

A new **radiosonde**-balloon-borne system for measuring the vertical variability of aerosol **single-scattering**-optical properties using **low-cost sensors**.

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Abstract. This study presents a newly developed balloon-borne AeroSonde system equipped with calibrated low-cost optical particulate matter sensors (SPS30) for vertically resolved aerosol optical measurements. Calibration of the sensors against reference instruments (Aurora 4000 nephelometer and **LAS-Laser Aerosol Spectrometer (LAS)** 3340) enabled the estimation of scattering coefficients (ASC), scattering Ångström exponent (SAE), and effective particle radius (R_{eff}), with Pearson correlation coefficients exceeding 0.88. The best agreement was obtained for ASC, while SAE and R_{eff} showed substantially larger uncertainties, limiting their use to qualitative discrimination between fine- and coarse-mode particles.

The AeroSondes were deployed for the first time during measurement campaigns in June and August 2025 over southeastern Poland. Soundings with vertical resolution below 10 m reached altitudes of 10–27 km a.g.l. during episodes of long-range transport, including North American biomass-burning (**BB**) plumes and Saharan dust intrusions. The vertical distribution of aerosol layers observed by the AeroSonde is consistent with active remote sensing measurements, showing good agreement in both the optical layering structure and the absolute values of extensive aerosol properties, with correlation coefficients ranging from 0.74 to 0.81. The extended vertical sounding range allows the estimation of column-integrated quantities, such as aerosol optical depth, as well as their contributions from individual layers, for example, within the planetary boundary layer.

These results demonstrate that low-cost, balloon-borne AeroSonde sensors can provide reliable vertical profiles of aerosol properties, supporting enhanced spatio-temporal coverage and improved evaluation of atmospheric aerosol models.

1 Introduction

Aerosol properties exhibit pronounced vertical variability that strongly influences their radiative effects, interactions with clouds, and atmospheric lifetimes (IPCC, 2021; Li et al., 2022)(Li et al., 2022; IPCC, 2021). Accurate characterization of the vertical structure of aerosols is therefore essential for understanding their impacts on weather, air quality, and climate (Su et al., 2020). Aerosols within the planetary boundary layer (PBL) often differ substantially from those in the free troposphere in their optical, chemical, and microphysical properties (Su et al., 2022; Chang et al., 2023)(Chang et al., 2023; Su et al., 2022).

These contrasts lead to distinct radiative behaviours and cloud interaction potentials. Consequently, vertically resolved aerosol observations are indispensable for improving radiative transfer calculations, validating satellite retrievals, and constraining atmospheric models (~~Bazo et al., 2023; Mei et al., 2025~~) ([Mei et al., 2025](#); [Bazo et al., 2023](#)).

- 25 Vertical profiles of aerosols can be obtained using both in situ and remote sensing techniques. Recent advances in instrumentation have enabled increasingly detailed profiling of aerosol optical and microphysical characteristics (Dobracki et al., 2025; Papanikolaou et al., 2022). Ground-based and satellite-borne lidar systems have been widely employed to retrieve extinction, depolarisation, and absorption profiles (~~Harshvardhan et al., 2022; Denjean et al., 2020; Pistone et al., 2019; Cai et al., 2022~~), (~~Wang et al., 2019b~~) ([Cai et al., 2022](#); [Harshvardhan et al., 2022](#); [Denjean et al., 2020](#); [Pistone et al., 2019](#); [Wang et al., 2019b](#)).
- 30 However, lidar observations are often constrained by signal attenuation in dense aerosol layers, operational challenges in complex or urban environments, and retrieval uncertainties associated with assumed aerosol types. ~~Compact lidar systems such as COBALT (Carson et al., 2017) demonstrate the potential of miniaturised, high-resolution technologies for boundary-layer applications, yet their deployment remains limited~~ [To validate the lidar observations, balloon-borne measurements could be used, such as those performed by Compact Optical Backscatter Aerosol Detector \(COBALD\) \(Brunamonti et al., 2021\), a](#)
- 35 [lightweight aerosol backscatter detector](#).

- In situ measurements from aircraft campaigns provide the most direct and accurate characterisation of aerosol properties (~~Harshvardhan et al., 2022; Denjean et al., 2020; Pistone et al., 2019; Cai et al., 2022; Wang et al., 2019b~~) ([Cai et al., 2022](#)), ([Harshvardhan et al., 2022; Denjean et al., 2020; Pistone et al., 2019; Wang et al., 2019b](#)). Nevertheless, the high operational costs and limited spatial and temporal coverage of aircraft observations restrict their routine use. Alternative approaches using
- 40 unmanned aerial vehicles (UAVs), tethered balloons ([Kalnajs and Deshler, 2022; Kezoudi et al., 2021; Brunamonti et al., 2021](#)), and other innovative platforms have gained increasing attention for profiling the lower troposphere and near-surface pollution layers (~~Zhu et al., 2025; Georgia et al., 2023; Eckert et al., 2024; Kuebel et al., 2024; Ferrero et al., 2019; Chilinski et al., 2019~~), (~~Markowicz et al., 2025~~) ([Markowicz et al., 2025; Zhu et al., 2025; Eckert et al., 2024; Kuebel et al., 2024; Georgia et al., 2023](#)) ([Ferrero et al., 2019; Chilinski et al., 2019](#)). Further progress has been achieved through the use of cable cars (~~Zawadzka et al., 2017~~)
- 45 ([Posyniak et al., 2021](#)) ([Posyniak et al., 2021; Zawadzka et al., 2017](#)), mobile urban systems (Seidel et al., 2016), and ~~high-rise installations (Hao et al., 2022; Quan et al., 2025; Chiliński et al., 2025)~~ [measurement systems deployed on tall buildings or towers \(Chiliński et al., 2025; Quan et al., 2025; Hao et al., 2022\)](#). Despite continued developments (Moormann et al., 2025), most current systems remain constrained by payload capacity, vertical range, or operational complexity.

- There is therefore a continuing need for cost-effective, flexible, and high-vertical-resolution platforms capable of routine in
- 50 situ aerosol profiling. To address this gap, we developed AeroSonde, a novel radiosonde-based system designed to measure vertical profiles of aerosol optical and microphysical properties, with a particular focus on [long-range transport of aerosol \(e.g., biomass burning \(BB\) aerosol, dust, volcanic\)](#). The system can operate with tethered balloons, UAVs, or free-flying radiosondes, enabling measurements across diverse environments—from urban pollution layers to remote BB regions. The primary objective of this study was to assess the AeroSonde’s performance and demonstrate its capability for vertical aerosol profiling. For this
- 55 purpose, initial field deployments were conducted at the Poland-AOD atmospheric observation site in Strzyżów (Poland) (Markowicz et al., 2021) during episodes of elevated aerosol loading associated with long-range BB aerosol and mineral dust

transport in summer 2025. In the absence of ~~reference observations~~independent in situ reference measurements, remote sensing measurements were used to evaluate the optical properties retrieved from the AeroSonde.

The structure of this paper is organised as follows. Section 2 describes the AeroSonde, the set of instruments, and the measurement site. Section 3 outlines the calibration procedures and evaluates instrument performance. The section 4 presents the observational results, followed by a discussion of their implications in the Section. 5. The main conclusions and perspectives are summarised in the Section. 6.

