A CFD EVALUATION OF WIND INDUCED ERRORS IN SOLID PRECIPITATION MEASUREMENTS

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ABSTRACT

The aero-dynamic response of solid precipitation gauges when exposed to the wind is responsible for a significant reduction of their catching performance. This effect is known as the "exposure problem" and consists in the modification of the space/time patterns of the undisturbed airflow operated by the gauge itself or the employed wind shield, causing the deformation of the snowflakes trajectories. Existing infield analyses of the wind induced error (Rasmussen et al., 2012) confirmed that the collection efficiency (*CE*) systematically decreases by increasing the horizontal wind speed (*Uw*). The relevance of the exposure error can be quantified, e.g. for a Geonor T-200B gauge equipped with a single Alter shield, as *CE* = 0.2 when Uw ≥ 6 m/s (Thériault et al., 2012). This configuration is adopted as part of the R3 reference system in the ongoing WMO/CIMO Solid Precipitation InterComparison Experiment (SPICE).

The increasing computing capabilities of modern parallel HPC systems allow the employment of Computational Fluid Dynamics (CFD) tools in studying the wind induced under-catch. The present analysis is aimed at understanding the large CE scattering observed infield and the role of turbulence in the exposure problem. The numerical analysis includes the geometry of a single Alter Geonor T-200B vibrating wires gauge. The turbulent airflow in the proximity of the gauge is obtained by running both time-dependent (Large Eddies Simulation) and time-independent (Reynolds Averaged Navier-Stokes) simulations. Finally, the CE values under different U_w conditions are evaluated by means of a Lagrangian tracking model for the snowflakes trajectories. The influence of the snow particles size and water content, corresponding to dry and wet snow conditions, on the trajectories is analyzed. The results will be illustrated in comparative form between the different methodologies adopted and the existing infield CE evaluations based on double shield reference gauges.

1) INTRODUCTION

The catching-type instruments are widely adopted by the national meteorological services and still demonstrate an high level of accuracy achievable when calibration and correction techniques are applied (Duchon [2008]; Lanza and Stagi [2008]). The traditional tipping-bucket gauges (TBG) and more modern weighing gauges (WG) are both characterized by a gravitational measurements principle. The formers are generally employed for rainfall observations meanwhile the latter is particularly suited for mixed liquid/solid and low precipitation estimates. Yet, specific problems exist that systematically impact on the accuracy of the TBG and WG measurements, often related to the time-varying character of precipitation and the environmental conditions.

A comprehensive analysis of the WG and TBG precipitation measurements accuracy should be subdivided in accordance to the classification of the error sources in instrumental and environmental. The instrumental errors are related to the sensor specifications and their nature is often systematic, allowing for the application of correction methodologies based on laboratory tests. The gauge sensitivity, its sampling characteristics, the measuring range are all limitations that tend to decrease the quality of precipitation intensity measurements especially when provided at short time resolutions. That is, the counting performance of the measuring instrumentation is generally determined by instrumental factors. The environmental errors are those caused by the impact of the weather conditions at the collector and other disturbing factors affecting the correct functioning of the gauge (not attributable to the instrumental characteristics). Typical environmental errors are caused by the gradients of atmospheric temperature, the wind speed and the solar radiation.

A strong interest in the wind-induced undercatch was demonstrated over the past decades leading to the commonly accepted adoption of wind shielding elements around the gauge. Such interest was demonstrated during the past WMO comparative experiments (Struzer [1971]; Sevruk and Hamon [1984]; Goodison et al. [1998]) where the catching issues showed a crucial importance in the assessment of accurate solid precipitation measurements. It has been indeed largely observed that the aerodynamic response of the gauge is responsible for a significant reduction of the snow gauge collection efficiency (CE). This is due to the deflection of the trajectories in the proximity of the gauge orifice (a problem also defined as “gauge exposure” by Folland [1988]). Since the comprehensive understanding of this systematic error has not been achieved yet, the assessment of the exposure problem has been also recognized as a central objective of the current WMO SPICE field campaign (Nitu et al. [2012]). In recent years Nešpor and Sevruk [1999], Constantinescu et al. [2006] and Thériault et al. [2012] provided new information based on the successful application of computational fluid-dynamics (CFD) tools for the numerical simulation of the wind-induced error. The coupling of advanced air turbulence models with algorithms for the evaluation of the precipitation particle trajectories is a promising methodology of investigation that will benefit from the increasing computation capabilities of high performance computing (HPC) systems.

