Lidar-radar synergistic method to retrieve ice, supercooled and mixed-phase clouds properties
Answers to referees

First, we would like to thank the Anonymous Referee 3 for his/her times and very useful comments that helped us to significantly improve the paper. Please find hereafter our answers and related corrections in blue color. In addition, we have attached a updated version of the paper below. Figures labeled with a letter refer to those included in the answers, and those labeled with a number to those included in the updated version of the paper.

Answers to Anonymous Referee 3

The paper demonstrates an expansion of the radar-lidar synergy retrieval product varpy, the algorithm underlying the successful DARDAR-CLOUD and related CloudSat-CALIPSO retrieval products, to include supercooled liquid and mixed-phase clouds. The principle is that in clouds identified as mixed-phase by the DARDAR-MASK synergistic radar-lidar target classification produce, the radar observations are used to constrain the retrieval of ice, and the lidar measurements are used to constrain the retrieval of liquid cloud. The retrieval is demonstrated using a single 10 minute case study of high-latitude mixed-phase boundary layer clouds observed by a coordinated aircraft underflight of the A-Train during the ASTER campaign.

This is an important issue in spaceborne detection and retrieval of clouds, especially relating to cloud-radiation interactions, and an expansion of the family of DARDAR products is welcome, as is any chance to evaluate spaceborne retrievals with field campaigns.

Overall the paper is well-written, the algorithm is thoroughly described, and the plots are produced to a good standard and are easy to understand. Some of the limitations of this study are discussed by the authors ; however, there could be a clearer distinction between the limitations of the retrieval and those of the evaluation using the field campaign data, and both could do with expanded discussion to consider their implications, such as for application to a DARDAR product.

I recommend this paper for major revisions, subject to addressing the following comments.

Major comments :

- What are the macrophysical implications of the in-situ profile demonstrating that neither the radar nor the lidar are sampling the entire cloud ? Is there an indication from the in-situ data whether the cloud is mixed-phase through its entire depth, or does it transition to ice cloud ? This is obviously a wide-ranging issue relating to all spaceborne radar-lidar observations, but it seems there's a bit of information here from the in-situ measurements that's worth commenting on.

  ▶ Since the lidar signal is attenuated, it cannot detect the entire cloud profile and the radar is limited in this case down to an altitude of 500 m due to ground clutter. As a result, radar and lidar alone cannot determine the phase of the entire cloud profile. However, we can see in Fig. 4 that *in situ* measurements detect both crystals (with CPI and PN) and liquid water droplets (with FSSP and PN) down to around 400 m. Below this altitude, the cloud phase cannot be determined. Nevertheless, we can have information on the cloud phase using the asymmetry parameter g from the polar nephelometer (PN) measurements. Jourdan et al. 2003, 2010 have shown that g values measured by the PN are usually less than 0.8 in ice clouds and around 0.84 - 0.85 in liquid-phase clouds. Besides, GAYET et al. 2002 estimates the uncertainties of g at 4 %. Figure A shows the cloud phase classification from remote sensing (curtain, panel (a)) and the asymmetry parameter g (dots on panel (a) and line on panel (b)) from *in situ*. The parameter g indicates the predominant presence of mixed-phase or liquid water between 1 and 1.5 km altitude (corresponding to the mixed-phase layer indicated by the radar-lidar classification). Below 1 km altitude, the phase is predominantly ice, with some areas of mixed phase, presuming the lesser presence of water droplets up to 400 m altitude.

