

## REVIEWER#1

### General comments:

The manuscript presents a method on target categorization of various aerosol, cloud and precipitation types with a focus to aerosol types, utilizing the attenuated backscatter coefficient (ATB) and volume depolarization ratio (VDR) at 910 nm from a Vaisala CL61 ceilometer located at Uccle, Belgium. The classification is based on fixed thresholds defined in a decision tree. The results are then evaluated using aerosol mixing ratios from CAMS model for the various aerosol types. The manuscript is timely and relevant, polarization-based classification algorithms are genuinely useful and single-wavelength lidars with polarization capability are increasingly utilized by the community. Despite the fundamental limitations of this approach, using 1 ATB + 1 VDR for target classification can still provide long-term insights and help build a coherent climatology of aerosols and clouds, which can be further applied to observational networks such as EUMETNET E-PROFILE and ACTRIS. The manuscript is well organized, supported by relevant literature, and offers a comprehensive discussion of the algorithm's strengths and limitations. Nonetheless, several passages are overly speculative, and some sections contain unnecessary repetition. The manuscript is suited for publication in Atmospheric Measurement Techniques and can be published after addressing the comments/questions listed below.

We sincerely thank the reviewer for the thorough, constructive, and encouraging evaluation of our manuscript. We greatly appreciate the positive assessment of the relevance and potential applicability of CONIOPOL for long-term aerosol and cloud monitoring within observational networks such as EUMETNET E-PROFILE and ACTRIS. We are also grateful for the recognition of both the strengths and the inherent limitations of a single-wavelength polarization-based classification approach. Your insightful comments have helped us improve the clarity, scientific rigor, and overall quality of the manuscript. In particular, we have carefully revised the manuscript to reduce speculative statements, remove unnecessary repetition, and clarify several methodological aspects.

Before addressing the individual comments, we would like to summarize the principal modifications made to the manuscript following the reviewers' suggestions:

- The manuscript has been substantially revised to better **highlight** the role of the **cloud-phase and precipitation classifications**, which are now more clearly presented as an integral component of CONIOPOL rather than as a secondary extension of the aerosol classification.
- The **title** has been **revised** to better reflect the full scope of CONIOPOL by explicitly referring to both **aerosols and hydrometeors**. This modification better represents the capabilities of the algorithm and is consistent with the strengthened presentation of the cloud-phase and precipitation classifications throughout the manuscript.
- The **classification methodology** has been refined by introducing explicit **transitional classes** for aerosols, cloud phase, and precipitation. These intermediate categories provide a more physically realistic representation of observations exhibiting mixed optical characteristics and reduce potential misclassification arising from overlapping depolarization signatures.

- The justification of the depolarization thresholds has been substantially expanded. The selection of the **depolarization thresholds** is now supported by a more comprehensive **review of the peer-reviewed literature**, including recent studies using polarization lidars at wavelengths comparable to the CL61, providing a stronger physical basis for the adopted classification scheme.
- The **CAMS comparison** with CONIOPOL has been substantially **revised**. The analysis is now performed on a **seasonal basis, extended vertically up to 10 km**, and complemented by a more detailed discussion of the physical interpretation, **statistical significance**, and **limitations of the comparison**.
- During the implementation of the newly introduced transitional classes, we identified an error in the classification mask affecting the **Smoke/Marine aerosol** category. In the previous version, this category was only considered when no cloud was detected. Consequently, Smoke/Marine aerosols located beneath or within cloudy conditions were inadvertently excluded from the statistics. This issue has now been corrected, resulting in a substantially higher occurrence of the Smoke/Marine category and a markedly improved correspondence with the CAMS aerosol fields.
- We also revised the treatment of **weakly depolarizing targets under cloudy conditions**. In the previous version, low-depolarization observations within clouds were systematically assigned to the Fog/Drizzle/Mist category, even when they were clearly disconnected from the surface. This **decision-tree branch has been removed**, leading to a more physically consistent classification and an increased occurrence of the Liquid Cloud (Droplet) category.
- To avoid ambiguity in the interpretation of weakly depolarizing aerosols, the **former "Hygroscopic Aerosol" category** has been **renamed "Continental Aerosol"**. This terminology more accurately reflects the physical nature of the classified particles and avoids confusion with the Smoke/Marine category, since both aerosol types are hygroscopic but are associated with distinct atmospheric environments. The revised discussion further demonstrates that these two categories exhibit different vertical occurrence profiles, consistent with their association with the continental and marine boundary layers, respectively.
- The presentation of the **normalized cumulative occurrence profiles** has also been **revised**. Instead of displaying monthly statistics, the revised manuscript now presents **seasonal occurrence profiles up to 15km**, providing a clearer representation of the dominant atmospheric regimes while improving consistency with the revised CAMS intercomparison, which is now analysed seasonally and extended vertically up to 10 km.
- The **showcase figure** has also been **updated**. During the revision process, **several display issues** were identified in the previous version (e.g. the omission of a secondary cloud layer in the graphical representation). These issues only affected the visualization and **did not affect the CONIOPOL classification itself** or any of the statistical analyses, which were produced directly from the classified data.

Specific comments:

1. The algorithm uses a decision tree to classify the various targets. At the moment, there is no inclusion or even discussion on the uncertainties associated with the ATB and VDR, the two essential parameters used in the classification, and their effect in the classification. These parameters undoubtedly influence the results of the target classification, and therefore, a comprehensive sensitivity analysis is needed. The authors mention that calibrating the CL61 instrument is essential. This can be done within 5-10 % uncertainty (O'Connor et al., 2004, Hopkins et al., 2018, Looschelders et al., 2025). In addition, temporal averaging (and potentially vertical averaging) modifies the measured parameters and may interfere with the hard-set thresholds used in the classification. This raises two important questions: How sensitive is the classification to calibration biases and temporal averaging, and which parameter is the most sensitive? The manuscript would benefit from explicit recommendations and a clear discussion of its limitations from this perspective.

O'Connor, E. J., A. J. Illingworth, and R. J. Hogan, 2004: A Technique for Autocalibration of Cloud Lidar. *J. Atmos. Oceanic Technol.*, 21, 777–786, [https://doi.org/10.1175/1520-0426\(2004\)021<0777:ATFAOC>2.0.CO;2](https://doi.org/10.1175/1520-0426(2004)021<0777:ATFAOC>2.0.CO;2).

Hopkin, E., Illingworth, A. J., Charlton-Perez, C., Westbrook, C. D., and Ballard, S.: A robust automated technique for operational calibration of ceilometers using the integrated backscatter from totally attenuating liquid clouds, *Atmos. Meas. Tech.*, 12, 4131–4147, <https://doi.org/10.5194/amt-12-4131-2019>, 2019.

Looschelders, D., A.Christen, S.Grimmond, et al. 2025. “Inter-Instrument Variability of Vaisala CL61 Lidar-Ceilometer's Attenuated Backscatter, Cloud Properties and Mixed-Layer Height.” *Meteorological Applications*32, no. 5: e70088. <https://doi.org/10.1002/met.70088>.

We thank the reviewer for this important comment. We agree that uncertainties in the optical parameters used by the decision tree, as well as the temporal and vertical scales applied during preprocessing, may affect a threshold-based classification and therefore need to be explicitly assessed.

In response to this comment, we have added a dedicated sensitivity analysis to the revised manuscript (Sect. 4.7 and Figs. A1–A2), specifically addressing the sensitivity of CONIOPOL to attenuated backscatter (ATB), volume linear depolarization ratio (VDR), their combined perturbation, and the temporal–vertical filtering scale.

First, the sensitivity to ATB calibration uncertainty was assessed by applying relative perturbations of  $\pm 5\%$  and  $\pm 10\%$ . Since PPOL is also used as an absolute signal threshold within the aerosol classification branch, the same relative perturbation was simultaneously applied to PPOL to maintain consistency within the sensitivity experiment. The results show that CONIOPOL is comparatively robust to realistic ATB

calibration biases: even for  $\pm 10\%$  perturbations, the overall classification remains largely unchanged, with modifications mainly affecting observations located close to fixed ATB thresholds.

Second, the sensitivity to VDR was evaluated using absolute perturbations of  $\pm 0.01$  and  $\pm 0.02$ . These values were derived from the observed variability of VDR at the base of liquid water clouds (Fig. 1), where near-zero depolarization is expected. Because PPOL and XPOL are measured successively by the CL61, this observed variability provides an empirical estimate of the short-term variability affecting the measured VDR. For the sensitivity experiment, the same absolute perturbation was applied across the VDR range. We explicitly acknowledge in the revised manuscript that this assumption may not fully characterize VDR uncertainty for strongly depolarizing targets and that these perturbations should therefore be interpreted as controlled sensitivity scenarios rather than as a complete uncertainty characterization. Negative perturbed VDR values were set to zero because negative depolarization ratios are not physically meaningful.

The VDR experiments produced a larger redistribution of classifications than the corresponding ATB perturbations. Importantly, these changes occurred predominantly between neighbouring categories separated by a VDR threshold, rather than producing arbitrary transitions across the classification scheme. This was particularly evident for the transitional aerosol classes (e.g. mixed aerosol, dust/ice, and ash/dust/ice) and neighbouring hydrometeor categories. The newly introduced intermediate classes therefore also provide a means of accommodating the natural overlap of optical properties and measurement variability close to the decision boundaries.

