Reply to Reviewer #1

We would like to thank you again for providing helpful comments regarding our manuscript. We communicated with the manufacturer regarding the shape of the pulse and added one discussion paragraph to reply to the referee's comments. We hope the content in the second revision will be satisfactory and suitable for publication. The point-by-point responses are made below.

1. *Corrections to the number concentration using pulse width analysis.*

   The first issue lies in the assumptions that go into doing a coincidence correction based on the transit time. The primary assumption assumes that differences in the actual pulse width (PW), compared to the expected, are mainly a result of flow velocity variations or multiple particles in the beam. Hence, the authors go to a lot of effort to model the flow around the sonde and in the particle deliver system but never do they acknowledge that the large variations in PW are like a result of the non-uniform beam intensity and non-uniform beam geometry. Without taking these factors into account, something requires inforrmation and cooperation from the manufacturer, the correction factors that are derived are meaningless. The probability of coincident can be calculated quite directly since the sample volume of the sonde seems to be known. Why isn't this done?

   Regarding the beam characteristics, the manufactures disclosed to us an example of the result of a beam profiler (a captured image: Fig. 1). As we can see, the beam intensity is not necessarily uniform and is weakened outside. The heterogeneity of the laser beam would cause the change of pulse shape. Examples of the pulse shape are shown in Fig. 2. The pulse shape is not a rectangle but a smoothed shape, making a shorter pulse length in smaller voltage (i.e., smaller particle).

   Although we can not manage this issue technically, we can estimate the expected relationship between pulse intensity (I_{55}) and pulse length (PSW) and compare the observed results. Now, we assume the pulse shape is not a rectangle but a sine curve due to the heterogeneity of the laser beam. Considering the I_{55} is recorded under condition > 0.3V, the following condition would hold:

   $$\frac{I_{55}}{2} \times sin(2\pi(\frac{PSW_o}{PSW_e} + 0.25) + 1) = 0.3 \quad (1)$$

   Here, PSW_o and PSW_e are observed and expected PSW, respectively. As an ideal case, the condition of PSW_e=1.0 is considered here. The examples of the pulse shape are shown in Fig. 3. The smaller pulse intensity provides a short pulse length. The relationship between I_{55} and PSW_o derived using Eq. (1) is shown in Fig. 4a (a black line). The data observed in the Arctic regions are mostly on the black line, suggesting that the CPS counted the particles as a single particle in case of the smaller

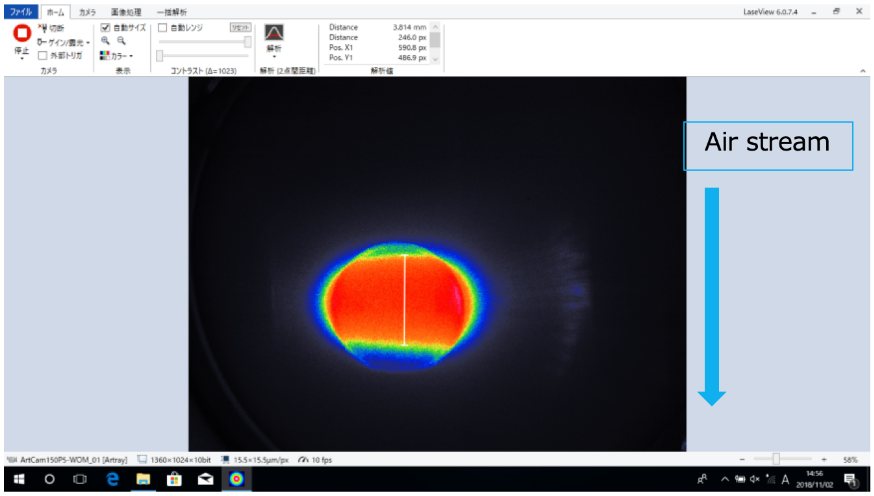

Figure 1: A capture image of beam intensity in the CPS inlet across the air stream using a beam profiler. (provided by SHINYEI Technology, Co., Ltd.)

