

Summary

This work proposed and tested modifications to a rain collector's rim to minimize airflow perturbations due to its shape. The authors utilized CFD to test the performance of the proposed rain gauge design and tested a variety of inclination angles, rim thicknesses, rim widths, and collector areas under a range of wind speeds (1-20 m/s). The final proposed design appears to largely outperform the existing gauge designs it was compared against, with higher raindrop catch ratios across a wide range of drop sizes (0.25-8 mm). This finding holds true for liquid precipitation, but the existing design compared against performs better for smaller particles in solid precipitation. While the work itself is interesting, the writing needs improvement, and some critical details are unaddressed and should be resolved before publication.

Major Comments

1. Overall, the writing style of the manuscript makes it difficult to follow.
 - 1.1. The introduction, in particular, is quite dense and not all that clear. It is very difficult to follow in the current organization. After reading the introduction, I did not understand why a new rain gauge design is needed. The introduction discusses updrafts induced by non-aerodynamic rain gauge designs, but it does not discuss the impacts on collection efficiency.
 - 1.2. The challenges in writing style made it difficult to understand the implications of the results. For example, in the abstract, the new design is simply reported as “better” than existing gauges without quantification.

As requested by the reviewer, the writing style was revisited. In particular, the introduction was extensively rewritten and shortened to improve clarity. The reviewer's points were addressed in the text, emphasising the importance of improving the overall performance of precipitation gauges in windy conditions, as well as the implications of the presented results.

2. Given the focus on rim design, it is somewhat surprising that the manuscript largely avoids discussing splashing. Much work has gone into designing/redesigning the edges of hydrometeor collectors (e.g., the work done on the Parsivel2; Battaglia et al. 2010) to address this phenomenon. It is unclear to me whether the impacts from splashing are smaller than the impacts from an optimal rim design in the context of aerodynamics. I feel this needs to be addressed, either by contextualizing it with the literature or exploring it in the simulations. What percentage of the total hydrometeors in the Lagrangian Particle Tracking simulations hit the rim?
 - 2.1. This is more confusing given that the “best” design was rejected at the start of Section 4 due to an increase in splashing expected.

The work of Battaglia et al. (2010), mentioned by the reviewer, is barely relevant to the discussion of splashing and the optimisation of collector shape for rain gauges, as it focuses on evaluating the accuracy and quality of snow crystal measurements using a Parsivel optical disdrometer. The splashing issue is not mentioned in that paper. The outer shell of the Parsivel disdrometer was designed to prevent drops from pooling on its surface and dripping into the laser beam, rather than to prevent splashing. However, splashing remains an issue and is a significant source of measurement bias for disdrometers. The discussion about border effects in that paper concerns the possibility of snow crystals crossing the sensor at the border of the laser beam and being partially detected, rather than splashing.

Several authors have reported on the effect of splashing on rain gauge measurements, as estimated from field experiments. The results indicate that, compared with wind-induced bias, wetting or evaporation, for example, splashing generally has a minor effect on precipitation measurements (see, for example, Sevruk, 1982; Dunn et al., 2025).

In the revised manuscript, we have included a more in-depth discussion of the splashing issue, distinguishing between splash-in and splash-out effects. While the latter is mostly eliminated by following WMO guidelines for shaping the internal funnel of the collector, the former depends strongly on the surface area and inclination of the gauge rim (or the presence of external surfaces near the gauge collector, such as a windshield). A flat and large rim design may increase splash-in. Furthermore, as stated in the manuscript, a large, almost flat rim design has further drawbacks, such as increasing the probability of debris entering the collector, as well as snow deposition, capping and potential fragility. For this reason, the selected slightly less performant design is preferable for actual use in the field.

We agree with the reviewer that using a numerical approach to quantify the splashing-related bias would be a significant advancement. To the best of our knowledge, no numerical models have yet been applied (and validated) in the literature to quantify such bias. Investigating this would require a different numerical simulation framework and approach, including a breakage model for drops impacting the rim. This would largely exceed the scope of the present work.