2) METHODOLOGY

The numerical investigation on the wind induced errors of solid precipitation gauges described in this work is aimed at the accurate evaluation of the gauges undercatch generally observed due to the instrument exposure to severe wind.

The analysis was carried out by performing three-dimensional computational fluid-dynamics simulations of the air flow realized around a single Alter shielded Geonor T200B vibrating wire gauge under different wind conditions. A sketch of the modelled geometry is reported in Fig.1.

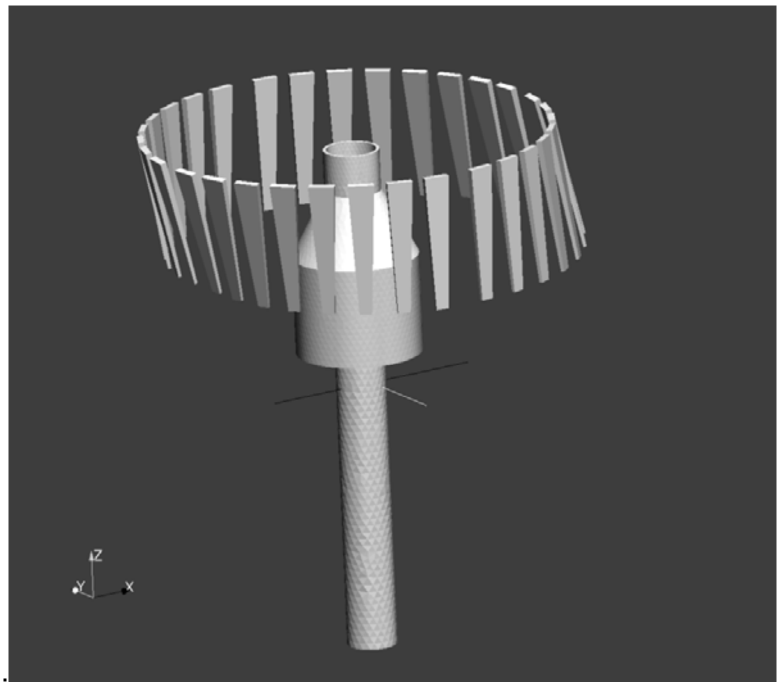

Fig. 1 Geometries of the Geonor T200B and single Alter windshield elements as modelled for the CFD simulations.

In order to acquire additional information about the role of turbulence ($10^4<Re<10^5$) on the deformation of the snowflakes trajectories, the activity was conducted by testing both time-invariant and time-variant models, respectively Reynolds Averaged Navier-Stokes equations (RANS) and Large Eddy Simulations (LES).

A set of 8 free stream air velocities has been tested for LES methodology in order to cover a set of horizontal wind speeds within $1<U_w<8$ m/s. The spatial domain has been discretized with a hybrid finite volumes grid composed by 5.5M tetrahedral cells in the free-stream zones and 22M prisms to refine the boundary layers in proximity of the gauge/shield surfaces. The RANS model was run by simulating ten wind speeds ($1<U_w<10$ m/s) for two different geometries representatives of a Geonor T200B gauge installed with and without the single Alter windshield. An higher number of RANS tests had been possible thanks to the lower computation requirements of this model.

The CFD models have been parallelized over 512 threads and executed at the Yellowstone HPC system (National Center for Atmospheric Research).

A Lagrangian approach was used to compute the particles trajectories accepting the assumption that the hydro-meteors motion does not interfere with the air flows. Another important simplification has been used by disregarding the possibility of collisions, coalescences and breakups between the falling particles. The microphysical characteristics of the precipitation were modelled by adopting a two parameters power law $Y(d_p)=ad_p^b$ (Rasmussen et al., 1999) where d_p is the equivalent diameter of the particles and $Y(d_p)$ represents their bulk volume, the density, the terminal velocity and the cross-sectional area. The values of *a* and *b* are reported in Table 1 according to the variable to be modelled.

