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Full title: "Consistency test of precipitating ice cloud retrieval properties obtained from the observations of different instruments operating at Dome-C (Antarctica)"

This is a very interesting paper that describes a unique set of instrumentation at a site in Antarctica that take data useful for studying ice clouds without supervision. The instrumentation consists of a Fourier transform spectroradiometer (REFIR-PAD), a depolarization lidar, and a micro-rain radar (MMR). From my own experience with satellite imager-based observations of ice clouds over polar regions, the retrievals are problematic and the issue is having some sort of ground truth with which to assess them. The methodology described in this article provides a very important step towards being able to provide a "truth" set for satellite-based comparisons, at least from my own limited perspective.

The paper would benefit from more work on the results section and revisions to some of the figures before publication. Suggestions for improving the grammar are provided in an uploaded edited version of the manuscript. Further suggestions are provided below for the authors to consider.

Major comment:

The data provided by the instrumentation at Dome-C could be very instrumental for improving the retrieval/description of precipitating ice cloud properties in the Antarctic. If there were retrievals at the time of polar-orbiting imager overpasses, the intercomparisons would be useful to a broad remote sensing community. The manuscript would be strengthened by making the case for how much data are needed and what might be necessary for increasing the quantity and reliability of the products. How much data are needed over how long a time period? Are results available every day? Is the data processing fully automated? Are the products available to the scientific community? What is the daily coverage? How would you improve the analysis given more data? In other words, make the case for what you are doing here and what would be gained by continuing this data collection and analysis effort. There are four case studies provided - how many more cases are necessary for your goals? More clarity of the current and future effort and goals should be provided, given that this manuscript will be referred to in future work.

We thank the reviewer for the constructive comments which gave us the opportunity to improve our paper. We have worked trying to address all requests.

During the 18 days accounted for in the analysis, a total number of 678 REFIR-PAD measurements colocated with MRR observations are considered. This dataset covers a very small time frame which does not allow an accurate evaluation of satellite sensor performances due to the scarcity of nadir collocated overpasses.
Nevertheless, collocated satellite passive measurements at any observational zenith angle are examined to investigate the opportunity of accounting for additional information in the analysis. For the present case the Infrared Atmospheric Sounding Interferometer (IASI, https://www.eumetsat.int/iasi) and the Moderate Resolution Imaging Spectroradiometer (MODIS, https://modis.gsfc.nasa.gov) are considered. The analysis of the L2 satellite products for IASI (https://www-cdn.eumetsat.int/files/2020-12/IASI%20Level%202_%20Product%20Generation%20Specification.pdf) and MODIS (https://atmosphere-imager.gsfc.nasa.gov/sites/default/files/ModAtmo/MOD06-ATBD_2015_05_01_2.pdf) highlights the difficulties in identifying the cloudy conditions, which

are otherwise determined by the ground-based sensors. In case of IASI the cloudy conditions are individuated in 55% of the 131 collocated observations while MODIS classifies as cloudy the 38% of the collocated 73 pixels. Moreover, given the low confident classification no cloud properties retrieval is available for the considered cases.
We totally agree with the reviewer that the use of ground-based observations can be used as truth to assess the capability of satellite sensor to identify atmospheric conditions and their retrieval products. Nevertheless, since long records from ground-based measurements are required to test L2 satellite products when strict co-location constrains are set, we preferred to not include this analysis in the present work.
For your information, we are performing a comparison between satellite (passive and active) L2 products with ground-based derived products (at Dome-C) on an extended time frame. Preliminary results are showing significant differences among multiple satellite sensors performances; it is our hope to submit our findings in a very near future.