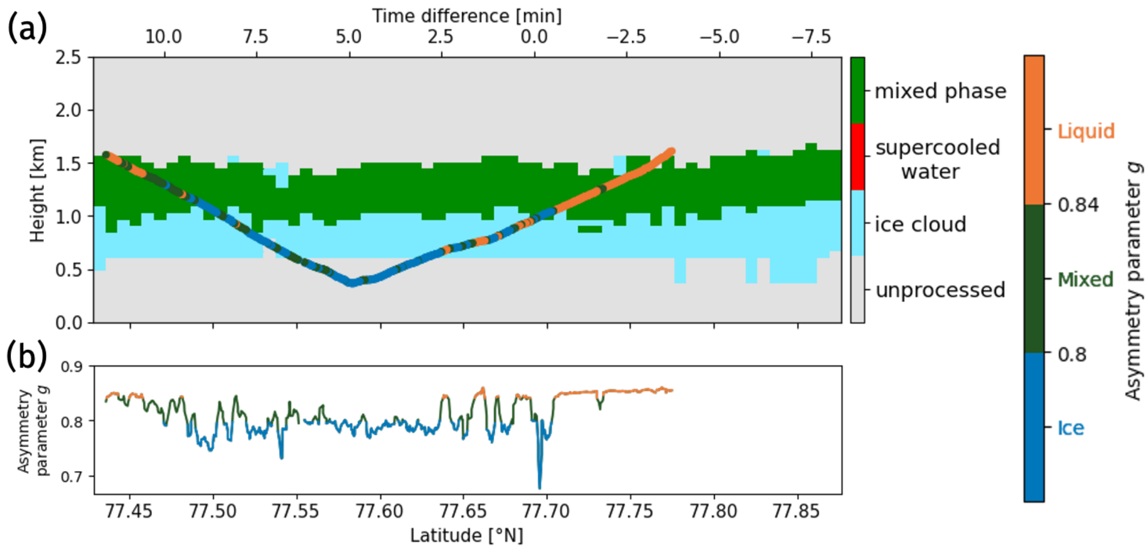

FIGURE A – Panel a) : Cloud phase classification (curtain) and asymmetry parameter g from the Polar Nephelometer (dots) as a function of the altitude and latitude. Panel b) : Asymmetry parameter g as a function of the latitude. The asymmetry parameter on both panel share the same colorbar.

- Further to this, what are the implications for DARDAR-CLOUD's existing ice retrievals in mixed-phase cloud (Table 5) ? I'm not asking for a change of scope of the present paper ; however, it would be interesting to compare varpy-mix and varpy-ice in the present case study to explore the effect of interpreting lidar extinction in these two very different ways.

  ▶ We have processed the same case with VarPy-ice and the results are presented in Figure B (dark blue dots). In addition, Table A shows the mean absolute error and mean percent error for VarPy-mix and for VarPy-ice. It is difficult to make conclusions from this comparison, since the lidar is not used in this case by VarPy-ice (the retrieval is performed using radar data only). On the other hand, the retrieval of ice properties by VarPy-mix is constrained by the simultaneous retrieval of supercooled water properties.

Properties	**VarPy-mix**		**VarPy-ice**	
	Mean absolute error VarPy-mix	**Mean percent error VarPy-mix**	**Mean absolute error VarPy-ice**	**Mean percent error VarPy-ice**
α_{ice}	7.2×10^{-4} m^{-1}	398 %	5.6×10^{-4} m^{-1}	204 %
IWC	2.9×10^{-2} g. m^{-3}	75 %	3.4×10^{-2} g. m^{-3}	62 %