Table 1: Parameters a_X and b_X of eq .4 (Rasmussen et al., 1999) for the computation of the snowflake terminal velocity (subscript w_T), volume (V_p), bulk density (ρ_p) and cross-sectional area (A_p)

	a_{WT}	b_{WT}	a_{Vp}	b_{Vp}	$a_{\rho p}$	$b_{\rho p}$	a_A	b_A
Dry snow	107	0.2	π/6	3	0.017	-1	π/4	2
Wet snow	214	0.2	π/6	3	0.072	-1	π/4	2

The Lagrangian tracking model (LTM) has been adapted to solve both the time-averaged (RANS airflows) and the time-dependent (LES airflows) cases by computing the particle trajectories for a set of 16 diameters and two different type of particles (representing dry and wet snow). The snowflakes initial positions were located on a vertical seeding window located upstream the gauge geometries (Figure 2).

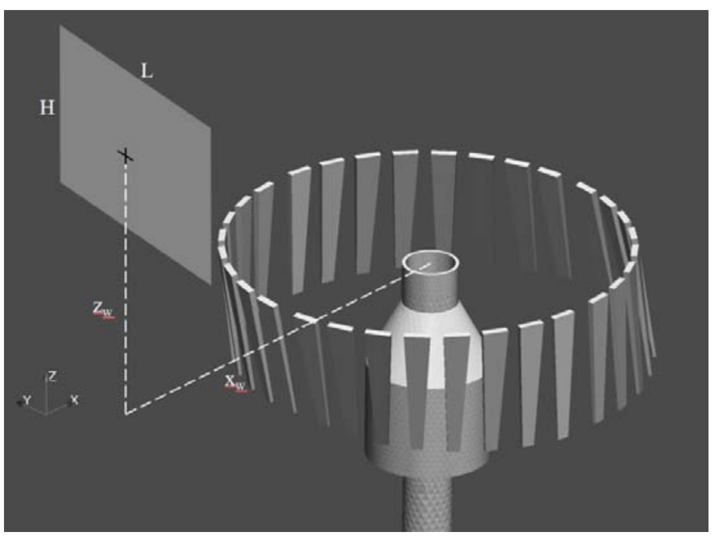

Fig. 2: Sketch of the particle initial positions plane. The Lagrangian trajectories model initialized the particle initial positions on a rectangular “seeding window” (H × L) located at a xw (mm) stream-wise distance from the gauge orifice center and a zw (mm) vertical displacement.

The collection efficiency *CE* was estimated as the ratio between the precipitation entering the gauge and the same quantity realized in the ideal case of null aero-dynamic deformation of the airflow. Firstly, the number of entering trajectories is counted and a Marshall-Palmer particle size distribution is applied for calculating the corresponding precipitation volume collected by the gauge. The total $CE(U_w)$ is therefore computed for a given wind speed by integrating the collected volumes over the tested particle diameters.

3) RESULTS AND DISCUSSION

The airflows resulting from the RANS and LES simulations are generally characterized by a complex spatial structure clearly dependent on the single Alter and the Geonor T200B geometries. The overall positive effect brought by the installation of the windshield is confirmed by Figure 3 which shows the magnitude of velocity ***U*** (m/s) fields in proximity of the gauge. In fact, the light grey colour zones surrounding the collector indicate airflow regimes that are weaker with respect to the free stream condition (dark grey areas). On the other hands, the time-dependent LES solutions revealed a strong production of vorticity due to the upwind shield elements with a propagation of eddies toward the gauge orifice.

