainties'

The authors have taken into consideration each of the referee's suggestions regarding the lack of several references in the manuscript. The references directly advised by the referee have been added (*c.f.* points 26 and 44), along with new additional references chosen by the authors:

6. Introduction- Liou [1986] is cited, but is quite old and there are now a number of other references present more updates reviews. These other reviews should be cited
The authors agree that the reference to Liou [1986] is now old and that, even we believe that this paper should still be recognized, other more recent ones should be added. Therefore the studies by Stephens et al. [1990], Lohmann and Roeckner [1995], and the book by Lynch et al. [2002] have been added to complete the references.

23. The discussion of various variational schemes. There are missing references here, for instance Watts et al. [1998] and Baran et al. [2003]
The two references advised by the referee have been added to the text, along with a more recent reference to a study by Watts et al. [2011] that utilize the optimal estimation method for retrieval of ice and liquid cloud properties from multispectral observations.

33. Dubuisson et al. [2008] but Baran [2005] demonstrated the same results
The reference to the study by Dubuisson et al. [2008] in the subsection 3.3.4 have been preferred by the authors as it is directly based on the sensitivity of channels of IIR to the shape and it size distribution of ice crystals, and also uses the same ice cloud properties as in our study.

Finally, the authors would like to answer a few comments in more detail:

38. Figure numbers do not match captions please change accordingly.
We thank the referee for bringing this mistake to our attention, and apologize for the inconvenience that it may have caused regarding the global comprehension of the manuscript. The error was caused by technical mistakes in the compilation of the original Latex file, but fortunately did not affect the online ACPD version. It has now been corrected

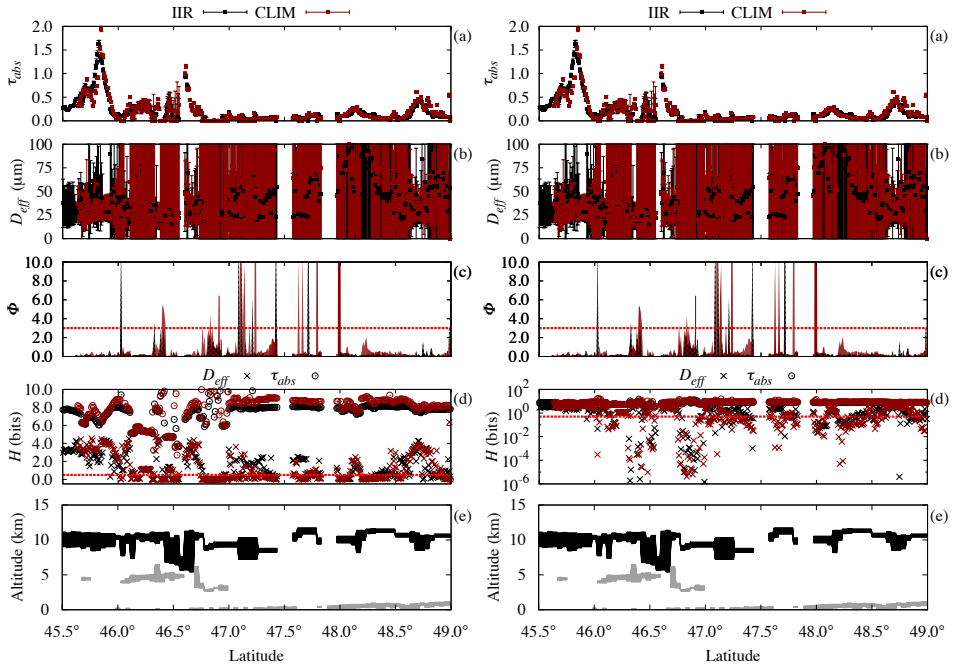

Figure 1: Results of the retrievals made along the 25 May 2007 leg, using CLIMAT-AV (red) and IIR (black) measurements. (a) Retrieved cirrus absorption optical thickness with error bars. (b) Retrieved effective diameters with error bars. (c) Final values of the cost function. (d) Final information content H in bits [Rodgers, 2000] on each retrieved parameter (crosses for D_{eff} and circles for τ_{abs}). (e) Cloud profile used in the retrievals (cirrus are plotted in black color and liquid water clouds in grey color).

39. Note also that where ϕ is high, retrieved De diverge the most. Also, Figure 1d please expand y-axis for points below noise as these are difficult to see as they appear to be close to zero.

It could also be understood that when De cannot converge towards a value that allows the forward model to be coherent with the measurement vector (with their respective uncertainties), the cost function ϕ is high. The authors nevertheless agree with the referee concerning the difficulties to see what appears close to zero in figures 1d, 5d, and 7d. A logarithmic expansion of the y axis has thus been attempted (see right-hand side of Fig. 1). However, it appears that the range of the expansion must be very large in order to include all the data, and it consequently becomes difficult to see what happens above the noise level. We believe that this figure is important to help the reader to understand if the information content is higher than the noise level, and how high it is above the latter. The precise value of the information content under the noise level therefore does not seem to be essential for the comprehension of the figure. We nevertheless acknowledged the referee's suggestion by reducing the range of the y-axis ([-0.5:10] instead of [0:15]) in figures 1d, 5d, and 7d, as presented in the left-hand side of Fig. 1.