2 Data and methods

2.1 Measurement site

The SolarAOT Radiative Transfer Station in Strzyżów (49.878°N, 21.861°E; 444 m a.s.l.), located on Niebylecka Hill in the Carpathians, southeastern Poland, represents a rural background site with minimal urban influence. The station is located approximately 200 m above a small town and about 5 km away from it in the horizontal direction. ¹ Operational since August 2013 as an ~~AERONET~~Aerosol Robotic Network (AERONET) site, it is equipped with a polarized CIMEL sun photometer (Markowicz et al., 2021). The site provides continuous observations of standard meteorological variables, radiative fluxes, columnar and in situ aerosol properties, and vertical aerosol distribution and thermodynamic structure of the troposphere.

2.2 Measurement setup

The measurement setup combines the newly developed AeroSonde system and a standard Vaisala RS41 radiosonde attached to a single balloon, together with complementary instrumentation including a Raymetrics LB10-V-D200 lidar and ground-based aerosol instruments (Section 2.2.2). The integrated dataset enables the evaluation of vertical aerosol profiles in conjunction with thermodynamic soundings, surface optical measurements, and model simulations.

2.2.1 AeroSonde

To establish a new methodology for measuring and retrieving vertical profiles of aerosol ~~single-scattering properties;~~scattering properties, the AeroSonde, a new sounding system, was developed (Fig. 2). The AeroSonde is equipped with the following sensors: an SPS30 particulate matter sensor, a pressure sensor (type LPS22HB), a temperature and relative humidity sensor (SHTC3), and a GPS (L76K module) receiver (Fig. ~~3a2b~~). The ~~GPS sensor is an advanced multi-GNSS receiver supporting GPS, BeiDou, GLONASS, and QZSS constellations. It is equipped with an active ceramic antenna and a low-noise amplifier, ensuring fast and accurate positioning with a tracking sensitivity of -162 dBm. The module operates with a mass of the~~ AeroSonde is 105 g without the housing and 175 g with the housing. Its dimensions are 90 mm in length, 60 mm in width, and 40 mm in height. The AeroSonde operates with an average power consumption of approximately ~~41 mA in active mode and 360 μ A in standby mode~~125 mA.

¹ ~~accessed 21 September 2025.~~

Particulate matter sensor SPS30, manufactured by Sensirion (<https://sensirion.com/products/catalog/SPS30>, accessed on 21 September 2025), is an affordable, compact instrument for aerosol measurement. The device features a measuring chamber with a 660 nm laser diode, photodiode detector, and focusing optics. A small integrated fan ensures consistent airflow through the chamber. The SPS30 provides I²C and UART outputs, reporting mass concentrations for PM₁, PM_{2.5}, PM_{4.0}, and PM₁₀ fractions, as well as data in six particle size bins and the typical particle size (TPS). Measurements are computed from laser scattering intensity using proprietary onboard algorithms; however, the manufacturer does not disclose algorithmic details. Following the procedure outlined by Markowicz and Chilinski (2020), sensor-derived data can be used to estimate secondary aerosol parameters, including the aerosol scattering coefficient (ASC), the scattering Ångström exponent (SAE), and the effective aerosol radius (R_{eff}).

The data acquisition process is managed by the Raspberry Pi RP2040 electronic system, which also handles wireless data transmission over LoRaWAN with the LoRa SX1262 module to the ground-based receiver. The temperature and relative humidity sensors are mounted on the electronic board and are not intended for atmospheric measurements, but rather for monitoring the operating conditions of the electronic components.

~~Additionally, the system is equipped with a servo-based release mechanism that allows the balloon to be detached, enabling the probe to descend safely to the ground (Fig. 3b). The user can set the pressure threshold at which the servo mechanism is activated to release the measurement system. This system will be used only when the aerosol event is expected in the lower and middle troposphere, because only in such cases can the AeroSonde be found close to the launching site. For the upper-layer event, the particle counter and the weather sensor will allow profiling of aerosol particles up to the lower stratosphere; however, in this case, the AeroSonde will not be retrieved.~~

The AeroSonde's data transmission system is based on the LoRaWAN standard. The AeroSonde is equipped with an omnidirectional “rubber duck” antenna (Fig. ~~3e,d~~2d,e), typically made of a rubber or plastic housing with a copper or aluminium radiating element. Such an antenna is a half-wave, 5dBi, and terminated with a BNCSmart connector, allowing direct connection to the gateway or via a pigtail cable. The data transmission frequency band follows the EU 863–870 MHz specification.

The GPS sensor is an advanced multi-GNSS receiver supporting GPS, BeiDou, GLONASS, and QZSS constellations. It is equipped with an active ceramic antenna and a low-noise amplifier, ensuring fast and accurate positioning with a tracking sensitivity of -162 dBm.

The data receiver system consists of a ChirpStack LoRaWAN Network server with multiple routers (Semtech SX1302/SX1303) and two antennas — one omnidirectional (12 dBi) and one directional antenna (12C65VBZ type, 12 dBi), which is manually adjustable. Data from the AeroSonde is transmitted at a frequency of 1 Hz. Proper data reception was confirmed even when the horizontal distance between the probe and the receiving station exceeded 100 km, and the vertical separation surpassed 25 km. The AeroSonde dataframes were double timestamped by onboard GPS and by the ground station with it's-its own GPS receiver and network time protocol client. The ground station time source allows sub-second time stamping for the purpose of clock-based time-of-flight geolocation.

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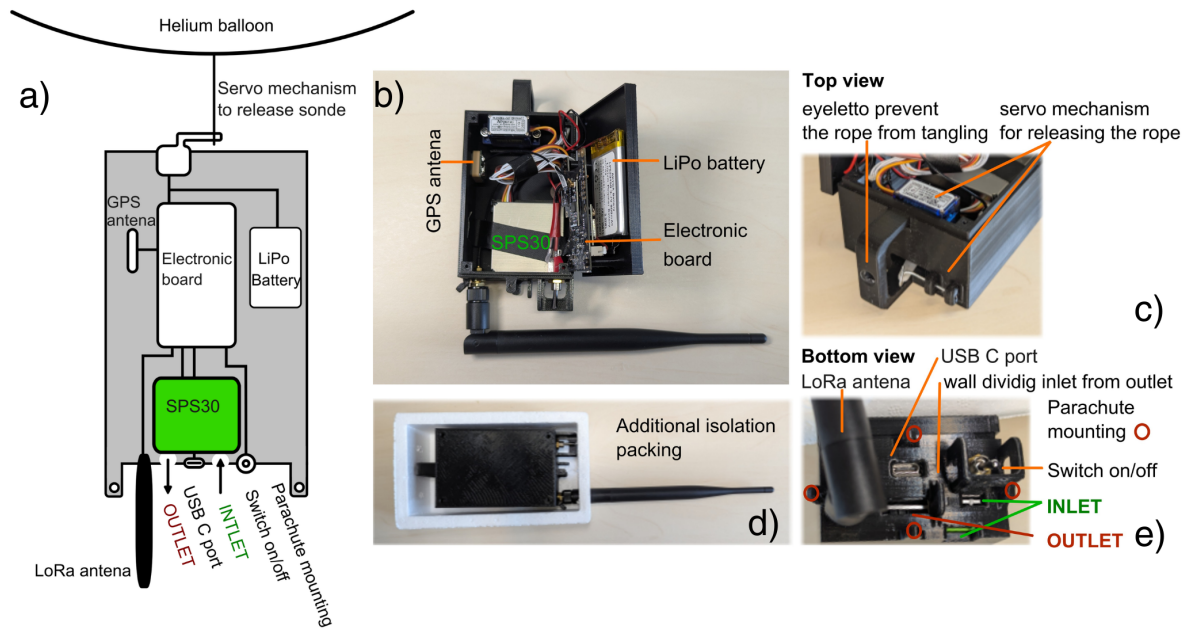


Figure 1. Diagram of the AeroSonde construction showing labeled main components (a) and AeroSonde setup shown from multiple angles (b-e).