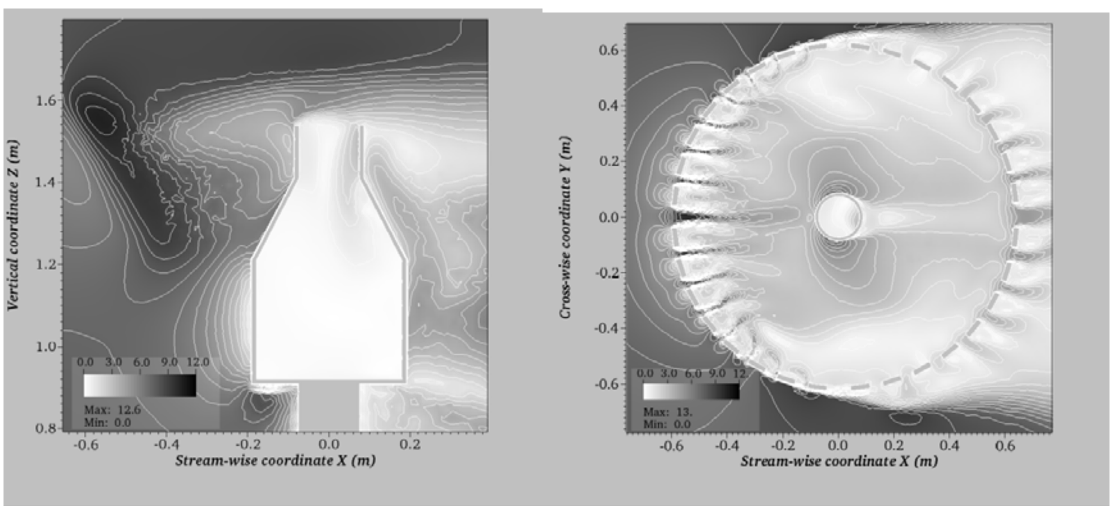

Fig.3: Time-averaged (RANS) magnitude of velocity ***U*** (m/s) color plots simulated for a wind flowing according to the x axis direction (U_w=8 m/s). Left panel: vertical plane (y=0 m) passing through the snow gauge symmetry axis. Right panel: horizontal plane (z=1.52 m) located 1 cm belows the collector level.

The energy density spectra of the air velocity sampled in the free space between the windshield and the gauge is characterized by complex turbulent components which constitute matter of ongoing analysis.

A visualization of the particles trajectories computed by the LTM highlights the formation of clusters and divergence zones caused by the aerodynamic response of the windshield elements and the snow gauge geometries (see e.g. Figure 4). Clusters of trajectories are responsible of high *CE* values if the concentrated particles bundle crosses the gauge collector. Figure 5 demonstrates that such condition is verified for time-dependent LES simulations when U_w=2 m/s meanwhile the time-averaged RANS methodology showed a similar behavior for U_w=3 m/s. Higher wind speeds are characterized by a quick decrease of *CE* due to the shift of the particle convergence downstream the gauge orifice.

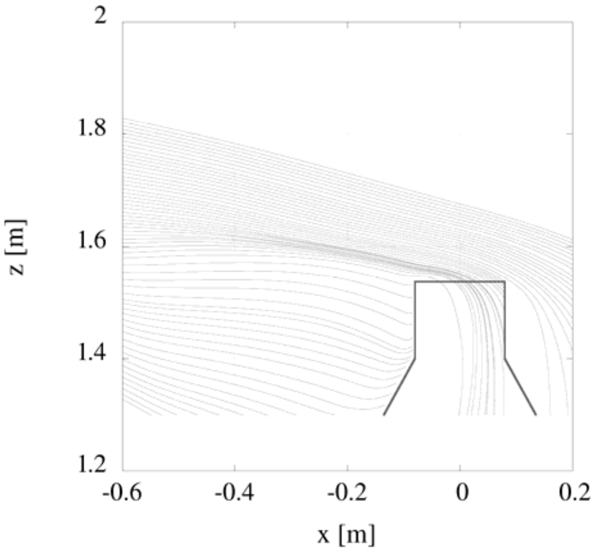

Fig. 4: Vertical profiles of the snow particles (flowing from left to right) computed for a wind speed U_w=2 m/s, dry crystals and equivalent diameter d_p=1 mm. The particle trajectories are deformed in the upstream zone due to the aerodynamic effect of the singl Alter shield.

Furthermore, adoption of a LES approach permitted to reveal the noticeable time variability of the exposure problem overcoming the limitations of other CFD analysis described in literature that are typically based on RANS models. To account for the time-dependency of the LES airflow the set of particle trajectories was re-computed six times by initializing their motion at different starting times with respect to the evolving air velocity field. Each of these attempts brought to different CE curves, revealing the influence of turbulence on the trajectories paths. An overall CE curve is then computed by averaging six time-dependent CE realizations and a comparison with the RANS results is proposed on Figure 5.

