Answer to Referee #2'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 very thankful to the reviewer #2 for carefully reading our paper and making useful comments and recommendations. We are also very grateful for his interest in our novel methodology and support for publication.

General comments:

We are pleased to see the recognition that the referee shows towards our attempt to precisely quantify the impact of forward model uncertainties on the retrievals, as it clearly was one of the main motivations for this study. As stated in the introduction to our manuscript, we believe that it is nowadays absolutely necessary that retrievals (*i.e.* of cloud properties) must be provided along with precisely determined uncertainties. Luckily, this belief is well spread nowadays, and numerous studies have shown how the optimal estimation approach can be useful in this matter. It however stays crucial, when using this approach, to precisely quantify and account for the impact of the uncertainties attached to each non-retrieved parameter used in the forward model. This fact does not only appear to be important for the quality of the retrievals, but can also help to understand the capacities of the approach. For instance, as illustrated in section 4.1, an analysis of the impact of the non-retrieved parameters on the forward model indicates which of them should be better constrained, or eventually retrieved, for ameliorating the global quality of the retrievals. We therefore fully agree with the referee that this represents a key component of our study, and are pleased that this concern appears to be clear when reading the manuscript. On the other hand, we also fully acknowledge the referee's comment regarding the fact that few of our major conclusions are really unexpected. We indeed do not pretend with this study to conclude with unexpected results, as the retrieval of ice cloud properties using a set of thermal infrared measurements is today widely known and understood. Our motivation was rather concentrated on the presentation of an example of approach that allows attaching precise uncertainties to the retrievals, and that provides useful tools for judging of the quality of the latter. We would nevertheless like to add to this point that our retrieval methodology allows taking into account the presence of liquid water clouds underneath the cirrus layer, which is not yet a well spread quality in actual retrieval methods. In this study, it is only shown that liquid cloud layers may have a strong impact on the retrievals when their properties are poorly constrained. But a following paper will present how our novel methodology can be modified in order to retrieve simultaneously the properties of these underlying liquid cloud layers.

Specific comments:

Comment 1: We fully agree with the referee that a good comprehension of the sensitivity of the measurement to the state vector's components is very important for the global understanding of the results. The Split-Window clearly is a very interesting method for analyzing the sensitivity of ice cloud properties to infrared measurements. Numerous papers have described these results, and in the manuscript we for instance cite the study by Dubuisson et al. [2008] that presents a very detailed analysis of Split-Window arches by simulating IIR measurements, using a forward model configuration that is very similar to ours (identical ice crystal models, radiative transfer code, etc...). Their conclusions can therefore be perfectly adapted to under-

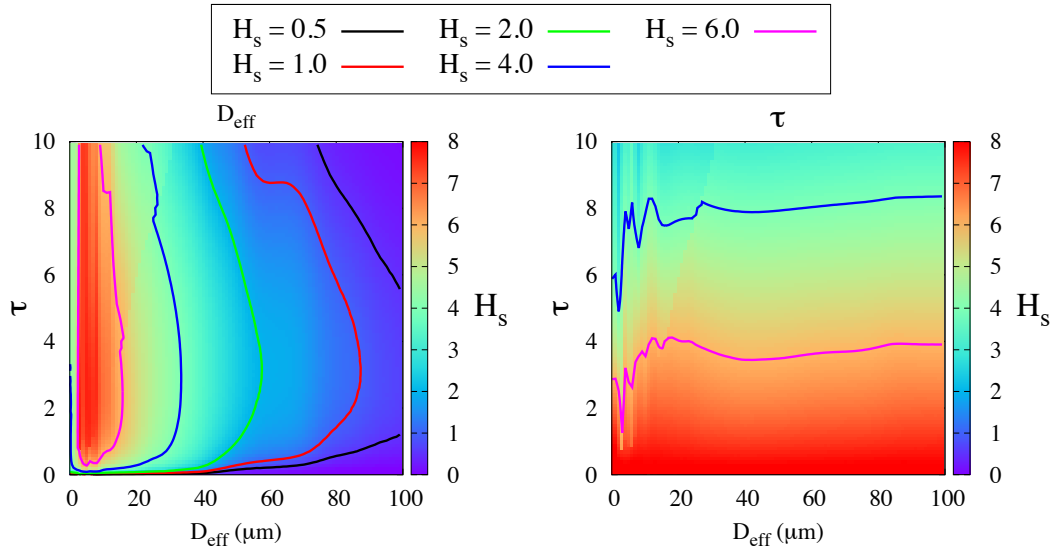

Figure 1: Theoretical information content on each parameter to be retrieved

stand the sensitivity of our forward model to different parameters. We nevertheless acknowledge that, for the reader's better comprehension, a reference to this paper should have been made earlier, and have now placed it just after the presentation of the measurement and state vectors.