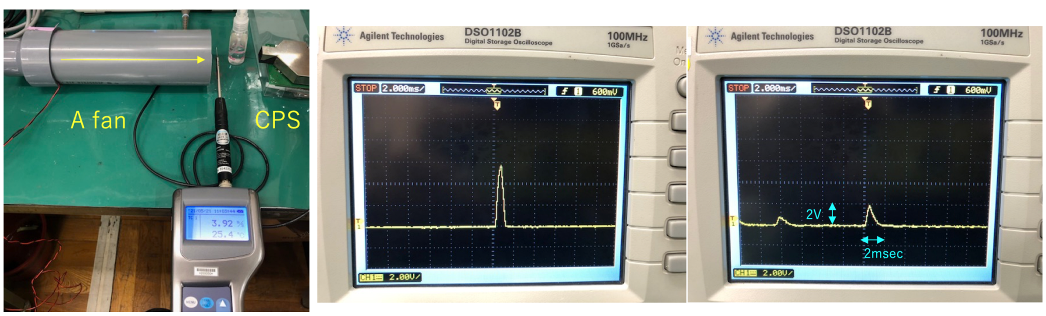

Figure 2: Pulse shapes observed by an oscilloscope in a laboratory. (provided by MEISEI Electric, Co. Ltd.)

pulse intensity ($I_{55} < 3$ V). For the larger pulse intensity ($I_{55} > 3$ V), the overlapping would occur but was not significant for our data (Arctic regions).

Because the shorter PSW_o for smaller particles allows counting the more particles in a unit time, we can also estimate the countable particle number in a unit time (e.g., 1 sec). Fig. 4b shows the upper limit for the countable particle numbers as a function of I_{55}. If the background number concentration is very low (e.g., 1000 particles s^{-1}, a black line in Fig. 4b), then every size can be detected as a single particle. In the case that the concentration is relatively high (e.g., $> 2000\ s^{-1}$), however, particle overlap is potentially expected for the larger particles. In such a situation, the value of PSW_o can be considered an overlap factor for particle overlap. In our case, the background number concentration is low (typically <1500 particles^{-1}) and the majority of the observed particles have relatively small sizes; thus, the effect of the overlap factor (around 1.5 or less) on estimating the total count is relatively small compared with

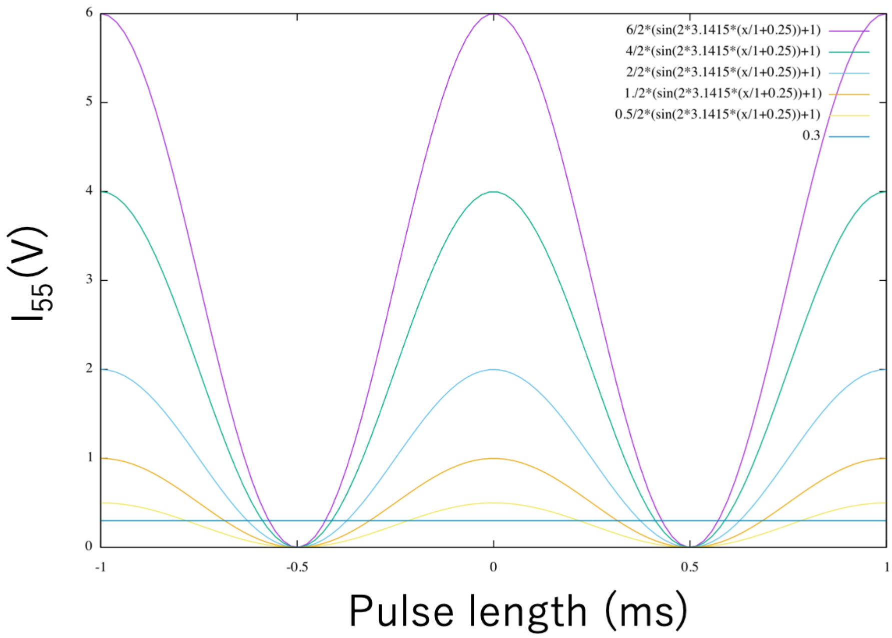

Figure 3: Examples of pulse shapes estimated by Eq. (1).

the effect of collection factor (=7.5).

