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

Author Response to Anonymous (Referee #1)

Authors' response: We respect the reviewer's perspective and the candid nature of their responses, the central theme of which is the perceived unoriginality of the method used in this study the results presented. In the responses that follow, we will articulate how the present work builds upon previous studies in new ways, with novel and impactful results.

This study proposes that fall speed influences the collection efficiency of unshielded gauge using computation fluid dynamics (CFD). The authors claim that they are using a new method to study gauge collection efficiency and, with this method, that they are the first to demonstrate the impact of fall speed on the gauge collection efficiency.

Authors' response: This is the first CFD study to develop a universal collection efficiency transfer function based on wind speed and hydrometeor fall velocity, which is broadly applicable, novel, and important. The hydrometeor fall velocity can be measured by a variety of instruments for both rain and snow and the use of this transfer function can dramatically improve experimental collection efficiency estimates as shown in Part II. Previous studies have certainly used CFD to study gauge collection efficiency for shielded and unshielded gauges, and have attributed differences in results to differences in hydrometeor characteristics, including fall velocities. These studies are described and referenced clearly in the manuscript. This manuscript presents a new method in that it is the first CFD modelling study to: (1) characterize precipitation gauge collection efficiency explicitly in terms of wind speed and fall velocity; (2) show that collection efficiencies are similar for different hydrometeor types with identical fall velocities; and (3) develop a universal transfer function based on wind speed and hydrometeor fall velocity. We will revise the manuscript to better highlight the innovations.

In fact, these have already been done with a similar approach:

1) Thériault et al. (2012), Colli et al. (2016a,b) used CFD to study gauge collection efficiency for snow.

Authors' response: Neither of these studies develops a collection efficiency transfer function with wind speed and hydrometeor fall velocity.

Thériault et al. (2012) developed transfer functions with wind speed for specific hydrometeor types (radiating assemblage of plates, dendrite, heavily rimed dendrites, hexagonal plates, lump graupel, dry snow, and wet snow), with a different transfer function for each hydrometeor type. The contribution of Thériault et al. (2012) is captured in the current manuscript in a number of places (ln. 69-79, 91-93, 469-471, 492-495, 501-503, 562-564, 568-570, and 596-597). Colli et al. (2016a,b) did not develop a collection efficiency transfer function.

There are also other studies that have used CFD to study gauge collection efficiency for rain and snow, including the work of Nešpor and Sevruk (1999), Colli et al. (2015), Baghapour et al. (2017), and Baghapour and Sullivan (2017), as described in the manuscript. These studies also did not develop a collection efficiency transfer function with wind speed and hydrometeor fall velocity.

Further, the details of the modelling approach used in the present study differ from those used in the previous studies identified by the reviewer. These differences are discussed in the manuscript (Sect. 4.1, 4.2, and 4.4.1) and are summarized in Table A1, below.

Table A1: Summary of Thériault et al. (2012), Colli et al. (2016a,b), and present study numerical collection efficiency models.

	Thériault et al. (2012)	Colli et al. (2016a,b)	Present study
Numerical model	Reynolds-averaged Navier-Stokes (RANS) k-ε	Reynolds-averaged Navier-Stokes (RANS) k-ω, Large-eddy simulation (LES)	Favre-averaged Navier-Stokes (FANS) k-ε
Gauge	Geonor T-200B	Geonor T-200B	Geonor T-200B
Gauge geometry (orifice)	Not specified ~1 cm orifice thickness	Not specified ~1 cm orifice thickness	Refined orifice thickness (3.15mm) and length (360 mm) to match actual gauge
Shield	Single-Alter	Unshielded, Single-Alter	Unshielded
Mesh	0.35 M cells	Tetrahedra and prisms, 1.5 M – 29.5 M cells	Structured, 8.3 M cells
Inlet turbulence intensity	Not specified	0 %	5 %
Precipitation type	Dry snow, wet snow, radiating assemblage of plates, hexagonal plates, dendrite, graupel, and heavily rimed dendrite	Dry snow, wet snow	Orographic rain, thunderstorm rain, dry snow, wet snow, ice pellet, snow, dendrites, rimed dendrites, columns and plates, dendrites and aggregates of plates