Most of the instrumentation used in this work operates in continuous and unattended mode at Dome-C. In particular, REFIR-PAD provides an infrared spectrum every 12 minutes, while the MRR and the lidar provide measurements every 1 and 10 minutes, respectively. HALO-CAMERA acquires continuously since 2020 but it does not work during the winter period when the moon is not present. ICE-CAMERA performs a scanning of the precipitating ice crystals hourly, because it requires more time to complete all needed operations. Unfortunately, data were not always available because of some problematic related to this kind of measurements. In fact, for example the accumulation of the ice on the screen obstructs the scanning plate and makes it necessary to clean it before start measuring over. This procedure requires the intervention of the Concordia staff if it happens during the Antarctic winter period. This is why only four cases were discussed in detail in the paper, since they correspond to those days when also the ICE- or HALO-CAMERA images were available for the comparison with the retrieval products. Basically, REFIR-PAD, lidar and MRR provide continuous measurements every day, while ICE/HALO-CAMERA are actually not available every days due to occasional technical issues of maintenance.

We agree with the reviewer that more data would improve the analysis, in particular the comparison between Z_e retrieved from the REFIR-PAD spectral radiances and those measured by the MRR would be enhanced and made more reliable by collecting a larger number of measurements. This is the reason we need to continue the work by acquiring more data at Dome-C. However, the results shown in the paper prove that the methodology discussed is valid for the assessment of the particles size distribution at Concordia in case of precipitating ice clouds and it also shows the goodness of the retrieval procedure of the ice/mixed cloud optical properties from the infrared spectra in these conditions.
The following sentence was added in the Conclusions:
"We are confident that by extending the analysis of at least five more years the results would gain in quality and reliability. Furthemore, still within future perspective, the possibility of collect more retrieval of effective size of the precipitating crystals together with the Doppler velocity provided by the MRR, could allow to derive a new analytic relationship between the particle fall velocity and diameters, which is still missing for ice crystals as far as we know. This relationship could be used to directly estimate the size distribution from the radar power spectra".

Even though the retrieval products of precipitating ice clouds are clearly not always available every days, because these events are not so frequent and the MRR is sensitive only to the larger particles, the retrieval products of not precipitating events are available everyday. In fact, the routine of the analysis is fully automated and provides the retrieval products of the atmospheric profiles and clouds parameters continuously.

The products will be available to the scientific community within a partnership of scientific collaboration. The PNRA projects provide that the collected data will be available to the scientific community one year after they will be concluded.

We added the following sentences in the text on line 100:
"It was installed on the roof of the PHYSICS shelter in a zenith-looking observation geometry providing one measurement every minute".

On line 115 :
"The photographs are analyzed to sort and classify the precipitating ice crystals depending on their habit and sizes and they are hourly provided unless work of maintenance or cleaning are needed causing a lack of data".

on line 120 :
"HALO-CAMERA is a sky imager installed on the shelter roof since 2019 operating mostly continuously used..."

Minor comments:

The verb tenses change often in the manuscript - suggest aiming for as much consistency as possible.

Corrected in the text

Introduction, line 20: please define the term cloud effect and perhaps cloud forcing, which is used in line 54. That is, describe the components of the radiation budget in broad terms for the reader.

On line 20:
We replaced "Cloud effect can be either ..." with "Clouds can be responsible either of a net cooling... "

On line 29:
"The radiative forcing caused by these clouds, defined as the differences between the total flux in the presence of cloud and one in clear sky condition (Intrieri et al. 2002), influences the Surface Radiation Budget .. "

Line 150: The figure - be specific about which figure is being referred to here.

Corrected in the text.

Figure 6: there are basically two figures set side-by-side in Figure 6, and the details are difficult to see in the left plot (panels a through d). Would it be possible to separate the two panels so that the details are easier to discern?

Figures were separated.

Lines 166-170: the description of realistic ice particles from this area (Dome-C) is quite interesting, and I would hope that the authors will consider expanding their interpretation of the observations from the ICE-CAMERA photographs, especially in precipitating conditions for the case study dates.

