The Role of Free-Stream Turbulence in Attenuating the Wind Updraft above the Collector of Precipitation Gauges

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ABSTRACT

In operational conditions, wind is the main environmental source of measurement biases for catching-type precipitation gauges. The gauge geometry induces a deformation of the surrounding airflow pattern, which is generally characterized by relevant updraft zones in front of the collector and above it. This effect deviates the trajectories of the lighter hydrometeors away from the collector and thus is responsible for a significant reduction of the collection performance. Previous approaches to this problem, using computational fluid dynamics simulations and wind-tunnel tests, mostly assumed steady and uniform free-stream conditions. Wind is turbulent in nature, though. The role of natural free-stream turbulence on collection performance is investigated in this work for the case study of a calyx-shaped precipitation gauge and wind velocity between 10 and 18 m s^{-1} . The unsteady Reynolds-averaged Navier–Stokes model was adopted. Turbulent conditions were simulated by imposing constant free-stream velocity and introducing a fixed solid fence upstream of the gauge to generate the desired turbulence intensity. Wind-tunnel measurements allowed validating numerical results by comparing measured and simulated velocity profiles in representative portions of the investigated domain. Results revealed that in the case of turbulent free-stream conditions both the normalized magnitude of the flow velocity and the updraft above the collector are reduced by approximately 20% and 12%, respectively. The dissipative effect of the turbulent fluctuations in the free stream has a damping role on the acceleration of the flow and on the updraft. This would result in a reduced undercatch with respect to literature simulations that employed the traditional uniform free-stream conditions.

1. Introduction

National weather services commonly adopt catching type gauges for operational in situ precipitation measurements. These instruments are equipped with a collector (funnel) to convey precipitation into a container, where

the collected amount of water is measured by means of different technologies. Modern recording instruments mainly use tipping-bucket, floating or weighing techniques (see, e.g., [WMO 2014](#), chapter 6).

Both instrumental and environmental factors act as sources of systematic errors in precipitation measurements, and can be adjusted by means of correction

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curves. Instrumental factors such as the systematic mechanical error of tipping-bucket rain gauges and the dynamic response of weighing gauges can be corrected after dynamic calibration in the laboratory (Lanza and Stagi 2008; Colli et al. 2013). Among the environmental factors, wind is the main influencing variable for precipitation measurements. Any precipitation gauge, indeed, presents an obstruction to the prevailing wind and the incoming airflow is deformed when wind overtakes the precipitation gauge. Wind generally accelerates above the collector of the instrument, while vertical upward velocity components arise upwind of the collector (Warnick 1953). This aerodynamic effect induced by the gauge body deflects the hydrometeors (liquid/solid particles) away from the collector (Folland 1988; Nešpor and Sevruck 1999). The main factors of influence are the gauge geometry, the wind speed and the characteristics of precipitation, including the particle size distribution and precipitation intensity (Thériault et al. 2012; Colli et al. 2015).

Wind-induced errors were studied in the literature using different approaches—field measurement campaigns, numerical simulation, and wind-tunnel (WT) experiments—with the aim of formulating correction curves to calculate the actual precipitation falling to the ground. Nevertheless, the implementation of correction curves in operational conditions is still rare. Sevruck (1982) reported that the typical magnitude of the wind-related losses (undercatch) for the precipitation amount is 2%–10% in case of liquid precipitation and 10%–50% in case of solid precipitation. Pollock et al. (2018) reported an observed undercatch of about 10% to 23% for liquid precipitation at a lowland and upland sites, respectively. Further studies focusing on solid precipitation (Rasmussen et al. 2012; Colli et al. 2015) showed collection losses up to 70%–80%.