A very rough estimate of the splash-in could be obtained as:

$$\frac{V_s}{V} = \frac{[\pi(R + s)^2 - \pi R^2] \int_0^{D_{max}} V(D) \cdot N(D) \cdot f(D, U, w, r, \alpha, \dots) dD}{\pi R^2 \cdot \int_0^{D_{max}} V(D) \cdot N(D) dD}$$

where V_s is the splash-in volume, V is the correct volume collected, R is the radius of the collector, s is the width of the rim, $N(D)$ is the number of drops of diameter D , $V(D)$ is the drop volume, and f is the splashing coefficient. The latter indicates the volume fraction of each drop that enters the collector producing a measurement bias, which depends on various unknown variables. The ratio between the splash-in volume and the expected volume can also be written as:

$$\frac{V_s}{V} = \frac{s}{R} \left(2 + \frac{s}{R} \right) \cdot \bar{f}(U, r, \alpha, \dots)$$

This indicates that splash-in depends on the ratio between rim width and collector size squared. A relatively modest increase in the rim width can therefore have a non negligible impact on splashing (even if not precisely quantified). While not being the only reason, this consideration supports our choice of a narrower rim, that would indicatively produce about 2.2 times less splash-in than the larger rim tested, while still performing very close in terms of aerodynamic performances.

Battaglia, A., Rustemeier, E., Tokay, A., Blahak, U., & Simmer, C. (2010). PARSIVEL snow observations: A critical assessment. Journal of Atmospheric and Oceanic Technology, 27(2), 333-344. <https://doi.org/10.1175/2009JTECHA1332.1>

Sevruk, B., Methods of Correction for Systematic Error in Point Precipitation Measurement for Operational Use, Operational Hydrology Report 21, World Meteorological Organization, Geneva, Switzerland, 1982.

Dunn, R.E., Fowler, H.J., Green, A.C. and Lewis, E. (2025), Tipping-bucket rain gauges: a review of the undercatch phenomenon, and methods for its reduction and correction. Weather, 80: 196-205. <https://doi.org/10.1002/wea.7736>

3. The gauge used for comparison switches between subsections. In Section 3.1, the Lambrecht rain[e]H3 is used; in Section 3.2, the EML SBS-500 is used. In Section 3.3, the AES Nipher gauge is used. Finally, in Section 4, we switch back to the EML SBS-500. This makes comparing the results extremely difficult, and the text does not clearly explain why the authors switched between these three gauges.

This was done to compare the investigated aerodynamic solutions – which had been improved through various stages of design development – with rain gauges offering progressively higher performance.

The first geometry uses a simple straight inclined rim, that is similar to the rim of the Lambrecht rain[e]H3. A better performing solution was then compared with an existing and well-known aerodynamic design, which is currently one of the best performing gauges (without shielding) in strong wind. Finally, the geometry providing the best performance was compared with a shielded gauge designed for solid precipitation. Although not as common as other designs, the AES Nipher is one of the best performing gauges on the market thanks to its integrated windshield.

The revised manuscript was improved for readability and clarity by adding a clearer explanation of the motivations behind the comparisons made.

4. The overcollection of large drops (e.g., Figure 5) seems like a bigger problem than the undercollection of small drops from a mass sense, but this is not addressed. How does the total collection of mass change between these designs? This is addressed in the discussion section, but should be discussed earlier, especially since the over collection appears to be diminished when building together all of the individual parameters.

We do not entirely concur with the reviewer on the fact that overestimation of large drops is a bigger problem than small drops underestimation. This is since in precipitation events

(even for high precipitation intensity) the liquid water content associated with drops $> 1\text{mm}$ quickly decreases with increasing the drop diameter (see e.g. Cauteruccio et al. 2024, Figure 12). Furthermore between 60% and 90% (depending on RI) of the total precipitation volume is associated with drops having a diameter equal or smaller than 2 mm.