However, a good understanding of the sensitivity of each retrieval parameter to the measurements can also be obtained by using the information theory, through for instance a theoretical information content analysis (prior to the retrievals). The latter seems more novel and adapted to our optimal estimation approach. It also possesses the advantage to be based on real sensitivity calculations (from the Jacobian matrix) and to include the errors from the forward model. Such analyses have been effectuated prior to this study, and we have attached two figures to this response in order to provide a concrete example to the referee: Fig. 1 presents theoretical values of the partial information content on the effective radius (left) and on the optical thickness (right) for different cloud configurations (τ_{abs} varying from 0 to 10, and D_{eff} from 0 to 100 μm). Similarly to the Split-Window method, we observe a very strong information (far from the noise limit of 0.5) from the measurements on the optical thickness, and much less information on the effective radius when the latter increases. It is also possible to look quantitatively at the expected uncertainties that would be obtained on each parameter, as presented in Fig. 2. This type of figures clearly shows what to expect from our methodology, as the theoretical values presented here are very coherent with the retrievals showed in the manuscript. We nevertheless have decided during the writing process not to include them in this paper. A proper analysis of such figures would indeed necessitate the addition of a full major section, while this paper is aimed at a global presentation of our approach. For these reasons, we do no wish to include too many sensitivity analyses in the present paper. We however strongly acknowledge their high importance, as such analysis will be much more central in the aforementioned following paper using this methodology.

Comment 2: We do not expect to observe differences between the retrieval obtained using IIR and CLIMAT-AV. The comparisons between the retrievals from both instruments are use-

