General Comments:

This manuscript describes an icing tunnel test facility that may be of interest to the atmospheric science community. The fundamental operation of this system is similar to existing icing tunnels, however, there is no comparison to icing tunnels that have been in existence for nearly 50 years. Of particular interest is the icing tunnel in Ottawa, Canada that is operated by the National Research Council. A description of the NRC icing tunnel can be found at https://nrc.canada.ca/en/research-development/nrc-facilities/altitude-icing-wind-tunnel-research-facility, and early papers describing experiments in the tunnel are by Strapp and Schemenauer (1982) and King et al. (1985). The NRC icing tunnel has unique advantages over the Braunschweig tunnel, specifically the NRC tunnel is capable of particle speeds up to 100 m s^{-1} and altitudes to 40,000 ft (12 km). The Braunschweig maximum particle speed of the Braunschweig tunnel is 40 m s^{-1} and it has not capacity to simulate altitude. This is unfortunate since research aircraft fly at various altitudes and all large aircraft fly at speeds that are at least twice the maximum speed that the Braunschweig tunnel can produce. The manuscript needs to discuss how the limitations of the Braunschweig tunnel influence their results.

Understanding discrepancies between drop concentrations and drop size distributions (DSDs) measured by various probes is of critical importance for cloud physics, albeit icing studies rely more on bulk quantities such as MVD and LWC. MVD and LWC are presented and discussed in great detail, but there is almost no quantitative discussion of drop concentrations and DSDs from the PDI, FCDP and Shadowgraphy instrumentation. The manuscript needs to include additional figures that show correlations between reported drop concentrations and DSDs measured by PDI, FCDP and Shadowgraphy.

The PDI measures LWC using eqn. 4, which proportional to the product of total drop concentration and corrected volume mean diameter. The manuscript should also show how LWC compares using this technique with LWC computed by integrating the complete DSD. The comparison should be shown as a function of MVD and drop concentration.

The manuscript compares LWC measurements from the FCDP, PDI and RCT using the WFR as a standard. It is implied that LWC using WFR as a standard is very repeatable, on the order of 7%. In Section 4 a statement refers to Section 3 as justification for this, but far as I can tell in Section 3, this repeatability comes from the literature, not from actual tunnel tests. Yet, I assume there were LWC repeatability tests, similar to the MVD tests shown in Fig. 5, so please point out where I missed the LWC repeatability tests or include figures showing results from them. Now, that said, based on the large amount of scatter shown in Figs. 12 – 14, either the tunnel flow characteristics or the measuring techniques, or both, appear to be contributing much more variability to LWC than the 20% figure quoted in the text. It would be useful to show a complete uncertainty analysis for the WFR and test instruments measurements, but this is likely to be outside the scope of this paper. However, the manuscript should address tunnel and instrument LWC uncertainties in a more rigorous manner, not just quote the literature.

The sample conditions of these tests (droplet concentrations sometimes exceeding 2000 cm^{-3}) are typically only found in polluted environments. This, plus the slow droplet speed, limit the usefulness of the results of these experiments. These limitations need to be discussed in detail in the manuscript.

The poor sampling statistics for drop diameters > 30 microns (Figs 4 and 7) definitely introduce uncertainties in the LWC results that need to be addressed more rigorously.

Finally, it should be pointed out that without a rigorous uncertainty analysis of the absolute accuracy of the tunnel, all of the quoted accuracies are not absolute, but instead relative. That is, in addition to the random error associated with tunnel properties, there is some degree of undetermined bias error that is not considered. This needs to be emphasized in the manuscript, albeit, hints of this are included in some of the references cited.

Specific Comments:

1. Introduction

Page 2: When mentioning the cloud probes used by Ide (1999) and Cober et al. (2001), the manuscript should describe the resolution and size range of these probes so results can be compared with tunnel results.

2. Experimental Setup

Add a table (perhaps as a supplement) indicating the mean operating conditions for all of the data sets presented in this manuscript (Velocity, Temperature, RH, Air Pressure, Water Pressure, Water mass flow). This would be helpful to understand the scope of conditions for each type of drop measurement system. Also, list the number of data sets collected for each drop measurement technique (e.g., FCDP: 100 samples at 20 m s^{-1}, 200 samples at 30 m s^{-1}, 300 samples at 40 m s^{-1}). Based on the data plotted in Fig. 11, it appears that the PDI datasets greatly exceed those of any other probe. This could be due to the high particle rejection rate and very low sample volume of the PDI. Please explain.

