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

Author Response to Anonymous (Referee #2)

In this work the authors presented "A new method for assessing collection efficiency using wind speed and hydrometeor fall velocity", but this methodology, based on CFD simulations and Lagrangian particle tracking model have been previously used in the recent literature (e.g. Thériault et al. 2012, Colli et al. 2016a,b). The Geonor precipitation gauge has been studied in these works in both shielded and unshielded configuration.

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. Previous studies, including those of Thériault et al. (2012) and Colli et al. (2016a,b), have certainly used CFD simulations and Lagrangian particle tracking to study collection efficiency for Geonor gauges in shielded and unshielded configurations. These studies, as well as others that used CFD to study gauge collection efficiency for rain and snow (e.g. Nešpor and Sevruk, 1999; Colli et al., 2015; Baghapour et al., 2017; and Baghapour and Sullivan, 2017), are described and referenced clearly in the manuscript. None of these studies developed a collection efficiency transfer function based on the wind speed and hydrometeor fall velocity, as in the present study; hence, this is a new method. 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.

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). The contributions of Colli et al. (2016a,b) do not develop a collection efficiency transfer function. There are also modelling differences between the present study and each of these two earlier studies, as shown in Table A1 (below) and discussed in the manuscript.

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-e

Gauge	Single-Alter shielded Geonor T-200B	Unshielded and single-Alter shielded Geonor T-200B	Unshielded 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

One of the main conclusion of this work is the relation between "Collection Efficiency" (CE) and the particle fall velocity instead of the particle diameter as shown in Colli et al. 2016b. However, for wet and dry snow they use the relation proposed by Rasmussen et al. 1999 to calculate the particle fall velocity as a function of the particle diameter. Furthermore, in equation 9 and 17 the authors reported the formulas for the "overall Collection Efficiency" for rain and snow respectively. In these equations is highlighted that the fall velocity is a function of the particle diameter (D) and therefore the overall CE depends only on the wind speed and D. For this reason, there is no novelty in this approach.

Authors' response: The statement by the reviewer that "the fall velocity is a function of the particle diameter (D) and therefore the overall CE depends only on the wind speed and D" would certainly apply to situations where the hydrometeor type and fall velocity dependence with size is known, only one hydrometeor type is present, and the size distribution of hydrometeors is known. This is essentially what has been shown in the previous studies by Thériault et al. (2012) and Colli et al. (2016b). This is **not** what is shown in the present study. Further, neither of these previous studies considered fall velocity explicitly in the collection efficiency formulation, as it is in the present study.

The present study shows that a single transfer function based on wind speed and hydrometeor fall velocity, developed herein, can accurately capture collection efficiencies across a wide range of wind speeds without explicit knowledge of the hydrometeor type, size distribution, or intensity, and in situations where multiple hydrometeor types are present. By using the fall velocity, which is a singular, observable parameter, it is possible to describe the collection efficiency without any further knowledge of the hydrometeors. It is not apparent from the work of Colli et al. 2016b that the collection efficiency for different hydrometeors with the same fall velocity (rain, wet snow, and dry snow) would be similar despite large differences in the hydrometeor diameter, density and mass. For example, using the present approach, a small raindrop with a fall velocity of 0.5 m s^{-1} is assigned the same collection efficiency as a spherical dry snow hydrometeor with the same fall velocity. There is significant novelty in the approach developed in this study, as adjustments based on fall velocity are more broadly applicable than those developed in previous studies that require knowledge of the hydrometeor size and type.

With respect to the specific formulations used, Eqs. 9 and 17 derive the overall collection efficiency by integrating over the hydrometeor size distribution. The sizes here correspond to the equivalent diameters of water droplets as described in ln. 245-

246, which differ from the values of Rasmussen et al. (1999) based on the hydrometeor size. For snowfall, the power law values in this study are given by Langleben (1954) as described in ln. 206-264 and shown in Table 4. Substituting the fall velocity expression with equivalent drop diameter (Eq. 16) into the overall collection efficiency expression (Eq. 17) would indeed provide different collection efficiency curves for different hydrometeor types, as the relationship between the hydrometeor size and fall velocity is different. These differences are shown in Fig. 9 for different liquid and solid precipitation types and intensities.

L 175: a) The authors use the relation proposed by Rasmussen et al. 1999 to calculate the terminal velocity, and they stated that "hydrometeor density was chosen to provide the desired hydrometeor fall velocity", but in the work of Rasmussen et al. the density value relations are provided for both wet and dry snow. How did the authors vary the hydrometeor density?

