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.

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 Applications32, 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 ±5% and ±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 ±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 ±0.01 and ±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 ±10% and VDR ±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 × 10 window to 5 × 5 and 15 × 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 ±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 rations 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#3'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 alwayspresent (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, EGUsphere [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 3×10^{-6} m^{-1} 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 × 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/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.

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 3**9**9-401: 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.