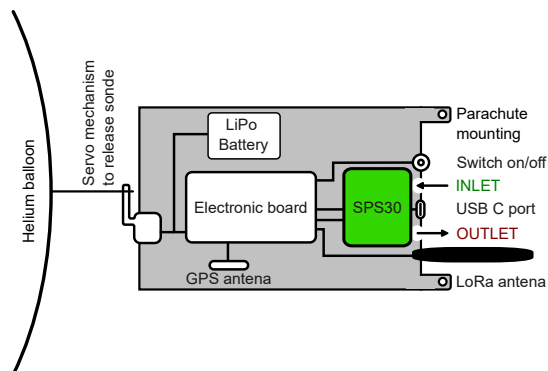


Figure 2. Diagram of the AeroSonde construction showing labeled main components.

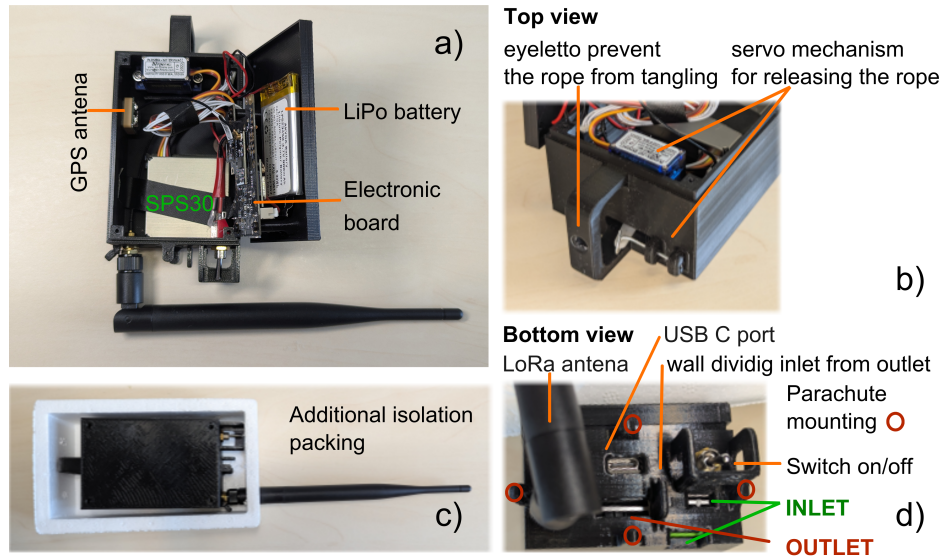


Figure 3. AeroSonde setup shown from multiple angles.

and focusing optics. A small integrated fan ensures consistent airflow through the chamber. The SPS30 provides I²C and UART outputs, reporting mass concentrations for PM₁, PM_{2.5}, PM_{4.0}, and PM₁₀ fractions, as well as data in six particle size bins and the typical particle size (TPS). Measurements are computed from laser scattering intensity using proprietary onboard algorithms; however, the manufacturer does not disclose algorithmic details. Following the procedure outlined by Markowicz and Chilinski (2020), sensor-derived data can be used to estimate secondary aerosol parameters, including the aerosol scattering coefficient (ASC), the scattering Ångström exponent (SAE), and the effective aerosol radius (R_{eff}). Additionally, the Aerosonde system is equipped with a servo-based release mechanism that allows the balloon to be detached, enabling the probe to descend safely to the ground (Fig. 2c). The user can set the pressure threshold at which the servo mechanism is activated to release the measurement system.

Vaisala radiosonde RS41 is an instrument for upper-air profiling, providing accurate measurements of temperature, humidity, pressure, wind, and position up to 40 km altitude (Lee et al., 2021, 2022) (Lee et al., 2022, 2021). Temperature measurements have an uncertainty between $\leq 0.11^\circ\text{C}$ (ground) and 0.17°C (in-situ). Relative humidity (RH) uncertainty is 0.5–2 % RH at room temperature and ranges from 0.9 % to 1.4 % RH at low temperatures. Pressure readings are SI-traceable, and GPS-based algorithms minimize the combined uncertainty. The uncertainty of wind speed is 0.15 m/s, while the wind direction uncertainty is 2° for wind speeds above 3 m/s. A Vaisala radiosonde was deployed together with an AeroSonde as part of the measurement payload to profile the atmosphere.

2.2.2 Other instruments

In addition to in situ measurements from the aerosonde, ground-based remote sensing instruments were used to provide complementary information on aerosol properties and their vertical distribution. Lidar observations provide insight into the vertical structure of the atmosphere and support the interpretation of aerosol layering observed by the aerosonde. Sun photometer measurements provide column-integrated aerosol optical properties, such as aerosol optical depth, which are used together with lidar signals in the Klett–Fernald–Sasano inversion algorithm to retrieve aerosol optical properties (Sanchez-Barrero et al., 2026), (Klett, 1985; Sasano et al., 1985; Fernald, 1984).

It should be noted that lidar-derived quantities (e.g., AEC) and in situ measurements (e.g., ASC) represent different optical properties and are associated with different uncertainties. Therefore, lidar observations were used for qualitative comparison and consistency assessment of aerosol vertical structures rather than for direct validation of the aerosonde data. Additional in situ instruments (e.g., nephelometer, aethalometer, Laser Aerosol Spectrometer) were used to characterize aerosol scattering and absorption properties at the surface, but also to calibrate the SPS30 sensors.

The **Raymetrics LB10-V-D200 lidar** operates at 532 nm using an Nd:YAG laser emitting 70 mJ pulses of 6–8 ns duration at 20 Hz repetition rate (Zieliński et al., 2012; Papayannis et al., 2007). The expanded beam divergence is < 0.3 mrad. Backscattered signals are collected by a 200 mm Cassegrain telescope with a field of view of 0.5–2 mrad and filtered through a 0.5 nm interference filter. Signal acquisition uses both analogue and photon-counting modes, with 7.5 m vertical and 50 s temporal resolution. Geometric overlap effects are negligible above approximately 500–700 m a.g.l.

The polarized variant of the **CIMEL CE-318 sunphotometer** extends the capabilities of the classical sun-sky photometer by adding polarimetric sensitivity across its spectral channels. The instrument operates at a standard set of band-pass filters centered at 340, 380, 440, 500, 675, 870, 940, 1020, and 1640 nm, combining a silicon photodiode (for UV–NIR) and an InGaAs detector for the 1020 / 1640 nm channels. This configuration allows retrieval of aerosol optical depth (AOD), column water vapor, and enhanced microphysical properties such as the complex refractive index, size distribution, and particle non-sphericity by combining intensity and polarization measurements. The instrument operates as part of the global AERONET network (Holben et al., 1998), ensuring standardized calibration procedures, unified data processing, and long-term consistency with other sites worldwide.