Authors' response: The hydrometeor density was not varied in this study. As described in Sect. 2.2, the hydrometeor density for wet snow and dry snow was determined from the hydrometeor diameter and fall velocity using a spherical drag model (ln. 175-178). The size and fall velocity relationship for spherical wet snow and dry snow hydrometeors follows that of Rasmussen et al. (1999), which was used in previous studies (Thériault et al., 2012;Colli et al. 2016b). The drag coefficient for spherical hydrometeors is given by Henderson (1976) based on the relative hydrometeor to air velocity. This drag formulation closely matches that of Haider and Levenspiel (1989) used in previous studies (Baghapour and Sullivan, 2017). Fig. 5 shows collection efficiencies are similar for hydrometeors with the same fall velocity despite differences in type, size, density, and mass (Table 2). This enables the development of a collection efficiency transfer function based on wind speed and hydrometeor fall velocity, independent of hydrometeor type, size, density, and mass.

L 175: b) Are these density values realistic? or are they used only to obtain the fall velocity the authors desired?

Authors' response: The density values provided in Table 2 are realistic for spherical hydrometeors with the diameter and fall velocity relationship provided by Rasmussen et al. (1999) and used in previous studies (Thériault et al., 2012; Colli et al. 2016b). The results of this study show that across rain, ice pellet, wet snow, and dry snow hydrometeors, collection efficiency results are highly sensitive to the wind speed and hydrometeor fall velocity, and relatively insensitive to differences in hydrometeor density across hydrometeor types.

L 175: c) The smaller particle of wet snow has a density value greater than water, is it right?

Authors' response: For wet snow, the density increases rapidly with decreasing size below approximately 3 mm, as shown in Table 2 in the manuscript. Comparing between the 1.0 m s^{-1} fall velocity hydrometeor (with 0.22 mm diameter and 1.35 kg m^{-3} density) and 1.25 m s^{-1} fall velocity hydrometeor (with 1.7 mm diameter and 0.3 kg m^{-3} density) in Table 2 shows the rapid decrease in the diameter and increase in the density as the fall velocity is reduced. While a density above 1 kg m^{-3} is unrealistic, it was included to show the results at the edge of this low fall velocity range, despite slightly over-shooting the density of water. It is worth noting that higher densities for wet snow (2.88 kg m^{-3} and 1.44 kg m^{-3}) were included in the modelling analysis of Colli et al. (2016b) for 0.25 mm and 0.5 mm diameter hydrometeors. This overestimation of the density at small hydrometeor sizes may be due to errors in the power law relationship between hydrometeor diameter and fall velocity at small hydrometeor diameters, which is beyond the scope of the present study to assess further.

Fig. 5 and 6 : in figure 5 the authors showed the "collection efficiency" for different precipitation types and fall velocities respect to wind speed.

Authors' response: We agree with this statement.

It is clear from the figure that there are differences in the CE values of different precipitation type but with the same fall velocity.

Authors' response: We agree there are differences, and these are already discussed in Sect. 3.2 in the paper.

Furthermore, the authors used only part of these data to obtain the "empirical collection efficiency expression" showed in figure 6, but this relation has been used to calculate the "overall Collection Efficiency" for all the particle types. How do this affect the obtained results?

Authors' response: Selected curves were chosen representative of each hydrometeor type to span the range of possibilities in a uniform and unbiased way. This does not significantly affect the obtained results. This is described in Sect. 3.3.

We will modify the discussion in Sect 3.3 to further highlight this point, including adding the RMSE results for rain (0.04), ice pellets (0.02), wet snow (0.02), and dry snow (0.05) compared with the collection efficiency transfer function to further describe the agreement of the transfer function with the CFD results. We also recommend including all the CFD results from Fig. 5 with the transfer function fits in Fig. 6 to better show the performance of the transfer function relative to the entire CFD modelling dataset.

Results from this transfer function using the "overall collection efficiency" are compared with Colli et al. (2016b) dry snow and wet snow results and show good overall agreement (Fig. 8) despite modelling differences as discussed in Sect. 4.4.1. The transfer function is also directly assessed with experimental results for rain, snow and mixed precipitation over a wide range of environmental conditions in the Part II manuscript, showing good agreement (Tables 4 and 7).

