Unshielded precipitation gauge collection efficiency with wind speed and hydrometeor fall velocity. Part II: experimental results

Author Response to J. Kochendorfer (Referee #2)

General comments

Part II of, "Unshielded precipitation gauge collection efficiency with wind speed and hydrometeor fall velocity" is the experimental companion to the Part I paper, which describes a modelling experiment. Part II tests the transfer function created in Part I, and it goes further to modify this transfer function based on the experimental results. It demonstrates that hydrometeor fall velocity can be used in a practical way to improve the adjustment of unshielded precipitation measurements. These improvements are impressive and significant.

Like Part I, the manuscript is well-written and easy to follow, and it is definitely worth publishing.

Authors' response: Thank-you!

Specific comments

Ln. 65 – 67. This is a misinterpretation of those results. In addition to the uncertainty of the adjustment, it overlooks the fact that adjusted measurements increase the magnitude of errors multiplicatively. For example, if the gauge measurement has an inherent uncertainty of 0.1 mm, with CE = 0.5, after adjustment the uncertainty will be doubled along with the measurement. Two single Alter gauges agreeing with each other with an uncertainty of 0.09 mm does not imply that they can be adjusted without increasing the uncertainty. I accept that there is significant room for improvement in our transfer functions, but I find it very difficult to believe that adjusted unshielded measurements will ever be as accurate as well-shielded measurements. I am afraid that someone reading between the lines here might take that to be the suggestion.

Authors' response: Dr. Kochendorfer makes a good point here. We will remove the reference to the comparison of replicate configurations of weighing gauges (Ln. 65-67).

Ln. 112. Change, "using similar methodology" to, "using *a* similar methodology" or, "using similar *methods*."

Authors' response: Updated to "using a similar methodology".

Ln. 172 and Eq (2). Why was *h* chosen for precipitation, instead of *P*?

Authors' response: *h* was originally chosen to refer to precipitation accumulation as a height in units of mm. *h* has been revised to *P* to make the linkage with precipitation clearer and to match the terminology of previous publications. Thank-you.

Ln. 269 – 270. This makes me wonder about the details and physics of the POSS averaging. How is the hydrometeor fall velocity calculated by the POSS when there is mixed precipitation, and/or when there is significant variability in the types of hydrometeors simultaneously present? I am guessing that for the purposes of transfer functions, ideally the fall velocity would be representative of the total mass of water falling, but perhaps it is actually weighted towards the average by volume?

Authors' response: The POSS is an X Band (3cm wavelength) radar that measures the Doppler velocity spectrum from which the hydrometeor size distribution is derived. This has been described in detail in previous publications, including its use for precipitation typing; we refer the reviewer to the following publications for the details (Sheppard, 1990; Sheppard and Joe, 1994, 2000, 2008). The advantage of the POSS is that it rapidly measures the Doppler spectrum from a very large volume compared to other disdrometers, which measure individual particles with more limited sampling (e.g. Thies LPM, OTT Parsivel2). For large hydrometeors (say 5 mm), the sample volume is about the size of a small room. Several hundred Doppler/hydrometeor spectra are measured and reported every minute. There is on-ongoing research for snow and mixed precipitation type retrievals. We agree that ideally, the fall velocity would be representative of the total mass of water falling, but the complexities of hydrometeor drag, density, and mass are confounding factors still to be resolved. While the present approach of estimating the event fall velocity from the 30-minute average appears to perform well overall, further study to better characterize the fall velocity distribution and changes over 30-minute time periods could lead to further improvements in the model under specific conditions such as mixed precipitation.

Ln. 289. I apologize in advance, because I hate it when reviewers ask me these types of questions, but how was the threshold fall velocity of 1.93 m s^{-1} selected?

Authors' response: The threshold of 1.93 m s^{-1} was determined by varying the fall velocity threshold in 0.01 m s^{-1} increments over the measurement fall velocity range in Table 2. This mean fall velocity threshold provided the lowest RMSE for the HE1 transfer function. A similar approach was used to derive the fall velocity threshold for HE2. We will add this information to the manuscript.

