**General assessment**

This manuscript presents an observational analysis of aerosol and dust layers using the novel balloon-borne AeroSonde system and multiple ground-based remote-sensing instruments, trajectory analysis, and supporting observations. The study aims to demonstrate that low-cost balloon-borne AeroSonde sensors can provide reliable vertical profiles of aerosol properties and improve spatio-temporal observational coverage for aerosol model evaluation.

The topic is relevant for the atmospheric science community, particularly for studies of long-range aerosol transport, and vertical aerosol structure. The use of multiple datasets and observational approaches has the potential to provide useful insights into aerosol layering and transport pathways.

However, in its current form the manuscript is overly lengthy and contains a large amount of descriptive material and repetitive figures, which makes it difficult to clearly identify the main scientific contributions and new findings. Several sections require clarification of methodology, improved structure, and stronger interpretation of the results. In addition, instrument uncertainties and data interpretation aspects are either missing or insufficiently discussed.

For these reasons, I believe the manuscript requires major revision before it can be considered for publication. Below I provide detailed comments intended to help the authors improve the clarity, scientific robustness, and readability of the work.

**General comments**

The manuscript is very dense and contains a large amount of descriptive information, some of which does not directly contribute to the main scientific findings. The authors are encouraged to:

- Shorten descriptive sections where possible.
- Focus on the key scientific objectives and new findings.
- Reduce repetition between sections.
- Move supporting or secondary information to supplementary material if appropriate.

The manuscript should include a clearer discussion of sensor calibration, measurement uncertainties, instrument intercomparability and possible biases in aerosol optical and particle measurements. This is particularly important when combining multiple datasets.

Re: We thank the reviewer for the detailed and constructive assessment of the manuscript. We acknowledge the concerns regarding the length, structure, and balance between descriptive and analytical content, as well as the need for clearer discussion of uncertainties and methodology.

In response to these comments, we have substantially shortened and restructured the manuscript, particularly the Results section, to improve clarity and focus on the main scientific findings. Redundant descriptions have been reduced, and several figures have been removed or moved to supplementary material.

The revised manuscript places stronger emphasis on the evaluation and capabilities of the AeroSonde system as a proof-of-concept observational tool.

Since the Sensirion SPS30 is primarily designed as a particulate matter (PM) sensor, it would be important for the manuscript to present the PM measurements obtained. Currently, the discussion focuses mainly on derived optical quantities (e.g., ASC, SAE), while the primary measurements reported by the sensor are not shown or analyzed in detail. Including the PM time series and/or vertical profiles would help readers better understand the original sensor response, its variability with altitude, and its relation to the retrieved optical properties. Furthermore, presenting the PM data would allow a clearer assessment of coarse-mode particle contributions and potential sensor limitations under dust-dominated conditions, which are relevant for several of the case studies discussed in the manuscript. I recommend that the authors include representative PM profiles or distributions in the results section and discuss how they relate to the derived aerosol optical parameters.

Re: We have added representative PM vertical profiles to the Results section (see Fig. 8 and Fig. 11), which illustrate the variability of the primary sensor measurements with altitude and provide additional context for the interpretation of the derived optical properties.

Figures 5–9 appear repetitive and may not all be necessary in the main manuscript. The authors may consider presenting one representative figure in the main text to illustrate the methodology and key findings, while moving the remaining figures to the Appendix or Supplementary Material. This would help improve the readability and flow of the manuscript while still making the full set of results available to interested readers.

Re: The corresponding parts of the Results section have been revised, and three of the mentioned figures were removed as part of the restructuring.

Several parts (particularly in the results) read more like descriptive reporting of meteorological conditions rather than scientific analysis. The authors should improve the discussion by interpreting the observations more clearly, linking results to the study objectives, explaining the physical mechanisms behind the observations, highlighting the new insights provided by the study. For instance, Sections 4.1 and 4.2 require improvement. Currently it reads more like a general meteorological description rather than a scientific analysis.

Re: In response to the comments from both reviewers, the journal's scope, and our own reassessment of the manuscript, we have substantially shortened and restructured the Results section in order to improve its clarity, coherence, and overall readability.