This discussion has been included in a new section of ”5.4 Limitation of CPS sondes.”

2. *Poor statistics on particle size and shape.*

   The second issues, that of poor statistics on particle size and shape, concerns how effective radius, LWC and shape are derived. The data transmission rate, according to the authors and manufacturer, is 25 bytes/second. The manufacturer has chosen to use this to transmit size and shape information for only the first six detected particles each second. According to the drawings, the sensitive sample area presented to particles in the inlet is 1 cm2. Since the flow velocity is approximate 5 ms-1, this means that the CPD will be detecting approximately 500 cm3 per second. Even if the cloud concentrations are very small, for example 10 cm-3, this will be 5000 particles/second. If the CPD can only transmit size information on the first six out of these 5000 particles, this is only 0.12% of the particles. Statistically speaking, the probability that these 6 particles represent the parent population is less than 1%. This by itself makes the CPD of limited use, but what is even more unfortunate is that the size that is derived from these six particles will be heavily biased toward smaller sizes, give the generally log normal size distribution of droplets in cloud where smaller droplets dominate the number concentration, i.e. the first 6 particles samples will mostly likely be in the smallest droplets. Likewise, in a mixed phase cloud, the liquid phase will predominate so that the polarizatio ratio will be biased

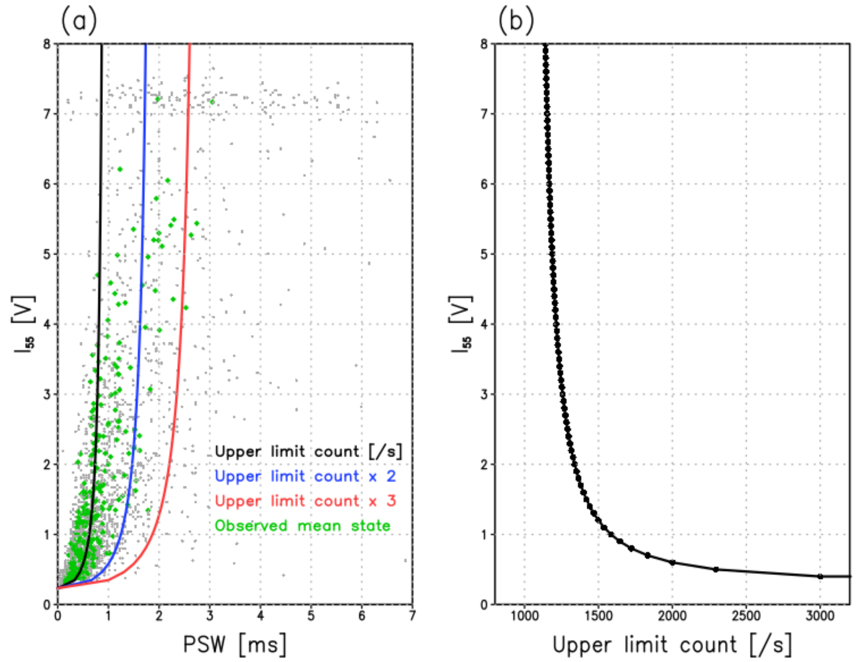

Figure 4: (a) Estimated relationship between PSW and I_{55} (a black line) in case of PSW_e = 1.0. Blue and red lines indicate the overlap factor to correct the count for each situation of the number concentration. Gray dots are the same plot in Fig. 6 of the main text. Green dots indicate the mean state for each second after applying cut-off value of PSW (PSW_c). (b) Upper limit of countable particle number as a function of I_{55} in case of PSW_e = 1.0.

toward the droplets rather than ice.