3.1. PDI

In this section it is noted that "The PVC has the greatest effect on the smallest size classes. Their influence on the LWC, on the other hand, is very small." We have performed an independent analysis of the FCDP data set from this icing tunnel and determined that the peak of the particle mass size distribution is between 8 um and 10 um. Therefore in this study the vast majority of drops are very small (see PDI PSD in Figure 4 for confirmation where the mode is ~6 um). Given these concerns, the manuscript should include more details of the PDI small drop corrections and better quantify the errors. From Chuang et al 2008: "At very small droplet sizes, diffraction can become significant relative to refraction, and lead to oscillations in the φ versus d relationship at the smallest drop sizes, primarily in the size range below 4 µm, but with some effects up to ∼8 µm."

3.2. FCDP

The description of the FCDP sample volume is fairly convoluted. It is sufficiently described as SV=SA*TAS, where the SA is defined by calibration for a fixed qualification criteria. The SA is defined by laboratory calibration like that described in Faber et al. (2018). See the Table's section of the review for more details.

In paragraph 3 it should be noted that the CDP and FCDP have similar operating principals, but the improved optics and electronics in FCDP allow for accurate sampling in higher particle concentrations (see comments on Table 2 below). The FCDP also differs from the older FSSP-100 probe in that the qualifier detector uses a slit aperture (200 µm x 800 µm), which was first introduced on the FSSP-300 probe with data described by Brenguier et al. (1998).

Lance et al. (2010) note that accurate sizing of the CDP instrument to ~200 cm^{-3} before being influenced by coincidence. However, improvements in the CDP (new limiting apertures) increased accuracy such that only 27% undercounting is estimated at concentrations of 500 cm^{-3} (Lance 2012). This level of uncertainty is still problematic. The FCDP was designed to incorporate the improvements of the CDP as well as reduce particle coincidence (the dominant source of error) by reducing the laser beam waist from 200 µm to 80 µm). Flight tests indicate reasonable agreement for LWC between the FCDP and hotwire probes for small droplet concentrations as high as ~1000 cm^{-3}. The conditions in this study exceed these typical atmospheric conditions, so the FCDP uncertainty for these high drop concentrations range is not well described.

In paragraph 3, the authors cite up to a 50% uncertainty from Baumgardner 2017, but it should be noted that this quoted uncertainty (10 to 50% for light scattering probes), includes “Mie ambiguity, collection angles, coincidence, nonsphericity and shattering.” In this study all droplets are assumed to be spherical, and shattering is minimal for the FCDP, so the 50% uncertainty does not apply here.

3.3. Shadowgraphy

Overall the Shadowgraphy technique is poorly described. More details of the instrument and post-processing are required such that the test could be replicated and verified by another group. In the last sentence from this section the data inter comparison is considered” almost identical.” This statement requires quantification.

3.4. Rotating Cylinder Technique

Stallabrass (1987) should be Stallabrass (1978)

4.1. Repeatability

See General Comments.

Paragraph 2: “see section 4.1” within section 4.1, should be “see section 3.1”.

Paragraph 4: “see section 4.2” within section 4.1, should be “see section 3.2”.

4.2. Comparison of MVD measurements

Paragraph 3: “A low sensitivity of the FCDP to larger particle sizes (> 30 µm) may cause or contribute to the measured deviation of the FCDP with respect to the PDI for large droplets.”

Is there evidence that the FCDP has a low sensitivity to larger drops? If so, provide a reference. The number of sampled drops is relatively low, due to the small sample volume and low concentration of larger drops, but this is true for all single-particle devices, including the PVI. Also, with long runs in an icing tunnel this should not be an issue, assuming the tunnel properties are repeatable, as claimed in Section 4.1.

Paragraph 3: “The transit time filter applied to the FCDP data during post-processing to reduce coincidence causes a rejection of droplets that have a too long transit time compared to the mean reverence [sic] velocity and thus reduces the droplet size spectrum evaluated as valid by large droplets.”

Is there any evidence to support this assertion? If so, please provide the evidence, a reference, or sound physical explanation.