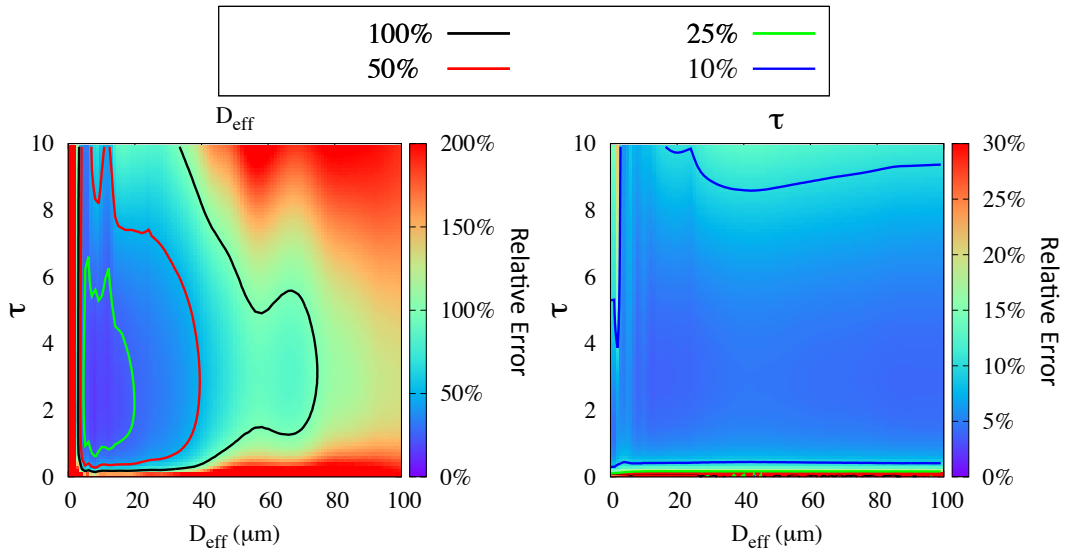

Figure 2: Expected relative uncertainties on each parameter to be retrieved

ful because they consolidate the results of a previous validation study of IIR measurements (as explained in section 2). Sourdeval et al. [2012] have directly compared collocated IIR and CLIMAT-AV brightness temperature measurements, and have found them to be very similar but not perfectly identical. Biases have been noticed, and could be explained - using brightness temperature simulations - by the fact that the altitude of both instruments is very different and that their radiometric signature is not truely identical. Without precise information on cirrus properties, precise BT simulations were however only possible in clear-sky areas and the biases could not be studied in the presence of cirrus. We therefore seek in this manuscript to show that similar results are obtained when applying IIR or CLIMAT-AV measurements to our retrieval method. This should demonstrate that simulations can also explain the observed biases in the presence of clouds, as the differences of altitude and of radiometric signature have been accounted for. This result certainly consolidates the validation study by Sourdeval et al. [2012]. We however agree that these explanations were ambiguous in the manuscript, and they have been consequently rewritten in the revised version (4th paragraph of the introduction and last paragraph of section 2). The motivations to compare IIR operational products to our retrievals could also appear ambiguous and more explanations have been added in the revised manuscript. Such comparisons aim to strengthen the validity of both products, since identical measurements but different approaches are used for the retrievals.

Comment 3: We apologize for the figures being mislabeled and for the inconvenience this mistake may have caused to the referee while reading our manuscript. This was due to an error in the Latex file used for compiling the version sent to the referees, but luckily did not influence the online ACPD version of the paper. The error has been solved in the revised version.

Comment 4: A presentation of the relative impact of each source of uncertainties on the forward model (and therefore on the retrievals) is presented in the section 4.1, and more precisely in Fig. 3. As stated by the referee, this figure corresponds with the case study of the 16

May 2007, which is representative of a thin cirrus. The conclusions obtained from this case study can nevertheless be perfectly generalized to the other case studies presented in the paper, and the same analyses have therefore not been repeated for brevity reasons. We again agree with the referee that more sensitivity studies (on the impact of the choice of the ice crystal, atmospheric profiles, surface temperature, etc...) would be very interesting for the global understanding of the problem but may necessitate a whole new section in this paper, that seems already long. Besides, as rightly indicated by the referee in the general comments, these results may be well expected. The aforementioned study by Dubuisson et al. [2008] also studied in detail the impact of ice crystal shapes on the brightness temperatures, and their conclusions are perfectly applicable to our study. We would like to note (as indicated on page 20) that we also have effectuated sensitivity analyses by comparing the value of the cost function obtained at the end of the retrievals after changing the ice crystal model, but without any conclusive results.

Comment 5: In the second paragraph of the introduction, the authors refer to the general advantage of airborne campaigns where in situ estimates and remote sensing observations are often combined to improve our understanding of clouds. Therefore, an emphasis placed on the uncertainties attached to in situ estimate may not be useful in this context.

Comment 6: We are grateful to the referee for this clarification. The following sentence has been added on page 20, along with other modifications: 'It should however be noted that, despite the fact that correlations between measurements have been neglected in our study, these correlations may still exist and consequently limit the amount of pieces of information to be retrieved. The accurate retrieval of an additional parameter could therefore necessitate the addition of new independent measurements to the measurement vector.'

Technical comments:

We are thankful to the reviewer for helping us clarify the manuscript through these technical comments. Several words may have been misused as none of the authors is a native English speaker. The use of 'comfort' has for instance been replaced by 'consolidate' or 'appear to be consistent' through the entire revised manuscript. 'Short areas' has been replaced by 'case studies', 'led' by 'performed', and 'sensibility' by 'sensitivity'. A number of other mistakes or similar ambiguous words have also been spotted and corrected in the revised version.

References used in this answer:

Dubuisson, P., Giraud, V., Pelon, J., Cadet, B., and Yang, P. Sensitivity of Thermal Infrared Radiation at the Top of the Atmosphere and the Surface to Ice Cloud Microphysics. *Journal of Applied Meteorology and Climatology*, **47**(10):2545–2560, 2012/03/21 2008.

Sourdeval, O., Brogniez, G., Pelon, J., C.-Labonnote, L., Dubuisson, P., Parol, F., Josset, D., Garnier, A., Faivre, M., and Minikin, A. Validation of IIR/CALIPSO Level 1 Measurements by Comparison with Collocated Airborne Observations during CIRCLE-2 and Biscay '08 Campaigns. *J. Atmos. Oceanic Technol.*, 2012.