In our observations, the typically observed counts were around 2000 L^{-1}, which corresponds to 1000 particles s^{-1}. Because the phase-detection depends on the first six particles per second (i.e., 0.6 % of 1000 particles), the representation of size distribution in every second might be insufficient. However, the fact that the corrected number concentration matched with the OPC measurements reveals that the correction method in this study would be applicable for the clouds under relatively low number concentration without particle overlapping. The reason would be related to the collection efficiency of the CPS housing. Considering the collection efficiency of 13.3% derived from section 3.4, the number of expected particles pass across the CPS inlet would be 133 particles s^{-1}. Considering that it usually takes tens of seconds to observe a few hundred-meter-thick clouds, it should be noted that each first six particles during the assent are not selectively counted. Assuming the mean state of the clouds in five seconds (i.e., a 25-m thick cloud layer), 30 particles are available for estimating the size and phase of particles (more than 20% of expected particles). This condition represents the total size distribution under a 90% significant level with 10% permissible error. Of course, one should pay attention to the clouds when high number concentrations and larger particles are expected. In mixed-phase clouds, the liquid phase droplets might predominate due to smaller particles, introducing the biased DOP value toward the droplets rather than ice. Choice of the DOP threshold between ice and liquid is also challenging (in this study, 0.5 was proposed as the DOP threshold). Overall, the instantaneous value obtained by the CPS sonde does not represent the cloud characteristics at the level sufficiently, in particular under relatively higher number concentration with larger droplets; however, the situation under relatively lower number concentration with smaller droplets allows the CPS sondes to measure the mean state of the clouds.

This discussion has been included in a new section of ”5.4 Limitation of CPS sondes.”

What is puzzling is why the manufacturer chose to waste the limited data transmission by sending individual article information. They could have instead, compiled a size distribution of 5 or 6 channnels, with increasing width. 25 bytes is 200 bits. 12 bits is 4096 counts, so that a size distribution, percentage of ice and some housekeeping could have been encoded much more efficiently thatn the current configuration.

The manufacturer considers updating the system to be able to count more particles efficiently in the near future.

3. Other modifications

   Based on the discussion in section 5.4, we modified several sentences in the abstract, conclusion, and Fig. 13.

Reply to Reviewer #3

We would like to thank you for providing helpful comments regarding our manuscript. We substantially modified the content based on Reviewer #1, who asked us the shape of the beam and the resultant effect on the particle counts. We communicated with the manufacturer regarding the shape of the pulse and added one discussion paragraph (section 5.4: Limitation of CPS sondes) to reply to the referee's comments.

Replies to minor comments:

- Subsection 5.1: Were there no satellite overpasses during the field campaign and in particular in spatial and temporal proximity of the balloon launches? Using some satellite remote sensing data to compare with the observations is probably more useful than using a reanalysis from a global circulation model.

  Thank you for the suggestion. Initially, we tried to find opportunities for simultaneous observations with the CloudSat path. However, we were not able to match the satellite path. The validation with other observing systems is, of course, desirable for future campaigns.

- Subsection 5.2: Is there a possibility to put particles of arbitrary size randomly in the CFD modeling data? By putting particles into the flow, it would be possible to elucidate how much the measured data would be affected by sub-isokinetic sampling and if the applied detectability assumptions and the applied correction factor make sense for the actual liquid water path. These numerical experiments are not super complicated and can help a lot to understand how the actual particle size distribution relates to the measured particle size distribution. If the CFD model does not support tracer particles, using the sub-isokinetic flow and its effect on the particles in combination with Monte-Carlo simulations of particles in a volume could be a fallback option to quantify the measurement uncertainties more thoroughly.

  Thank you for providing us an idea to reduce the uncertainties of the collection factor. Unfortunately, our CFD model does not support tracer particles for putting the random size particles. So far, we have concentrated on estimating the collection factor using CFD; however, Reviewer #1 consistently insisted that we confirm the CPS beam geometry and its effect on the particle count. Therefore, an additional discussion paragraph was made in the 2nd revised version. The finding is that there are at least two types of correction factors: the first one is the collection factor related to the CPS housing, the other one is an overlap factor originated from the heterogeneity of the CPS beam. Based on the idealized estimation of pulse intensity (I_{55}) and pulse length (PSW), we found that the smaller particles tend to be observed frequently, although the inertial force is smaller than that of larger particles in front of CPS inlet. Therefore, the mixed effect in the observed size distribution makes the further quantification of the collection factor complicated. This would be strong guidance toward the manufacturer for further developing the CPS sondes shortly.

- Other modifications

  Based on the discussion in section 5.4, we modified several sentences in the abstract, conclusion, and Fig. 13.