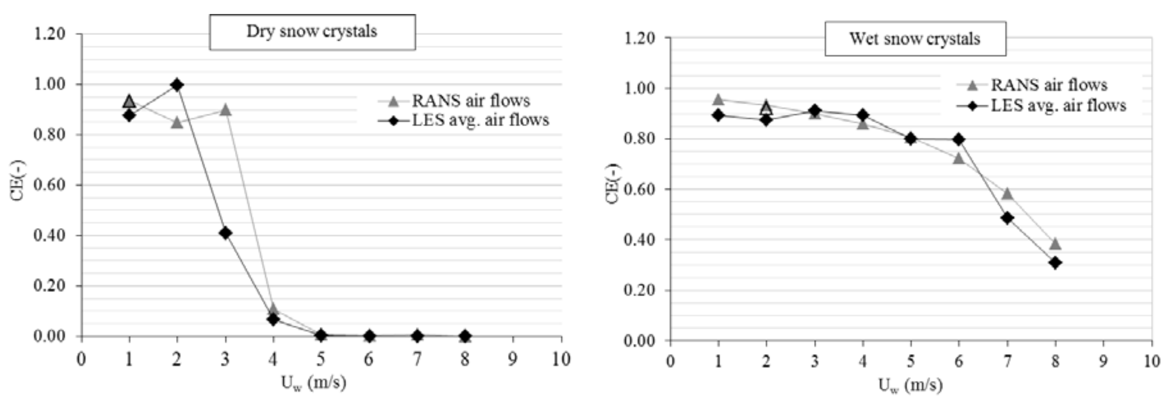

Figure 5: Collection efficiency CE (-) against the horizontal wind speed U_w (m/s) computed for the shielded snow gauge by using a RANS time-averaged (grey triangles) and a LES time-dependent (black diamonds) approach.

The results of the extended LES activity confirmed the relevant undercatch of solid precipitation by the tested measuring instrumentation under significant wind regimes especially in case of dry snow precipitation: in this case the collection efficiency of the gauge is null with horizontal wind speeds greater than or equal to U_w = 6 m/s. If the dynamic properties of the solid precipitation results in a better catching capability, the measurements errors associated with the exposure problem still remain significant with CE values lower than 75 % at wind speeds $U_w \geq 6$ m/s. The CE estimations provided in this work are appreciably lower than existing numerical simulation results obtained by using RANS models, revealing the unfavourable role of turbulence as already mentioned (Thériault et al., 2012; Nešpor and Sevruk, 1999). The noticeable difference between the dry and wet snow crystals CE figures demonstrated how critical is the choice of the ice particle physical parameterization on the computation of the falling trajectories by the Lagrangian model. This influence would lead to a certain variability of the $CE(U_w)$ results by adopting different empirical schemes of the particle density, volume and terminal velocity as available in the literature.

The existing attempts to assess the gauge collection efficiency based on infield observations show a large scattering of *CE* under fixed U_w values that can now be ascribed to the variety of snowflakes types occurring during different precipitation events (Thériault et al. 2012). A direct comparisons between the numerical simulation of the $CE(U_w)$ curves with the real-world data revealed that the two limiting cases of wet and dry snow embrace the infield collection efficiency estimates (Figure 6). It must be anyway accepted the presence of some extreme *CE* values related to the experimental nature of the infield estimations that assumes the DFIR wind shielded gauge measurements as the reference. That is, the actual DFIR gauge collection efficiency is itself influenced by the wind orientation and the air velocity fields actually realized within the DFIR fences and represents an open matter of discussion

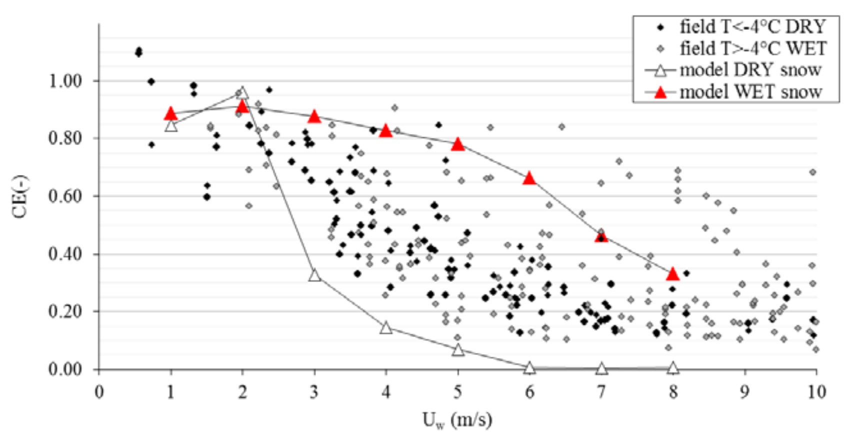

Figure 6: Comparison between infield (scale of gray diamonds) and modelled (black curve with white and red triangles) *CE* vs. the undisturbed horizontal wind speed U_w. The plot shows a classification of the field data based on the environmental temperature T separating the wet snow precipitations (0°C>T>−4°C) by the dry snow (T<−4° C). The infield measurements have been performed at Haukeliseter (Norway) and provided by the Norwegian Meteorological Institute.

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