Because ATB and VDR uncertainties may occur simultaneously, we additionally performed four combined experiments using the largest perturbations (ATB  $\pm 10\%$  and VDR  $\pm 0.02$ ). The resulting classification changes were predominantly controlled by the imposed VDR perturbation. At the global level, the combined response was also close to that expected assuming independent ATB and VDR effects, with differences below 0.2 percentage points for both investigated periods. These experiments therefore identify VDR as the dominant source of sensitivity among the two optical parameters investigated.

We also agree with the reviewer that temporal and vertical averaging may interact with fixed classification thresholds. To investigate this effect, we varied the two-dimensional median-filter kernel used during preprocessing from the reference  $10 \times 10$  window to  $5 \times 5$  and  $15 \times 15$  windows. Changing the filtering scale produced a broader redistribution than the ATB calibration experiments, particularly for heterogeneous and short-lived atmospheric features. Smaller kernels preserved more fine-scale variability, whereas larger kernels favoured spatially and temporally coherent structures at the expense of isolated features. Nevertheless, the principal classification patterns remained identifiable in both representative periods considered (April and August 2024).

Overall, the new analysis shows that CONIOPOL is comparatively robust to ATB calibration uncertainties of up to  $\pm 10\%$ , while VDR is the more sensitive of the two optical parameters. Sensitivity is primarily concentrated around fixed decision thresholds, where relatively small changes in the measured optical properties can shift observations between neighbouring classes. The temporal–vertical filtering scale represents an additional source of variability, particularly for heterogeneous atmospheric structures.

Following the reviewer's recommendation, these findings and their limitations are now explicitly discussed in the revised manuscript. We also provide practical recommendations emphasizing the need for regular monitoring of both ATB calibration and depolarization performance. In particular, the ATB calibration should be monitored to identify instrumental drift, while VDR performance should be regularly assessed using suitable low-depolarization targets such as liquid-water cloud bases. Finally, occurrence statistics and individual classifications close to decision thresholds should be interpreted with appropriate caution.

We thank the reviewer for raising this point, as the additional sensitivity analysis has substantially strengthened the characterization of the robustness and limitations of the CONIOPOL classification framework.

2. CAMS is used for validation, but the manuscript does not include studies showing known mismatches between CAMS and lidar measurements in smoke and dust cases. Furthermore, the comparison is carried out by partitioning the atmosphere into two regions: one below 1 km and one above from which conclusions are drawn. I would suggest including a more detailed and statistical meaningful comparison between the model aerosol mixing ratios and the lidar-based target classification. One possible improvement would be to include heatmaps showing the hit/miss ratios for the different aerosol and cloud categories, add a seasonal comparison, and segment the atmosphere in more detail, for example, to capture the high-level clouds as well. Although it is difficult to find an aerosol target classification available for the validation, the authors could consider published long-term aerosol classifications within Europe from EARLINET-ACTRIS networks. Cloudnet could provide some insights into the cloud/precipitation typing. Have the authors considered using the target classification from the closest Cloudnet station?

We thank the reviewer for these valuable suggestions, which have led to a substantial revision of the CAMS comparison.

First, following the reviewer's comment, the CAMS comparison is no longer presented as a validation, but as a conditional comparison intended to assess whether the aerosol classes identified by CONIOPOL are associated with physically meaningful aerosol environments represented by an independent atmospheric composition dataset. The revised manuscript also explicitly acknowledges the limitations of CAMS.

Second, the comparison methodology has been significantly expanded. In the original manuscript, the analysis was limited to two broad altitude ranges (<1 km and >1 km). In the revised version, the comparison is now performed throughout the atmospheric column up to 10 km. using successive 250 m altitude intervals, allowing a much more detailed investigation of the vertical structure of the different aerosol categories. Furthermore, the analysis has been extended to include a seasonal comparison, thereby highlighting the seasonal variability of the relationships between CONIOPOL classifications and CAMS aerosol fields.

Regarding the suggestion of hit/miss matrices, we considered this approach. However, such metrics require a common categorical reference. Since CAMS provides continuous aerosol mixing ratios rather than aerosol target classifications, and CONIOPOL provides qualitative aerosol categories rather than quantitative concentrations, a binary hit/miss analysis would require the introduction of arbitrary thresholds in the CAMS fields. We therefore considered the statistical comparison of aerosol mixing-ratio

distributions to be more appropriate and physically meaningful for evaluating the consistency between these fundamentally different datasets.

We appreciate your suggestion regarding the use of Cloudnet target classifications for evaluating the cloud and precipitation categories. We considered this possibility. However, the nearest Cloudnet stations (e.g. Cabauw and Jülich) are both located approximately 140 km from the Uccle site. At such a distance, the spatial and temporal variability of clouds and precipitation would make a direct comparison difficult to interpret, as differences would primarily reflect the evolution and displacement of atmospheric systems rather than the performance of the classification algorithms. Consequently, we considered that a comparison with the Jülich/Cabauw Cloudnet target classification would not provide a sufficiently robust assessment of the cloud and precipitation categories retrieved by CONIOPOL. We nevertheless agree that comparisons with collocated Cloudnet observations would constitute an excellent validation dataset where such measurements are available and represent an interesting perspective for future work.

3. Figure 1 appears rather early, without prior discussion of the choice and origin of the values shown, and before the requirements of the algorithm have been introduced. I recommend moving Figure 1 and the introduction of the typing scheme after Section 4.3.

Done in the revised manuscript.

4. Line 166: The minimum useful height in CL61 instrument is 40-50m above ground level according to Roininen et al. (2025) and Le et al., (2026) while there are a few studies reporting an artifact located between 80 and 150m that is not always present (Filioglou et al., 2025, Ve et al., 2026). How the selection of 33.6m is justified?

Roininen, R., Tuononen, M., Bircher-Adrot, S., Rüfenacht, R., O'Connor, E., Buxmann, J., Kotthaus, S., Van Hove, M., Diémoz, H., BELLINI, A., Fenner, D., Looschelders, D., Geiß, A., Wagner, F., and Mattis, I.: SOP CL61, Zenodo, <https://doi.org/10.5281/zenodo.14833761>, 2025.

Le, V., O'Connor, E. J., Filioglou, M., and Vakkari, V.: Operational performance of the Vaisala CL61 ceilometer for atmospheric profiling, EGU sphere [preprint], <https://doi.org/10.5194/egusphere-2025-6331>, 2026.

Filioglou, M., Tiitta, P., Shang, X., Leskinen, A., Ahola, P., Pätsi, S., Saarto, A., Vakkari, V., Isopahkala, U., and Komppula, M.: Lidar estimates of birch pollen number, mass, and CCN-related concentrations, Atmos. Chem. Phys., 25, 1639–1657, <https://doi.org/10.5194/acp-25-1639-2025>, 2025.

The altitude of 33.6 m was determined from the instrument-specific overlap function supplied by the manufacturer. This function, expressed as a percentage between 0 and 100%, describes the region of incomplete optical overlap, commonly known as the blind zone. According to Wagner et al. (2024), observations within the blind zone should be discarded; they define its upper limit as the height at which the overlap function reaches 3%. Consequently, all observations below this height were excluded from further analysis.

The 2D sliding-window consistency filter (previously DBSCAN) of CONIOPOL outputs masks the instrumental issues reported below 40–50 m. For consistency with recent CL61 studies, only measurements above 50 m are retained in the revised analysis. Regarding the artefact occasionally reported between approximately 80 and 150 m, we did not identify any systematic abnormal signature in the CONIOPOL output during the study period. The two-dimensional sliding-window consistency filter may additionally reduce the influence of isolated artefacts, although it cannot guarantee their complete removal. This limitation is now explicitly acknowledged in the revised manuscript. This will be explicitly stated in the section describing the 2D sliding-window consistency filtering.

Wagner, F., Geiss, A., Barnaba, F., Belegante, L., Bellini, A., Buxmann, J., Diémoz, H., Fenner, D., Kotthaus, S., Osborne, M., Ruefenacht, R., Ruiz de Morales Céspedes, J., and Van Hove, M.: JND European networks observing the atmospheric boundary layer: Overview, access and impacts - Chapter 2a: Automatic low-power Lidar and Ceilometer (ALC), Zenodo, <https://doi.org/10.5281/zenodo.11211873>, 2024

5. Line 173: The cloud base height reported in the ceilometer files uses the signal strength and strength of the change to determine the presence of a cloud. While in liquid clouds the condition is easily met, in optically thinner clouds, like cirrus, the cloud base height is shifted upwards, or the cloud can even go undetected if the visibility is not compromised (see Figure 7). In addition, a challenge which is also present in multi-wavelength lidar-based target classifications, is that intense aerosol layers (volcanic ash, dust, pollen) may be falsely classified as clouds, specifically as ice clouds. Although the authors chose to limit the analysis to the lowest 5 km, thereby excluding most high-level clouds, it would be important to address the long-term bias this constraint may introduce by the algorithm, if any. For example, in Figure 7 there are some high-level clouds showing variable LDR values at 23.30 UTC with no detected cloud base. Nevertheless, the algorithm still classifies these bins as clouds. This should be clarified.

We thank the reviewer for this careful observation. The apparent inconsistency in Figure 7 results from the figure itself rather than from the CONIOPOL algorithm. At approximately 23:30 UTC and also between 4:00 and 5:00 UTC, the CL61 cloud-base algorithm detected a second cloud-base layer. However, only the first detected cloud base was displayed in the original figure, giving the misleading impression that the high-level cloud was classified without an associated cloud-base detection. The figure has been corrected so that all cloud-base detections used by CONIOPOL are now displayed.