Hydrometeor model	Lagrangian uncoupled	Lagrangian uncoupled	Lagrangian uncoupled
Drag coefficient	Constant over hydrometeor trajectory	Constant over hydrometeor trajectory	Drag varies with relative hydrometeor to air velocity over trajectory
Injection plane	Not specified	Vertical	Horizontal
Model parameters studied	Wind speed, precip type, hydrometeor size distribution, turbulence	Numerical model, wind speed, precip type, hydrometeor size, shielding	Wind speed, fall velocity, precip type, precip intensity
Collection efficiency definition	$CE = \frac{\int_0^{D_{\max}} A_{inside}\left(D\right) N\left(D\right)}{\int_0^{D_{\max}} A_{gauge}\left(D\right) N\left(D\right)}$	$CE = \frac{\int_0^{d_{P\max}} V_w\left(d_p\right) A_{inside}\left(d_p, U_w\right) N\left(d_p\right) d_p}{\int_0^{d_{P\max}} V_w\left(d_p\right) A_{gauge} N\left(d_p\right) d_p}$	$CE_{\mathrm{R,Overall}} = \frac{\int_0^\infty CE\left(u_{\mathrm{w}}, u_{\mathrm{f}}\right) D^3 N_R\left(D\right) u_{\mathrm{f}}\left(D\right) \mathrm{d}D}{\int_0^\infty D^3 N_R\left(D\right) u_{\mathrm{f}}\left(D\right) \mathrm{d}D}$ $CE_{\mathrm{S,Overall}} = \frac{\int_0^\infty CE\left(u_{\mathrm{w}}, u_{\mathrm{f}}\right) D^3 N_{\mathrm{S}}\left(D\right) u_{\mathrm{f}}\left(D\right) \mathrm{d}D}{\int_0^\infty D^3 N_{\mathrm{S}}\left(D\right) u_{\mathrm{f}}\left(D\right) \mathrm{d}D}$
Derived transfer function	$\mathrm{CE}_{\mathrm{snow}}$ = f(wind speed) with unique transfer function for specific solid precip types	None	$\mathrm{CE}_{\mathrm{rain\&snow}}$ = f(wind speed, hydrometeor fall velocity) universal transfer function across rain and snow precip types Derived fall velocity cutoff for zero collection efficiency

2) Colli et al. (2016a) were the first to compute the flow field near an unshielded gauge as performed in this manuscript.

Authors' response: The Colli et al. (2016a) study is clearly referenced in the Part I manuscript (ln. 96-102). There is no claim that the present study is the first to compute the flow field near an unshielded gauge. Results using the approach from Colli et al. (2016a) are compared with those from the model used in the present study (see Figure 8 and discussion in Sect. 3.4.1), with differences in results between the studies attributed to differences in the models and approaches used.

3) Thériault et al. (2012) found a strong dependence between the gauge collection efficiency and fall speed. Indeed, it was conducted with a shielded gauge but the physical reasons are the same. The updraft upstream of the gauge tends to deviate

the slow-falling particles to fall in the gauge. For the same horizontal wind speed, slow-falling snowflakes have lower collection efficiency than faster-falling ones.

Authors' response: The authors recognize that the theoretical basis for how hydrometeor fall velocity can influence collection efficiency has been established using CFD simulations in Thériault et al. (2012) and other studies, and have discussed and referenced these studies in the present manuscript.

As noted above, the work of Thériault et al. (2012) is captured in the current manuscript in a number of places (ln. 69-79, 91-93, 469-471, 492-495, 501-503, 562-564, 568-570, and 596-597). This work concluded that "snowflakes fall at different terminal velocities and therefore interact differently with the deflected flow around the snow gauge," and discussed the importance of hydrometeor terminal velocity on the collection efficiency results for different crystal types. The results from the present study reinforce those findings, and build upon them by considering hydrometeor fall velocity more globally, and not within the limitations of prescribed snowflake/ice crystal types (dry snow and wet snow in Thériault et al., 2012).

The present study shows that collection efficiencies are similar for different hydrometeors with the same fall velocity, despite differences in size, density, mass etc. using a spherical drag model. It is not apparent from the work of Thériault et al. (2012) that a raindrop with the same fall velocity as a spherical wet snow or dry snow hydrometeor would have a similar collection efficiency, despite the large differences in the density. This is an important finding, as it enables the collection efficiency to be well characterized by the wind speed and fall velocity alone, and enables the development of an explicit CFD transfer function with wind speed and hydrometeor fall velocity dependence, which was not done in Thériault et al. (2012).