As suggested by the reviewer we widely extended sections 4.3.1 and 4.3.2.
From now on the figure numbers refer to those in the text. Regarding section 4.3.1:

"The MRR reflectivity time-height cross-section for the selected days 23 and 24 February 2020 are shown on the upper panels of Figs. 16 and 17. The data are not continuous because of the filtering procedure due to the sensitivity of the MRR to the largest particles. The corresponding color map of the backscattering and depolarization lidar signals are also shown on the right of Fig. 16. The depolarization lidar shows that precipitation starts from the passage of ice clouds between 02:00-04:00 UTC, when larger ice crystals formed as detected by the MRR signal, which reached a few dBZ above 0. Then the precipitations continued but with smallest particles, in fact the MRR signal decreases rapidly. On 24 February an intense precipitation started at 07:00 UTC and finished at about 22:00 UTC; this was composed of larger crystals as clear from the MRR signal in the upper panel of Fig. 17, in particular the signal reached about 3 dBZ at 11:30, 14:30 and 18:30 UTC.
Fig.15 also shows the comparison of the average crystal length L_{av} retrieved from REFIR-PAD infrared spectra (red diamonds) with those obtained from the ICE-CAMERA (blue dots).
Continuous MRR measurements and ICE-CAMERA data were available most of the time of both days as shown in Fig. 14.

Mixed-phase clouds passed above the site on 23 February between 08:00-09:00 UTC and 12:00-13:00 UTC, when their presence was detected by the lidar depolarization signal at around 200 m above the ground (indicated with black arrows) and, in particular, the supercooled water formed layers of 100 m and 300 m of thickness on the 23 and 24 February, respectively. The average retrieved precipitable water vapor (PWV) was found equal to 1.33 and 0.98 mm on the days 23 and 24 February, respectively, while the average cloud temperatures about -40 and -39 °C. The average temperature of the water layers was found equal to -31 °C, which is acceptable since supercooled water can exist down to -40 °C.
In the first mixed-phase cloud time slot, the retrieval provided an average ice fraction γ equal to 0.47 with LWP equal to 0.62 g/m^2 while in the second time slot values were equal to 0.56 and 1.5 g/m^2.

The lower panels in Figs. 14 and 15 indicate that the values of the average crystal lengths retrieved from REFIR-PAD and those estimated from ICE-CAMERA varied between 700–1200 μm and 700-1000 μm, respectively, and they are mostly in very good agreement for most of the cases, particularly on day 23 February.

Figs. 18 and 19 show the photographs took by the ICE-CAMERA at 04:10 UTC and 08:10 UTC on the days 23 and 24 February 2020, respectively. These times were selected because were close to the strong precipitations detected both by the lidar and the radar, as we can note from Figs. 16 and 17, when the sun was still rised and generating the halos. In Fig. 20 is also shown the photograph at the 18:03 UTC of the 24 February right before the intense precipitation detected by the lidar and radar (Fig. 17), where we can see the presence of columns aggregates (or clusters) and rimmed rosettes beside the hexagonal columns. The crystal habits were automatically catalogued by the internal algorithm, and labeled with the green labels. The solid column crystal are represented by hexagonal columns (label hexpri) or bullet (label bullet), which are columns with a tip at one end; aggregates (irrgra, clusters) were also found, together with bullet rosettes (rosette) or rimed rosettes (rimros). In general, some elements needed to be discarded since represent volatile material (label fiberr) produced by the main building of the station.

Ice crystal shown in Fig. 18 on the day 23 February indicate that almost only column-like crystals were present. On the contrary, the photograph in Fig. 19 on the day 24 February, shows also a little component of bullet rosettes.

The prevalence of hexagonal columns was confirmed by the detection of well distinguishable solar halos in the HALO-CAMERA images at the same times as shown in Fig. 21 for the both mentioned days. In fact, the right panel shows that the phase functions of the smooth columns, aggregate and bullet rosettes ($\sigma_r = 0$) present a strong scattering peak at 22 °, which is responsible for the most intense halos, while for the roughest particles ($\sigma_r = 0.50$) the function is smoother without the peaks: the parameter σ_r reported in Fig. 21 indicates the degree of rougheness with larger values denoting rougher particle surfaces, in particular, values 0 (smooth surface), 0.03 (moderate roughness) and 0.50 (severe roughness) were assumed as described in Yang et al. (2013). Since, as found by Forster et al. (2022), plate-like and hexagonal column-like crystal have a SCF (smooth crystal fraction) higher than solid bullet rosettes and columns aggregates, as also confirmed by the measurements performed by Lawson et al. (2006) at South Pole, the presence of the 22 ° confirmed the high occurrence of hexagonal columns".