TABLE A – Comparison between VarPy-mix and VarPy-ice for the ASTAR case

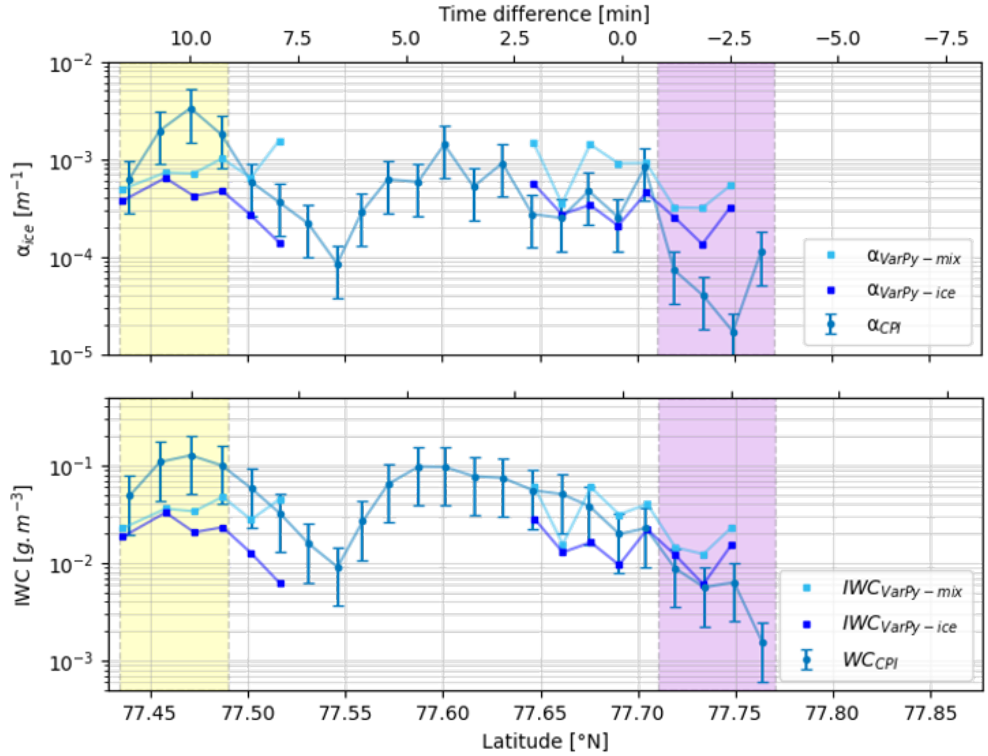

TABLE B – Comparison between VarPy-mix and VarPy-ice for the ASTAR case

- In the purple part of the case study, where varpy-mix ice extinction is much higher than that measured in-situ but the IWC is about right, does this imply a significant bias in the retrieved ice effective radius ?

  ▶ We have calculated the ice and liquid effective radii for *in situ* using Equations A and B (where ρ_i and ρ_w are the ice and water density respectively). Figure 6 shows the effective radii calculated for *in situ* and the values retrieved by VarPy-mix. We can see that the ice effective radius calculated from the *in situ* (CPI) are much larger than those retrieved by VarPy-mix, especially in the purple part. On the other hand, the liquid effective radius retrieved by VarPy-mix is larger than the values calculated for *in situ* (FSSP). It is important to note that the ice effective radius retrieved by VarPy-mix with the HC LUT cannot be higher than 164 μm, as shown in Figure C. As a result, it could not reach the effective radii measured by the CPI in the purple zone. To improve our comparison, we include in the revised manuscript (Section 3) the comparison between effective radii retrieved by VarPy-mix and those calculated from in situ data (in the same way as for extinction and water contents). In addition, following a question from Anonymous Referee 1, we also include a comparison of the concentrations retrieved by VarPy-mix and those calculated from CPI and FSSP PSDs.

$$r_{e,\text{ice}} = \frac{2}{3}\frac{\text{IWC}_\text{CPI}}{\alpha_\text{CPI}\cdot\rho_\text{i}} \quad \text{(A)} \qquad\qquad r_{e,\text{liq}} = \frac{2}{3}\frac{\text{LWC}_\text{FSSP}}{\alpha_\text{FSSP}\cdot\rho_\text{w}} \quad \text{(B)}$$