Paragraph 5: “According to Lance et al. (2010), an additional source of error of the CDP might be the external geometry of the probe, which can alter the measured cloud particle size distribution.”

This statement does not apply to the FCDP because it has “anti-shattering tips” that minimize droplet splashing, whereas the CDP Lance used did not (at that time) have anti-shattering tips. The CDP can be equipped with anti-shattering tips now.

4.3. Comparison of LWC measurements

See General Comments, also:

Paragraph 6: "This can only be explained by higher particle number concentrations measured by the FCDP compared to the PDI."

Please provide particle concentrations and size distributions for the FCDP and PDI for the relevant wind tunnel datasets. Following the example in Figure 7, the authors should indicate when the PDI and FCDP sampling statistics are poor (<100 particles per bin) and possibly remove these data from consideration.

5.0. Summary

Page 17 Paragraph 2: "The characterization of cloud droplet distributions with particle sizes > 100 μm poses new challenges for droplet measurement techniques." Some Optical Array Probes are well suited to particle measurement in this range, specifically the 2D-S, which is commonly utilized for icing tunnel measurements of larger drops.

References

Biter, C. J., et al., 1987: The drop-size response of the CSIRO liquid water probe. *J. Atmos. Oceanic Technol.* **4**, 359-367.

Brenguier, Jean-Louis, et al., 1998: Improvements of droplet size distribution measurements with the Fast-FSSP (Forward Scattering Spectrometer Probe). *J. Atmos. Oceanic Technol.*, **15**, 1077-1090.

King, W. D., et al., 1985: Icing wind tunnel tests on the CSIRO liquid water probe. *J. Atmos. Oceanic Technol.*, **2**, 340-352.

Korolev, A., et al., 2013: Modification and tests of particle probe tips to mitigate effects of ice shattering. *J. Atmos. Oceanic Technol.*, **30**, 690-708.

Lance, S., 2012: Coincidence errors in a cloud droplet probe (CDP) and a cloud and aerosol spectrometer (CAS), and the improved performance of a modified CDP. *J. Atmos. Oceanic Technol.*, **29**, 1532-1541.

Strapp, J. W. and R.S. Schemenauer, 1982: Calibrations of Johnson-Williams Liquid Water Content Meters in a High-Speed Icing Tunnel. *J. Appl. Meteor.*, **21**, 98–108, https://doi.org/10.1175/1520-0450(1982)021<0098:COJWLW>2.0.CO;2

Figures

Figure 2: Add mean and variance values to each plot. It would also be helpful to add time-series data for the PDI, FCDP and Shadowgraphy (counts/sec or conc/sec). Perhaps it would be better to add the probes' time-series as a new figure.

Figure 4: Add additional accumulated size distributions for the FCDP and Shadowgraphy. If possible, overlay distributions from all three methods on the same figure indicating Concentration, LWC and MVD for each.

Figure 5: Add R^2 values.

Figure 6: Based on the results in Figure 2, the conditions (Temp, RH) are not necessarily stable for the initial portion of the sample run. As such, it is hard to separate the MVD discrepancy as a function of true fluctuations vs counting statistics. Show size distributions for the initial 10^3 droplets and the final 10^3 droplets.

Figure 7: This plot is very useful, but as with Figure 4 it should be amended to include lines for FCDP and Shadowgraphy. It may also be helpful to interpolate the higher resolution PDI data into the FCDP size bins for

a more accurate comparison. Note that the FCDP size bins are chosen to smooth out Mie bumps and to improve sampling statistics for the larges drops. Add a dashed line to indicate the threshold for rejecting data due to inadequate data points in a bin (e.g., 100 counts bin^{-1}).

<u>Figure 9</u>: These plots are useful, but additional plots should be added to show correlation with LWC and Concentration.

<u>Figure 11</u>: It hard to visually separate the WFR grey region from the PDI data points. Considering switching this plot to color or making individual scatter plots for PDI, FCDP and RCT.

<u>Figure 14</u>: Combine with Figure 12, and include sample plots for FCDP.

Tables

<u>Table 1</u>: Include the model number of the PDI in the caption.