40. Another useful quality control is the number of iterations required to minimize the cost function, does this number increase when the cost is high?

We agree with the referee that the number of iterations can be useful to verify the quality of the retrievals. The Levenberg-Marquardt iterative method is utilized to find the most likely values of the state vector that will allow to tend towards the zero of the derivative of the cost function. A high number of iterations will therefore indicate that the cost function is very likely to be high. We however believe that the uncertainties on the retrievals, the value of the cost function, and the information content all together already allow to estimate the quality of the retrievals. The number of iterations is also seen to possess less physical meaning. The latter can be influenced by the choice of the iterative method: For instance, the 'regulation coefficient' of the Levenberg-Marquardt method should allow to reduce the amount of iterative steps by comparison with the Gauss-Newton method. The distance between the *apriori* (which is taken as the 'starting' state vector) and the solution may also influence the number of iterations, while it does not relate to the quality of the retrievals.

41. How do the PDFs look between the instruments, for retrieved De and tau, if data is quality controlled used H and f?
The PDFs between the instruments for the retrieved effective radius and optical thickness are presented in Fig. 2 attached to this response. These PDFs have been quality controlled using H (H must be higher than 0.5) and ϕ (ϕ must be lesser than 3.0). Despite the absence of a thorough statistical analysis of correlation between the PDFs, we can globally observe good similarities between the retrievals of both instruments (as it was already concluded in the manuscript when comparing superimposed retrievals). Slight differences in the retrievals of the effective radius during 18 October 2008 can be observed, but it must be remembered that very large uncertainties are attached to these values. The use of such PDFs would therefore necessitate to also present for each PDF the average value uncertainties attached to the retrievals contained in each bin. Despite the interest of these results, the authors decided not to include such PDF studies since the information they add to our analysis seems too little, and the manuscript is already long.

46. As noted Figures 2 and 3 do not seem to be discussed in the main body of the text
Figure 2 is discussed at the end of the second paragraph of section 4.1, which analyses the value of the cost function presented in Fig. 1c. This figure is helpful because it emphasizes the fact that the retrievals allow the forward model and the measurements to be extremely coherent. Fig. 3 is discussed in the third paragraph of section 4.1, which analyses the impact of each group of non-retrieved parameters on the errors attached to the forward model.

47. Page 20, line 6 onwards Baran et al. [2003] show how it is possible to discriminate between ice crystal models using optimal estimation theory. Furthermore, Baran and Francis [2004] demonstrate the necessity of combining solar and infrared measurements to discriminate between ice crystal scattering models
As it is indicated in the section of the manuscript referred to in this comment, the authors have attempted to discriminate between ice crystals models by comparing the value of the cost function obtained at the end of the retrievals when using different ice crystal shapes. This method seems similar to the analysis of the measurement residual presented by Baran et al. [2003]. An example of results is given in Fig. 3 attached to this response. It can be observed that the value of the cost function in Fig. 3 c on the left-hand side is globally smaller than its value on the right-hand side. It means that, in this example, the Solid Column model (which is the model chosen by the IIR operational algorithm) allows the forward model to be more

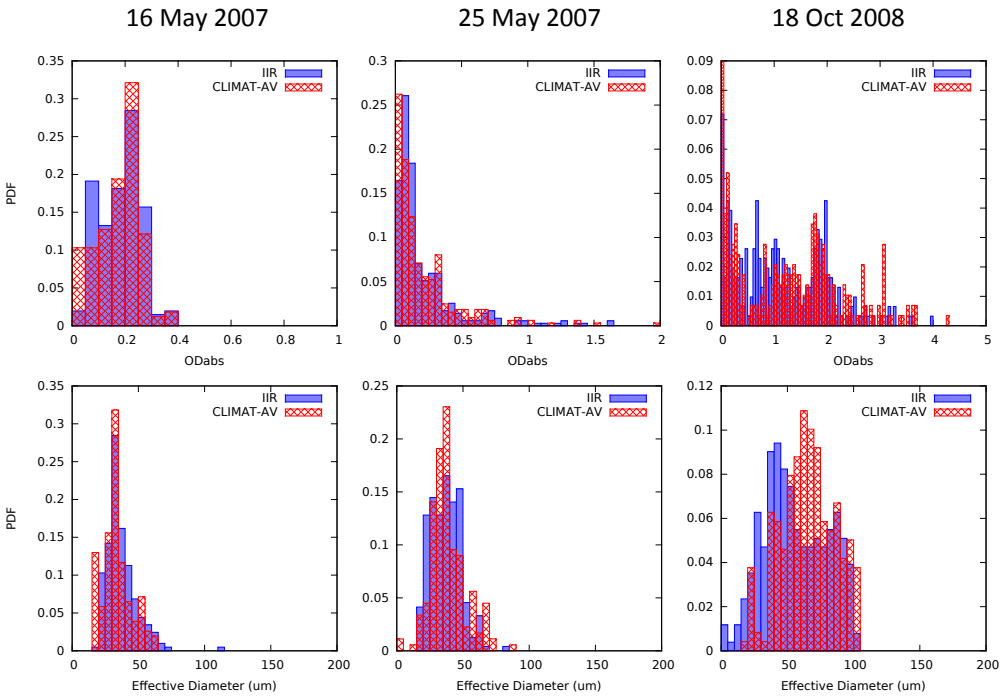

Figure 2: PDFs of the effective diameter and absorption optical thickness retrieved using IIR (in blue) and CLIMAT-AV (in red) measurements, for each campaign day.