We also added on the right side of Fig. 18, beside the halos images, the plot of the simulated phase functions at 532 nm of columns, aggregates and bullet rosettes with different grade of roughness as shown here below in Fig.1:

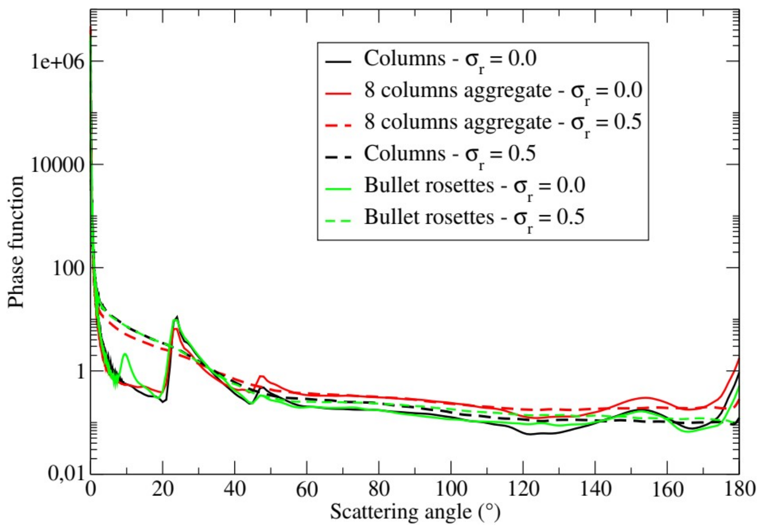


Fig. 1. *HALO-CAMERA images for the days 23 (left) and 24 (middle) February 2020. On the right panel the simulated phase functions at 532 nm for the three habits considered with roughness $\sigma_r = 0$ (smooth crystal surface) and $\sigma_r = 0.5$ (severe rough crystal surface).*

Regarding section 4.3.2:

"During 21 April 2020, strong precipitiations occurred between 08:00-15:00 UTC and between 17:00-24:00 UTC as we can see from the lidar signal on the lower panel of Fig. 22, while the radar reflectivity reachead 5 dBZ. The larger particles formed between 18:00-21:00 UTC as detected by MRR in the upper panel of Fig. 22. On 24 April, an intense precipitation detected by the backscattering lidar started at 03:00 UTC and continued until 15:00 UTC, while the MRR detected the Doppler signal from 05:30 UTC up to 11:00 UTC showing a strong reflectivity signal around 10:00 UTC.

Some photographs from ICE-CAMERA were available for the comparison as shown in the lower panels of Fig. 24 and 25. Unfortunately, on the 23rd, only a single ice scan measurement was

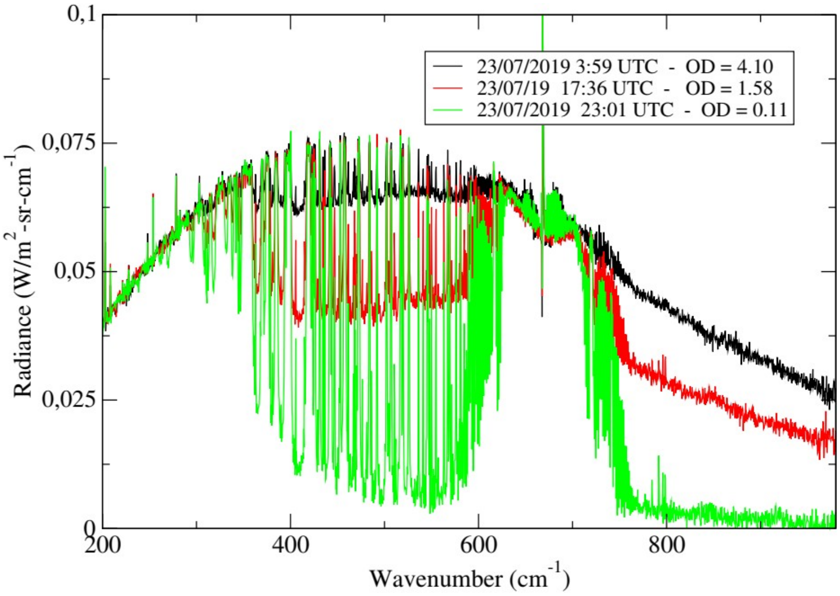
actually provided by the ICE-CAMERA at 03:03 UTC and it did not overlap in time with the radar data. However, the comparison of the 21 April shows a good agreement with the retrieved L_{av}. The MRR reflectivity shows high signal values, up to 8 dBz, between 19:00-21:00 UTC on 21 April and between the 06:00-11:00 UTC on 23 April.
Also during 21 April, a mixed-phase cloud with supercooled water occurred between 19:00 and 20:00 UTC at about 200 m above the ground.