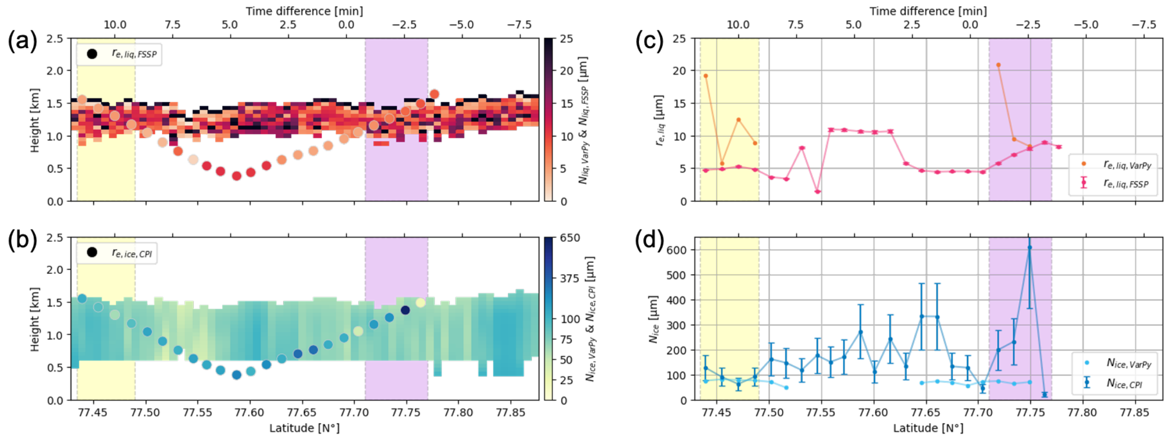

FIGURE 6 – The panels (a) and (b) represent the liquid (a) and ice (b) effective radii from VarPy-mix retrievals (curtain) and *in situ* probes (dots) regarding the latitude and the height. The panels (c) and (d) share the same ordinate axis and represent the liquid (c) and ice (d) effective radii from VarPy-mix retrievals and *in situ* probes regarding the latitude. The error bars of *in situ* measurements (uncertainties from Table 6) are displayed in panels (c) and (d). The yellow and purple shading represents the latitude range where mixed-phase retrievals are compared with *in situ*.

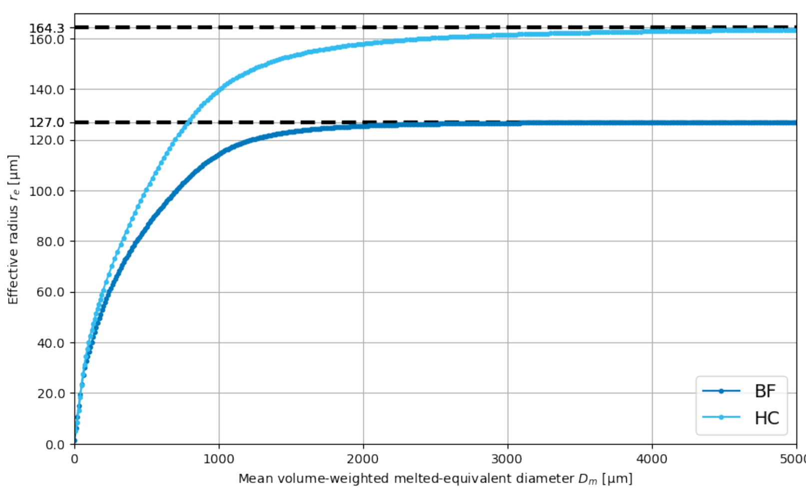

FIGURE C – Comparison between ice effective radius from BF and HC LUT.

- The evaluation of the retrieval is summarized using the mean absolute and mean percentage errors, indicating impressive performance in most cases ; however, more information is available here that could be expanded upon, especially relating to the bias. In addition to the table, is it possible to use a plot that shows either the PDF of the retrieval compared to the in-situ data, or the distribution of errors, to retain more of this information. ▶ We have calculated the percent error regarding in situ measurements for each value when VarPy-mix retrievals are available (seven values for liquid properties and fourteen values for ice properties). The results are shown in Figure D. It is interesting to look at these distributions to better assess the comparison. We can see that the errors seem to vary according to the cloud area analyzed. Unfortunately, the number of values is limited to draw conclusion. If the liquid water content retrieval is biased low, as appears to be the case here, is this a systematic bias or could we expect a different result in other case studies ? Please comment on these uncertainties.▶ Indeed, it is possible that this bias may change. However, we have not yet compared VarPy-mix retrievals with other in situ measurements. It would be interesting to carry out a study comparing VarPy-mix retrievals with other in situ measurements, for example on a larger data set and over different world regions.