The **AE31 Aethalometers** (Aerosol Magee Scientific, Slovenia) provide real-time measurements of light transmission through a spot on a quartz fiber filter tape (Pall Q250 quartz) and report the attenuation (ATN) at several wavelengths: 370, 470, 520, 590, 660, 880, and 950 nm (Bernardoni et al., 2021)(Hansen et al., 1984). The data at each wavelength is expressed as the concentration of equivalent black carbon (Hansen et al., 1982; Petzold et al., 2013)(Petzold et al., 2013; Hansen et al., 1982), assuming black carbon is the sole absorber. However, the method has key limitations, including artifacts from light multiple-scattering and aerosol loading (Weingartner et al., 2003; Arnott et al., 2005; Collaud Coen et al., 2010)(Collaud Coen et al., 2010) (Arnott et al., 2005; Weingartner et al., 2003). The aerosol absorption coefficient (AAC) is computed according to the methodology by (Segura et al., 2014), which applies corrections for the loading and multiple-scattering effects. The loading correction was applied using the parameterization proposed by (Weingartner et al., 2003), where the correction factor depends on the aerosol attenuation and accounts for the non-linear filter response during particle accumulation. For this purpose, the f factor of 1.12 (at 520 nm) is used (see Eq. 8 in (Weingartner et al., 2003)). The multiple-scattering correction accounts for the en-

hanced optical path length within the filter and for scattering by particles embedded in the filter matrix. It was applied using
175 wavelength-dependent correction coefficients C as reported by (Segura et al., 2014). In this study, a single value of $C=3.90$ (at
520 nm) was used, as only one wavelength was analyzed in the case of AAC.

The **Aurora 4000** polar nephelometer (Acoem Ecotech, Australia) can measure light scattered by aerosol particles over a
broad range of angles and is also capable of determining total scattering and backscattering coefficients (Teri et al., 2022; Ran et al., 2023)
(Ran et al., 2023; Teri et al., 2022). The instrument features an LED array light source, which, along with a backscatter shutter,
180 can be adjusted to different positions. This design enables the measurement of total scattering (from 9° to 170°) and scatter-
ing across 17 distinct angular segments at three wavelengths (450 nm, 525 nm, and 635 nm). Data processing for the Aurora
4000 incorporates several corrections: zero calibration based on Rayleigh scattering, adjustments for non-Lambertian illumina-
tion effects, and corrections for angular truncation errors (Müller et al., 2011; Markowicz et al., 2021)(Markowicz et al., 2021),
(Müller et al., 2011).

185 The **Laser Aerosol Spectrometer 3340** (LAS; TSI Inc., USA) measures aerosol particle number concentrations across 99
size channels, covering an aerodynamic diameter range from $0.09\ \mu\text{m}$ to $7.5\ \mu\text{m}$ (TSI Incorporated, 2024). The integration of
wide-angle optics and an intracavity He-Ne laser extends the instrument's measurement range (Moore et al., 2021).

The data from the abovementioned instruments were recorded on a PC system synchronized via an NTP server.

The data analysis was supported by whole sky images acquired using a UVC G4 Bullet camera, with the aim of detecting
190 cloud cover. In addition, we used **atmospheric soundings** data from the Tarnów WMO 12575 station located about 60 km
from the Strzyżów site.

2.2.3 Models data

We employed the LAGrangian ANalysis TOol (LAGRANTO) model to compute back-trajectories for identifying source
regions and the International Cooperative for Aerosol Prediction Multi-Model Ensemble (ICAP-MME) to analyze dust and
195 smoke AOD along these trajectories.

LAGRANTO is a widely used Lagrangian trajectory model for atmospheric research, applied to the analysis of transport
processes, flow structures, and source–receptor relationships (Wernli and Davies, 1997; Sprenger and Wernli, 2015)
(Sprenger and Wernli, 2015; Wernli and Davies, 1997). The model computes forward and backward trajectories using a fourth-
order Runge–Kutta integration scheme, with wind fields interpolated horizontally and vertically from gridded meteorological
200 data. Owing to its flexibility and robustness, LAGRANTO has been widely applied in studies of atmospheric dynamics and
in the interpretation of in situ and remote-sensing observations (Madonna et al., 2014; Duchi et al., 2014; Pfahl et al., 2008),
(Sodemann et al., 2008)(Duchi et al., 2014; Madonna et al., 2014; Pfahl et al., 2008; Sodemann et al., 2008). The current version
of the model is available online at the official project website: <https://iacweb.ethz.ch/staff/sprenger/lagranto/>.

In the present research, the LAGRANTO air-mass back-trajectories were computed using the LAGRANTO (Lagrangian
205 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).
Operational analyses at six-hour temporal resolution were employed, with wind fields interpolated onto a $0.5^\circ \times 0.5^\circ$ longi-

tude/latitude grid. Data from the lowest 97 model levels (out of 137 total) were used, corresponding to approximately 10–12 km altitude (upper troposphere/lower stratosphere). ~~The model was run with Backward trajectories of 240 h were calculated, with the model run at a 3-minute time resolutions, and output was retrieved for locations along temporal resolution and output retrieved along the~~ AeroSonde trajectories.

Smoke and dust aerosol optical depth was retrieved from the **International Cooperative for Aerosol Prediction Multi-Model Ensemble (ICAP-MME)** forecast. The ICAP-MME is a multi-model ensemble with all members equally weighted (Sessions et al., 2015). Output is generated daily with $1^\circ \times 1^\circ$ resolution at 00:00 UTC for 6-hourly forecasts out to 120 h with a 1-day latency (Xian et al., 2019). Within ICAP-MME, BB 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). For this research, AOD_{smoke} and AOD_{dust} at 550 nm were retrieved for all time points of chosen backtrajectories.

2.3 Data processing

2.3.1 Lidar data processing

The range-corrected lidar signals were used as input to the inversion procedure for retrieving the aerosol optical properties. To obtain the range-corrected signal, a dead-time correction was first applied, followed by subtraction of the background estimated by averaging the raw signal above 100 km, and finally multiplication of the signal by the square of the range. The lidar signals were constructed by combining photon-counting and analog channels: signals in the 5–10 MHz range were merged, while the photon-counting channel was used below 5 MHz and the analog channel above 10 MHz, ensuring a continuous dynamic range for further analysis.

To reduce noise, the data were smoothed using a temporal running mean with a 250-s window (five times the native temporal resolution) and a vertical running mean with a 37.5-m window (five times the native vertical resolution). The noise detection algorithm was then applied to the smoothed signal. The procedure consisted of: (i) identification of local extrema; (ii) application of a vertically moving 225-m window (30 times the vertical resolution), within which the fraction of extrema relative to the total number of data points was calculated; and (iii) flagging regions as noisy when this fraction exceeded 45 %. For these flagged regions, an additional vertical running mean with a 225-m window was applied. ~~This approach effectively suppressed the noise while preserving the sharp structure of the aerosol~~ The threshold of 45 % was chosen empirically, based on inspection of multiple profiles and iterative testing.

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 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). Cloud-contaminated parts of the lidar profiles were replaced using linear interpolation between adjacent cloud-free layers.

240 Vertical profiles of the aerosol extinction coefficient (AEC) were retrieved using the backward Klett algorithm (Klett, 1981), which assumes a constant lidar ratio (LR), defined as the ratio of the ~~aerosol-extinction-coefficient~~ AEC to the backscatter coefficient. The algorithm can be initialized in two ways: by prescribing an LR (hereinafter referred to as Klett LR) or by constraining the solution using the measured AOD (Klett AOD). In the second case, the Klett–Fernald–Sasano method (~~Klett, 1985; Fernald, 1984; Sasano et al., 1985~~) (Klett, 1985; Sasano et al., 1985; Fernald, 1984) was applied, with the LR adjusted to achieve consistency between the vertically integrated extinction and the observed AOD (see Appendix A1 for details). Two Klett-based approaches were applied to account for different observational constraints. The Klett LR method does not require measurement information and can therefore be used under all conditions, including periods without AOD measurements (e.g., nighttime), but it depends on the assumed constant lidar ratio, which introduces uncertainty. In contrast, the Klett AOD approach constrains the AEC using measured AOD, therefore limiting occurrences of unrealistic values.