The average retrieved precipitable water vapor (PWV) was found as higher as 2.46 mm for the day 21 April and 1.33 mm on 23 April, while the average cloud temperatures was equal to about -33 and -38 °C, respectively. The average temperature of the water layer occurred during the REFIR-PAD and MRR measurements was found equal to -23 °C and it was placed between 200 and 500 m above the ground. In this case γ was found on average equal to 0.58 and LWP equal to 9.5 g/m^2.

From ICE-CAMERA photograph in Fig. 24 we can see that on day 21 April at 19:03 UTC, in the middle of the second precipitation when mixed clouds passed, mostly columnar habits with a minor component of rosettes was present. On 24 April at 03:03 UTC, when the precipitation started and 1 hour and half before the MRR signal was detected, the falling ice crystals were mostly rosettes, as clear from ICE-CAMERA photograph shown in Fig. 25. Unfortunately, for these days the HALO-CAMERA images were not available".

Figure 10: Despite reading multiple times through the discussion pertinent to the results in this figure, it is difficult for me to interpret the comparison between REFIR-PAD and MRR of the intercept (No) and the optical depth since the results are on a log-log scale. There is a very wide range of results especially in the OD. Are there conditions where the results might compare more closely? Would results collected over a long time period be used to improve the retrieval process? Some discussion would be helpful here.

We agree. We have updated Fig. 10 by showing only the plot of D_{ei}-OD_i. We used a linear scale for the effective diameters. We added Fig. 2 (now Fig. 11 in the text) to show the variability of the retrieved ODs and their effect on the spectral radiances.



<u>Fig. 2</u>. *Variability of the cloudy spectra detected by REFIR-PAD during the day 23 July 2019.*

We added the plots in Fig. 5 (now Fig. 14 in the text) of the N_o expressed in cm^{-5} and the slope $\Lambda=(\mu+3)/L_m$ in cm^{-1} as a function of the cloud temperature (T_{cld}) to compare them with the results shown in Heymsfield et al. (2013, 2002) and Wolf et al. (2019), finding a good accordance.