**Specific comments**

Line 35: also balloon-borne observations, recommended papers to cite:

Kalnajs, L. E., & Deshler, T. (2022). A new instrument for balloon-borne in situ aerosol size distribution measurements, the continuation of a 50 year record of stratospheric aerosols measurements. Journal of Geophysical Research: Atmospheres, 127, e2022JD037485. https://doi.org/10.1029/2022JD037485

Kezoudi, M., Tesche, M., Smith, H., Tsekeri, A., Baars, H., Dollner, M., Estellés, V., Bühl, J., Weinzierl, B., Ulanowski, Z., Müller, D., and Amiridis, V.: Measurement report: Balloon-borne in situ profiling of Saharan dust over Cyprus with the UCASS optical particle counter, Atmos. Chem. Phys., 21, 6781–6797, https://doi.org/10.5194/acp-21-6781-2021, 2021.

Re: We added suggested references in the sentence: "Alternative approaches using unmanned aerial vehicles (UAVs), tethered balloons (Kalnajs and Deshler, 2022; Brunamonti et al., 2021; Kezoudi et al., 2021)., and other (...)"

Line 50: "in the absence of reference measurements", here authors mean reference in-situ?

Re: We thank the Reviewer for pointing out the need for clarification. Here, by "reference observations," we refer to independent in situ measurements of aerosol optical properties that could serve as a direct validation dataset for the AeroSonde retrievals. As such measurements were not available during the campaign, we relied on remote sensing observations for the evaluation of the retrieved optical properties. We therefore modified the sentence from:

"in the absence of reference measurements."

to: "In the absence of independent in situ reference measurements".

Sections 4.1 and 4.2 require improvement. It would be beneficial to shorten and merge the sections in order to create a more coherent and clear narrative that connects meteorological conditions, aerosol observations and transport pathways.

Re: The Results section has been revised and shortened as part of the restructuring, as mentioned above.

Line 323: "revealed aerosol layers from ground up to 6.5 km". Please clarify: Which instrument detected these layers? How were aerosol layers distinguished from clouds?

Re: The corresponding parts of the Results section have been removed as part of the restructuring.

We added a paragraph to the method section: "Aerosol layers were identified based on the analysis of lidar backscatter profiles at 532 nm. In the absence of depolarization measurements, the distinction between aerosol and cloud layers was based on signal intensity and temporal continuity. Cloud-contaminated parts of the lidar profiles were replaced using linear interpolation between adjacent cloud-free layers. Cloud presence was additionally assessed using an all-sky camera and vertical pointing infrared radiometers integrated within the microwave radiometer system, based on brightness temperature measurements (PolandAOD, 2025)."

Line 327: Transport from Canada is mentioned. Please clarify: At which altitude this transport occurred. Whether the authors checked for wildfire activity in Canada on that day. If so, please provide supporting references or datasets.

Re: The transport from Canada occurred in the free troposphere and upper troposphere/lower stratosphere, as indicated by the backward trajectories initialized at altitudes corresponding to the observed aerosol layers, which is depicted in the Fig 5b.

Regarding wildfire activity, the ICAP-MME product used in this study provides a consistent representation of biomass burning aerosol through its multi-model framework. As it is explained in Kaiser et al. 2012 and Sessions et al., 2015 all data on emissions from BB are derived, to some extent, from MODIS (Moderate Resolution Imaging Spectroradiometer) active fire hotspot counts. Therefore, the elevated AOD_smoke values along the trajectories over central and eastern Canada provide indirect but consistent evidence of BB influence.

To improve clarity, we have added a short explanation of the ICAP-MME framework and its linkage to satellite-based fire detection in the revised manuscript: "Within ICAP-MME, biomass burning emissions are based on the Global Fire Assimilation System, which assimilates fire radiative power derived from the Moderate Resolution Imaging Spectroradiometer active fire products (Kaiser et al., 2012)."

Line 329: AERONET observations are mentioned. Please specify: The exact site of the AERONET station, distance from the measurement location, whether the observations were collocated in time with the event

Re: The AERONET observations were obtained from the Strzyżów site (SolarAOT Radiative Transfer Station), which is the same location where the AeroSonde measurements were conducted. This information is provided in Section 2.1 of the manuscript, where the measurement site is described. Therefore, the AERONET data are collocated with the AeroSonde observations (distance ~0 km).