We have also substantially expanded the discussion to address the limitations associated with cloud-base retrieval. The revised manuscript now explains that the cloud-base information is obtained directly from the Vaisala CL61 algorithm and discusses how missed cloud detections or false cloud detections over dense aerosol layers may propagate through the CONIOPOL decision tree. We further clarify that these effects are generally localized because the decision tree is applied independently at each observation and combines cloud-base information with attenuated backscatter, VDR, PPOL intensity, and a two-dimensional sliding-window consistency filter.

Finally, the occurrence analysis has been extended to the full CL61 measurement range (15.4 km a.g.l.), allowing the occurrence of the ice-crystal category to be analysed throughout the atmospheric column. The manuscript now explicitly discusses the limitations of cloud-base detection at high altitude,

particularly for optically thin cirrus, and the implications for the interpretation of the reported occurrence statistics.

6. Figure 2: Could the authors clarify how many height bins within the liquid cloud layer were considered, and what altitudes are represented in the figure?

Yes, we add in the revised manuscript the following description:

- Cloud bases were selected according to this category when the volume linear depolarization ratio (VDR) was below 0.1, the retrieval CBH ranged between 1000 and 4000 m, and the standard deviation of the CBH remained below 15 m over a 10-minute interval.

- The data points from the range gates located 57.6, 62.4, 67.2, and 72 m below the retrieval CBH were used without smoothing, provided that the attenuated backscatter remained greater than  $3 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$  across all selected gates. Data points were selected below the retrieved CBH because Vaisala ceilometers typically report the CBH slightly above the altitude of maximum backscatter (Wagner et al., 2024).

7. Line 215: Earlier in the text and again at the end of this paragraph, it is stated that the profiles are temporally averaged over 30s, yet Line 215 indicates that a 30min window is used for noise estimation. Why was such a long time interval chosen?

We thank the reviewer for identifying these discrepancies. After carefully revisiting the manuscript, we found that two preprocessing parameters reported in the original text corresponded to an earlier development version of CONIOPOL rather than to the final implementation used to generate the results. Importantly, this discrepancy concerned the methodological description only; all results presented in the manuscript were generated using the final processing configuration described below.

First, the reference to a 30 min noise estimation window was incorrect. In the final version of CONIOPOL, the noise level is estimated for each 30 s profile. Estimating the noise over a 30 min period could be affected by transient atmospheric conditions, particularly cloud transitions that modify the solar background illumination. The 30 min interval mentioned in the original manuscript originated from a running stationarity test of the noise that was implemented during the early development of CONIOPOL but was not retained in the final processing scheme. The manuscript has been corrected accordingly.

Second, the description of the Gaussian smoothing parameters was also inherited from this early development version. The CONIOPOL algorithm used throughout this study has always applied a two-dimensional Gaussian filter with standard deviations of (0.3, 0.3) samples in time and range, whereas the values of (3.0, 3.0) reported in the original manuscript were mistakenly carried over from the preliminary implementation. In addition, the manuscript has been revised to explicitly describe the preceding  $10 \times 10$  median filtering step, which has always been part of the final processing chain but was inadvertently omitted from the original description.

The revised manuscript now provides a complete and accurate description of the preprocessing applied prior to the classification, fully consistent with the implementation used to generate the results presented in this paper.

8. Lines 256-261: The gauge and CL61 observations have temporal resolutions of 1 h and 10 min, respectively. The authors attribute part of the discrepancy to these differences in temporal resolution.

However, why were the CL61 observations not averaged to match the gauge's 1-hour resolution, rather than speculating about whether the mismatch arises from this source? A brief justification would strengthen the interpretation.

We thank the reviewer for this comment. You are absolutely right that there is no need to rely on a hypothetical effect of temporal resolution when the two datasets can be directly compared at the same temporal resolution. We have therefore revised the analysis and the corresponding figure by aggregating the CONIOPOL observations to the same 1-hour temporal resolution as the AWS measurements.

The revised comparison shows that CONIOPOL generally reports a higher precipitation occurrence than the AWS, with differences ranging from approximately 5 to 13%. This positive bias is statistically significant during autumn and winter. A plausible contribution to this discrepancy is the more frequent occurrence of fog, mist, and drizzle-like conditions during these seasons, for which discrimination from precipitation remains challenging using the CL61 optical measurements alone. In addition, as now discussed in the sensitivity analysis (Sect. 4.7), VDR variability may cause observations close to hydrometeor classification thresholds to shift between neighbouring categories. However, the sensitivity analysis does not allow us to quantify how much of the observed CONIOPOL–AWS difference can be attributed to this effect.

We also note that the AWS precipitation occurrence values for November, December, and January differ from those presented in the previous version of the manuscript. Corrections were made to the AWS database after the initial analysis, and the revised figure therefore uses the updated and corrected observational dataset.

The corresponding text and figure have been revised accordingly.

9. Section 4.4: LDR plays a central role in the classification, and published values at 910 nm are still limited. It would improve clarity in this section if the authors explicitly indicated which values refer to 910 nm and which are taken from studies at other wavelengths.

We have added numerous peer-review references to support our choices in defining the different target classification, and we introduced intermediate classes to better account for overlapping depolarization ranges between categories, while prioritizing studies using wavelengths similar to ours due to the strong spectral dependence that can exist for certain aerosol categories. At 910 nm, the molecular contribution to the measured VDR is substantially reduced compared with shorter lidar wavelengths because of the strong wavelength dependence of Rayleigh scattering. Consequently, in particle-dominated layers, VDR is expected to approach the particle depolarization signature, although VDR and PDR are not formally equivalent. The reference to the Vaisala white paper has been removed, as it was not peer-reviewed, as correctly pointed out by Reviewer #3.

10. Line 289: Pollen types are also overlapping (Cao et al., 2010).

Cao, X., Roy, G. A., and Bernier, R.: Lidar polarization discrimination of bioaerosols, *Opt. Eng.*, 49, 116201, <https://doi.org/10.1117/1.3505877>, 2010.

In the revised section (4.4) defining the target classification (see revised manuscript), we refer to this study, noting that it was conducted under controlled laboratory conditions. In real atmospheric conditions, the VDR is lower due to mixing with other atmospheric constituents and, at greater distances from the source, due to a decrease in pollen concentration.

11. Line 295: How is the fresh vs aged smoke considered in the algorithm? Could the authors provide some insights?

We thank the reviewer for this comment. Fresh and aged smoke are not explicitly separated in CONIOPOL algorithm. This choice is due to the substantial overlap in VDR values between fresh and aged smoke, as well as the strong influence of hygroscopic growth, mixing state, and measurement wavelength (910 nm).

As a result, VDR alone does not provide sufficient discriminatory power to robustly distinguish smoke aging states. Therefore, both fresh and aged smoke are included within a single smoke class, with variability implicitly accounted for through the observed range of optical properties.

A clarification has been added in Section 4.4 of the revised manuscript.

12. Line 355: Which microphysical properties you are referring to?

We refer to the statement in the next sentence, namely the discrimination of cloud phase. The first sentence has been removed as it was redundant and not necessary.

13. Line 356: Are temperature profiles available for this case? The liquid layer is most probably in sub-freezing temperatures as there is a melting layer at around 3 km modifying the LDR values (see for example, at 4 and after 6 UTC). In this context, some solid precipitation is being misclassified as dust (around 4 UTC). Also, some thin precipitation bits are missed in the classification but that is inevitable given their high temporal variability.

We thank the reviewer for this insightful comment. We agree that temperature profiles would provide useful additional information for the interpretation of this case. However, CONIOPOL was intentionally designed as an observation-based classification algorithm relying exclusively on the optical properties measured by the CL61, without requiring ancillary meteorological information such as temperature profiles.

We agree that the presence of a melting layer around 2.5–3 km indicates a transition between liquid and solid hydrometeors, making the interpretation of the depolarization signal more complex. In the revised figure, a display error has been corrected: the initial part of the virga detected by CONIOPOL as ice crystals and dust/ice was not displayed correctly, giving the misleading impression that only the dust classification was present. The same display issue also occurred around 08:00 UTC. This visualization error had no impact on the CONIOPOL classification itself or on the subsequent analysis.

It should also be noted that preferentially horizontally oriented ice crystals may exhibit substantially reduced VDR when observed by a zenith-pointing lidar (Noël and Sassen, 2005). Under such conditions, the measured depolarization may decrease below the nominal ice-crystal threshold used by the decision tree, making the discrimination between ice crystals and highly depolarizing particles more challenging. The manuscript has been revised to explicitly discuss this intrinsic limitation of depolarization-based cloud-phase classification and to clarify that such situations may occur under specific atmospheric conditions. This mechanism may provide a plausible explanation for the apparent dust virga. In addition, virga may occasionally contain mineral dust transported within the same atmospheric layer, as reported by Karle et al. (2023), indicating that the coexistence of ice crystals and dust cannot be excluded.

Finally, we agree that very thin precipitation features may occasionally be missed because of their limited spatial extent and strong temporal variability. Such features are close to the spatial and temporal

resolution limits of the observations and are therefore not expected to significantly affect either the interpretation of this case study or the long-term occurrence statistics.

Noel, V. and Sassen, K.: Study of Planar Ice Crystal Orientations in Ice Clouds from Scanning Polarization Lidar Observations, *J. Appl. Meteorol.*, 44, 653–664, <https://doi.org/10.1175/JAM2223.1>, 2005.