250 The assumption of a constant LR introduces uncertainties, ~~particularly because aerosol mixtures as aerosol properties~~ within the PBL ~~can may~~ differ from those ~~within the transported layer of long-range transported aerosols~~ in the free ~~atmosphere~~ troposphere. Therefore, for smoke advection episodes, the assumed LR was based on the mean value reported in the literature for BB aerosol. A comprehensive list of LR values used in previous studies is provided in the Supplement of Adam et al. (2020). Based on this compilation, a mean LR value of ~~60.5 sr with a standard deviation of 27.5 sr~~ 60.5 ± 27.5 sr was adopted in this study.

255 For Saharan dust, an LR with a mean value of ~~50 sr and a standard deviation of 10 sr~~ 50 ± 10 sr was applied, following (~~Haarig et al., 2022; Szczepanik et al., 2023~~) (Szczepanik et al., 2023; Haarig et al., 2022).

To quantify the uncertainty of the retrieved extinction profiles, the Klett inversion was implemented within a Monte Carlo framework. For each realization, the reference height z_r at which the inversion algorithm was terminated was randomly selected from a uniform distribution between 0.7 and 1.0 km a.g.l. The initialization height, corresponding to a molecular (aerosol-free) atmosphere, was randomly selected from a uniform distribution between 13 and 16 km a.g.l. To reduce the impact of noise in the molecular region (assumed to be located above 13 km a.g.l.), a moving average with a window length of 30 range bins (corresponding to 225 m) was applied to the signal. Additionally, perturbations were applied to the temperature and pressure profiles used for the calculation of molecular optical properties. Assuming a temperature uncertainty of less than 0.2 K and a pressure uncertainty of less than 1 hPa, normally distributed random values within these uncertainty ranges were generated

265 and added to the temperature and pressure profiles at each height level in every Monte Carlo realization. These perturbed profiles were then used to calculate the molecular scattering coefficients required for the Klett inversion. Finally, the LR was randomly drawn from a normal distribution with a mean value of ~~60.5 sr and a standard deviation of 27.5 sr~~ 60.5 ± 27.5 sr for BB aerosol cases, and a mean value of ~~50 sr and a standard deviation of 10 sr~~ 50 ± 10 sr for Saharan dust cases.

The entire procedure was repeated 1000 for every lidar profile included in the analysis. The mean extinction profile and its standard deviation were subsequently calculated from the ensemble of solutions, providing an estimate of the uncertainty associated with the extinction coefficient retrieved using the Klett algorithm.

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AERONET AOD data at 500 nm corresponding to the measurement closest in time to the lidar observation were used to initialize the Klett algorithm without prescribing a fixed LR value. Instead, the AOD at 532 nm (AOD_{532} , derived from Eq. A3) was used as a constraint.

275 In the case of the constant AOD assumption, the Monte Carlo approach followed the same procedure; however, instead of perturbing the LR, the AOD was randomly perturbed using a normal distribution with a standard deviation of 0.01.

For the final extinction profiles obtained using both Klett approaches, additional in situ measurements were incorporated. Specifically, the ASC measured by a nephelometer Aurora 4000 and the AAC measured by an AE31 aethalometer were summed to derive an independent estimate of the ~~extinction-coefficient-(AEC)~~AEC. Subsequently, the extinction coefficient
280 was linearly interpolated between the lowest Klett retrieval height (0.7 km a.g.l.) and the surface, resulting in a continuous final extinction profile from the ground level upward.

2.3.2 Spatio-temporal adjustment of lidar profiles to AeroSonde observations

Since the ascent of the AeroSonde lasted about 1–2 h, the atmospheric layering could change significantly during this period. ~~To quantify the impact on extinction retrievals, two approaches were compared: (i) profiles obtained from range-corrected signals averaged over the ascent up to 12 km (above this altitude, the atmosphere was optically clean, and profiles were therefore not retrieved), and (ii) profiles~~ That is why profiles used in the analysis were obtained using a spatiotemporal matching procedure. This approach involved aligning the AeroSonde and lidar data in time, height, and horizontal position. It was assumed that the horizontal wind speed was horizontally homogeneous at a given altitude z . ~~For details of those approaches, see Appendix A2.~~
Horizontal wind speed and direction were obtained from the co-launched Vaisala RS41 radiosonde measurements. Time
290 synchronization between the instruments described in Sec. 2.2.1, 2.2.2 ensured consistent temporal alignment between the datasets and enabled time matching of the measurements. For details of this approach, see Appendix A2.

3 AeroSonde processing, calibration, and data evaluation

The calibration and data evaluation process aimed to verify the consistency and accuracy of the optical sensors used in the study, as well as to assess their performance under real atmospheric conditions. Measurements were conducted at the Radiative
295 Transfer Laboratory (RTL) of the Institute of Geophysics, University of Warsaw, during the summer of 2025. Five SPS30 sensors were installed inside a meteorological shield to protect them from precipitation. The average Pearson correlation coefficient across all instrument pairs was 0.97 for PM_{10} and PM_1 , and 0.99 for TPS when 1-hour averaging ~~of the data~~ was applied. In contrast, for the original 1-second data (without averaging), the correlations decreased to 0.89 for PM_{10} and 0.90 for PM_1 . The mean relative differences were 8.9 % and 8.7 % for PM_{10} and PM_1 , respectively. Significantly larger differences
300 (38 % for PM_{10}) were observed for the non-averaged data (1-s resolution), which corresponds to the statistical noise of the detectors. In the case of TPS, the absolute mean difference between all SPS30 pairs was $0.023 \mu\text{m}$, corresponding to a relative difference of 4.5 %. These results demonstrate that the discrepancies among the readings of the low-cost SPS30 sensors were surprisingly small. Additionally, two experiments were conducted to evaluate the instrument’s time constant and its performance under low atmospheric pressure conditions. In the first experiment, the sensor was placed in a chamber with a very high
305 aerosol concentration (PM_{10} in the order of $200\text{--}300 \mu\text{g}/\text{m}^3$). The sensor’s response to a sudden change in conditions showed that the time constant did not exceed a few seconds, typically being less than five seconds. For typical balloon ascent rates

of 3-4 m/s, this corresponds to a vertical resolution of no worse than 15-20 meters. The sensor's performance under reduced pressure was tested in a laboratory vacuum chamber, modified to enable fan speed (revolutions per minute, RPM) measurements over a pressure range from 1000 to 50 hPa. One of the three wires of the SPS30's flow-inducing fan — corresponding to the tachometric (tachometer) output — was connected to an Arduino board to count pulses associated with fan rotations. The results indicated that the fan speed remained stable at approximately 6000 RPM throughout the experiment (Fig. A1 see Fig. S1 in the Supplement), confirming that SPS30 airflow does not require correction for altitude (pressure) effects.