In field measurement campaigns, precipitation collected by a gauge installed in operational conditions is compared with a suitable reference. The so-called pit gauge provides the reference measurement for liquid precipitation (Lanza and Vuerich 2009), while the double-fence intercomparison reference is usually adopted for solid precipitation (Nitu et al. 2018). The numerical approach, based on computational fluid dynamics (CFD) simulations, reduces the time and resources needed to investigate different configurations by varying the wind speed, type of precipitation and gauge geometry. The validation of numerical models can be obtained by comparison with WT measurements, obtained in controlled laboratory conditions. After validation, numerical simulation of precipitation particles trajectories leads to estimate the collection efficiency and to quantify the wind-induced errors.

Nešpor and Sevruck (1999), conducted numerical simulations on three cylindrical gauges of different size while varying the shape of the collector rim and the wind speed. Assuming uniform free-stream conditions, they obtained the airflow velocity field (magnitude and directional components), using a time average approach, and then computed the liquid particles trajectories. The flow velocity and turbulent kinetic energy fields obtained from the simulations were validated by comparison with WT measurements. The raindrop trajectories were computed using a simplified model, which neglects the interaction between particles and the effect of the particles on the air (one-way coupled model). This simulation scheme was adopted also by Thériault et al. (2012) and Colli et al. (2015, 2016a,b) for solid precipitation, by increasing the details of the computational mesh to better capture the airflow features. Shielded and unshielded gauge configurations were studied in both time-averaged (Reynolds-averaged Navier–Stokes) and time-dependent [large-eddy simulation (LES)] approaches.

A very large dataset of field measurements of solid precipitation was provided by the Solid Precipitation Intercomparison Experiment (SPICE) (Nitu et al. 2018) organized by the World Meteorological Organization (WMO). This project involved about 20 field sites for three years (2011–13) in an experimental campaign to assess the impact of automation on the measurement of snowfall, snow depth and solid precipitation in cold climates. The wind effect was also considered and correction curves were formulated (Wolff et al. 2015; Kochendorfer et al. 2017; Buisán et al. 2017). The analysis of real-world data allows to account for the intrinsic turbulence of the airflow, which is generally neglected when using a CFD approach and in WT tests. Natural wind fields are indeed characterized by turbulent fluctuations, especially near to the ground where precipitation gauges are located.

The numerical and WT studies cited above neglected the free-stream turbulence and assumed that turbulence is only generated by the interaction of the airflow with the gauge. In all previous works presented in the literature, CFD simulations assumed a steady and uniform incoming flow at fixed horizontal wind speeds, whereas WT experiments were conducted in low free-stream turbulence conditions. The present work aims to investigate the role of free-stream turbulence on the airflow above the collector of a precipitation gauge. This was quantified based on the comparison between the aerodynamic response of the gauge under uniform and turbulent free-stream conditions, assessed by means of both CFD simulations and WT tests.

Although traditional catching type precipitation gauges usually have cylindrical or “chimney” shapes, with the increasing awareness of the wind effect on collection

FIG. 1. (a) The EML Kalyx aerodynamic rain gauge, and (b) the numerical model of the gauge.

performance new precipitation gauges characterized by aerodynamic shapes have been recently developed. The airflow patterns above gauges of various geometries and the benefits of the aerodynamic shape, were shown using results of CFD simulations (Colli et al. 2018) and supported by field investigations (Pollock et al. 2018). Specifically, Colli et al. (2018) showed that the turbulent kinetic energy induced by the flow-gauge interaction above the collector for the calyx-shape gauge is about one-third of that generated by gauges with cylindrical or “chimney” shape. For this reason, in order to better single out the role of free-stream turbulence on the airflow features above the gauge collector we focused, in the present work, on the calyx-shape precipitation gauge.