Karle, N. N., Sakai, R. K., Fitzgerald, R. M., Ichoku, C., Mercado, F., and Stockwell, W. R.: Systematic analysis of virga and its impact on surface particulate matter observations, *Atmospheric Meas. Tech.*, 16, 1073–1085, <https://doi.org/10.5194/amt-16-1073-2023>, 2023.

14. Sect 6.1.1: It is unclear how the percentages are calculated and even more importantly why they can exceed 100%.

We thank the reviewer for this comment. The monthly occurrence definition was clarified in the revised manuscript to avoid ambiguity.

For each category, the monthly occurrence is calculated as the percentage of hourly periods in which the corresponding category is detected in at least 60% of the available observations within that hour, relative to the total number of hourly periods available during the month. Multiple categories may coexist within the same hourly period because different aerosol and hydrometeor types can occur simultaneously at different altitudes. Consequently, category occurrences are not mutually exclusive and their sum may exceed 100%.

15. Line 472: ‘.....above 1000m’. What is the upper limit of this comparison? Is it the 5 km as mentioned earlier or higher?

We thank the reviewer for this comment. Following your earlier suggestion, the analysis has been substantially revised to provide altitude-resolved statistics rather than using broad altitude intervals. The previous discussion referring to "above 1000 m" has therefore been removed and replaced by a more detailed analysis at successive altitude levels. As a result, this ambiguity regarding the upper altitude limit no longer applies in the revised manuscript.

16. Line 549: ‘The observed difference in total dust mixing ratio detected by CONIOPOL...atmospheric processes.’ The algorithm itself is not providing the dust mixing ratio. Rephrase the sentence.

We thank the reviewer for pointing this out. We fully agree that CONIOPOL does not retrieve aerosol mixing ratios. In the revised manuscript, this sentence has been removed as part of the substantially revised altitude-resolved CAMS comparison. Throughout the revised analysis, CAMS mixing ratios are now explicitly described as being associated with CONIOPOL classifications rather than retrieved or detected by CONIOPOL.

Technical corrections:

The same acronym is defined more than once in the manuscript. For example, the LDR acronym has two different definitions. It is the Linear Depolarization Ratio (Line 15, Line 50, Line 87) or the Volume Linear

Depolarization Ratio (Line 156). The Volume Linear Depolarization ratio is used here, and the text should be updated throughout to avoid any confusion with the particle linear depolarization ratio.

We thank the reviewer for this comment. We have revised the Introduction to explicitly distinguish between the volume linear depolarization ratio (VDR) and the particulate linear depolarization ratio (PDR), and to clarify their respective physical meanings. To avoid misleading the reader, the term volume depolarization ratio (VDR) is now explicitly used whenever referring to depolarization measurements, and this terminology is consistently adopted throughout the remainder of the manuscript and in the abstract.

Line 39: Reference is missing

Done, we add in the revised manuscript the following references of Haywood and Boucher (2000) and Pappalardo et al. (2014).

Haywood, J. and Boucher, O.: Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review, *Rev. Geophys.*, 38, 513–543, <https://doi.org/10.1029/1999RG000078>, 2000.

Pappalardo, G., Amodeo, A., Apituley, A., Comeron, A., Freudenthaler, V., Linné, H., Ansmann, A., Bösenberg, J., D'Amico, G., Mattis, I., Mona, L., Wandinger, U., Amiridis, V., Alados-Arboledas, L., Nicolae, D., and Wiegner, M.: EARLINET: towards an advanced sustainable European aerosol lidar network, *Atmos Meas Tech*, 7, 2389–2409, <https://doi.org/10.5194/amt-7-2389-2014>, 2014.

Line 46: Reference is missing

Done, we explicitly refer to ACTRIS in the revised manuscript, citing Laj et al. (2024) as a reference.

Laj, P., Myhre, C. L., Riffault, V., Amiridis, V., Fuchs, H., Eleftheriadis, K., Petäjä, T., Salameh, T., Kivekäs, N., Juurola, E., Saponaro, G., Philippin, S., Cornacchia, C., Arboledas, L. A., Baars, H., Claude, A., Mazière, M. D., Dils, B., Dufresne, M., Evangeliou, N., Favez, O., Fiebig, M., Haeffelin, M., Herrmann, H., Höhler, K., Illmann, N., Kreuter, A., Ludewig, E., Marinou, E., Möhler, O., Mona, L., Murberg, L. E., Nicolae, D., Novelli, A., O'Connor, E., Ohneiser, K., Altieri, R. M. P., Picquet-Varrault, B., Pinxteren, D. van, Pospichal, B., Putaud, J.-P., Reimann, S., Siomos, N., Stachlewska, I., Tillmann, R., Voudouri, K. A., Wandinger, U., Wiedensohler, A., Apituley, A., Comerón, A., Gysel-Beer, M., Mihalopoulos, N., Nikolova, N., Pietruczuk, A., Sauvage, S., Sciare, J., Skov, H., Svendby, T., Swietlicki, E., Tonev, D., Vaughan, G., Zdimal, V., Baltensperger, U., Doussin, J.-F., Kulmala, M., Pappalardo, G., Sundet, S. S., and Vana, M.: Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS): The European Research Infrastructure Supporting Atmospheric Science, *Bulletin of the American Meteorological Society*, 105, E1098–E1136, <https://doi.org/10.1175/BAMS-D-23-0064.1>, 2024.

Line 93-94: Indeed! Two great examples are CALIOP and currently ATLID!

Yes indeed, we have included a reference to ATLID in the revised manuscript but not for CALIOP that is designed with two-wavelength polarization lidar (Winker et al., 2007).

Winker, D. M., W. H. Hunt, and M. J. McGill (2007), Initial performance assessment of CALIOP, *Geophys. Res. Lett.*, 34, L19803, [doi:10.1029/2007GL030135](https://doi.org/10.1029/2007GL030135).

Line 185: “Calibrated in manufactory” → calibrated by the manufacturer or calibrated at the Vaisala factory.

“Calibrated against a reference instrument” We rephrased: “The attenuated backscatter data provided by the CL61 are calibrated against a reference instrument that was calibrated at factory (Wagner et al. 2024) using the cloud calibration method proposed by O’Connor et al., (2004)”.

Lines 399-401: Unclear sentence. Consider rephrasing.

We thank the reviewer for pointing out that these sentences were unclear. In the original manuscript, this discussion was intended to demonstrate that the different aerosol and cloud categories did not exhibit a common background occurrence, thereby suggesting limited overlap between the predefined classes.

However, the revised version of CONIOPOL now explicitly introduces (intermediate classification to account for situations in which multiple categories coexist within the same neighbourhood. This new framework directly addresses potential overlaps between classes, making the previous discussion redundant and potentially confusing.

To improve the clarity of the manuscript, we have therefore removed these sentences from the revised version.

## REVIEWER#2

### General comments

The authors introduce a new algorithm to identify aerosol types from the measurements of the new Vaisala CL61 ceilometer with depolarisation capabilities automatically and in near real-time. The algorithm CONIOPOL is described in detail how the use of the backscatter profile, the depolarisation, and the cloud base height, by filtering, smoothing, and a threshold-based classification and clustering method is combined to allow the monitoring of aerosol and clouds and their seasonal variability.

The algorithm design and the necessary procedures as calibration procedures are described and verified using measurements from a one-year record in 2024-2025 of the CL61 instrument at Uccle, a long-running, well recognised atmospheric monitoring station in Belgium. The algorithm is able to distinguish a wide range of aerosol types, such as ash dust, mix aerosol, ice crystals, classifies hygroscopic aerosols, and detects different precipitation states.

This manuscript is well organised and offers a valuable contribution to the use of automatic classification of aerosol by adding the depolarisation ratio for networks of low-cost instruments as E-Profile and should be published after addressing the suggestions below.

We sincerely thank the reviewer for the careful evaluation of our manuscript and for the positive assessment of our work. We greatly appreciate the recognition of the scientific value of CONIOPOL and its potential for the automatic near-real-time classification of aerosols and clouds using polarization measurements from the CL61. We are particularly grateful for your acknowledgement of the detailed description of the algorithm, its verification using a one-year dataset, and its potential applicability to operational networks such as E-PROFILE. Your constructive suggestions have helped us improve the clarity, accuracy, and overall quality of the manuscript. We have carefully considered each comment and revised the manuscript accordingly.

Before addressing the individual comments, we would like to summarize the principal modifications made to the manuscript following the reviewers' suggestions:

- The manuscript has been substantially revised to better **highlight** the role of the **cloud-phase and precipitation classifications**, which are now more clearly presented as an integral component of CONIOPOL rather than as a secondary extension of the aerosol classification.
- The **title** has been **revised** to better reflect the full scope of CONIOPOL by explicitly referring to both **aerosols and hydrometeors**. This modification better represents the capabilities of the algorithm and is consistent with the strengthened presentation of the cloud-phase and precipitation classifications throughout the manuscript.