Sections 3.4.3 and 4.43: in these sections (Results and Discussion sections) the authors highlight the dependency of overall CE with precipitation intensity. This topic is addressed in the recent work of Colli et al. 2020. Do the authors compare their results with that work?

Authors' response: The authors recommend that the work of Colli et al. (2020) is added to the introduction and referenced in the discussion (Sect. 4.4.3) with respect to the dependence of overall collection efficiency on precipitation intensity for a given hydrometeor type. Their findings support the results of the present study using the transfer function based on wind speed and hydrometeor fall velocity developed herein. It is important to note that the work of Colli et al. (2020) is for a single-Alter shielded Geonor gauge, and is not directly comparable to this work using an unshielded Geonor gauge. The work of Colli et al. (2020) also does not develop an explicit transfer function equation based on CFD modelling results to be directly compared with experimental results, as is developed in the present study. Instead, transfer function fit coefficients are derived experimentally, with different coefficients for each test site at temperatures below -4 °C.

The present approach is fundamentally different than that of Colli et al. (2020), in which wind speed and precipitation intensity (determined from the measured gauge accumulation) are used to adjust the measured gauge accumulation. While this enables adjustments to be performed at sites where only precipitation gauge and wind speed measurements are available, the collection efficiency 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 of the present manuscript. 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 general, in this work the authors reproduced methodologies used in previous works and there are no significant improvements or novelty.

Authors' response: The authors disagree strongly that there are no significant improvements or novelty in this work. This is the first CFD modelling study to: (1) characterize precipitation gauge collection efficiency with respect to 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 that is broadly applicable across both liquid and solid precipitation types.

Previous studies have developed different transfer functions with wind speed for different snowfall crystal types (Thériault et al., 2012) or based on the wind speed and precipitation intensity for snowfall (Colli et al., 2020). The approach in Thériault et al. (2012) requires specific knowledge of the hydrometeor type, and has not been demonstrated to be viable for situations in which more than one precipitation type is present (e.g. both liquid and solid precipitation, different snowflake types) or the precipitation type is unknown or different from the specific crystal types considered; this makes it difficult to implement operationally. The approach in Colli et al. (2020) requires knowledge of the precipitation intensity, which is not independent from the gauge accumulation, considers temperatures below -4 °C only, and does not address the challenge of accurately adjusting liquid and/or solid precipitation at temperatures where either or both of these types may be present. The collection efficiency transfer function using fall velocity developed in the present study addresses these limitations and is broadly applicable. That stated, the authors acknowledge the limitations of the spherical hydrometeor model and recommend the study of non-spherical hydrometeors for future work (ln. 524-525).

With respect to the Reviewer's statement that "the authors reproduced methodologies used in previous works," the authors do not claim to be the first to use a CFD model and Lagrangian particle tracking to study the collection efficiency of hydrometeors for Geonor gauges. Previous studies using these approaches have been discussed and referenced in the manuscript. Similarities and differences in the approaches and results are discussed in the manuscript and in the responses above.

Furthermore, there are a few points the authors need to clarify, like e.g. the choice of the particle density values and the use of an unique empirical CE relation for different precipitation types and they need to evaluate how these impact on the results.

Authors' response: As discussed above (response to comment regarding L175), the density values used in this study are for spherical hydrometeors matching the diameter and fall velocity relationship provided by Rasmussen et al. (1999) and used in previous studies. The method by which the density values were determined is important to clarify, but it should be reiterated that the collection efficiency results in this study are highly sensitive to the wind speed and hydrometeor fall velocity and relatively insensitive to differences in hydrometeor density across hydrometeor types.

With respect to evaluating how a "unique empirical CE relation for different precipitation types" impacts results, the transfer function was developed using a uniform and unbiased approach, providing low RMSE values when fit to all modelled datasets including rain (0.04), ice pellets (0.02), wet snow (0.02), and dry snow (0.05). It is also assessed against wet snow and dry snow modelling results from Colli et al. (2016b) and demonstrates good overall agreement (Fig. 8). Further, this transfer function is directly applied to experimental results in the Part II manuscript and shows very good agreement over a wide range of conditions, supporting the modelling methodology and establishing further the fundamental role of hydrometeor fall velocity on gauge collection efficiency. The agreement between the modelling and experimental results suggests that this approach may be universally applicable across different climate regions and sites, demonstrating its potential for improving estimates of precipitation accumulation globally.

Reference:

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.