2. Method

The airflow pattern above the collector of an aerodynamic precipitation gauge was analyzed in two airflow configurations by means of CFD simulations and WT experiments. The test gauge was the Kalyx-RG tipping-bucket aerodynamic gauge, manufactured by Environmental Measurements Limited (EML). In a first configuration, the incoming flow was imposed steady and uniform, with no significant turbulence intensity of the incoming airflow upstream of the gauge. In a second configuration, the free-stream turbulence was simulated by using a fixed solid fence with a regular square mesh located upstream of the gauge. In this second configuration the obtained turbulence intensity upstream of the gauge was about 0.10. Two wind regimes were investigated per each configuration, with incoming

horizontal mean wind velocity equal to 18 and 10 m s^{-1} , respectively. CFD simulations were performed using the open-source OpenFOAM numerical solver, adopting the unsteady Reynolds-averaged Navier–Stokes (URANS) model and the shear stress tensor (SST) $k-\omega$ closure model. Simulation results were processed to compute the velocity profiles (magnitude and components) in representative portions of the domain. Validation was provided by reproducing the two airflow configurations in WT tests and measuring the horizontal and vertical velocity profiles (magnitude and components) at fixed positions using velocity probes.

a. The numerical model

As compared with the most common tipping-bucket rain gauges (having a cylindrical shape) the Kalyx-RG (Fig. 1a) is an aerodynamic inverted conical shaped gauge with a smaller size. The instrument has an orifice diameter D equal to 0.13 m and height equal to 0.192 m. The model of the gauge geometry was prepared in the standard triangulation language format (Fig. 1b) using a 3D CAD software.

By means of spatial discretization, the computational mesh and domain were defined. The three Cartesian coordinates were set with the x axis orientated along the streamwise direction, the y axis along the crosswise direction and the z axis along the vertical direction. For the uniform airflow configuration, the spatial computational domain consists of a $5 \times 2 \times 2 \text{ m}^3$ box, and is decentralized downward to optimize the computational cost and ensure full development of the airflow wake downstream of the gauge.

FIG. 2. (a) Mesh refinements around the precipitation gauge, and (b) the CFD mesh and domain for the configuration with a solid turbulence-generating fence positioned upstream of the gauge.

For the turbulent case, the computational domain was stretched upstream by 1 m in order to introduce a turbulence-generating fence composed by a regular square mesh of thickness equal to 0.02 m and spacing equal to 0.15 m. The three-dimensional spatial domain was discretized using an unstructured hybrid hexahedral/prismatic finite volume mesh. The quality of the mesh was checked by using the geometry parameters of orthogonality, skewness and aspect ratio. The computational domain was subdivided in refinement boxes stretched along the downwind direction, with increasing refinement of the mesh when approaching the gauge body (Fig. 2a) and the turbulence-generating fence (Fig. 2b). The number of cells in the configuration with the turbulence-generating fence was more than 2 times the steady-uniform case, that is, 2.7×10^6 and 1.2×10^6 cells, respectively. The refinement boxes allowed to better solve the equation of motion in the region affected by large gradients of velocity and pressure. For this reason, three refinement layers were introduced close to the gauge surface and the minimum dimension of the nearest cells to the geometry is about 1/3 of the collector rim thickness. To check that the grid size near the gauge surface was consistent with the use of a wall function (see, e.g., Menter and Esch 2001), so that the computational burden is reduced, the wall y^+ was calculated. The wall y^+ is a nondimensional distance defined as

$$y^+ = (u_\tau y_n)/\nu_a, \quad (1)$$

where y_n is the height from the wall to the midpoint of the wall-adjacent cells, ν_a is the kinematic viscosity of the air, and u_τ is the friction velocity.

In the simulations, the average value of y^+ is about 15, the median is 12, and most values (90%) are below 30, with the larger values occurring in the downwind part of the gauge; therefore, a scalable wall function was adopted. This allowed to model the flow velocity with linear and logarithmic profiles below and above a

threshold value defined at $y^+ = 11.067$ by Menter and Esch (2001).