- The **classification methodology** has been refined by introducing explicit **transitional classes** for aerosols, cloud phase, and precipitation. These intermediate categories provide a more physically realistic representation of observations exhibiting mixed optical characteristics and reduce potential misclassification arising from overlapping depolarization signatures.
- The justification of the depolarization thresholds has been substantially expanded. The selection of the **depolarization thresholds** is now supported by a more comprehensive **review of the peer-reviewed literature**, including recent studies using polarization lidars at wavelengths comparable to the CL61, providing a stronger physical basis for the adopted classification scheme.
- The **CAMS comparison** with CONIOPOL has been substantially **revised**. The analysis is now performed on a **seasonal basis, extended vertically up to 10 km**, and complemented by a more detailed discussion of the physical interpretation, **statistical significance**, and **limitations of the comparison**.
- During the implementation of the newly introduced transitional classes, we identified an error in the classification mask affecting the **Smoke/Marine aerosol** category. In the previous version, this category was only considered when no cloud was detected. Consequently, Smoke/Marine aerosols located beneath or within cloudy conditions were inadvertently excluded from the statistics. This issue has now been corrected, resulting in a substantially higher occurrence of the Smoke/Marine category and a markedly improved correspondence with the CAMS aerosol fields.
- We also revised the treatment of **weakly depolarizing targets under cloudy conditions**. In the previous version, low-depolarization observations within clouds were systematically assigned to the Fog/Drizzle/Mist category, even when they were clearly disconnected from the surface. This **decision-tree branch has been removed**, leading to a more physically consistent classification and an increased occurrence of the Liquid Cloud (Droplet) category.
- To avoid ambiguity in the interpretation of weakly depolarizing aerosols, the **former "Hygroscopic Aerosol" category** has been **renamed "Continental Aerosol"**. This terminology more accurately reflects the physical nature of the classified particles and avoids confusion with the Smoke/Marine category, since both aerosol types are hygroscopic but are associated with distinct atmospheric environments. The revised discussion further demonstrates that these two categories exhibit different vertical occurrence profiles, consistent with their association with the continental and marine boundary layers, respectively.
- The presentation of the **normalized cumulative occurrence profiles** has also been **revised**. Instead of displaying monthly statistics, the revised manuscript now presents **seasonal occurrence profiles up to 15km**, providing a clearer representation of the dominant atmospheric regimes while improving consistency with the revised CAMS intercomparison, which is now analysed seasonally and extended vertically up to 10 km.
- The **showcase figure** has also been **updated**. During the revision process, **several display issues** were identified in the previous version (e.g. the omission of a secondary cloud layer in the graphical representation). These issues only affected the visualization and **did not affect the**

**CONIOPOL classification itself** or any of the statistical analyses, which were produced directly from the classified data.

Specific comments:

The LDR is defines several times in the introduction for linear depolarisation ratio. In one case it is also used for volume depolarisation ratio (line 155) and in one case for particle linear depolarization ratio (line 585). Please clarify what is used in the algorithm.

We thank the reviewer for this comment. We have revised the Introduction to explicitly distinguish between the volume linear depolarization ratio (VDR) and the particulate linear depolarization ratio (PDR), and to clarify their respective physical meanings. To avoid misleading the reader, the term volume linear depolarization ratio (VDR) is now explicitly used whenever referring to depolarization measurements, and this terminology is consistently adopted throughout the remainder of the manuscript and in the abstract.

Fig. 8: and paragraph 6.1.1.: It is unclear what is meant by occurrence, if it can exceed 100%? 5% occurrence means 5% of all observed categories? During which time frame?

We thank the reviewer for this comment. The monthly occurrence definition has been clarified in the revised manuscript to avoid ambiguity.

For each category, the monthly occurrence is calculated as the percentage of hourly periods in which the corresponding category is detected in at least 60% of the available observations within that hour, relative to the total number of hourly periods available during the month. Multiple categories may coexist within the same hourly period because different aerosol and hydrometeor types can occur simultaneously at different altitudes. Consequently, category occurrences are not mutually exclusive and their sum may exceed 100%.

Fig. 9: The text of the axes and captions should be readable without turning around the graphs.

Done in the revised manuscript.

Line 460 – 467: Intercomparison with CAMS: please explain in more detail how the CAMS values are assessed conditionally on CONIOPOL detections in both time and altitude, and why this leads to multiple use of the CAMS values.

We thank the reviewer for pointing out that the original description of the CAMS comparison was insufficiently detailed. Following this comment, the methodology has been completely revised and rewritten.

The revised manuscript now provides a detailed description of both the temporal and vertical matching procedures. Since CAMS aerosol profiles are available every 3 h, the corresponding CONIOPOL observations are aggregated over the same 3 h interval. This interval is divided into three consecutive 1 h periods, and a CAMS profile is associated with a given aerosol category only when the category is detected during at least 60 % of the available CONIOPOL observations in at least two of the three hourly periods. This persistence criterion ensures that only persistent aerosol layers are retained for the comparison.

The vertical comparison has also been substantially improved. Instead of considering only two broad altitude ranges as in the original manuscript, the revised analysis is now performed throughout the atmospheric column up to 10 km using successive 250 m altitude intervals. This provides a much more detailed characterization of the vertical relationships between CONIOPOL classifications and CAMS aerosol fields.

The sentence referring to the "multiple use" of CAMS values has been removed, as it no longer reflects the revised methodology. The updated manuscript now describes the comparison procedure unambiguously and explains the statistical analysis performed within each altitude interval.

Fig. 10 and 11: Please explain more clearly, how these box plots show a good or bad agreement between CAMS and CONIOPOL results. It is not that obvious.

Figures 10 and 11 have been replaced by a more detailed altitude-resolved analysis.

### REVIEWER#3

In this article, the authors present an algorithm called CONIOPOL, that aims to classify aerosols based on measurements from single-wavelength polarization lidar. They apply this algorithm to one year (feb 2024-feb 2025) of ground-based lidar data at 910.55 nm from the CL61 instrument operated at Uccle (Belgium). They document the output of the classification and compare it with CAMS data.

The subject is important, relevant to contemporary problems, and well within the scope of ACP. The correct identification of aerosol nature, and its documentation as a function of altitude (especially in the boundary layer) is key to making progress on documenting air quality and on quantifying the indirect influence of anthropogenic pollution on climate through aerosol-clouds interactions like the Twomey effect. To reach that goal, fruitful approaches include the development of reliable, well-documented algorithms to classify aerosols that can be applied systematically to easily-deployable operational lidar measurements. The continuous datasets obtained this way provide information essential to build long-term climatologies.

The manuscript is well-written, the figures are generally well-designed and convey a clear message. The algorithm is described with precision, the impact of many choices is discussed and well documented. There are several points that should be clarified before publication.

We sincerely thank the reviewer for the careful and thoughtful evaluation of our manuscript. We greatly appreciate the positive assessment of the relevance and scientific importance of our work, as well as the recognition of the potential of CONIOPOL to provide systematic aerosol classification from operational single-wavelength polarization lidar measurements. We are particularly grateful for the acknowledgement of the clarity of the manuscript, the quality of the figures, and the detailed description and justification of the algorithm. Your constructive comments have been extremely valuable in helping us further improve the manuscript. We have carefully addressed all of the points raised, clarified the methodology where necessary, and revised the manuscript accordingly.

Before addressing the individual comments, we would like to summarize the principal modifications made to the manuscript following the reviewers' suggestions:

- The manuscript has been substantially revised to better **highlight** the role of the **cloud-phase and precipitation classifications**, which are now more clearly presented as an integral component of CONIOPOL rather than as a secondary extension of the aerosol classification.
- The **title** has been **revised** to better reflect the full scope of CONIOPOL by explicitly referring to both **aerosols and hydrometeors**. This modification better represents the capabilities of the algorithm and is consistent with the strengthened presentation of the cloud-phase and precipitation classifications throughout the manuscript.

- The **classification methodology** has been refined by introducing explicit **transitional classes** for aerosols, cloud phase, and precipitation. These intermediate categories provide a more physically realistic representation of observations exhibiting mixed optical characteristics and reduce potential misclassification arising from overlapping depolarization signatures.
- The justification of the depolarization thresholds has been substantially expanded. The selection of the **depolarization thresholds** is now supported by a more comprehensive **review of the peer-reviewed literature**, including recent studies using polarization lidars at wavelengths comparable to the CL61, providing a stronger physical basis for the adopted classification scheme.
- The **CAMS comparison** with CONIOPOL has been substantially **revised**. The analysis is now performed on a **seasonal basis, extended vertically up to 10 km**, and complemented by a more detailed discussion of the physical interpretation, **statistical significance**, and **limitations of the comparison**.
- During the implementation of the newly introduced transitional classes, we identified an error in the classification mask affecting the **Smoke/Marine aerosol** category. In the previous version, this category was only considered when no cloud was detected. Consequently, Smoke/Marine aerosols located beneath or within cloudy conditions were inadvertently excluded from the statistics. This issue has now been corrected, resulting in a substantially higher occurrence of the Smoke/Marine category and a markedly improved correspondence with the CAMS aerosol fields.
- We also revised the treatment of **weakly depolarizing targets under cloudy conditions**. In the previous version, low-depolarization observations within clouds were systematically assigned to the Fog/Drizzle/Mist category, even when they were clearly disconnected from the surface. This **decision-tree branch has been removed**, leading to a more physically consistent classification and an increased occurrence of the Liquid Cloud (Droplet) category.
- To avoid ambiguity in the interpretation of weakly depolarizing aerosols, the **former "Hygroscopic Aerosol" category** has been **renamed "Continental Aerosol"**. This terminology more accurately reflects the physical nature of the classified particles and avoids confusion with the Smoke/Marine category, since both aerosol types are hygroscopic but are associated with distinct atmospheric environments. The revised discussion further demonstrates that these two categories exhibit different vertical occurrence profiles, consistent with their association with the continental and marine boundary layers, respectively.
- The presentation of the **normalized cumulative occurrence profiles** has also been **revised**. Instead of displaying monthly statistics, the revised manuscript now presents **seasonal occurrence profiles up to 15km**, providing a clearer representation of the dominant atmospheric regimes while improving consistency with the revised CAMS intercomparison, which is now analysed seasonally and extended vertically up to 10 km.
- The **showcase figure** has also been **updated**. During the revision process, **several display issues** were identified in the previous version (e.g. the omission of a secondary cloud layer in the graphical representation). These issues only affected the visualization and **did not affect the**

**CONIOPOL classification itself** or any of the statistical analyses, which were produced directly from the classified data.