The observed overestimation is because wind can divert large drops inside the collector (upwind) but is unable to divert the same number of drops (or more) outside the collector (downwind). This effect was already noted for some gauges in the work of Cauteruccio et al. (2020). Since this effect is not desirable (even if small in terms of total precipitation volume) the design producing overestimation was discarded in favour of a more complex parametrization that avoids the problem.

Results indicate that compared to a cylindrical gauge, with wind-induced losses typically between 3% and 18%, our design increases the average collected volume of liquid precipitation by about 5%. For solid precipitation, our design shows an average increase of around 15%, when compared with wind-induced losses averaging between 68% and 81% for a Nipher shielded gauge.

However, to compare results in terms of total collection of mass a DSD must be assumed. While this was done in the manuscript to allow comparison with other gauges, assuming a DSD in the optimization phase may introduce a dependency on local climatology that, in our opinion, should be avoided. A specific comment on large drops overestimation is now included in the revised version of the manuscript.

Cauteruccio, A., & Lanza, L. G. (2020). *Parameterization of the collection efficiency of a cylindrical catching-type rain gauge based on rainfall intensity*. *Water*, 12(12), 3431. <https://doi.org/10.3390/w12123431>

Cauteruccio, A., Chinchella, E., & Lanza, L. G. (2024). *The overall collection efficiency of catching-type precipitation gauges in windy conditions*. *Water Resources Research*, 60(1), e2023WR035098. <https://doi.org/10.1029/2023WR035098>

5. The data availability statement is lacking. While the simulations may be too large to transfer (I cannot validate this as no size information is given), namelists/configuration files should be made publicly available. Further, I do not believe that, in the current form, the study is replicable as required by AMT policy, as the rain gauge design is not available as any sort of CAD file.

The total simulation data amounts to around 830 GB, with trajectories accounting for approximately 400 GB of this. All the numerical schemes used to reproduce the simulations are described in the text, along with any hypotheses and assumptions made. The methodology chapter provides a detailed description of the geometrical construction, the computational domain and the mesh used, including scaled drawings and conceptual schemes. Further minor geometric details have been included in the revised manuscript to improve clarity and reproducibility. In our opinion, providing a CAD file would not improve

the reproducibility of our work, but would limit access to the data to users of a specific commercial software package.

Minor Comments

1. The particle model omits turbulence, which is an understandable choice. However, that makes the comparison against the AES Nipher gauge challenging, as the shield necessarily increases turbulence. This should be addressed in the manuscript.

The Lagrangian particle model omits particle to particle interactions and uses a steady state velocity field (uncoupled approach), however no assumption on turbulence was made inside it. The only assumption on turbulence is made in the CFD model, where a $k-\omega$ SST turbulence model was used to solve the URANS equations. The same model was also used in the work of Cauteruccio et al. (2024) to evaluate the performances of the AES Nipher, ensuring a fair comparison between the two instruments. A brief comment was added in the text for clarity.

Cauteruccio, A., Chinchella, E., & Lanza, L. G. (2024). The overall collection efficiency of catching-type precipitation gauges in windy conditions. *Water Resources Research*, 60(1), e2023WR035098. <https://doi.org/10.1029/2023WR035098>

2. If the authors want to extend applications to solid precipitation, they should also mention/present results on how airflow may affect mixed precipitation or graupel, which will have different particle sizes and densities than liquid and snow.

Wind induced bias is strongly influenced by hydrometeor density. The choice of presenting results for liquid precipitation and dry snow was made since they represent the two extremes of the range of hydrometeor density. Wet snow and graupels, having a density that is in between that of liquid water and dry snow, would provide results (in terms of CR) that are in-between what was already presented. We acknowledge that this behaviour is not linear and it is not possible to extrapolate performance based on density alone. This is especially true in terms of total precipitation volume (CE), since the DSD differs between rainfall, graupel, wet snow and dry snow. However, in our opinion, the inclusion of results for wet snow and graupel would exceed the scope of this work, making also the paper unnecessarily long. However, a comment on this topic was added in the text to provide a more complete discussion.