The AERONET data used in the analysis were selected as the measurements closest in time to the AeroSonde launch. The exact launch times of the AeroSonde are provided in the revised manuscript in Table 3, while the corresponding AERONET observations are listed in Table 4.

Lines 330–333: When discussing cloud layers, it would be useful to include: Cloud base and top heights, cloud thickness, cloud phase (if known). This would provide a clearer picture of the atmospheric structure during the event.

Re: We agree that providing additional information on the vertical extent of the cloud layer improves the description of the atmospheric structure. We have therefore corrected the previously reported cloud heights and expanded the description to include both cloud base and cloud top.

During the measurement period, the cloud layer initially extended from approximately 7 to 11 km, and later descended to a range of about 5 to 7 km. This information has been added to the revised manuscript.

A more detailed characterization of cloud properties (e.g., phase or microphysical properties) is beyond the scope of this study, which focuses on aerosol profiling. However, we agree that the vertical extent of the cloud layer is important for interpreting the lidar signal and aerosol distribution.

Line 351: “All LAGRANTO trajectories…” Please clarify whether the word “all” refers to: all altitudes, all trajectory starting points, all time steps. The trajectory configuration using LAGRANTO trajectory model should also be described more clearly.

Re: Here, “all LAGRANTO backtrajectories” refers to the full set of trajectories computed for this day, initialized at the selected altitudes corresponding to the analysed aerosol layers. We have clarified this in the revised manuscript. We changed sentence from “All LAGRANTO backtrajectories ….”

to: “All computed LAGRANTO backtrajectories for this day, initialized at altitudes corresponding to the analysed aerosol layers, except for the lowest ones (around 1 km), indicate transport of BB aerosol from Canada (Fig. 7, 8).”

Also, we added missing information on model configuration: “In the present research, air-mass back-trajectories were computed using the LAGRANTO (Lagrangian Analysis Tool) trajectory model via its FTP-based remote computation service hosted at ETH Zürich. The LAGRANTO model was driven by three-dimensional wind fields from the European Centre for Medium-Range Weather Forecasts (ECMWF). (...) Backward trajectories of 240 h were calculated, with the model run at a 3-minute temporal resolution and output retrieved along the AeroSonde trajectories.”

Line 352: “the trajectories were relatively straight and consistent”. This statement is vague. Please clarify in terms of what metric, for example: directional variability, wind shear, transport pathway stability

Re: We agree that the phrase “relatively straight and consistent” was too vague. We intended to describe the qualitative similarity of the trajectories, namely that they followed comparable pathways, intersected similar regions over Canada, and did not exhibit strong curvature or highly variable transport patterns. As no quantitative metric (e.g., directional variability or wind shear) was applied in this analysis, we have revised the wording to more clearly reflect this qualitative assessment. We rewrote the sentence from: “The trajectories were relatively straight and consistent, spanning altitudes between 4 and 9 km a.s.l. in the morning and between 2 and 8 km a.s.l. in the afternoon.”

to: “The trajectories followed similar pathways, intersecting comparable regions over Canada, and did not exhibit strong curvature, spanning altitudes between 4 and 9 km a.s.l. in the morning and between 2 and 8 km a.s.l. in the afternoon.”

Line 360: “What does this mean for the Poland region?” The interpretation of the trajectory results over Poland needs clarification. It is not clear what implication the authors intend to draw for this region.

Re: We rewrote this sentence to explain this. Changed from: “During the third measurement period, the observation region was located between a low-pressure system over the United Kingdom and a high-pressure system over Eastern Europe.”

to: “The second case covers measurements made on 29 August 2025, when the observation region lay between a low-pressure system over the United Kingdom and a high-pressure system over Eastern Europe, resulting in southwesterly flow over the region, favoring the advection of air masses from lower latitudes.”

Line 369: The term “dust cloud” is used. Please clarify whether this refers to: a dust layer, dust mixed with cloud droplets or a dust plume. The terminology should be more precise.

Re: We agree that the term “dust cloud” was imprecise and potentially misleading. In this context, we intended to refer to cloud layers located above the dust aerosol layers, not to dust mixed with cloud droplets or a dust plume. The terminology has been corrected in the revised manuscript to avoid ambiguity.