## Main comments

My main issue with the article is that I can't understand the origins of the values of depolarization ratio used as thresholds for the classification. The article mentions (L. 256-288) a UK field campaign with as reference only this document :

<https://www.vaisala.com/sites/default/files/documents/WEA-MET-WhitePaper-CL61-B212267EN-A.pdf>

This document is not a peer-reviewed article, it reads more like an advertisement for Vaisala. It does not present the field campaign, explain which experiments made it possible to link specific depolarization ratios with specific aerosol types, or discuss the reliability of CL61 retrievals. Most importantly, I could not find in this document the numbers used in the CONIOPOL algorithm present in figure 1. One figure in the report shows the approximate ranges of typical LDR values for different particle types, but it is not clear where the ranges come from, or even to which wavelength they apply. The document refers to another "full report" being available from Vaisala on request. As long as the experiments and studies which led to these values, which are key to the classification, are not available and peer-reviewed, it will not be possible for me to recommend publication. This effort should involve relating the uncertainties of depolarization ratio measurements with the classification output.

We thank the reviewer for this important comment regarding the origin and justification of the depolarization ratio thresholds used in the classification scheme. We fully agree that the transparency and physical basis of these thresholds are essential for the robustness and reproducibility of the proposed CONIOPOL algorithm.

We agree that the Vaisala white paper (CL61 documentation) is not a peer-reviewed publication and is therefore no longer used as a primary justification for the threshold values. In the revised manuscript, Section 4.4 has been substantially clarified to explicitly document the origin of the depolarization threshold values adopted in CONIOPOL. These thresholds are now supported by peer-reviewed lidar studies spanning wavelengths from 355 to 1565 nm, with particular attention to aerosol-specific spectral dependence. Because much of the available literature reports PDR rather than VDR, the applicability of these values to the VDR measured by the CL61 is now explicitly discussed with respect to wavelength and molecular contribution.

At 910 nm, the molecular contribution to the measured VDR is substantially reduced compared with shorter lidar wavelengths because of the strong wavelength dependence of Rayleigh scattering. Consequently, in particle-dominated layers, VDR is expected to approach the particle depolarization signature, although VDR and PDR are not formally equivalent.

In response to your important remark regarding uncertainty, we have also added a dedicated sensitivity analysis (Sect. 4.7; Figs. A1–A2) to quantify how variations in the measured VDR propagate through the threshold-based classification. Absolute perturbations of  $\pm 0.01$  and  $\pm 0.02$  were applied to VDR, and the resulting classifications were compared pixel by pixel with the reference classification. The analysis shows that classification changes occur primarily for observations close to the decision thresholds and predominantly involve transitions between neighbouring categories. These results, together with the introduction of transitional classes, provide an explicit representation of overlapping depolarization regimes and a quantitative assessment of the classification sensitivity to VDR variability.

We believe that these modifications significantly improve the transparency, physical basis, and reproducibility of the classification scheme, and we thank the reviewer for this valuable comment, which has led to a substantial improvement of the manuscript.

My second concern is that I had trouble following some of the reasoning : the article makes the point that LDR by itself does not contain enough information to uniquely identify several aerosol types (for instance distinguish volcanic ash from dust), but still argues that distinct categories of aerosols are mandatory and proceeds to classify separately aerosol types that have overlapping LDR distributions. I would appreciate it if the authors could clarify their reasoning here (see also several minor comments addressing this point). I do not see the point of uniquely labelling detections as ash or volcanic dust, while recognizing that this classification requires additional information (back-trajectory analysis, geographic source attribution) to be interpreted correctly. This opens the door to misinterpretations of the algorithm output. Uncertainties on aerosol identification should be visible in the output, and the algorithm should refrain from providing certain classifications when certainty is not possible.

We thank the reviewer for this insightful comment. We agree that the original wording of Section 4.4 could suggest an apparent contradiction. This reflects our attempt to simplify the presentation of the algorithm while simultaneously minimizing misclassification and maximizing the identification of atmospheric targets using the limited information available from a single-wavelength depolarization measurement.

The objective of the algorithm is not to uniquely identify aerosol species from volume linear depolarization ratio (VDR) alone, as this is not possible given the overlap of depolarization signatures among several aerosol types. Rather, the proposed classification provides the most informative and operational partitioning of the observations permitted by the available measurements. The defined classes should therefore be interpreted as best-estimate aerosol regimes, not as definitive aerosol identifications.

To account for the intrinsic ambiguity of VDR-based classification, transitional classes have been introduced where appropriate (e.g. aerosol mixtures and mixed cloud phases), and the revised manuscript now explicitly states that several aerosol classes, such as dust and volcanic ash, cannot be unambiguously separated using VDR alone. These categories are retained because they correspond to distinct physical aerosol types reported in the literature and are relevant when complementary information, such as air-mass back trajectories, geographical source attribution, or additional optical parameters, is available. The manuscript now emphasizes that such external information is required for a confident interpretation of these classes.

In response to the reviewer's comment, Section 4.4 has been revised to better distinguish between the intrinsic limitations of VDR and the methodological choices made to provide a physically consistent and

operational classification framework. The text now explicitly states that ambiguous cases should be interpreted with caution and, where appropriate, in conjunction with complementary observations.

Another issue with the article is that in my view, comparison with output from CAMS is not akin to validation. If we assume that the representation of aerosols in CAMS is close to reality, there is no need for lidar-based aerosol classification anymore, since we can just use CAMS. Actually, the point of lidar-based aerosol classification is to provide constraints to CAMS reanalyses through assimilation. Comparing output of CONIOPOL with CAMS can provide reassurance that lidar-based classifications are overall reasonable, but these classifications should provide additional information compared to CAMS (otherwise, what's the point?), and thus differences with CAMS should be expected. In my point of view, actual validation involves comparison of retrievals with in-situ measurements, for instance. Of course it is significantly harder and expensive to obtain in-situ data, and I do not expect the authors to provide new measurements during the review process. They should, however, refrain from identifying the comparison exercise with CAMS as validation, discuss it as useful comparison, and recognize its possible limitations.

We thank the reviewer for this important comment and fully agree that a comparison with CAMS should not be presented as a formal validation of the CONIOPOL algorithm. We have therefore substantially revised this section of the manuscript to clarify both the objective and the limitations of the comparison.

First, we have removed the terminology referring to "validation" throughout the manuscript when discussing the comparison with CAMS. The revised text now explicitly states that the purpose of the analysis is to assess whether the aerosol environments identified by CONIOPOL are associated with statistically distinct aerosol conditions represented by an independent atmospheric composition model, rather than to validate the algorithm against a reference dataset.

Second, the methodology has been rewritten to emphasize the fundamentally different nature of the two datasets. We now explain that CONIOPOL provides qualitative aerosol classifications, whereas CAMS provides grid-cell averaged aerosol mixing ratios, making a direct comparison of aerosol concentrations inappropriate. Instead, CAMS aerosol mixing-ratio distributions are analysed conditionally according to the corresponding CONIOPOL classifications in order to determine whether each CONIOPOL category is associated with statistically distinct aerosol environments.

To ensure a consistent comparison, the temporal and vertical matching procedures have also been described in greater detail. Because CAMS profiles are available every 3 h, CONIOPOL observations are aggregated over the corresponding 3 h interval, and a CAMS profile is associated with a given aerosol category only when that category is detected during at least 60 % of the observations in at least two of the three constituent hourly periods. Furthermore, the statistical comparison is performed within successive 250 m altitude intervals to account for the different vertical resolutions of CAMS and CONIOPOL. The corresponding sample size is now reported in the figures to facilitate the interpretation of the statistical significance.

The CAMS comparison has also been substantially expanded with respect to the original manuscript. Rather than relying on a single integrated comparison, the revised analysis now evaluates the relationship between CONIOPOL classifications and CAMS aerosol fields throughout the atmospheric column up to 10 km. In addition, a seasonal analysis has been introduced, allowing the behaviour of each aerosol category to be assessed under different atmospheric conditions. These new analyses provide a more

comprehensive assessment of the consistency between CONIOPOL classifications and CAMS aerosol environments than was presented in the original version.

Finally, the discussion has been rewritten to explicitly acknowledge the limitations of the comparison. We now emphasize that CAMS does not represent ground truth and remains affected by uncertainties in emissions, transport, aerosol parameterizations, and spatial averaging, while CONIOPOL provides local, observation-based classifications without retrieving quantitative aerosol concentrations. Consequently, differences between the two datasets are expected and should not be interpreted as deficiencies of either product. Rather, the statistically significant differences observed between CAMS aerosol environments associated with the various CONIOPOL categories provide independent evidence of the physical consistency of the CONIOPOL classifications, while highlighting the complementary information provided by high-resolution lidar observations.

