

1 Unshielded precipitation gauge collection efficiency with wind speed 2 and hydrometeor fall velocity. Part II: experimental results

3 Author Response to Anonymous Referee #1

4 This manuscript shows that the RMSE of the collection efficiency can be significantly reduced if the fall speed derived from
5 the Precipitation Occurrence Sensor System (POSS) is used. The paper is well written and shows new findings as the POSS
6 can be used to improve the adjustment of solid precipitation. Nevertheless, I think that the text could be more concise for
7 clarity and key information are missing. They are listed below. I recommend major revisions.

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9 Major comments:

10 1. Introduction:

11 i) A few references are missing. 1) Colli et al. (2020) should be added to the paragraph discussing methods to improve the
12 adjustment of solid precipitation. Colli et al. (2020) showed that the precipitation intensity improvements the adjustment of
13 solid precipitation at given wind speed. 2) Chubb et al. (2015) also proposed that the precipitation rate as could be used to
14 adjust solid precipitation measurements.

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16 Colli, M., Stagnaro, M., Lanza, L. G., Rasmussen, R. and Thériault, J. M. (2020). Adjustments for wind-induced undercatch
17 in snowfall measurements based on precipitation intensity, *Journal of hydrometeorology*, 21, 1039-1050.

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19 Chubb, T., Manton, M. J., Siems, S. T., Peace, A. D., & Bilish, S. P. (2015). Estimation of Wind-Induced Losses from a
20 Precipitation Gauge Network in the Australian Snowy Mountains, *Journal of Hydrometeorology*, 16(6), 2619-2638.

21 **Authors' response:** We thank the reviewer for identifying these references, and will add them to the introduction.

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24 ii) What is the goal of the study? A summary of the methodology is given in the last few paragraphs but it never stated the goal
25 clearly.

26 **Authors' response:** We will state the goal of the study more clearly in the introduction: "In this work, transfer functions
27 incorporating hydrometeor fall velocity are developed to reduce the uncertainty (RMSE) in collection efficiency and
28 precipitation accumulation estimates from unshielded Geonor T-200B3 precipitation gauges." The authors also propose stating
29 the goal earlier in the introduction, instead of only in the last paragraph.

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32 2. The methodology section is incomplete.

33 i) a description of the CFD simulations is missing. The relevant information from Part 1 should be added to the methodology
34 of this manuscript.

35 **Authors' response:** We recommend that a brief description of the CFD model and simulations is added to the methodology
36 introducing the CFD transfer function (Sect. 2.4). We are wary of too much overlap with the Part I manuscript, which includes
37 a detailed description of the CFD model and simulations. Within the present manuscript (Part II), the CFD transfer function is
38 presented in the introduction (ln. 96-101) and methodology (ln. 208-216), with reference to the Part I manuscript.

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41 ii) A description of the method used to develop the transfer functions, in particular, the fall speed threshold values given in
42 Section 3.1 should be added.

43 **Authors' response:** We will clarify this in the manuscript. The fall velocity and temperature ranges presented by precipitation
44 phase in Section 3.1 (Table 2) summarize the event-based experimental observations from the POSS and a temperature sensor
45 in an aspirated shield, respectively, and are independent from the methodology used to develop the transfer functions. The
46 descriptions of the methods used to develop the HE1 and HE2 transfer functions in Section 3.3 should be expanded to include
47 more detail regarding the fall velocity threshold values. For the HE1 function, the fall velocity threshold was varied over the
48 measured fall velocity range in 0.01 m s^{-1} increments, with the threshold of 1.93 m s^{-1} found to provide the lowest overall
49 RMSE for the experimental dataset. For the HE2 transfer function, the fall velocity threshold was varied over the measurement
50 fall velocity range in 0.01 m s^{-1} increments, with the threshold of 2.81 m s^{-1} found to provide the lowest overall RMSE. Details
51 regarding the wind speed threshold for the CFD transfer function are provided in the Part I manuscript (Sect. 3.3), but can be
52 reiterated in Section 2.4 of the present manuscript for clarity. For the KCARE transfer function, ln. 202-205 in the manuscript
53 describes the methodology for determining the temperature threshold T_i .

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56 3. Section 3.1: How are the air temperature and fall speed threshold values determined in the study?

57 **Authors' response:** The derivation of the air temperature and fall velocity thresholds used in the study are addressed in the
58 response to comment 2ii above.

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61 In Table 2, the fall speed values for the precipitation type categories overlap. For example, snow events could also be mixed
62 events if the temperature is $<0.5 \text{ }^\circ\text{C}$ and the precipitation falls at $< 2.32 \text{ m/s}$. It should be clarified in the text.