The low-cost optical particle sensors (SPS30) were calibrated against reference-grade aerosol instrumentation. The ASC and the SAE were referenced to an Ecotech Aurora 4000 integrating nephelometer, while the R_{eff} was derived by comparison with the TSI 3340 LAS. For the ASC derived from the SPS30 sensors, a non-linear regression model was applied to convert particulate mass concentration to ASC, expressed as:

$$ASC = a \cdot \sqrt{PM_{10}} + b \cdot PM_{10}, \quad (1)$$

where a and b are empirical calibration coefficients determined by non-linear least-squares fitting. ~~This parameterization reflects the fact that scattering intensity does not scale linearly with particle mass, particularly under varying particle size distributions and refractive indices~~ (The proposed relationship between ASC and PM_{10} , specifically the inclusion of both a linear and a square-root term, is supported by simulations conducted as part of this study. Lorenz-Mie simulations for spherical particles (Fig. S2) show that this functional form provides a good approximation of both the simulated and observed data, effectively capturing the combined effects of particle number concentration and particle size evolution. This suggests that the non-linear regression reflects the underlying physical processes governing aerosol behavior, including changes in particle size due to hygroscopic growth and coagulation. This interpretation is consistent with the findings of (Malm and Hand, 2007), who showed that mass scattering efficiency (i.e. g-Malm and Hand (2007)), the ASC to PM_{10} ratio) is a non-linear function of particle size. However, if the particle size distribution remains constant and only the particle number concentration varies, a linear relationship between ASC and PM_{10} would be expected. Figure 4a presents a scatter plot of PM_{10} from the SPS30 sensors versus ASC from the Aurora 4000 at 525 nm. Blue dots indicate the averaged values from five sensors compared with the reference instruments (Aurora and LAS). The regression for ASC exhibits slightly non-linear behavior, particularly at low concentrations (below $5 \mu\text{g m}^{-3}$). Nevertheless, a very high coefficient of determination ($R^2 = 0.96$) indicates good agreement between PM_{10} and ASC from the Aurora 4000. The root mean square error (RMSE) is 5.1 Mm^{-1} , corresponding to only 3.8 %. These results are consistent with previous studies (Markowicz and Chilinski, 2020; Markowicz et al., 2025) (Markowicz et al., 2025; Markowicz and Chilinski, 2020), which demonstrated that optical low-cost sensors can reliably measure ASC. The SAE from the SPS30 sensors was calibrated against reference values obtained from the Aurora 4000 nephelometer using a second-order polynomial regression based on the SPS30's typical particle size (TPS):

$$SAE = c_0 + c_1 \cdot TPS + c_2 \cdot TPS^2, \quad (2)$$

where TPS represents an optical parameter derived from the SPS30 sensor, and c_0 , c_1 , c_2 are the fitted coefficients. However, since the exact method by which TPS is derived remains unclear, it is difficult to predict the precise functional form of these

relationships a priori. Despite this uncertainty, the polynomial fits provide reasonable approximations, capturing the general trends observed in the data. This non-linear behavior is consistent with previous studies, which have shown that key optical parameters, such as the Ångström exponent, are non-linearly related to particle size (Schuster et al., 2006). Nevertheless, further studies are needed to refine these relationships and better understand the underlying physical processes. The agreement between SAE from the SPS30 and the Aurora 4000 reference is noticeably weaker (Fig. 4b; $R^2=0.78$, RMSE = 0.24). This reflects both the limitations of the SPS30 in retrieving this parameter and the relatively high uncertainty of SAE even in professional nephelometer measurements. Nevertheless, the SPS30 can still be used to distinguish particle types characterized by different size distributions — for example, BB aerosol versus mineral dust or anthropogenic pollution (Sousan et al., 2021) (Kuula et al., 2020; Tryner et al., 2020). Similarly, the R_{eff} was estimated from the SPS30 TPS values by comparison with the LAS (TSI 3340) measurements. A quadratic regression model was applied:

$$R_{\text{eff}} = d_0 + d_1 \cdot TPS + d_2 \cdot TPS^2, \quad (3)$$

where TPS represents an optical parameter derived from the SPS30 sensor, and d_0 , d_1 , d_2 are the fitted coefficients. As in the case of SAE, the R_{eff} can be estimated, albeit with relatively high uncertainty (Fig. 4c; RMSE = 0.019 μm). Table 1 summarizes the calibration statistics for all five SPS30 sensors against the Aurora 4000 nephelometer and the LAS instrument. The consistently high coefficients of determination confirm the strong agreement between the SPS30 sensors and the reference instruments. In contrast, the calibration of SAE and R_{eff} is meaningful only when measurements include a sufficiently broad range of aerosol size conditions — particularly during episodes dominated by coarse-mode particles such as mineral dust or marine sea spray. Such conditions were present in our dataset, as indicated by elevated TPS values reported by the SPS30 sensors. In contrast, datasets without these episodes (with TPS typically ranging between 0.4 and 0.55 μm) provide too limited a dynamic range to enable reliable calibration of SAE or R_{eff} .

The uncertainties of defined parameters (ASC, SAE, R_{eff}) are calculated from the calibration curve error (Table 1) and the reference instrument (Aurora 4000 and LAS) error

$$\delta ASC = \sqrt{\delta fit_{ASC}^2 + \delta ASC_{Aurora}^2}, \quad (4)$$

where δfit_{ASC} is uncertainty of ASC calibration fit (Eq. 1) and δASC_{Aurora} is the uncertainty of Aurora ASC. For the remaining two quantities (SAE and R_{eff}), an analogous equation applies.

The total uncertainty of the ASC measured with the Aurora 4000 was estimated by combining relative and absolute uncertainty components. Based on previous intercomparison studies and manufacturer data (Anderson and Ogren, 1998), (Müller et al., 2011; World Meteorological Organization, 2016; Ecotech Pty Ltd, 2011) (World Meteorological Organization, 2016), (Müller et al., 2011; Anderson and Ogren, 1998; Ecotech Pty Ltd, 2011), typical values of the relative uncertainties of individual components are span calibration (2.5 %), zero check (2 %), illumination/cosine response (5 %). In case of the truncation correction, the uncertainty depends on particle size and for fine particles is about 5 %, while for coarse mode it can be up to 33 % (Teri et al., 2022). Therefore, this term is estimated based on SAE as follows:

$$\delta ASC_{trunc} = 0.05 + 0.28(1 - SAE/2.0). \quad (5)$$

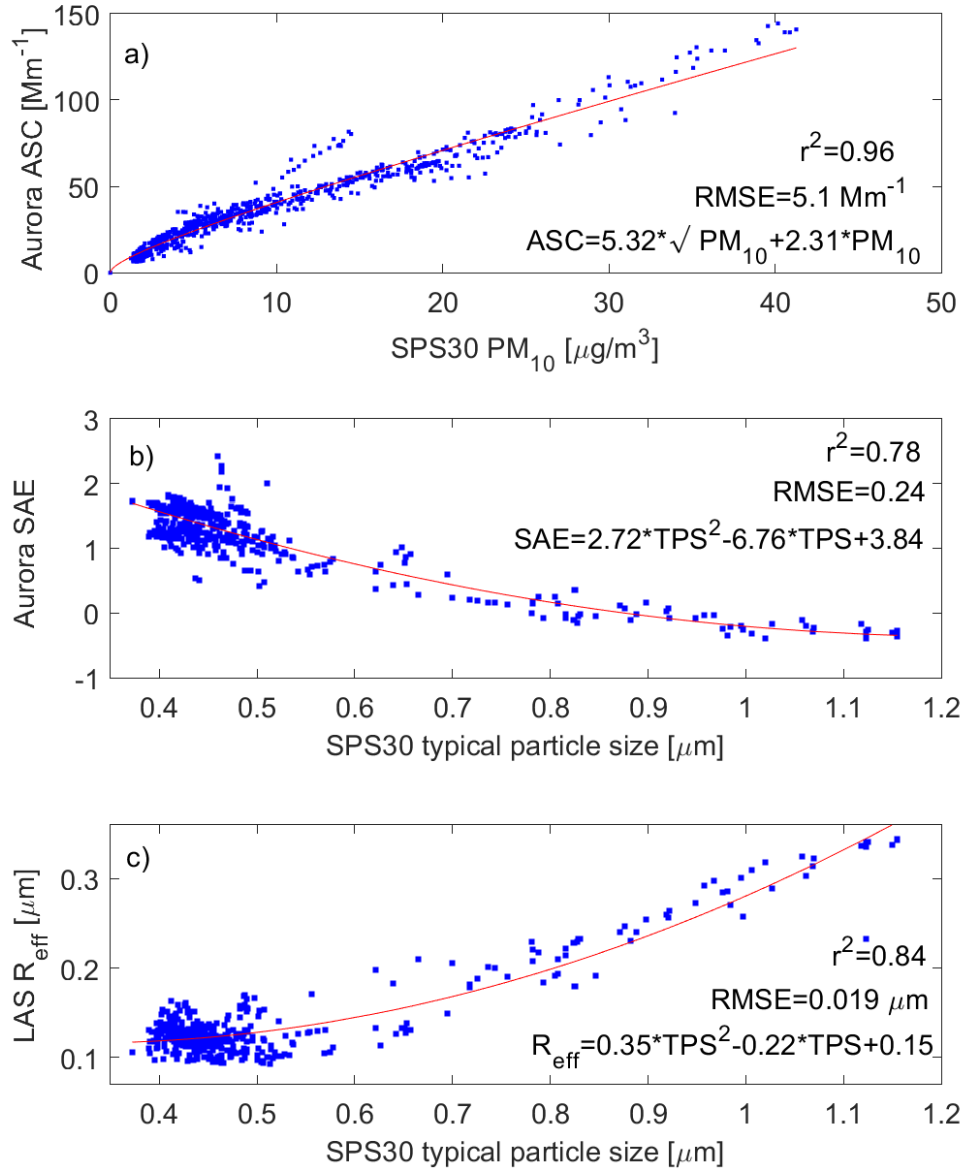


Figure 4. Scatter plot and regression fit (red lines) of the 1-h mean (a) the PM_{10} from SPS30 and ASC at 525 nm from Aurora 4000, (b) SPS30 typical particle size [μm] and SAE from Aurora 4000, and (c) SPS30 typical particle size and effective radius from LAS 3340, both in [μm]. Data from five SPS30 sensors are averaged and visible as one point.

Table 1. Statistics of SPS30 sensor calibration versus Aurora 4000 and LAS devices.

Quantity	Fit parameter	Sensor number				
		1	2	3	4	5
ASC	a	5.05 ± 0.54	5.26 ± 0.57	5.73 ± 0.85	4.85 ± 0.54	5.12 ± 0.89
	b	2.33 ± 0.13	2.36 ± 0.14	2.15 ± 0.20	2.27 ± 0.13	2.49 ± 0.22
	R^2	0.97	0.96	0.91	0.97	0.92
	RMSE (Mm^{-1})	4.8	4.9	7.7	4.9	7.3
SAE	c_0	3.68 ± 0.31	3.66 ± 0.36	3.67 ± 0.39	3.99 ± 0.35	3.74 ± 0.37
	c_1	-6.54 ± 1.03	-6.34 ± 1.08	-6.06 ± 1.22	-7.23 ± 1.12	-6.24 ± 1.18
	c_2	2.66 ± 0.74	2.47 ± 0.76	2.19 ± 0.85	3.04 ± 0.78	2.31 ± 0.82
	R^2	0.81	0.80	0.78	0.81	0.79
	RMSE	0.24	0.25	0.26	0.24	0.25
R_{eff}	d_0	0.16 ± 0.02	0.17 ± 0.02	0.14 ± 0.03	0.15 ± 0.03	0.14 ± 0.03
	d_1	-0.25 ± 0.08	-0.27 ± 0.08	-0.20 ± 0.08	-0.21 ± 0.08	-0.19 ± 0.08
	d_2	0.37 ± 0.06	0.38 ± 0.06	0.34 ± 0.06	0.34 ± 0.06	0.33 ± 0.06
	R^2	0.87	0.87	0.88	0.87	0.88
	RMSE (μm)	0.018	0.019	0.018	0.018	0.018

Assuming these errors are statistically independent, the combined relative uncertainty was estimated using the root-sum-square method. For the mean values listed above, the resulting total relative uncertainty of ASC is approximately 14 %. Since such relative uncertainty produces unrealistically small values of absolute uncertainty during very clean conditions, the absolute error is added. It accounts for instrumental baseline drift, zero offset, and electronic noise. We assume that this uncertainty is about 1 Mm^{-1} . The total uncertainty δASC_{Aurora} of the scattering coefficient was thus calculated as:

$$\delta ASC_{Aurora} = \sqrt{\delta_{cal}^2 + \delta_{zero}^2 + \delta_{trunc}^2 + \delta_{cos}^2 + \delta_{abs}^2}. \quad (6)$$

where $\delta_{cal}, \delta_{zero}, \delta_{trunc}, \delta_{cos}, \delta_{abs}$ are the uncertainties of span calibration, zero check, truncation error, cosine response, and absolute, respectively. The uncertainty of the SAE was then derived using standard propagation of uncertainty based on the SAE at two wavelengths (450 and 635 nm):

$$\delta SAE_{Aurora} = \frac{1}{|\ln(\lambda_1/\lambda_2)|} \sqrt{\left(\frac{\delta ASC_{Aurora, \lambda_1}}{ASC_{Aurora, \lambda_1}}\right)^2 + \left(\frac{\delta ASC_{Aurora, \lambda_2}}{ASC_{Aurora, \lambda_2}}\right)^2} \quad (7)$$

This approach provides a realistic estimate of the total uncertainty in both ASC and the spectral dependence of aerosol optical properties (SAE). ~~Absolute~~ The absolute uncertainty for SAE ~~significantly increases~~ increases significantly for small ASC. In the case of the LAS instrument, the uncertainty of R_{eff} was estimated during (Markowicz et al., 2026) two two-week campaigns in Sopot (Poland) in 2023. Comparison of LAS to NanoScan SMPS Nanoparticle Sizer spectrometer and Optical

Particle Sizer (OPS) 3330 devices allows us to estimate the R_{eff} uncertainty as $0.028 \mu\text{m}$. [Table 2 summarizes the measurement uncertainties of ASC, SAE, and \$R_{\text{eff}}\$ under different optical conditions.](#) The uncertainty in ASC shows only a weak dependence on pollution level, increasing slightly from approximately 35% at $\text{ASC} = 10 \text{ Mm}^{-1}$ to about 39% at $\text{ASC} = 200 \text{ Mm}^{-1}$. For SAE, the uncertainty decreases modestly with increasing ASC and declines more markedly with increasing SAE. In contrast, the uncertainty in R_{eff} exhibits only a weak dependence on its magnitude. Overall, the uncertainties associated with SAE and R_{eff} are substantial, indicating that these parameters can be retrieved from SPS30 measurements only with limited accuracy. For instance, for a typical SAE value of 1.50, the 95% confidence interval spans nearly the full range of observed SAE variability.

Table 2. Measurement uncertainties of ASC, SAE, and R_{eff} estimated from the SPS30 sensor for different ASC.

