Authors' response to comments from Anonymous Referee #1

Referee #1

Review of "Investigation of cirrus clouds properties in the Tropical Tropopause Layer using high-altitude limb scanning near-IR spectroscopy during the NASA-ATTREX Experiment", by Colosimo and coauthors, AMT-2023-85

The focus of this article is on the mini-DOAS (Mini Differential Optical Absorption Spectroscopy) instrument, and its operation on the NASA Global Hawk aircraft during the Airborne Tropical TRopopause Experiment. The instrument provides limb scanning observations in the near-IR, facilitating the identification of ice and liquid water. To use the instrument's capability, radiative transfer code was developed for this study. Comparison of the ice water path and ice water content retrieved from the instrument agreed reasonably well with the observations from the SPEC FCDP and the NOAA water vapor instrument.

I will focus on the observations with the particle probes (Hawkeye) and the comparison with the observations as this is my area of expertise. I'll let others comment on the radiative transfer calculations and instrument design and capability.

We would like to thank the referee #1 for providing valuable and constructive comments, as well as suggestions to improve the manuscript. Responses to these specific comments are provided below.

Main comments

Line 68. Hawk-eye is subject to considerable ice particle shattering. You briefly comment on this later in the article, but I think it should be here. Also, I'm not convinced that the shattering removal techniques for the small particles effectively reduces or eliminates shattering. We have quite a lot of good data to show this.

The Hawkeye instrument is subject to shattering under certain observational conditions, particularly in the presence of moderate to high concentrations of large ice particles, but most of the ATTREX flights did not encounter such conditions and had low evidence of shattering. Shattering has been mentioned later in the manuscript (line 451) to note our awareness of this issues, and the fact that corrections of this effect have been made (according to the cited reference) to improve data reliability. Further investigation of minor shattering artefacts are beyond the scope of the current work.

The aim of this section is to provide a list of the instruments involved in the ATTREX project that are relevant to this study, leaving the description of potential issues related to the use/application of their data to parts of the manuscript where the data are discussed. Nevertheless, we agree that mention of the shattering effect should be moved to this paragraph as a discussion of the operational limitation of the instrument. Consequently, we have moved the paragraph forward to Section 2, following the reviewer's suggestion.

Line 183-185, 487-489. Use LIDAR to get the IWC and IWP. You can use LIDAR extinction data and a relationship between extinction and ice water content to also get SIWC and ice water path and to compare with the mini-DOAS instrument. See Heymsfield et al. (2014). Heymsfield, A., D. Winker, M. Avery, M. Vaughan, G. Diskin, M. Deng, V. Mitev, and R. Matthey, 2014: Relationships between Ice Water Content and Volume Extinction Coefficient from In Situ Observations for Temperatures from 0° to −86°C: Implications for Spaceborne Lidar Retrievals. J. Appl. Meteor. Climatol., 53, 479–505.

We agree that the comparison of IWC and IWP LIDAR data to values obtained from the mini-DOAS would have provided further validation to our study. However, a direct comparison of the two remote sensing methods is quite challenging due to the very different viewing strategies, i.e., nadir vs limb as well as the averaging volumes (or kernels). In addition, the use of LIDAR as a tool to measure IWP also requires radiative transfer models, thus adding more uncertainty. We have therefore considered that the comparison of our results with two direct in-situ IWC measurements was sufficient to validate our methodology.

Line 266. Are the sizes of the particles imaged by the CPI (their maximum dimensions) consistent with those sampled by the FCDP, because it's possible that particles >50 microns were present. In Woods et al. (2018), CPI images of particles as large as several hundred microns are shown (their Figure 5).

We are aware of the limitations of the use of the Hawkeye-FCDP data. This instrument only measures particles between about 1–50 microns, relying on the Hawkeye-2D-S to cover a larger size range (10 microns to a few mm). We performed sensitivity studies and found that inclusion of larger particles in the radiative transfer models yielded unrealistic results. We therefore believe that these particles may not have been present at large concentrations in the air volume observed by our instrument. We agree that a more accurate description of the particle size distribution would have been beneficial for the presented methodology, but we consider that constraining the size range of the in-situ microphysical data for more direct comparison with the SIWP retrievals to be acceptable, given the scope of the paper.

Line 272, 448. Particle habit. I don't necessarily agree that the particles are quasi-spherical. Are the images from the CPI consistent with spherical particles ice density of 0.91 g/cm^3? You can clearly see this in Fig. 5 of Woods et al. (2018). Please comment on this. Also, see: Heymsfield, 1986: Ice particles observed in a cirriform cloud at −83 °C and implications for polar stratospheric clouds. Journal of Atmospheric Science, 43(8), 851–855.