Lines 33-37: be consistent with “see” and “see e.g.”

Done

Lines 45-55: These two paragraphs are very difficult to understand.

These paragraphs has now been largely rewritten and improved for clarity.

Figure 1: The proposed rain gauge design is helpful, but there is no comparison to existing gauges. Readers would benefit from including a comparison figure to Fig 1 that compares existing gauge design(s) to the proposed design (Lambrecht cylindrical, EML inverted-conical, AES Nipher shielded gauge compared later in the paper)

A schematic image of the three commercially available gauges was added in Figure 1 as suggested by the reviewer.

Line 120: superscripts were dropped for cm^2

The typo was eliminated and measurement units are now formatted correctly.

Line 153-154: it would be very helpful to label the angles here in the text (linking them to Fig 1)

Angles are now labelled as suggested by the reviewer.

Line 165: Why was only one inflow angle selected?

The choice of the final inflow angle was based on results from the two previously tested geometries. The initial simulations showed that a too steep angle produces higher separation layer and increases flow velocity. Meanwhile a shallow angle produces boundary layer separation in the front part of the rim, limiting the ability to control the position of the boundary layer. Furthermore, to limit the computational burden we avoided adding an additional optimization parameter that would have exponentially increased the required resources. This is partially explained in section 3.3, however a more in-dept explanation has now been added to the text.

Line 180: How is the phase 1 OpenFOAM model connected to the LPT model in line 191? Is the LPT model entirely separate, or is this using the background conditions from the OpenFOAM model from phase 1?

The OpenFOAM model is used to obtain the velocity field around the gauge body. The obtained velocity field is then used as input for the LPT model providing the aerodynamic disturbance that drops experience during their fall. The writing of this paragraph has now been improved for clarity to avoid confusion.

Line 180: 5 m/s as a baseline is fine, but the phrasing of “is a common occurrence in the field” is a bit odd

The comment was removed as too generic and not contributing significantly to the discussion.

Line 180: Uref should be defined as undisturbed wind speed

Done.

Line 234: This is a different theta than before.

Notation is now uniform throughout the text.

Figure 2: It would be very useful to have the angles written on the figure.

Figure 2 was modified according to the reviewer suggestion.

Line 197: What does it mean that the releasing positions were in regularly set grids? Are they populating every grid point?

Particles were inserted in the domain along regular grids with a 4 mm spacing. The grid is not correlated to the calculation mesh but simply used as a set of starting points for trajectories. The grid width and spacing are constant while grid length was increased for smaller particles. The position of this grid was computed so that the particle released in the centre of the grid would reach the centre of the gauge collector under a constant wind velocity throughout the domain. The grid size (in particular its length) was evaluated to ensure that even in a disturbed wind field all possible trajectories can reach the gauge collector. A more detailed explanation has now been added to the revised manuscript to better describe how particles are inserted in the domain and improve clarity.

Figure 3: The white bar on Figure 3b is extremely difficult to see.

The colour scale was improved for Figure 3b and all the following figures where the same scheme was used.

Figure 10: this is extremely difficult to interpret. I cannot tell the difference between the triangles and circles.

Figure 10 and Figure 9 were modified using larger symbols to improve readability.

Line 297: “Larger rims tend to produce lower separation layers and limited flow acceleration.” Figure 6 seems to show that smaller rims lead to lower separation layers and flow acceleration.

In figure 6 the profile corresponding to the lower separation layer (presenting also the lowest flow acceleration) is the one indicated with $\alpha = 0^\circ/r = 1.5$. This indicates the largest rim that was simulated in our work, since r is inversely proportional to the rim width, meanwhile $r=4$ indicates the narrowest rim that was simulated. Further emphasis was added in the definition of r in the paper to avoid confusion.

References: Gunn and Marshall 1958, Rasmussen et al. 1999 DOI links are broken, Nipher et al. 1878 DOI link leads to the wrong paper

DOI are now correct.