The title focuses on the aerosol identification part of CONIOPOL, while the article shows the algorithm classifies atmospheric features between aerosol types, liquid/ice clouds, and precipitation. In my view, the impact of the article would be improved by focusing solely on aerosols and removing the cloud/precipitation results.

We thank the reviewer for this comment.

While we agree that aerosol identification is the central objective of CONIOPOL, the inclusion of cloud and precipitation classes is intentional and fundamental to the design of the algorithm rather than an ancillary extension. From an operational air-quality perspective, aerosols cannot be interpreted independently from cloud and precipitation processes, which strongly modulate aerosol optical properties through activation, scavenging, and signal attenuation. Moreover, precipitation-related processes such as virga can play an important role in enhancing the vertical redistribution of particles, such as mineral dust, through sublimating precipitation and the generation of local turbulence (Karle et al., 2023).

For these reasons, we consider that removing cloud and precipitation results would reduce both the physical consistency and the operational relevance of the methodology. To better represent the capabilities of CONIOPOL, which also classifies hydrometeors, we have revised the title accordingly by explicitly referring to hydrometeors. This modification better reflects the comprehensive yet operational nature of the algorithm while maintaining its emphasis on aerosol identification.

Following your comment, we have also revised the manuscript to better emphasize the role of the cloud-phase and precipitation classifications throughout the paper. In particular, their contribution to the physical consistency of the aerosol classification and to the overall operational framework of CONIOPOL is now more clearly described in both the methodology and the discussion.

Karle, N. N., Sakai, R. K., Fitzgerald, R. M., Ichoku, C., Mercado, F., and Stockwell, W. R.: Systematic analysis of virga and its impact on surface particulate matter observations, *Atmospheric Meas. Tech.*, 16, 1073–1085, <https://doi.org/10.5194/amt-16-1073-2023>, 2023.

Finally, the CONIOPOL algorithm takes among its input cloud base detections, and apparently assumes they are perfect. The impact of cloud misdetections is not discussed. The algorithm assumes that cloud

detection and aerosol detection are independent, which is not necessarily the case. Cloud detections, however, can include aerosols and vice-versa. In other words, the signal ranges of clouds and aerosols do overlap, and misclassifications do happen, for instance in presence of optically thick aerosol layers. The study should try to evaluate the sensitivity of results to errors in the cloud detection and cloud base retrievals.

We thank the reviewer for this valuable comment. We agree that the limitations associated with the CBH detection algorithm were insufficiently discussed in the original manuscript. The Discussion has therefore been substantially expanded to clarify the role of CBH information within CONIOPOL and its potential impact on the classification.

The revised manuscript now explicitly states that the CBH information is obtained directly from the operational Vaisala CL61 cloud-base detection algorithm and is not recalculated within CONIOPOL. We also clarify that CBH information is only one of several decision criteria used by the algorithm, together with attenuated backscatter, VDR, PPOL intensity, and the two-dimensional sliding-window consistency filter. Consequently, cloud-base retrieval errors may influence, but do not uniquely determine, the final classification.

Following your suggestion, we now discuss the two main sources of potential misclassification. First, optically thin liquid and ice clouds that remain undetected by the cloud-base algorithm are processed through the aerosol branch of the decision tree and may therefore be classified as smoke/marine aerosol and dust/ice, respectively. Conversely, dense aerosol layers, such as mineral dust or volcanic ash, may occasionally satisfy the cloud detection criteria, locally activating the cloud branch and leading to ice-crystal classifications within portions of the aerosol layer. Because the decision tree is applied locally, such errors are expected to affect primarily the observations for which the erroneous CBH information modifies the decision-tree branch, rather than necessarily affecting an entire atmospheric layer.

We also added a discussion of the intrinsic limitations of the CL61 cloud-base retrieval, supported by the recent intercomparison study of Looschelders et al. (2025), which showed that CBH detection is generally robust for boundary-layer clouds but becomes more uncertain for optically thin cirrus because of the reduced signal-to-noise ratio at high altitude.

Regarding your suggestion to perform a sensitivity analysis, we agree that this would be valuable. However, a quantitative assessment would require an independent reference for cloud-base detection (e.g. collocated cloud radar or Cloudnet observations), which is not available at the Uccle site for the study period. We have therefore discussed the expected impact of cloud-base retrieval errors and identified a dedicated sensitivity analysis using independent cloud observations as an important direction for future work.

Looschelders, D., Christen, A., Grimmond, S., Kotthaus, S., Fenner, D., Dupont, J.-C., Haeffelin, M., and Morrison, W.: Inter-Instrument Variability of Vaisala CL61 Lidar-Ceilometer's Attenuated Backscatter, Cloud Properties and Mixed-Layer Height, *Meteorol. Appl.*, 32, e70088, <https://doi.org/10.1002/met.70088>, 2025.

Minor comments

L. 13: Thanks for teaching me the word "coniology"!

We thank the reviewer for this comment.

Figure 1 : why do the colors mean in the diagram? (red, orange, etc.)

We agree that the original colour scheme did not convey any additional information and therefore did not enhance the interpretation of the figure. We have therefore simplified the colour scheme and retained only three colours to distinguish the main categories: orange for aerosols, blue for clouds, and grey for precipitation.

Figure 1, legend: "cloud base height" is not a lidar measurement. It is a retrieval, with all the attached uncertainties and interpretation issues.

We thank the reviewer for this clarification. We have revised the caption of Figure 1 to specify that cloud base height is obtained as a lidar-derived retrieval product, and not a direct measurement, in order to avoid any ambiguity regarding its observational status.

L. 50: The article should explicitly address the difference between volume depolarization ratio (which is affected by the ratio between signal contributions from particles and molecules) and particulate depolarization ratio (only due to particles), and be explicit which one it is referring to. "Linear" depolarization ratio is often assumed to refer to the particulate depolarization ratio (as in Burton et al. 2015) in opposition to the plain "depolarization ratio" often used to refer to the volume depolarization ratio. CALIOP measures volume depolarization ratio, while the HSRL ATLID measures separately Mie and Rayleigh backscatters and thus provides the particulate depolarization ratio.

We thank the reviewer for this comment. We have revised the Introduction to explicitly distinguish between the volume linear depolarization ratio (VDR) and the particulate linear depolarization ratio (PDR), and to clarify their respective physical meanings. To avoid misleading the reader, the term volume depolarization ratio (VDR) is now explicitly used whenever referring to depolarization measurements, and this terminology is consistently adopted throughout the remainder of the manuscript and in the abstract.

L. 200: multiple scattering within the cloud is generally not noticeable in ground-based lidar measurements

We thank the reviewer for this comment. We agree that the original statement was too general and could be misleading. In the revised manuscript, we have clarified that multiple scattering within liquid clouds may induce a slight increase in the measured VDR, as reported by Vakkari et al. However, this effect remains limited and is further minimized by using only the first range gates at the cloud base, in the absence of drizzle or precipitation, for calibration monitoring. The text has been revised accordingly.

L. 215-225: Around this section, it would be helpful to document the variability of depolarization ratios in various SNR and target situations at the spatial and temporal averaging used by the authors. Figure 2 shows that the authors trust their values of depolarization are accurate within  $\pm 0.02$ , which is quite precise. Since the CONIOPOL algorithm is threshold-based, documenting the variability of depolarization would help the readers understand the reliability of classification output.

We thank the reviewer for this important comment. We agree that documenting the variability of the measured VDR is particularly important for a threshold-based classification scheme such as CONIOPOL.

In the revised manuscript, we have therefore expanded the characterization of the VDR variability under the temporal and vertical resolution used by CONIOPOL. In particular, the new Fig. 6 presents the vertical distribution of VDR during precipitation events, including the median, interquartile range, and 90th percentile for both warm- and cold-season conditions. This additional analysis illustrates the observed VDR variability within different hydrometeor regimes and provides the observational basis for the precipitation-phase thresholds adopted in CONIOPOL.

In addition, following this comment and the related recommendation concerning classification uncertainty, we have added a dedicated sensitivity analysis (Sect. 4.7; Figs. A1 and A2) to explicitly quantify how VDR variability propagates into the CONIOPOL classification. Absolute VDR perturbations of  $\pm 0.01$  and  $\pm 0.02$  were applied to the measurements, and the resulting classifications were compared pixel by pixel with the reference classification. The  $\pm 0.01$  and  $\pm 0.02$  values were derived from the variability observed at the base of liquid-water clouds (Fig. 1), where very low depolarization is expected. We emphasize in the revised manuscript that these values are used as controlled sensitivity scenarios and should not be interpreted as a uniform measurement uncertainty applicable to all VDR values or target types.

The sensitivity analysis shows that VDR is the dominant source of sensitivity among the optical parameters investigated. However, classification changes occur primarily for observations located close to the fixed VDR decision thresholds and predominantly involve transitions between neighbouring classes rather than arbitrary changes across the classification scheme. This behaviour is now explicitly discussed in the revised manuscript and provides a quantitative assessment of the reliability and limitations of the threshold-based classification.

We believe that the combination of the additional characterization of observed VDR variability in Fig. 6 and the dedicated sensitivity experiments now provides a substantially clearer assessment of how depolarization variability affects the CONIOPOL classification.