4) Colli et al. (2020) used the precipitation intensity as done in this manuscript to adjust the collection efficiency.

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

The impact of precipitation intensity on the collection efficiency was also suggested by Chubb et al. (2015) using field measurements.

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

Authors' response: The transfer function developed in the present study uses the wind speed and hydrometeor fall velocity to adjust the collection efficiency. This is fundamentally different from adjustments based on the wind speed and precipitation intensity (determined from the measured gauge accumulation) used by Colli et al. (2020) and Chubb et al. (2015). The transfer function developed in the present study can be used to estimate collection efficiencies for different hydrometeor types and intensities, representing the hydrometeor properties in terms of the corresponding fall velocity. Results using this approach are shown in Fig. 10 and discussed in Sections 3.4.3 and 4.4.3 of the present manuscript. It is important to note that both of the studies identified by the reviewer develop explicit transfer functions with wind speed and precipitation intensity based on experimental results and not directly based on modeling results as in the present study. In the case of Colli et al. (2020), different fit coefficients are determined for each of the Marshall, CARE, and Haukeliseter field test sites with collection efficiency results studied at temperatures below -4 °C.

Using the precipitation intensity approach enables adjustments to be performed at sites where only precipitation gauge and wind speed measurements are available. However, the degree of the gauge adjustment (obtained from the precipitation intensity and gauge measurement) is not independent from the measured value to be adjusted. This could be problematic for adjusted precipitation accumulation estimates, as gauge measurement uncertainties can be propagated through both the measured gauge accumulation and the collection efficiency transfer function. It is also difficult to apply this approach across different hydrometeor types (e.g. rain and snow), as different types can have different fall velocities and associated collection efficiencies, even for the same precipitation intensity. As shown in Fig. 10, the range of collection efficiencies that can be obtained across rain and snow increases with increasing wind speed for a given precipitation intensity. This makes it difficult to apply an intensity-based approach over temperature ranges where liquid and/or solid precipitation types can be present. The fall velocity transfer function developed in the present study can be applied more broadly across different precipitation types, and the collection efficiency adjustment is determined independently from the gauge accumulation, with separate instruments for measuring the wind speed, precipitation fall velocity (e.g. a Precipitation Occurrence Sensor System (POSS), as shown in Part II), and precipitation accumulation.

In particular: Section 1: The introduction is very long and the goal is not stated clearly. The literature review is incomplete. What are the authors trying to do exactly? If it is showing that CFD can be used to show the dependence of the collection efficiency on the fall speed, it has already been done before.

Authors’ response: The goal of this work is to develop a computationally cost-effective, universally applicable, and quantitative transfer function for adjusting unshielded precipitation gauge measurements with wind speed and hydrometeor fall velocity. We agree that this can be stated more clearly, and will do so in the revised version of the Part I manuscript.

The introduction describes previous studies that have established the practical and theoretical basis for the present study. The contributions of Thériault et al. (2012) and Colli et al. (2016a, b) are described in the introduction, among other studies. The introduction length was required to ensure that previous studies related to the present work were clearly described. It is important to note that none of the previous studies above develop a CFD transfer function based on wind speed and hydrometeor fall velocity as is done in the present study. If the reviewer is suggesting that the literature review is incomplete because the studies by Colli et al. (2020) and Chubb et al. (2015) are not discussed, inclusion of these references could be considered for the revised version of Part I. Recognizing both the length of the introduction (as noted by the reviewer), and the fact that these studies are fundamentally different than the present study (as noted in the previous response), these studies were not included in the original submission.

Section 2: The simulations described in section 2.1 were already done in Colli et al. (2016a).

Authors' response: The work of Colli et al. (2016a) is described in the introduction (ln. 91-102) and the numerical modelling results from the present study are compared with those from both Colli et al. (2016a) and Baghapour et al. (2017) in Sect. 3.1 and shown in Fig. 3. The reductions in the peak normalized velocity above the gauge with the present model compared with Colli et al. (2016a) are attributed to refinement of the gauge geometry, including the orifice thickness, among other factors as discussed in Sect. 4.1. The comparison of results from different models provides a useful benchmark as models are refined and improved over time, and allows the impacts of model changes to be assessed.

The collection efficiency computed in section 2.3 were first used in Colli et al. (2020).