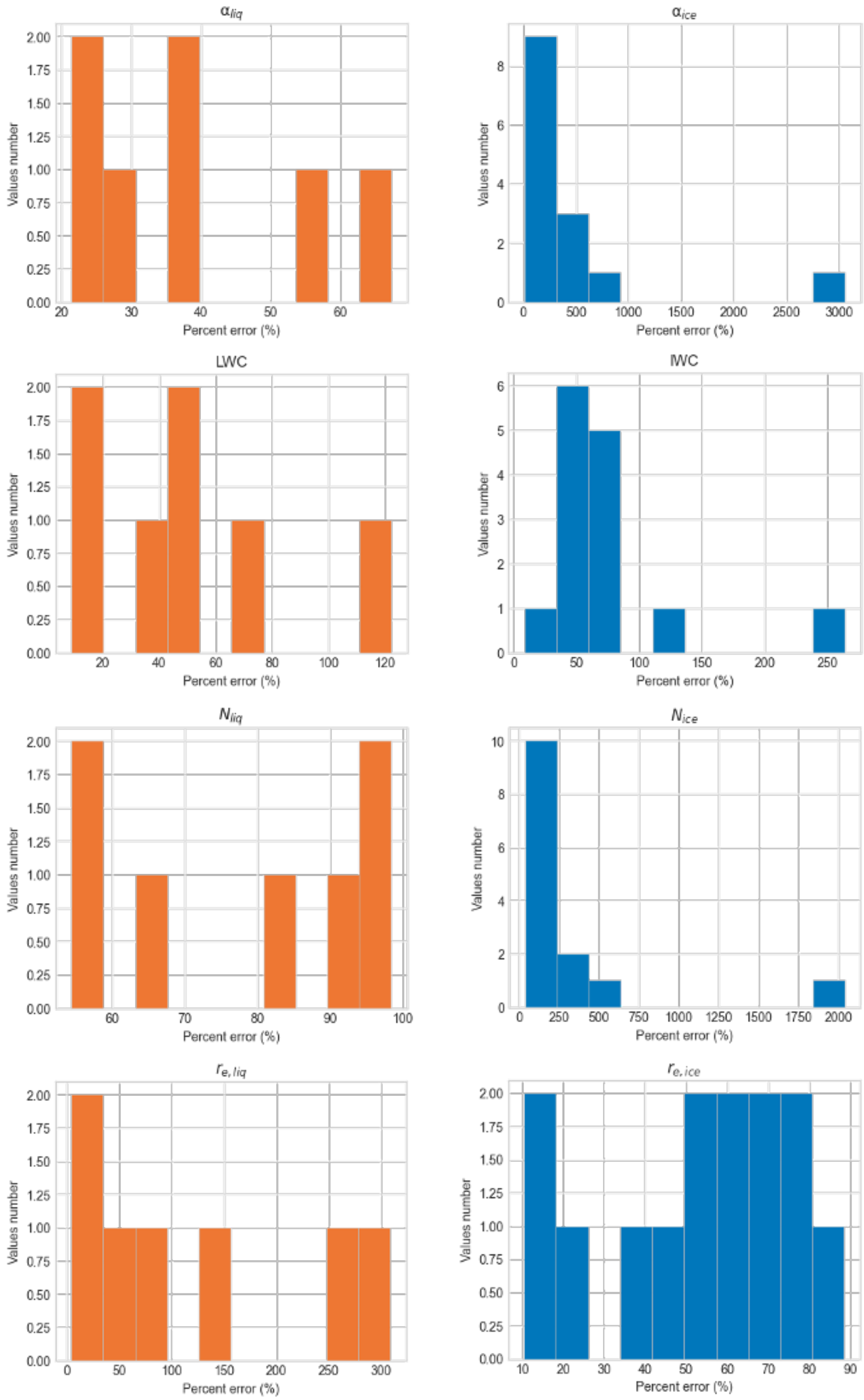

FIGURE D – PDF for each variable.

- There is some ambiguity about the mass-size relation that is used. It is clear from the method section and conclusion that both the Heymsfield and Brown and Francis relations are implemented as LUTs in VarPy, and the coefficients for both are given. In the algorithm description we are told "For both VarPy-ice and -mix, both LUT are used to retrieve the ice properties" (L156-7) but in the result section the results are shown for the Heymsfield mass-size relation only (L360-2). Does the selection of the Heymsfield relation indicate that these results are better than those using Brown and Francis, and can the authors (or the reader) conclude anything from this ? Is there any value in showing both results ? Are there any cases, e.g. in the purple section where a large error in the retrieved effective radius is implied, where the other mass-size relation may improve the performance ? It is a strength of the VarPy algorithm to be able to answer these questions, so please expand on this or resolve the ambiguity.

  ▶ The wording of the sentence (L156-7) is indeed unclear, and we propose replacing it with : "For both VarPy-ice and -mix, both LUT can used to retrieve the ice properties and one must be selected