The finite-volume CFD simulations were performed based on the solution of the URANS equations. The URANS model provides the Eulerian description of the air velocity components U_i over the three-dimensional spatial domain in time-average terms. In the URANS model, the Reynolds stress tensor is used to represent the transfer of momentum due to the turbulent fluctuations u'_i , where the subscript indicates the spatial direction while the apex denotes the turbulent component of the flow velocity. The general expression for the velocity field is assumed as

$$U_i = \overline{U}_i + u'_i, \quad (2)$$

where the bar indicates the mean operator.

The solution requires the introduction of a closure model based on the (specific) turbulence kinetic energy k , the dissipation per unit mass ε , and the turbulent specific dissipation rate ω reported below and defined as in Wilcox (2006). In this approach, k is expressed by means of turbulent fluctuation u'_i of the flow as

$$k = 0.5(\overline{u'_i u'_i}). \quad (3)$$

Also, ε is the rate at which k is converted into thermal internal energy per unit mass and is given, for incompressible flow, by

$$\varepsilon = \nu \frac{\partial u'_i}{\partial x_k} \frac{\partial u'_i}{\partial x_k}, \quad (4)$$

where ν is the kinematic viscosity of the air. Then ω is related to k by means of the kinematic eddy viscosity ν_t :

$$\omega \sim k/\nu_t. \quad (5)$$

The SST k - ω closure model was adopted here so as to switch to a k - ε behavior in the free stream far from the

FIG. 3. (a) The EML Kalyx rain gauge and the turbulence-generating fence in the DICCA WT, the flow direction being from right to left, and (b) a detail of the Cobra pressure probe used to measure the local flow velocity near the gauge collector.

object and to the k - ω model near the walls. Constantinescu et al. (2007), while investigating the shielding problem between two contiguous precipitation gauges, tested different numerical methods and concluded that the SST k - ω is more consistent with the LES results on the upstream gauge, in conditions that are similar to the present work.

The Navier–Stokes equation were solved numerically by employing the “pimpleFoam” solver of the open-source “OpenFOAM” software. The closure turbulence model was set using the “kOmegaSST” function. The fluid air was modeled as a Newtonian incompressible fluid with kinematic viscosity $\nu_a = 1.5 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ and density $\rho_a = 1.25 \text{ kg m}^{-3}$ at a reference environmental temperature $T_a = 20^\circ \text{C}$.

At the inlet of the computational domain (y - z plane) the undisturbed wind speed U_{ref} was imposed parallel to the x axis and was maintained uniform and constant in time while a null gradient condition was set for pressure. Atmospheric pressure and null gradient conditions for the velocity were imposed at the outlet (y - z plane opposite to the inlet). The lateral surfaces of the domain were set as symmetry planes. The ground and the gauge surface were assumed impermeable with a no-slip condition. In all computational cells of the spatial domain, initial conditions were imposed equal to U_{ref} for the velocity and equal to zero for the relative pressure.

b. Wind-tunnel tests

The experimental tests were performed in the WT of the Department of Civil, Chemical and Environmental Engineering (DICCA) of the Polytechnic School of the University of Genoa. It is a closed-loop subsonic circuit for aerodynamic and civil engineering experiments. The WT has a working section with a total length of 8.8 m and two different test sections, with a cross area of $1.7 \times 1.35 \text{ m}^2$ (width $\times$ height). The tests have been carried

out in the downstream section, which is placed at the end of the working section in order to install the turbulence-generating fence in the upstream section (Fig. 3a). In such a test section, the naturally developed wall boundary layer is 0.13 m. To carry out tests in uniform flow, the rain gauge was placed on an end plate (Fig. 3a). Two conditions for the incoming flow have been considered: 1) smooth flow characterized by a turbulence intensity $I_{\text{turb}} \approx 0.5\%$ and 2) turbulent flow, produced through a grid realized by square bars (Fig. 3a), characterized by $I_{\text{turb}} \approx 10\%$, calculated as

$$I_{\text{turb}} = [(2/3)k]^{1/2}/U_{\text{mag}}. \quad (6)$$

A static Pitot tube placed at the top of the test section was used to measure the reference wind speed U_{ref} . Local measurements of the wind speed were acquired using a fast-response multihole probe (a four-hole “Cobra” probe; Fig. 3b). The Cobra probe was mounted on a traversing system with three degrees of freedom, which allowed measurement at any coordinates of interest. Measurements were sampled at 2 kHz.