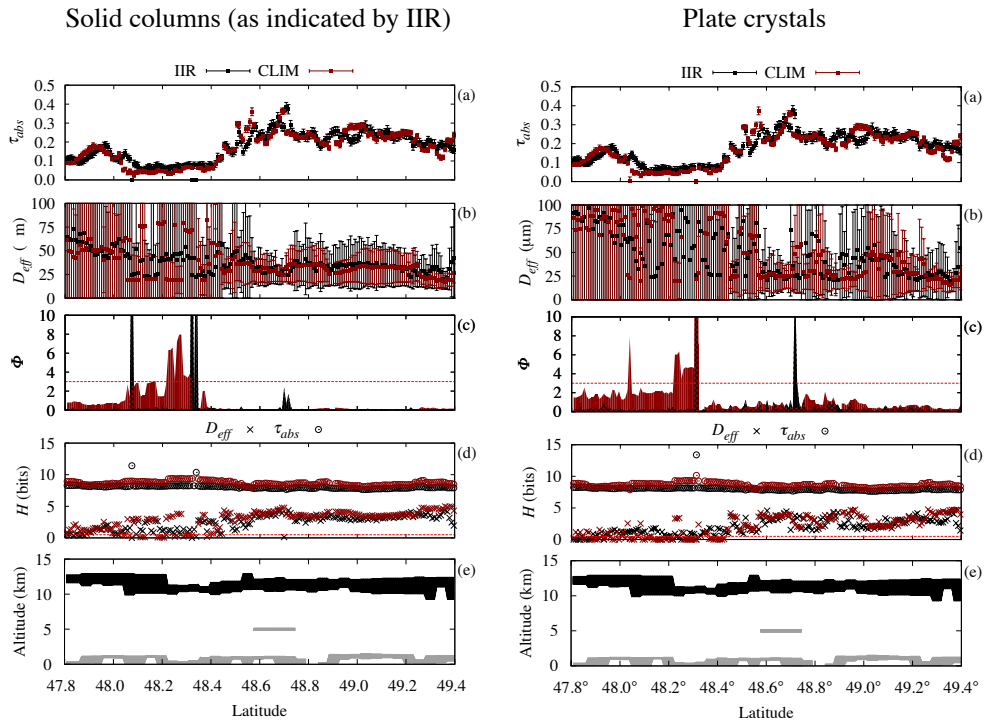

Figure 3: Similar to Fig 1, for 16 May 2007. The retrievals on the left-hand side and right-hand sides have been retrieved using Solid Column and Plate ice crystals, respectively

coherent with the measurements than the Plate model. The differences between the two cost functions are however small, and both cost functions globally are well under the noise limit. Therefore, more sets of measurements, for instance in the solar spectrum as suggested by the referee, would be necessary to discriminate the models better. The manuscript being already long, we have nevertheless decided not to include this analysis. The reference to Baran and Francis [2004] has however be added.

55. Page 29, please supply a reference for definition of De (Eq. 11). Moreover this definition is not the same as used for the space-based retrievals of De? If so please supply a correction so that comparisons are more meaningful

The reference to the paper by Gayet et al. [2006] given just after Eq. 11 is a good reference for the definition of the latter. This definition is maybe not as precise as the 'exact' calculation used for the space-based retrievals of De, but appears to be very useful for retrieving the effective diameter from IWC and a visible extinction. This formula has been successfully used in a number of previous studies for estimating the effective size (*e.g.* Gayet et al. [2002, 2004, 2006], Mioche et al. [2010]). Moreover link between Eq. 3 and 11 can be easily established by making a few assumptions (*i.e.* a constant density of ice crystals through the PSD, limit of the geometrical optics). An exact correction estimation of a possible bias between the two definitions does not seem easy to make, but we believe that the uncertainties attributed to the components of Eq. 11

will include it. The referee however interestingly puts a stress on the difficulty to use a parameter such as the ice crystal effective size that can quickly become ambiguous because of its numerous possible definitions, and can also loose its meaning when treating ensemble of ice crystal shapes.

56. On page 29 there is some discussion about shattering, is there any evidence in the CPI images of shattered artifacts? you will see small ice crystals in the presence of big ice crystals
The authors unfortunately did not have a direct access to the CPI images obtained during each campaign days. It has been discussed by Mioche et al. [2010] and also by Gayet et al. [2011] wether or not the in situ estimates obtained during CIRCLE-2 are strongly impacted by shattering, but without any unambiguous conclusion on this matter.

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