63 **Authors' response:** We agree to clarify this in the text. In Table 2, the temperature and fall velocity values are stratified by
64 the 30-minute precipitation type classification determined from the minutely POSS precipitation type output following the

65 methodology outlined in Sect. 2.3. As noted in the above response (comment 2ii), the experimental results summarized in
66 Table 2 and plotted in Figure 1 are not used to determine threshold values for transfer functions. These results are presented
67 in Section 3.1 to illustrate how multiple precipitation types, with different fall velocities, can be present within a given
68 temperature range, presenting a challenge for transfer function methods distinguishing different precipitation types by
69 temperature. The fall velocity thresholds for HE1 and HE2 were determined empirically to best capture the trends in
70 experimental results by minimizing the RMSE.

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73 4. Why not using the temperature thresholds used in Kochendorfer et al. 2017b, which are -2_C to +2_C, to discriminate the
74 precipitation types? Those are the threshold commonly used in the literature.

75 **Authors' response:** The results in this study illustrate the challenges of using ambient temperature as a proxy for precipitation
76 type, as multiple precipitation types – with different fall velocities – can be present within a given temperature range.
77 Precipitation types and fall velocities in this study were determined from the POSS instrument as described in Sect. 2.3. Fig.
78 1 shows the event-based results with 30-minute mean surface air temperature and fall velocity by POSS precipitation type
79 classification. It is apparent that in this -2 °C to +2 °C temperature range, a wide range of fall velocities and precipitation types
80 can be present. Accordingly, there is significant scatter in the collection efficiency results with respect to wind speed for this
81 temperature range, as shown in Fig. 2c.

82 The results in Tables 5 and 7 demonstrate that collection efficiencies and adjusted precipitation accumulation can be
83 determined with greater certainty (lower RMSE) at these temperatures using adjustments based on wind speed and fall velocity
84 relative to adjustments based on wind speed and temperature. The use of fall velocity provides a quantitative means for
85 adjustments to be performed across precipitation types (for example, mixed precipitation with a range of fall velocities) and
86 enables adjustments to be performed even under conditions where the precipitation type may be unknown or difficult to
87 determine (e.g. 'undefined' events).

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90 Minor comments:

91 1. Lines 81-83: Change hydrometeor type for “type of solid precipitation” or “type of snow” because the study was done for
92 solid precipitation. Add "fall speed" to the sentence because that is a key parameter of the study. The revised sentence could
93 be: “Theriault et al. (2012) demonstrated similar trends for snowfall, with collection
94 efficiencies varying significantly with the type of solid precipitation, fall speed and size distribution.”

95 **Authors' response:** We apologize for any confusion – this statement was made within the context of previous work involving
96 CFD simulations. The simulations presented in Theriault et al. (2012) investigated how collection efficiency varies with wind
97 speed depending on the specific snowflake type and selected slope size distribution value. Here, we can change “hydrometeor

98 type” to “type of solid precipitation,” as proposed. The linkage of the simulation results to theoretical terminal velocities
99 computed for snowflakes that were collected and photographed is captured in lines 82 to 84 of the present manuscript.

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102 2. Lines 171-173: The transfer function uses the accumulated precipitation while the CFD simulations uses the precipitation
103 intensity. Clarify this possible inconsistency.

104 **Authors’ response:** The CFD simulations are based on time-averaged simulation results and the collection efficiency is
105 derived from the ratio of the precipitation intensity captured by the gauge to the true precipitation intensity falling in air.
106 Integrating over a period of time (in this case 30-minutes) gives the collection efficiency as a function of the ratio of the
107 precipitation accumulation captured by the gauge to the true amount.

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110 3. Equation 3: Could you explain why this equation is relevant? If not, remove it.

111 **Authors’ response:** Equation 3 shows how the uncertainty in the experimental collection estimate scales with the magnitude
112 of precipitation accumulation for rain, as shown in Fig. 2a and discussed in Section 3.2. It is apparent from Eq. 3 and the results
113 in Fig. 2a that as the measured precipitation accumulations become smaller and approach the precipitation gauge measurement
114 uncertainty, the uncertainty in the measured collection efficiency estimates can become quite large. This is an important point
115 for understanding a component of the scatter in the collection efficiency results in Figs. 2b, 2c, and 2d, which is not readily
116 apparent when collection efficiency results are plotted as a function of wind speed.

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119 4. Lines 287-292: Why using 1.93 m/s as a threshold? It should be explained.

120 **Authors’ response:** We will update Sect. 3.3 with this explanation. The threshold of 1.93 m s⁻¹ was determined by varying
121 the fall velocity threshold in 0.01 m s⁻¹ increments over the measurement range of fall velocities (Table 2). This mean fall
122 velocity threshold provided the lowest RMSE for the HE1 transfer function.

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125 5. Lines 296-301: Why using 2.81 m/s as a threshold? It should be explained.

126 **Authors’ response:** We will update Sect. 3.3 with this explanation. The threshold of 2.81 m s⁻¹ was determined by varying
127 the fall velocity threshold in 0.01 m s⁻¹ increments over the measurement range of fall velocities (Table 2). This mean fall
128 velocity threshold provided the lowest RMSE for the HE2 transfer function.