Equation 7b. Given my comments on Part I this should come as no surprise, but I think that defining CE = 0.0 any under conditions is problematic.

Authors' response: Dr. Kochendorfer raises an important issue with the definition of the collection efficiency at high wind speeds in the transfer function. The authors recommend revising Eq. 7b, Table 1, and Fig. 4c for HE1 with a minimum collection efficiency of 0.2 and wind speed threshold of 5.75 m s^{-1}, following the general approach of Kochendorfer et al. (2017).

Ln. 299. Clarify that *CEHE2* decreases linearly with wind speed *at a given/fixed hydrometeor fall velocity*.

Authors' response: Updated. Thank-you.

Ln. 299 – 300. Explain how this works in practice. How were measurements that occurred when fall velocity was defined as zero treated? Were they simply removed from the analysis? How is the user of these functions supposed to adjust such measurements?

Authors' response: Over the test period there were no fall velocities of zero reported by the POSS and 30-minute mean fall velocities were ~1 m s^{-1} or higher. During non-precipitating periods the POSS does not output a fall velocity and these periods are not included in the 30-minute average. While fall velocities of zero were not encountered during this study, and would not be expected in general, the *HE2* transfer function is still defined in this case. In the case of zero fall velocity the collection efficiency decreases with wind speed alone as shown in Eq. 8a. In this case the collection efficiency decrease with wind speed will be faster than that for conditions where the fall velocity is higher.

Ln. 314 – 315, Figure 4 caption. Typo. I believe that the three occurrences of "*up*" in,"fall velocity *up* categories…" should be replaced with "*uf*".

Authors' response: Updated. Thank-you.

Ln. 352. Why wasn't the same temperature threshold technique used for *KUniversal*? At the risk of personifying a, "get off my lawn" attitude, I wonder how much of the improved performance of the *KCARE* adjusted measurements were caused by large errors in measurements that were over-adjusted using *KUniversal* above this temperature threshold? The largest improvement in RMSE includes some of these measurements, when T is between positive and negative 2 deg C (Table 8), and I am guessing that at least some of the very poorly measurements were warmer, larger events (Fig. 5b).

Authors' response: *KUniversal* was developed from the WMO-SPICE results for eight test sites and is used for comparison with the present study results from the CARE field test site. Modifications to *KUniversal* using the temperature threshold technique would need to be assessed based on the entire dataset (all eight sites) and is beyond the scope of this study. *KCARE* is developed from the CARE dataset for comparison with the site-specific fall velocity transfer functions developed in this study. Both *KUniversal* and *KCARE* are similar at colder temperatures but differ as the temperature increases. The improvement in the *KCARE* transfer function results are primarily attributed to this more rapid increase in collection efficiency with temperature, reducing the overadjustment of some events and increasing the underadjustment of some events between -5 °C and -2 °C and between -2 °C and 2 °C (as shown in Fig. 5 and Table 8). It is important to note that even the *KCARE* transfer function exhibits increased uncertainties at these warmer temperatures relative to transfer functions using fall velocity, as rain, mixed precipitation, and snow can occur with different collection efficiencies. These differences cannot be distinguished using temperature alone, resulting in increased uncertainties at these temperatures.

Ln. 504. A realistic vertical wind profile, with a zero-slip boundary condition at the Earth's surface, may be important for larger wind shields.

Authors' response: Thank-you. This is an important point for studying other shield and gauge combinations in the future. This note will be added to the manuscript.

Ln. 507 – 509. I agree that it is difficult to accurately adjust measurements at windy sites, but the 'limitation' described here is entirely avoidable. The collection efficiency was defined as zero above 7.19 m s-1 by choice, not by necessity.

Authors' response: We will revise the discussion for the HE1 transfer function to include a transfer function minimum collection efficiency of 0.2 for wind speeds above 5.75 m s^{-1} following the general approach of Kochendorfer et al. (2017).