Authors' response: The authors disagree that the collection efficiency formulation in the present study was first shown by Colli et al. (2020). The Sect. 2.3 methodology for calculating the true precipitation intensity falling in air from the hydrometeor size distribution, mass, and fall velocity over hydrometeor sizes in this study follows the approach of Nešpor and Sevruk (1999), as described in ln. 236-237. This is a common definition for precipitation intensity, and the same approach is used for rain and snow in this manuscript, where the size is based on the equivalent water drop diameter. Sect. 2.3 describes the methodology for deriving the overall collection efficiency with wind speed for a given hydrometeor size distribution for both rain and snow, using the collection efficiency transfer function with wind speed and hydrometeor fall velocity developed in Sect. 3.3.

Sections 3 and 4: Most results/discussion are not new and/or should be improved for clarity. For example:

1) Sections 4.1, 4.2: Same key findings as in previous studies.

Authors' response: The results from this study are compared with those from previous studies in Sections 4.1 and 4.2. The results in the present study were determined independently from those in previous studies, with differences in the specific approaches used. Identifying similarities among the results from the present and previous studies is valuable to the scientific community. Accordingly, the fact that some key findings were the same as in previous studies serves to reinforce and support those findings. That said, there are also differences in the key findings of the present study relative to previous studies, which adds new knowledge to the field.

Sect. 4.1 discusses the differences in the numerical modelling results presented in Sect. 3.1 relative to previous studies; specifically, Colli et al. (2016a) and Baghapour et al. (2017). The reductions in the peak normalized velocity above the gauge with the present model compared with Colli et al. (2016a) are attributed to refinement of the gauge geometry, including the orifice thickness, among other factors as discussed in Sect. 4.1. Sect. 4.2 discusses the collection efficiency results with wind speed and hydrometeor fall velocity for rain, ice pellet, wet snow, and dry snow hydrometeors. Fall velocity was not considered explicitly in the modelling approaches used in previous studies. The numerical results show collection efficiency results are similar for hydrometeors with the same fall velocity, despite differences in characteristics (size, density, and mass). This is a new and important finding that has not been demonstrated in previous studies. This finding supports the development of a universal transfer function with wind speed and hydrometeor fall velocity that is applicable across liquid and solid hydrometeor types.

2) Section 4.3: The threshold fall speed value is directly related to the minimum diameter of the size distribution discussed in Thériault et al. (2012) and Colli et al. (2016a, b) and Colli et al. (2020). Small particles falling slower are deflected by the updraft upstream of the gauge.

Authors' response: As described in the introduction (ln. 62-63), Nešpor and Sevruk (1999) demonstrated a hydrometeor size limit below which the collection efficiency was zero for smaller size hydrometeors for rain. This defines, not the minimum diameter of the drop size distribution, but the minimum size of hydrometeor with sufficient fall velocity to be captured by the gauge for a given wind speed. This threshold will change with wind speed, as for higher wind speeds, larger drop sizes with higher fall velocities are required to overcome the updraft and local airflow to be captured by the gauge. Colli et al. (2016b) shows that the hydrometeor size at which the collection efficiency is zero increases for 8 m s^{-1} wind speed relative to 4 m s^{-1} wind speeds for dry snow with an unshielded gauge, but does not develop an explicit formula relating wind speed to the minimum drop diameter, which will also be different for different hydrometeor types. The present study develops an explicit expression for this threshold based on the wind speed and hydrometeor fall velocity, based on the numerical model results, which is broadly applicable across hydrometeor types (Eq. 19). None of the three publications listed above derive an explicit expression for the hydrometeor fall velocity threshold (below which the collection efficiency will be zero) based on the wind speed and that is applicable across different hydrometeor types.

3) Section 4: Lines 565-569: It should be corrected as previous studies by Thériault et al. and Colli et al. also used a horizontal plan.

Authors' response: The Colli et al. (2016b) publication states the hydrometeors were injected from a vertical plane as described in ln. 568-569 in the present manuscript. The following description is provided in Colli et al. (2016b), "The initial positions of the simulated trajectories lay on an ideal vertical plane located upwind of the windshield and the orifice level. Figure 1 shows the selected seeding window and its location relative to the shield–gauge assembly." The Thériault et al. (2012) publication does not state whether hydrometeors were injected from a horizontal or vertical plane for the modelling analysis and the authors recommend that the reference to Thériault et al. (2012) in ln. 568 is removed.

Lines 573-577: The volumetric approach is what the gauge measures. When using the fall speed, it is the precipitation intensity as proposed in Colli et al. (2020).