beforehand." For this study, we arbitrarily chose the HC LUT. It is also the most recently implemented LUT in VarPy (proposed by Cazenave et al. 2019 for the new DARDAR-CLOUD v3 configuration). Furthermore, when comparing the retrievals made with the HC LUT and the BF LUT (shown in Figure E page 7), it can be seen that the difference between the two retrievals is relatively minor for these case.

Minor comments :

- Fig 2 (a) there is some contouring around noisy features in the lidar backscatter that make this panel difficult to interpret

  ▶ The colorbar limits have been modified to avoid this inconvenience (see Figure 2).

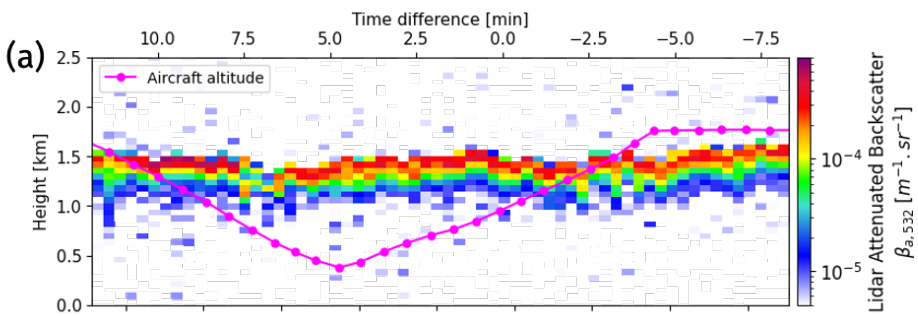

Figure 2 – CALIPSO attenuated backscatter.

- There are minor differences between the figures that surprise and confuse when comparing features between plots :
  - In Fig. 6 the colorbar labels face the other way to those on all other figures.
  - In Fig. 6 the format of the time and latitude labels, and their positions, are different from Fig. 5. This makes it difficult to line up the features visually.

    ▶ We have replaced Figure 6 with two new figures, showing the comparison between VarPy-mix and in situ retrievals for effective radii (Figure 6) and concentrations (see Figure 7 in the following version of the manuscript).