3. Results and validation

The main area of interest for our study is just above the gauge collector, where the modified airflow patterns may influence particle trajectories and, therefore, the precipitation collection. In this region, results were visualized in terms of normalized maps and profiles on the vertical along-wind symmetry plane of the gauge collector ($y = 0$). The magnitude U_{mag} and the vertical component U_z of the airflow velocity were reported and compared for the two free-stream turbulence configurations. Both were normalized using the undisturbed wind speed, U_{ref} , while the spatial coordinates were normalized with the gauge collector

FIG. 4. Simulated profiles of the normalized vertical velocity U_z/U_{ref} along the non-dimensional streamwise direction x/D , with D being the collector's diameter, at $y = 0$ and elevation $z = 0.1515D$ above the gauge collector (in gray with vertical dashed-line projections in black), for uniform free-stream velocity equal to $U_{\text{ref}} = 10 \text{ m s}^{-1}$ (red) and $U_{\text{ref}} = 18 \text{ m s}^{-1}$ (black).

diameter D (the origin of the axes is located at the center of the collector). The turbulence intensity profile and contour map along the streamwise direction were also reported. Validation of the numerical setup is provided below by comparing WT local measurements and numerical results, with the simulated profiles depicted with lines and markers denoting WT measurements.

To ensure the comparability of results for the uniform and turbulent free-stream conditions, that were obtained at different undisturbed wind speed ($U_{\text{ref}} = 18 \text{ m s}^{-1}$ and $U_{\text{ref}} = 10 \text{ m s}^{-1}$), the scalability of the results was preliminarily checked by performing CFD simulations under uniform free-stream conditions for both velocities. Figure 4 shows that the resulting normalized vertical velocity profiles along the streamwise direction are totally overlapped above the gauge collector. The gauge collector is painted in gray and black dashed lines indicate the edge projections.

Wind-tunnel measurements of the longitudinal profiles (at $y = 0$ and $z = 0.038D$) of the normalized vertical component of flow velocity and the turbulence intensity are depicted in Fig. 5 for the uniform (black points)

and turbulent (gray triangles) free-stream conditions. In both cases, the turbulence intensity increases above the collector due to the obstruction caused by the gauge body. As already observed by Warnick (1953), a significant updraft is expected to arise in front and above of the gauge collector, which is evident in Fig. 5.

As a result of the aerodynamic shape of the Kalyx gauge, the recirculating zone is confined above the gauge collector and the airflow pattern is characterized by upward components in the upwind part, upstream the center of the collector, and downward components in the downwind part. This had been shown by Colli et al. (2018) when comparing the numerically simulated aerodynamic response of other inverted conical shapes similar to the Kalyx gauge. Contrary to the turbulence intensity, the normalized vertical velocity components are less accentuated for the turbulent free-stream configuration than in a uniform free stream, with relative percentage differences of about 18% and 46% on the upwind and downwind edges, respectively (see Fig. 5). This behavior can also be observed in Fig. 6, where the normalized vertical

FIG. 5. Wind-tunnel measurements of the normalized vertical velocity U_z/U_{ref} and turbulence intensity I_{turb} along the nondimensional streamwise direction x/D , with D being the collector's diameter, at $y = 0$ and elevation $z = 0.038D$ above the gauge collector (in gray with vertical dashed-line projections in black), for the uniform (circles; $U_{ref} = 18 \text{ m s}^{-1}$) and turbulent (triangles; $U_{ref} = 10 \text{ m s}^{-1}$) free-stream experiments.

component of the flow velocity, along the vertical direction close to the upwind edge of the collector ($x = -0.568D$), decreases faster in the turbulent free-stream condition, reaching, for example, 0.015 at a normalized elevation of $0.68z/D$ rather than at $1.18z/D$ like in the uniform free-stream condition.