L234-237: I understand that the threshold of attenuated backscatter used to separate aerosols from clouds is itself based on distributions of attenuated backscatters observed with and without clouds. This sounds circular to me. I don't understand how the presence of clouds is decided in the first place? Is it based on other observations, or on the lidar measurements themselves? If so, cloud detection must be based on some kind of signal threshold. Why not use it to inform the design of the CONIOPOL algorithm?

We thank the reviewer for this valuable comment. We agree that the original wording was ambiguous and could give the impression that the cloud/no-cloud classification was derived using the same threshold as that employed in CONIOPOL, leading to an apparent circularity.

This is not the case. The cloud base height (CBH) used in CONIOPOL is taken directly from CL61 product and is treated as an external input to the algorithm. The cloud/no-cloud separation used to derive the attenuated backscatter threshold is therefore based on the presence or absence of a valid CBH retrieval, rather than on the threshold being defined in this study.

To clarify this point, we have revised the manuscript as follows: “The threshold for distinguishing aerosols from clouds and precipitation is determined empirically from the relative frequency distributions of

attenuated backscatter values conditioned on the presence or absence of CBH retrieval from CL61 product. Relative frequency distributions are constructed for both regimes, and the separation threshold is defined where their ratio exceeds unity. This provides a statistically based criterion independent of the CONIOPOL processing chain, which uses CBH as an external input.”

L. 278 and below: "LDR... cannot uniquely identify aerosol type on its own (...) aerosols are thus classified into an explicit category". I am confused by this section, and in particular this paragraph. First it states that LDR cannot be used to explicitly identify aerosols, since different aerosols can generate overlapping LDR distributions. It then concludes that aerosols are classified using explicit categories, which I understand to be in total contradiction with what was explained before. I understand that methodological choices are made to minimize misclassifications, but minimizing misclassifications is not the same as eliminating misclassifications. I find this section even more puzzling further down, when it addresses the fact that "dust and volcanic ash exhibit overlapping LDR values" but somehow argues that it is still possible (and even mandatory) to treat them as distinct categories. From these elements I would argue that the algorithm should, instead, treat them as the same category ("dust or volcanic ash"). Please make your point clearer here.

We thank the reviewer for this comment. This point is closely related to the reviewer's general concern regarding the interpretation of the aerosol classification framework, which has been addressed through a substantial revision of Section 4.4.

As clarified in the revised manuscript, the proposed classes should not be interpreted as unique aerosol identifications based solely on PDR. Rather, they represent aerosol regimes defined using physically motivated thresholds, while explicitly acknowledging that overlapping depolarization signatures may lead to ambiguous classifications. Transitional classes have been introduced where appropriate, and the text now emphasizes that complementary information (e.g. source attribution, air-mass back trajectories, or additional optical parameters) is required to unambiguously distinguish aerosol types with overlapping VDR values, such as mineral dust and volcanic ash.

We believe that the revised Section 4.4 resolves the apparent contradiction identified by the reviewer and better explains the rationale behind the proposed classification scheme.

L. 289-294: overlapping signals for different aerosol species could be taken into account by attributing a probability for each species, for instance depending on the LDR distribution of a given aerosol type. The overlapping part could also be labelled as "volcanic ash or dust", while the clearly distinct parts could be labelled "ash" and "dust".

We thank the reviewer again for this comment. As already mentioned, the revised manuscript clarifies that the CONIOPOL scheme explicitly distinguishes between pure and mixed categories when the VDR does not unambiguously correspond to a single aerosol type. These intermediate categories are introduced to account for overlapping depolarization signatures between different aerosol types.

A fully probabilistic attribution of aerosol species is not implemented in the current version of the algorithm, which remains based on deterministic thresholds.

L. 337-345: The article does not include the necessary information to understand what is being explained here. What exactly is the input of DBSCAN? It is "applied to a 2D grid" of what? What is the

output of this algorithm? Is the DBSCAN algorithm part of the design of the CONIOPOL algorithm? If so, why isn't it mentioned in Figure 1? What is the principle of that DBSCAN algorithm? Why is it helpful?

Thank you for this comment. We agree that the original description may have suggested a closer connection to DBSCAN than is actually the case. The procedure implemented in CONIOPOL is not a formal DBSCAN clustering algorithm. Instead, it consists of a two-dimensional sliding-window consistency filter applied to the CONIOPOL detections in the time–height domain.

The algorithm operates on successive  $5 \times 5$  windows comprising five consecutive profiles and five adjacent range gates, corresponding to 150 s in time and 24 m in the vertical dimension. Within each window, the occurrence frequency of each aerosol category is computed. Categories with a relative occurrence frequency greater than 0.4 are considered representative of a coherent local atmospheric structure, while isolated detections are suppressed. The maximum density category (MDC), defined as the category with the highest occurrence frequency within the window, is retained as the locally dominant aerosol type. If no category exceeds the threshold, the corresponding observation is considered indeterminate and no category is assigned.

The purpose of this procedure is therefore not to identify geometrically connected clusters, as in DBSCAN, but to improve the spatial and temporal consistency of the CONIOPOL classification by exploiting information from adjacent observations while accounting for the natural heterogeneity of atmospheric aerosol layers. To avoid confusion, we have revised Section 4.5 by removing the explicit reference to DBSCAN and replacing it with a complete description of the implemented sliding-window consistency filter.

L. 399-402: I don't understand the point being made here.

We thank the reviewer for pointing out that these sentences were unclear. In the original manuscript, this discussion was intended to demonstrate that the different aerosol and cloud categories did not exhibit a common background occurrence, thereby suggesting limited overlap between the predefined classes.

However, the revised version of CONIOPOL now explicitly introduces (intermediate classification to account for situations in which multiple categories coexist within the same neighbourhood. This new framework directly addresses potential overlaps between classes, making the previous discussion redundant and potentially confusing.

To improve the clarity of the manuscript, we have therefore removed these sentences from the revised version.

L. 454: "model simulations" my understanding is that CAMS forecast are not mere model simulations, but analyses that merge (through numerical assimilation) model simulations with observations of the atmosphere. One goal of CONIOPOL retrievals could be their assimilation in CAMS.

We thank the reviewer for this valuable comment. We agree that the term "model simulations" was not sufficiently precise in this context. The manuscript has therefore been revised to refer to the CAMS Global Forecast or, more generally, to an independent atmospheric composition model, rather than to simple model simulations. In addition, the CAMS comparison section has been substantially revised.

Figure 8: I don't understand how the frequencies shown here were calculated. Is it the ratio between the number of profiles containing a given particle type, divided by the number of profiles sampled over

the course of a given month? If so, the extremely small number of ice crystals is surprising. Ice clouds are fairly frequent throughout the year.

We thank the reviewer for this comment. For each category, the monthly occurrence was calculated as the percentage of hourly profiles in which the corresponding category was detected in at least 60% of the observations within that hour, relative to the total number of hourly profiles acquired during the month. This value is expressed as a percentage. We have clarified these points in the revised manuscript. We further clarified that multiple categories can be detected within the same profile due to the vertical coexistence of different aerosol and hydrometeor types. As a result, occurrences are not mutually exclusive and the sum of all category occurrences may exceed 100%.

Regarding the relatively low occurrence of ice crystals, this result should be interpreted in the context of the vertical range considered in the original analysis. The occurrence statistics were initially restricted to altitudes below 5000 m a.g.l., thereby excluding a large fraction of high-level ice clouds. In the revised manuscript, the occurrence analysis has therefore been extended to the full CL61 measurement range (up to 15.4 km a.g.l.) to provide a more comprehensive overview of cloud detection throughout the atmospheric column.

Figure 9: It would have been interesting to see the evolution of the cumulative fraction of ice within clouds (compared to ice + liquid) with temperature. One would expect it to remain constant with time.

We thank the reviewer for this interesting suggestion. We agree that analysing the fraction of ice within clouds as a function of temperature would provide an additional and complementary assessment of the cloud-phase classification. In the present manuscript, we chose to assess the physical consistency of the cloud classification through the normalized cumulative occurrence profiles. These profiles already show the expected vertical stratification of cloud phase, with Liquid Clouds predominantly confined to the lower troposphere, Mixed Clouds occupying the transition region, and Ice Crystals extending to the upper troposphere. Since atmospheric temperature generally decreases with altitude, these results provide an indirect indication of the physical consistency of the cloud-phase classification. We agree, however, that an explicit temperature-dependent analysis using collocated temperature profiles would constitute a valuable extension of this work and will be considered in a future study.

Fig. 10 B and D : these subplots are not particularly useful. The small number of values they show could be provided directly in the text, or integrated within subplots A and C.

Figures 10 have been replaced in the revised manuscript by a more detailed altitude-resolved analysis.

Fig. 11: I do not see any significant difference between the values shown in the left column (detection of smoke /marine) and the values shown in the right column (no detection). Please clarify in the text what you mean by "clear differences emerge" or find a way to make these differences clearer visually.

Figures 11 have been replaced in the revised manuscript by a more detailed altitude-resolved analysis.

L. 684 : "EarthCARE's ATLID polarisation lidar will provide vertically resolved particle-type information that single-wavelengths ALC cannot retrieve" -- ATLID itself is single-wavelength. Its added value lies in its high spectral resolution, which is able to separate particulate from molecular backscatter (and thus simplifies lidar ratio retrievals). ATLID being in orbit since June 2024, its aerosol type retrievals are

available today, and comparisons between the CONIOPOL output presented here and ATLID products could be made today by identifying a few ATLID overpasses of Uccle.

Thank you very much for the correction. I confused it with CALIOP... We have added the relevant details in the revised manuscript.