CPI images for that portion of the flight considered in this study mostly show spherical and quasi/spherical shaped particles, with virtually none of the other detectable habits present. The Heymsfield reference suggests they observed trigonal and columnar habits, but the observed ice particle population for ATTREX included very few trigonals, and few columns in comparison to quasi-spheroids. Also, in Woods et al. (2018), the authors often refer to spherical or quasi-spherical properties of the ice particles in their paper, in particular treating these properties as an a priori assumption for some methodologies. They have found that assuming spherical, which allows use of the FCDP data, is a good approximation within the larger uncertainty bounds of applying the FCDP measurements here. Decreasing the uncertainties inherent in the FCDP measurements is beyond the scope of the current work, but the authors do acknowledge the relevance of the comments and will consider such issues in future in-situ focused cloud and instrumentation studies.

From Woods et al. (2018) - Section 2: Measurements

- Page 6056: "*From the concentration and sizing, particle area and mass over this size range are estimated assuming spherical ice particles since the exact shape of the particles is not known.*"

- Page 6057: "*…the portion of the size distribution smaller than the cutoff is from FCDP observations (assuming circular area and spherical mass)*"

The validity of the assumption of spherical particles (and thus the use of a Mie code for calculating the optical properties) was also confirmed through the good agreement between the modeled and measured SIWP considered in this study.

The long averaging times of the mini-DOAS instrument are somewhat problematic.

The mini-DOAS data temporal resolution (and large averaging volume) can represent a challenge for a direct comparison with instruments at higher data frequency. In order to validate the retrieved mini-DOAS IWC, temporal smoothing was applied to data from the in-situ instruments. We are aware of the limitation of this comparison (as commented on in Section 4.3). However, the comparison still holds, showing the feasibility to retrieve comparable IWC using near-IR limb measurements.

Minor Comments

What were the temperatures sampled?

According to the in-situ data for that portion of the flight considered in this study (14–18km flight altitude), temperatures were recorded in the 185–210K range. The sentence: "*…where temperatures were recorded in the 185–210 K range*." has been added at the end of the existing paragraph in lines 483–484:

"*TTL cirrus cloud micro-physical properties were widely sampled during the ATTREX 2014 campaign, at altitudes ranging from 14 km up to the cold point tropopause (17.5–18 km), where temperatures were recorded in the 185–210 K range*."

Line 43-45. CALIPSO/CALIOP can readily detect thin TTL cirrus.

We rephrased the paragraph in line 43-45 as follows:
"*While cirrus clouds occur frequently in the TTL [Wylie and Menzel, 1999], they are often optically thin and thus difficult to observe. Spaceborne experiments have provided important information about the properties of these type of clouds [Winker, 2009; Winker 2010].* "

Line 70. Here you should mention how the IWC was derived from the Hawkeye instrument. You use the Hawkeye IWCs in Figure 8.

As explained in the reply to the comment for Line 68, the aim of this section is just to list the instruments that were part of the ATTREX payload, generating data related to the analysis carried out in this study. Hawkeye data provided the size distribution of the particles, which has been averaged for the portion of the flight considered, in order to evaluate the total volume. Knowing the density of ice, we evaluated the nominal ice water content (renamed IWC_0). The paragraph has been rephrased later in the text (lines 267–269) for a clearer explanation.

Line 123. Can LIDAR extinction be used to derive absorption cross-sections of ice? Can the two be related? You do have the LIDAR data.

LIDAR cannot be used to derive ice absorption cross section. The Cloud Physics Lidar instrument provides the extinction-to-backscatter parameter (among other output products) and not the absorption cross section. CPL also operates at three specific wavelengths: 1064, 532, and 355 nm, (McGill, 2002), that do not overlap with any strong ice absorption features between about 1450 nm to 1550 nm, used in the present study.

Eq. (5) and line 164. Is this the density of solid ice? Is Mice the ice water content (IWC)? That's what it should be.

Equation (5) is only a theoretical explanation of the SIWP, and the formula is not directly used for calculations in the analysis. SIWP is expressed in length units (um) so M represents the mass concentration of ice (or IWC), and ρ_{ice} the ice density. We agree that M_{ice} is equivalent to IWC, and this could be somewhat misleading to the reader. The term M_{ice} has been replaced with IWC in the text.

Line 300. I like the sensitivity tests you did, varying the concentration and examining the results.

We thank the reviewer for this kind comment.

Line 451-453. This should be inserted earlier, where Hawkeye is discussed.

As mentioned in the Line 68 comment, this sentence has been moved to Section 2.

Line 457-460. Does the discussion here relate to Figure 8b? You do discuss Figure 8b later, but it probably should be here. I really don't see the good agreement. Also, by "observations", do you mean the NOAA instrument?

We thank the reviewer for this comment. Answers to these two questions are next.

- No, this entire paragraph refers to Figure 8, panel (a). It was only to highlight how the nominal case represents the “best fit” when compared with the half (x0.5) and double (x2) cases.
- No, the term “observations” still refers to panel (a) in Fig.8, where SIWP is calculated from mini-DOAS observations.