The CFD simulations allowed computing the airflow variables in the whole spatial domain surrounding the gauge collector, differently to the WT measurements that were taken locally in representative positions of the domain. Figure 7 shows the simulated airflow fields in terms of normalized magnitude of the flow velocity and normalized vertical velocity component, for the uniform and turbulent free-stream conditions. For the normalized magnitude of flow velocity, the white band indicates the region where the flow velocity is equal to the undisturbed wind speed ($U_{mag} = U_{ref}$); this boundary separates the region characterized by accelerated airflow regime ($U_{mag} > U_{ref}$; red color) from the recirculating zone ($U_{mag} < U_{ref}$; blue color). For the normalized vertical component of the flow velocity, the white band indicates the region with a null vertical velocity component, while the red and blue colors characterize the updraft and downdraft regions, respectively. As already observed in the WT measurements, also in the numerical simulation results

the normalized magnitude of the flow velocity for the uniform free-stream configuration is about 20% larger than in turbulent conditions (see Fig. 7).

With the aim to validate numerical simulations, CFD results were compared with WT measurements. In Fig. 8, the normalized vertical velocity component at the upwind edge of the collector along the vertical direction at $y = 0$ (left) and the normalized magnitude of flow velocity along the streamwise direction at $y = 0$ and elevation $z = 0.075D$ (right) are represented for the uniform flow. Figure 9 depicts the same situations in turbulent free-stream conditions. A good agreement between WT measurements and numerical results was observed for the uniform free-stream condition along the vertical profile with differences on the order of $0.010U_z/U_{ref}$ at a few measurement elevations (see Fig. 8). Along the longitudinal profiles the quantitative velocity values differ in some positions but the airflow behavior is mostly kept. Similarly, for the velocity profiles illustrated in Fig. 9 under turbulent free-stream conditions, a good match between numerical simulation and experiments was observed along the vertical profile, with differences on the order of $0.030U_z/U_{ref}$ at a few measurement elevations. In Fig. 10, a comparison between the measured and simulated turbulence intensity is reported. The values of the turbulence intensity measured in

FIG. 6. Wind-tunnel measurements of the normalized vertical velocity U_z/U_{ref} along the nondimensional vertical direction z/D , with D being the collector's diameter, at $y = 0$, upstream of the gauge collector at $x = -0.568D$, for the uniform (circles; $U_{ref} = 18 \text{ m s}^{-1}$) and turbulent (triangles; $U_{ref} = 10 \text{ m s}^{-1}$) free-stream experiments.

the WT (white circles) are in consistent agreement with the contour line levels of the simulated numerical field. Few measurements, in the downwind part of the collector, differ from the numerical field up to a maximum of 0.1; these

differences can be justified because the Cobra probe is unsuited to measure reverse flow components and because in this region elevated gradients of turbulence intensity occurred, as can be observed close to the edge of the gauge.

4. Discussion and conclusions

The problem of wind-induced undercatch of precipitation gauges was first addressed numerically by Nešpor and Sevruck (1999) for liquid precipitation, and by Thériault et al. (2012) and Colli et al. (2015, 2016a,b) for solid precipitation. However, results of the numerical models adopted in these and other works are affected by the not negligible, simplifying hypothesis of uniform free-stream airflow conditions.

The comparison of simulated and measured airflow fields in the uniform and turbulent free-stream configurations for wind velocity between 10 and 18 m s^{-1} , as proposed in this work, provided insights about the role of turbulence in attenuating the aerodynamic response of precipitation gauges. Wind-tunnel measurements (Fig. 5) showed that the normalized updraft in the upwind part, upstream the center of the collector, and the downdraft in the downwind part are less accentuated in the turbulent free-stream configuration than in

FIG. 7. Color maps of the simulated (a),(b) normalized magnitude of flow velocity U_{mag}/U_{ref} and (c),(d) normalized vertical velocity U_z/U_{ref} in the vertical section along the streamwise direction at $y = 0$, for the (left) uniform and (right) turbulent free-stream conditions.