131 6. Figure 4: Did you try using boxplots instead of a scatter plot to show the collection efficiency? It could give an idea of the
132 scatter in the collection efficiency with wind speed.

133 **Authors' response:** Yes, this approach was considered. While the use of boxplots is useful for summarizing the distribution
134 of collection efficiencies across wind speed classes, or even wind speed and other classifications, it makes it more difficult to
135 trace the results for specific events across different classifications (e.g. precipitation type, temperature, and fall velocity)
136 because the events become lumped into boxes with only outliers shown. For example, looking at Fig. 2a, the two collection
137 efficiencies for rain above 1.3 correspond with very small accumulation values as discussed earlier (i.e. their values approach
138 the gauge measurement uncertainty). Looking at Fig. 2b, these events occur near 2 m s^{-1} and 5 m s^{-1} . Fig. 2c shows that one of
139 these events is between $-2 \text{ }^{\circ}\text{C}$ to $2 \text{ }^{\circ}\text{C}$ and one event is above $2 \text{ }^{\circ}\text{C}$. Fig. 2d shows that both of these events have fall velocities
140 above 2.5 m s^{-1} . The RMSE values summarized in Tables 3, 5, 6, 8, and 9 provide a useful measure of the scatter, as they
141 capture the spread/scatter between the measurement and transfer function as the transfer functions change continuously with
142 wind speed and temperature or fall velocity.

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145 7. Tables 3 to 9 could be put in an Appendix since that it is showing additional information. One could also do barplots instead
146 of Tables.

147 **Authors' response:** The authors appreciate the suggestion, but strongly recommend that Tables 3 to 6 remain in results Sect.
148 3.4 (Assessment of transfer functions: collection efficiency) and Tables 7 to 9 remain in results Sect. 3.5 (Assessment of
149 transfer functions: precipitation accumulation). The results in Table 3 capture the overall transfer function results and
150 demonstrate the improvement in the fall velocity transfer functions relative to current adjustments based on wind speed and
151 temperature. The other Tables demonstrate collection efficiency and precipitation accumulation RMSE by precipitation type,
152 temperature and fall velocity classifications, linking with the results and discussion associated with Figs. 4 and 5. The use of
153 Tables instead of bar plots has the advantage that the specific RMSE values are clearly shown for comparison with future
154 studies.

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157 8. Lines 477-479: The sentence: "While automatic . . . this work" seemed out of place. It may be better in the conclusion?

158 **Authors' response:** We feel that this statement fits best within the context of the Discussion, where it follows the discussion
159 of the time periods and accumulation thresholds used in this and other work, and establishes boundaries for the scope of this
160 work. We agree that it could also work well in the Conclusions section, but it would be more challenging to establish the same
161 context in that case.

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163 9. Line 505: The sentence: “The HE1 transfer function showed good results for snow, supporting its use for unshielded gauge.”.
164 I agree but Figure 3b (as an example) still shows lots of scatter in the collection efficiency for fall speeds associated with
165 snow/solid precipitation ($_1-2\text{ m/s}$). Add a short discussion?

166 **Authors’ response:** This is a good point, and one that we believe is already discussed in the manuscript. Based on the 0.10
167 collection efficiency RMSE for snow events as identified by the POSS in Table 4, the HE1 transfer function showed good
168 results, as stated in line 505. Looking at the 0.10 collection efficiency RMSE for HE1 at fall velocity values $\leq 1.5\text{ m/s}$ in Table
169 6 tells a similar story. However, in line with the reviewer’s point, the collection efficiency RMSE for HE1 in Table 6 is higher
170 (0.15) for events with fall velocity values between 1.5 m/s and 2 m/s. This higher RMSE value for HE1 is consistent with that
171 for events classified as mixed precipitation in Table 4. This limitation of HE1 is noted and discussed in lines 516-521 of the
172 manuscript.

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175 10. Lines 537-539: This sentence is not quite right and I think that it is an important point. The references from Kienzle (2008)
176 and Harder and Pomeroy (2013) should be after the word “instructive” because they developed a method to diagnose the
177 precipitation phase at the surface when the information aloft is not available. Theriault et al. (2012) suggested to use surface
178 temperature but did not develop a method to diagnose the type/phase of precipitation. At the end of the sentence, the authors
179 should refer to a paper that state the importance of the atmospheric conditions aloft to determine the type/phase of precipitation
180 at the surface such as for example Stewart et al. (2015).

181 Stewart, R. E., J. M. Theriault, and W. Henson, 2015: On the characteristics of and processes producing winter precipitation
182 types near 0_C. Bull. Amer. Meteor. Soc., 96, 623–639, doi:10.1175/BAMS-D-14-00032.1.

183 **Authors’ response:** Thank-you for pointing this out. We will update the references as suggested to improve the clarity of this
184 sentence.