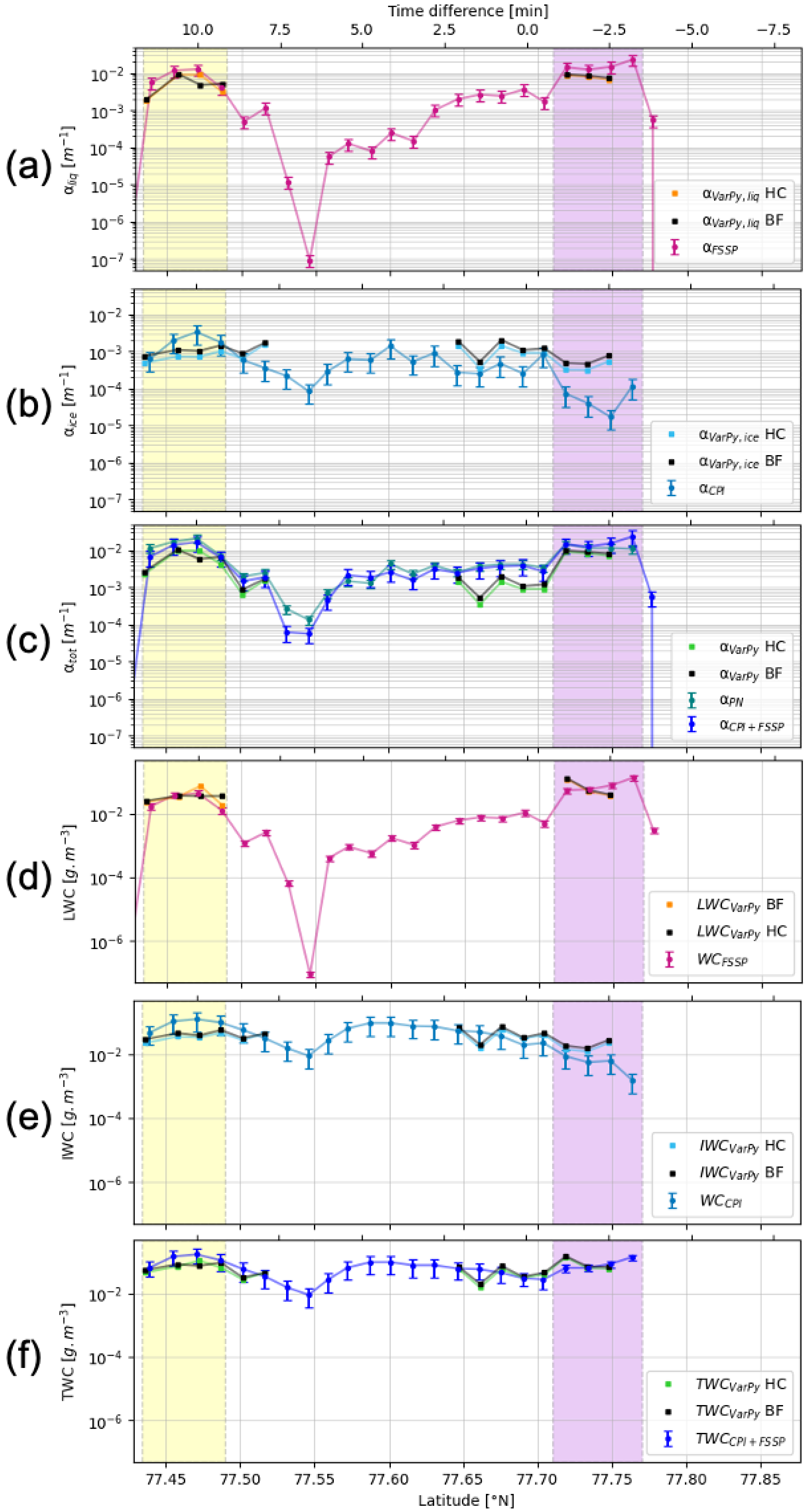

FIGURE E – Comparison between the HC and the BF LUT.

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