<u>Table 2</u>: Amend the table to include these values:

FCDP Beam Waist = 80µm
FCDP DOF Rejection Criteria = 0.9
FCDP Sample Area = 0.09mm^2
FCDP Size Range = 2-50µm
FCDP Serial number = 6
FCDP Calibration Date = 4/28/2017 (see sizing calibration curve below from manufacturer)

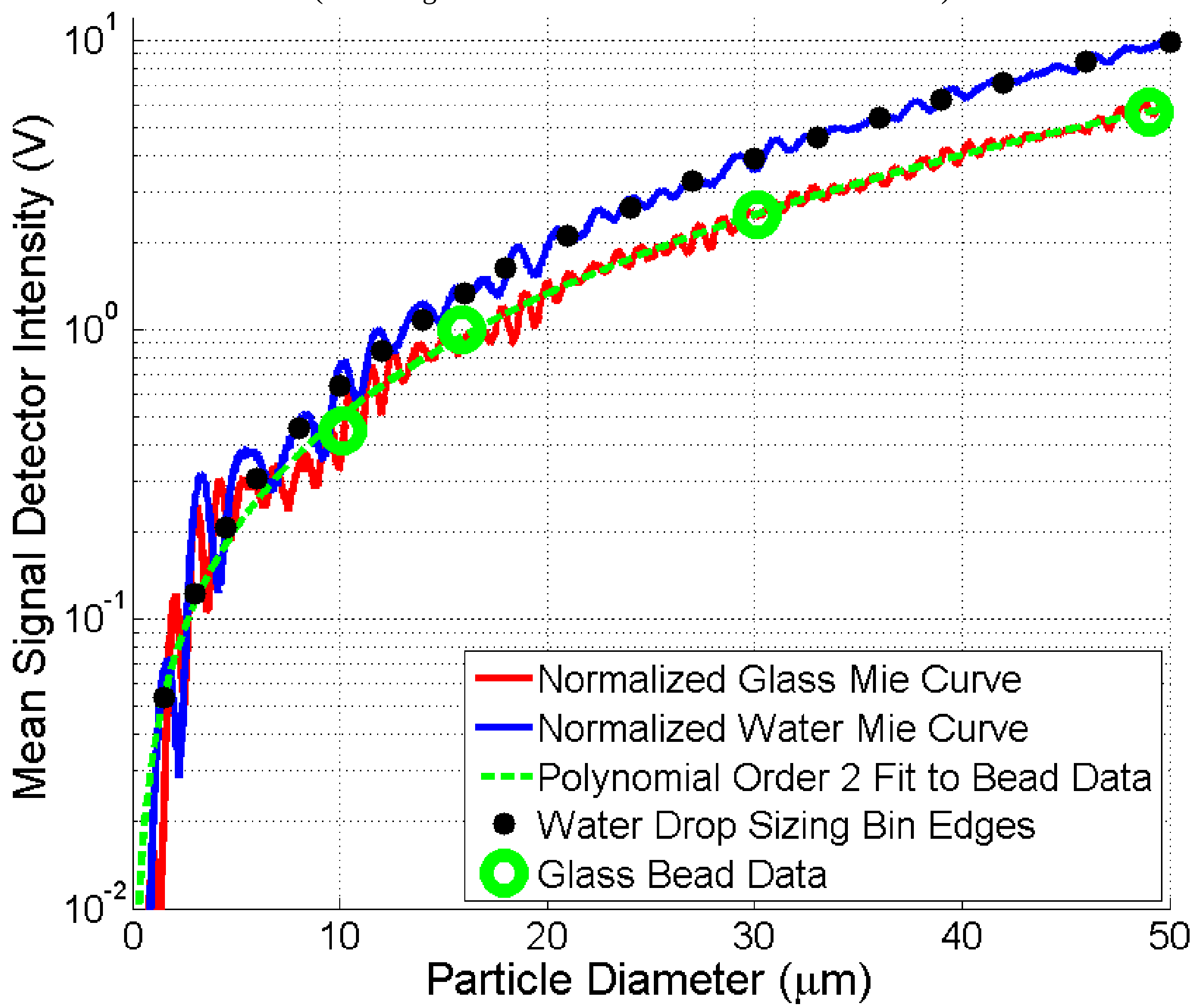

Table 3: Include details on the Shadowgraphy optical system similar to Table 1 for the PDI (wavelength, magnification, focal length, working distance, collection angle, etc.).

Table 4: Define the table column variables in the caption.