Authors' response: The Colli et al. (2020) reference is not relevant to this discussion. This section is referring to the comparison of the Colli et al. (2016) unshielded model results for wet snow and dry snow with those of the present study. Ln. 573-577 in the present manuscript refer to the approach of Colli et al. (2016b), which calculates the ratio of that captured inside the gauge to the true value falling in air. The fall velocity term is omitted in Eq. (12) in Colli et al. (2016b) in both the numerator and denominator integrals, which differs from the formulation used by Nešpor and Sevruk (1999) and that used in the present study. As stated in the manuscript, for the dry snow and wet snow comparison shown in Fig. 8, the difference between these two approaches is small.

Sections 4.4.2, 4.4.3 and 4.4.4: Most of the content are not new findings and are repetitive.

Authors' response: New findings are presented in Sections 4.4.2, 4.4.3, and 4.4.4, as well as relevant comparisons with previous studies. These sections discuss and contextualize the results from the universal transfer function with wind speed and hydrometeor fall velocity dependence that are presented in Sections 3.4.2, 3.4.3, and 3.4.4, respectively. Results from the new transfer function developed herein are studied over a range of hydrometeor types (both liquid and solid), precipitation intensities, and wind speeds. These sections highlight and discuss the variability in collection efficiency results due to these different factors for both snow and rain. This provides valuable context to help understand the limitations associated with performing adjustments based on the wind speed alone (Sect. 4.4.2), with wind speed and precipitation intensity (Sect. 4.4.3), and with wind speed and hydrometeor fall velocity (Sect. 4.4.4) across different hydrometeor types.

The relationship between collection efficiency and wind speed is discussed in Section 4.4.2 with respect to the approach of Thériault et al. (2012) for snowfall. Section 4.4.3 discusses the relationship between collection efficiency and precipitation intensity, comparing with findings from Jarraud (2008), and illustrating the new and important point that an intensity-based approach can lead to a range of collection efficiency values when multiple snowfall crystal habits are present or when both solid and liquid precipitation are present. Section 4.4.4 discusses how the spread in collection efficiency results across different precipitation types at a given wind speed is minimized by representing the hydrometeor properties in terms of fall velocity. This is a novel and significant finding, demonstrating how the new transfer function can be applied broadly across all hydrometeor types with no knowledge of their properties other than the fall velocity.

Given those, there is not enough novelty in this manuscript to be published. Since some of the results are needed for Part 2, I recommend merging both manuscripts. A methodology section that explains the CFD simulations should be added to Part 2.

Authors' response: The authors strongly disagree with the reviewer's claims that the work is not novel and will revise the manuscript to better highlight these points. To the authors' knowledge, this is the first CFD modelling study to: (1) characterize precipitation gauge collection efficiency with wind speed and fall velocity; (2) show that collection efficiencies are similar for different hydrometeor types with identical fall velocities; and (3) develop a universal transfer function based on wind speed and hydrometeor fall velocity. This work demonstrates the significant utility of such a transfer function for reducing uncertainties in adjusted precipitation accumulation estimates, and provides a foundation for future studies with non-spherical hydrometeor models and different gauge and shielding configurations used operationally.

The authors strongly recommend that the modelling results are maintained as a standalone paper to enable the modelling results, transfer function development, comparison with previous modelling studies, and discussion of the results to be clearly and fully described. As previous studies have shown, and as discussed in this study, the numerical modelling results are sensitive to a wide range of factors (e.g. gauge and orifice geometry, mesh, boundary conditions, turbulence model, hydrometeor drag model, hydrometeor type and characteristics…), and it is important that they are discussed in the context of the model and transfer function development.

The Part II manuscript uses the CFD transfer function and assesses it experimentally alongside existing transfer functions with wind speed and temperature dependence, as well as two new transfer functions with wind speed and fall velocity dependence. For Part II, the goal is not the justification of the approach from a modelling and fundamental perspective, but the experimental evaluation of transfer functions with wind speed and hydrometeor fall velocity alongside existing approaches with wind speed and temperature. Including the CFD model methodology, results, discussion and conclusions from Part I in the Part II manuscript would detract from the clarity of the Part II paper, as duplicate methodology, results, discussion and conclusion aspects would be required from the numerical modelling work. While the numerical modelling, analysis and transfer function development in Part I is fundamental to the transfer functions and results in Part II, this work is best-suited in its present form as a standalone paper.