We changed the sentence from: “Dust clouds were present above these layers but dissipated shortly after 15:00 UTC.”

to “Clouds were present above these layers but dissipated shortly after 15:00 UTC”.

Line 384: Strong winds are mentioned. Please discuss whether instrument performance may have been affected by strong wind conditions, including sampling efficiency, flow stability, measurement bias.

Re: The AeroSonde platform operates in a quasi-Lagrangian manner, as the balloon drifts with the ambient wind field. Therefore, the relative airflow at the inlet remains low, which minimizes potential biases related to strong horizontal wind speeds, such as sampling efficiency or flow distortion.

Line 392: “The reported ASC value…”. Please clarify: From which instrument this ASC value is derived. How it was calculated

Re: The ASC values reported in the manuscript are derived from the SPS30 optical particle sensors after calibration against reference-grade instrumentation. The full calibration procedure is described in detail in Section 3

Line 409: states that Reff increases with altitude. Please explain: Why is this behavior observed? Up to which altitude does this trend persist? Whether this could be related to size-dependent transport or another reason?

Re: Due to the reorganization of the results section, this fragment has been removed. However, it has been emphasized that both SAE and Reff are associated with large uncertainties. Although the calibration of the SPS30 sensor for different aerosol types clearly indicates the presence of a dominant fine or coarse aerosol fraction, drawing more detailed conclusions remains questionable.

**Lines 535–539:** The explanation of discrepancies needs to be expanded. Reason 1 mentions that mineral dust can substantially increase AEC due to absorption. Please quantify the associated uncertainty and provide references. Reasons 2 and 3: Why was information from the ceilometer depolarization ratio not used to correct or constrain the observations from the SPS30 sensor? This could potentially improve the interpretation of the particle measurements.

Re: We would like to clarify that no depolarization measurements were available in this study. The lidar system used operated at a single wavelength and did not include depolarization capability, and no ceilometer data were used. Therefore, it was not possible to use depolarization ratio information to constrain or correct the SPS30 observations. We agree that such information would be highly valuable, particularly for identifying nonspherical particles such as mineral dust and improving the interpretation of scattering measurements. This limitation will be explicitly clarified in the revised manuscript, and the inclusion of depolarization measurements will be considered as an important direction for future work.

We added additional explanation: “Mineral dust can substantially increase aerosol extinction due to absorption, with reported single scattering albedo values typically ranging from approximately 0.85 to 0.95 depending on composition and wavelength (Dubovik et al., 2002; Sokolik and Toon, 1999). This indicates a non-negligible absorption contribution, particularly in the presence of iron oxides, which may lead to underestimation of extinction when using scattering-based measurements alone.”

and: “It should also be noted that no depolarization measurements were available, as the lidar system operated at a single wavelength without polarization capability. Such measurements would enable the identification of nonspherical particles, such as mineral dust, and could therefore provide additional constraints to better interpret the observed discrepancies.”

Paragraph starting line 542: states that large particles were present in the layer, but no direct PM measurements are shown. How was this conclusion derived? Whether PM size distribution data are available? If so, these measurements should be included in the manuscript.

Re: We added the PM and aerosol concentration data as suggested (see Fig. 8 and Fig. 11 in the revised manuscript).

Lines 608–614: The conclusions provide a useful summary of the study; however, several statements appear somewhat stronger than what is supported by the uncertainty analysis presented earlier in the manuscript. Given the relatively large uncertainties reported for some derived parameters (particularly SAE and Reff), the authors should ensure that the conclusions remain fully consistent with the quantitative limitations of the measurements and retrieval methods.

Re: We agree with the reviewer that some statements in the conclusions were too strong given the reported uncertainties. We have revised the conclusions to reflect the limitations of the measurements better and to ensure consistency with the uncertainty analysis presented in the manuscript:

"This study presents and demonstrates a new balloon-borne measurement system (AeroSonde) designed to provide high-resolution, vertically resolved observations of aerosol optical properties, delivering profiles from the surface up to the upper troposphere and, in some cases, the lower stratosphere, with a vertical resolution of a few meters. The performance of the AeroSonde was evaluated across a limited number of case studies, which should be regarded as a proof-of-concept of the system's capabilities. The measurements enable the estimation of ASC profiles, SAOD, and AOD, and show potential for supporting the evaluation of reanalysis products and satellite-based aerosol retrievals."