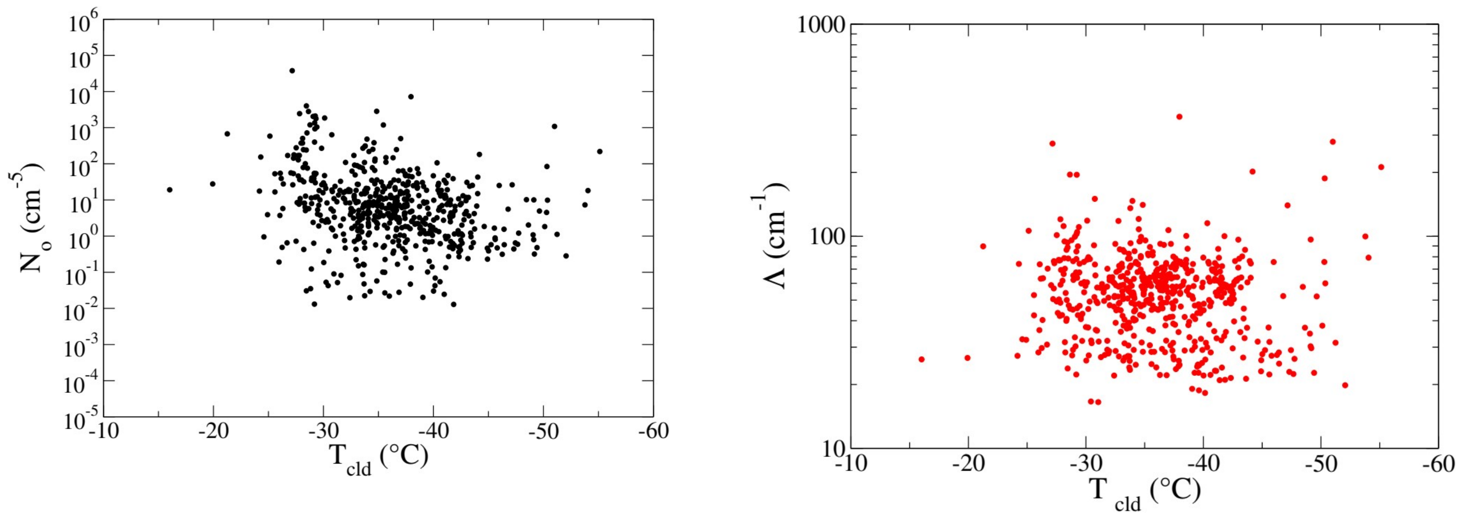


Figure 5. Left and right panels: intercept N_o and slope Λ as a function of the cloud retrieved temperature (T_{cld}).

Figure 12: For ease of interpretation for the reader, I think it would be helpful to break this figure into two different figures, one for each day. Perhaps consider making a 2-panel plot of the MRR reflectivity map above/below the lidar map for each day so that the figure is expanded to help interpretation. Another suggestion would be to draw a circle around the times when a supercooled liquid water cloud is present in the lidar map. My final suggestion would be to expand the discussion for each day to focus on results at different times through the day, i.e., describe the results in more detail. How does the MRR add information to the REFIR-PAD results?

We have implemented all changes suggested by the reviewer.
The MRR allowed to confirm the goodness of the retrievals of the PSD parameters (intercept and modal radius) from REFIR-PAD spectra, assuming the dispersion coefficient μ = 0,1,2. We have now assumed these range of values because of the dependence of this parameter on the cloud temperature as suggested by reviewer 2 and discussed in detail in Heymsfield et al. (2013, 2002). The results of the cloud parameters retrieval do not depend on the choice of μ since the downwelling infrared spectra detected by REFIR-PAD are not sensitive to this parameter as shown and discussed in detail in the answers to reviewer 2. However, the N_o change a little and need to be recalculated. Results of N_o and slope Λ are shown above in Fig. 5 as a function of the retrieved cloud temperature. Fig. 7 was updated by using μ = 1.
Then, MRR reflectivity data also allowed to assess which types of crystal habits better fit the measurements, finding that the best accordance is found mostly by assuming hexagonal columns and aggregates and, in smaller amount, bullet rosettes.

Figure 13: As noted earlier, the ice particle habit observations by the camera are quite interesting. Unfortunately, this figure shows exceptionally small images for two different days. It is difficult to make out any detail because the images are so small. Please

consider reworking these figures, perhaps making a separate figure for each day with fewer (but larger) ice particle images. It would also be of interest to discuss what habits are found for each of the case study dates, under the specific conditions of the day (temperature/humidity), and pointing to specific images. This is an important component of your analyses but these figures are not helpful.

We have separated all the figures requested. We also added in the section 4.3 the specific conditions of average temperature and precipitable water vapour for all cases.

Figure 15: same general comment as with Figure 12. Please consider separating this into two figures, one for each day. Furthermore, there is almost no interpretation of the results for these two days (21 and 23 April 2020) - the discussion should be expanded.

Figures were separated and discussion was expanded as suggested.

Figure 16: same general comments as for Figure 13. It is difficult to get any information from these images of the ice particles. But the images should be useful for supporting the analysis in Figure 15.

Section was expanded in the manuscript.

We have also applied the grama corrections suggested by the reviewer, in particular by uniforming the tense as much as possible.