FIG. 8. (left) Wind-tunnel measurements and simulated profile of the normalized vertical velocity U_z/U_{ref} at the upwind edge of the collector along the nondimensional vertical direction z/D , with D being the collector's diameter, at $y = 0$, and (right) normalized velocity magnitude U_{mag}/U_{ref} along the nondimensional streamwise direction x/D at $y = 0$ and elevation $z = 0.075D$ above the gauge collector (in gray with vertical dashed-line projections in black), for the uniform free-stream experiment ($U_{ref} = 18 \text{ m s}^{-1}$).

uniform free-stream conditions. This is ascribable to the energy dissipation induced by turbulent fluctuations. The dissipative effect of the free-stream turbulence also has a damping role on the acceleration of

the flow above the collector as demonstrated by CFD results (Figs. 7a,b).

This conclusion is consistent with the literature about the free-stream turbulence effect on the interaction of a

FIG. 9. As in Fig. 8, but for the turbulent free-stream experiment ($U_{ref} = 10 \text{ m s}^{-1}$).

FIG. 10. Vertical section of the simulated I_{turb} (colors, with contour-line levels in boldface type) along the streamwise direction at $y = 0$, and WT local measurements (white circles with lightface numbers) for the turbulent free-stream conditions ($U_{ref} = 10 \text{ m s}^{-1}$).

“bluff body” with the incoming airflow, as reported by various authors including, for example, [Kiya and Sasaki \(1983\)](#). While studying experimentally the free-stream turbulence effect on a separation bubble formed along a side of a blunt plate with right-angled corners, they concluded that the length of the separation bubble reduces significantly with increasing the turbulence intensity. Also, [Counihan et al. \(1974\)](#) proposed an analytical theory for the mean velocity behind a two-dimensional obstacle and derived that the wake strength decreases as the surface roughness in front of the obstacle (therefore, the free-stream turbulence) increases.

Our conclusions are consistent with the work of [Colli et al. \(2015\)](#) about the collection efficiency of precipitation gauges, in which a general overestimation of the wind-induced error when performing simulations under steady-uniform free-stream conditions was evident from the comparison with field observations.

This work is further substantiated by the performed WT validation of the gauge exposure problem for both turbulent and uniform free-stream configurations, that was yet lacking in the literature. In [Figs. 8 and 9](#) the simulated velocity profiles closely follow the experimental measurements; some differences arise along the streamwise direction in the region where the magnitude of flow velocity is low and beyond the gauge collector, in the turbulent wake. These differences are justified since the velocity values in such cases approach the minimum threshold velocity that the Cobra probe is

able to measure (about 2 m s^{-1} to get reliable values). Also, the Cobra probe is unsuited to measure reverse flow components. However, these inconsistencies occur in a region that is located beyond the key area of interest to assess the collection performance of the gauge and, therefore, have only a minor impact on our conclusions.

From the CFD results and the validation provided by WT observations, we conclude that accounting for the free-stream airflow turbulence in the simulation is required to avoid underestimation of the collection efficiency of precipitation gauges. This paper demonstrates that numerical derivation of correction curves for use in precipitation measurements as proposed hitherto in the literature is affected by a systematic overestimation of the wind-induced error due to the simplifying assumption of uniform free-stream conditions. A turbulent free stream is indeed the natural atmospheric condition of the wind impacting on operational precipitation gauges in the field. Since solid precipitation particles are more sensitive to the wind, neglecting the role of free-stream turbulence in the derivation of correction curves for solid precipitation measurements may lead to a large overestimation of the wind-induced errors.

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