The results indicate generally good agreement with lidar and AERONET observations, within the expected uncertainty range, and demonstrate that the SPS30 low-cost sensor is capable of capturing the main features of aerosol vertical structure. In particular, the system allows the identification of boundary-layer contributions and elevated layers associated with long-range transport. However, parameters such as SAE and Reff should be interpreted with caution and are better suited for qualitative characterization."

Lines 615–617: mentions that the vertical profiles of ASC measured by the AeroSonde are consistent with simultaneous lidar observations. While the comparison shown earlier in the manuscript is promising, this statement would benefit from explicit quantitative metrics, such as correlation coefficients, mean bias or normalized bias, RMSE values. Including such metrics in the conclusions would provide stronger support for the claimed agreement.

Re: We have added quantitative comparison metrics (including correlation coefficients and RMSE) to support the agreement between AeroSonde and lidar-derived ASC profiles:

“The vertical profiles of ASC measured by AeroSonde are consistent with simultaneous lidar observations, with Pearson correlation coefficients of 0.74–0.81 and RMSE values of 18.5–25.1 $Mm^{-1}$, confirming the system’s capability to resolve aerosol layering and optical properties.”

Lines 618–620: The reported AOD bias range of 0.01–0.12 relative to AERONET observations would benefit from additional context. For example, discussing whether this level of agreement falls within the expected uncertainty range of measurements.

Re: As this part of the Conclusions is intended to provide a concise summary of the main findings, we aimed to avoid expanding the discussion, particularly since these aspects are addressed in detail earlier in the manuscript.

Nevertheless, to provide better context, we have slightly rephrased this point from:
“AOD derived from AeroSonde agrees with AERONET values, with biases ranging from 0.01 to 0.12 depending on the case study and aerosol type.”

to:
“AOD derived from AeroSonde agrees with AERONET values, with biases of 0.01–0.05 for biomass burning and ~0.11 for the dust case, which is consistent with the higher uncertainty associated with coarse-mode aerosol and its vertical variability.”

Lines 621–623: The statement that the AeroSonde system is suitable for quantitative estimation of SAE and Reff should be reconsidered or slightly moderated. Earlier sections of the manuscript report substantial uncertainties, particularly for SAE (up to ±1.0), which may limit its applicability for robust aerosol-type classification. The authors may therefore wish to clarify that these parameters are primarily useful for qualitative interpretation or indicative characterization, rather than precise quantitative retrieval.

Re: We agree with the reviewer that the statement was too strong. We have revised the text to clarify that SAE and Reff derived from the AeroSonde should be interpreted primarily as indicative parameters, suitable for qualitative characterization rather than precise quantitative retrieval. We reworded this sentence to:

“Error analysis indicates that the AeroSonde is suitable for quantitative estimation of ASC, while SAE and Reff provide only a rough, qualitative characterization, particularly in terms of capturing vertical variability.”

Lines 624–628: The future work section appropriately highlights the need for improved calibration strategies. Given the importance of coarse-mode aerosols (e.g., mineral dust) in several of the presented case studies, it would be useful to explicitly mention improved calibration for coarse particles, further validation against reference-grade instruments, and expanded deployments under different aerosol regimes.

Re: We added the following sentences:

Future work should focus on improved calibration strategies, particularly for coarse-mode aerosols such as mineral dust and sea salt, which remain a known limitation of low-cost optical sensors. Additional validation against reference-grade instruments is also required to better quantify measurement uncertainties. Furthermore, extended deployments under a wider range of aerosol regimes would help to assess the robustness of the proposed approach.

Technical comment: The ordering of references in the text appears inconsistent. In some parts of the manuscript, references appear to be sorted by relevance, while in other cases they appear alphabetical or chronological. The authors should choose one consistent citation style and apply it.

Re: We thank the Reviewer for this comment. We acknowledge the inconsistency in the ordering of references. In the revised manuscript, we have standardized the citation style so that references are consistently ordered by publication year (from most recent to oldest), and for the same year, alphabetically.