Uncertainty		ASC [Mm^{-1}]				
		10	20	50	100	200
δASC [Mm^{-1}]		3.5	7.0	18.4	38.2	78.7
δSAE	SAE=1.0	1.17	1.12	1.10	1.10	1.10
	SAE=1.5	0.91	0.84	0.82	0.82	0.82
	SAE=2.0	0.72	0.63	0.60	0.60	0.59
δR_{eff} [μm]	R_{eff} =0.12			0.05		
	R_{eff} =0.15			0.07		
	R_{eff} =0.20			0.09		

4 Results

~~Measurements were conducted five times during three observation campaigns : (i) on 9 June at 21:00 UTC and 10 June at 16:15 UTC (BB aerosol influx case 1), (ii) on 7 August at 07:00 UTC and 15:20 UTC (BB aerosol influx case 2), and (iii) on 29 August at 15:20 UTC (-) captured a Saharan dust transport - (see Table 3)~~ The AeroSonde system was tested in summer 2025. Three observational campaigns were conducted, during which five vertical profiles were obtained - for details see Table 3. Measurement dates were selected based on meteorological conditions favorable for remote sensing observations, as well as the occurrence of long-range transport episodes in the middle and upper troposphere. During the first two campaigns (9 June at 21:00 UTC and 10 June at 16:15 UTC (BB aerosol influx case 1), (ii) on 7 August at 07:00 UTC and 15:20 UTC (BB aerosol influx case 2), and (iii) on 29 August at 15:20 UTC (-) captured a Saharan dust transport - (see Table 3) event. The mean ascent rate of the AeroSonde ranged from 2.7 to 3.9 m s^{-1} , reaching altitudes from 10 to 26.8 km. Such vertical velocity corresponds to a vertical resolution of at least 15–20 m for the SPS30 sensor.

4.1 Meteorological and aerosol conditions overview

~~9–10 June~~

Table 3. Summary of AeroSonde ascents conducted during the observation campaigns, including the date and launch time, the duration of ascent up to the maximum altitude where the signal from the AeroSonde was received, the maximum altitude where the signal was received, and the aerosol type with its main origin.

Date	Launch time (UTC)	Duration (h)	Max altitude (km)	Aerosol type	Origin
09 Jun 2025	21:00	0.75	10	BB	North America
10 Jun 2025	16:15	1.5	21.1	BB	North America
07 Aug 2025	07:00	2.5	25.3	BB	North America
07 Aug 2025	15:20	2.0	19.3	BB	North America
29 Aug 2025	15:20	2.5	26.8	dust	Sahara

Meteorological conditions on 9 and 10 June 2025 were governed by an extensive high-pressure system extending from the Azores to Central Europe, resulting in weak near-surface winds over southeastern Poland. Subsidence inversions were present at approximately 3.8 km on 9 June and around 1.7 km on 10 June. Due to strong wind speeds in the middle and upper troposphere, the AeroSonde experienced significant horizontal displacement (from approximately 75 to 120 km), mainly toward the east (BB case) and northeast (dust case, see Fig. 8a,b). No cloud cover was observed on 9 June (Fig. B1), while high-level cirrus and shallow convective clouds developed around midday on 10 June (Fig. B2). Under predominantly westerly flow in the upper troposphere, the ICAP forecast indicated a BB aerosol transport episode over Strzyżów between 9 and 11 June (Fig. B3). Peak AOD_{smoke} was expected to reach approximately 0.25 at 550 nm, contributing 47–53 % of the total AOD, estimated at around 0.3 on 5a). The balloon trajectories are approximately linear. Only for the highest trajectories is a change in direction observed in the lower stratosphere.

Fig. 5b shows the 3D trajectories of the AeroSonde platform carried by a balloon, highlighting the vertical variability of the ASC along the profiles. The color-coded ASC values show a clear tendency toward higher values in the lower and middle troposphere. With increasing altitude, ASC generally decreases, except for the profile acquired on 9 June, where an increase in ASC is observed near 10 June and exceeding 0.5 at the event peak (km. However, distinct elevated layers with enhanced ASC are intermittently observed, suggesting the presence of aerosol stratification and long-range transport features. These layers exhibit variability both within individual profiles and between different measurement days.

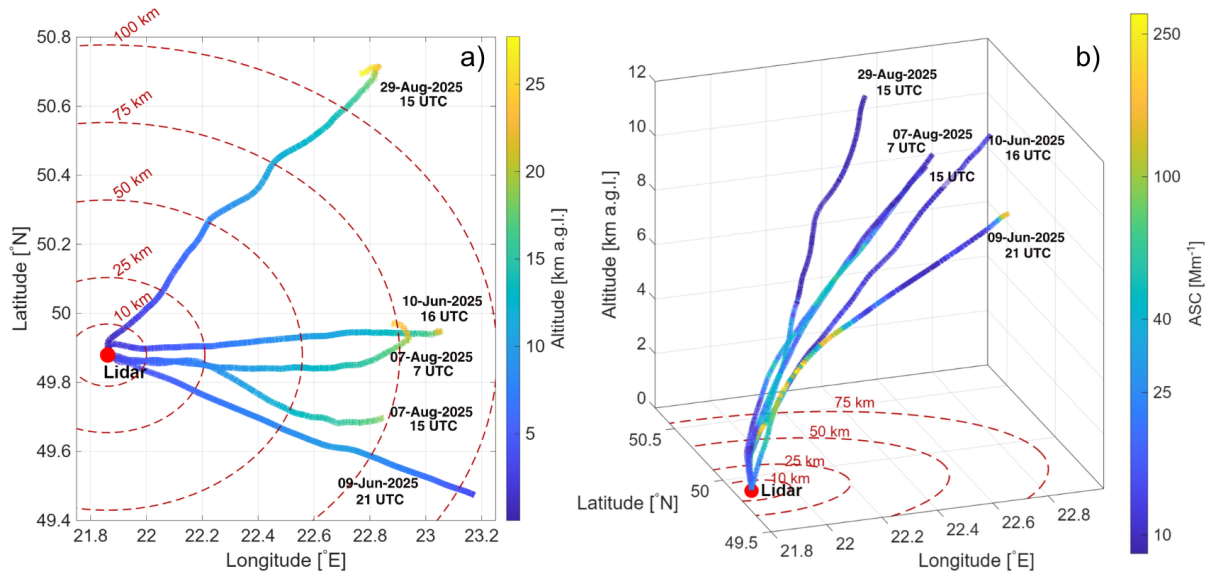


Figure 5. Trajectories of the AeroSonde launched from the lidar station (red marker): (a) Horizontal trajectories colour-coded by altitude (km a.g.l.), illustrating the vertical evolution along the flight paths. Labels indicate the launch date and time (UTC). Dashed red circles denote radial distances from the station, providing a reference for horizontal displacement. (b) Aerosol scattering coefficient (ASC) profiles derived from AeroSonde measurements, shown in geographical coordinates (longitude, latitude) and altitude (km a.g.l.). Trajectories are colour-coded by ASC (logarithmic scale) and restricted to the altitude below 12 km a.g.l. For clarity, trajectories from 7 August 2025 are labelled once, with both measurement times (07:00 and 15:00 UTC) indicated.

Due to the significant horizontal displacement of the sensors suspended beneath the balloon, the methodology described in Section 2.3.2 was applied to get the AEC profiles. Comparison between profiles of ASC retrieved from AeroSonde measurements and AEC profiles obtained using the Klett LR method (AEC_{LR} ; Fig. B3b)–

On 9 June, the range-corrected lidar signal (20a) and the Klett AOD approach (AEC_{AOD} ; Fig. B4) revealed aerosol layers extending up to approximately 6.5 km, with an additional layer above 9 km. The layers exhibited pronounced temporal variability, with gradual descent of the lower layers during the night and dissipation of the uppermost layer around 22:15 UTC (20b) was performed using 100 m vertical averages. Comparison was done for all available measurements, aggregated over all campaigns. For AEC_{LR} , ASC exhibits a Pearson correlation of $r = 0.81$ with an RMSE of 18.5 Mm^{-1} , while for AEC_{AOD} , the correlation is slightly lower ($r = 0.74$) with a higher RMSE of 25.1 Mm^{-1} . Both lidar retrievals show good agreement with AeroSonde-derived ASC, with the Klett LR method providing closer correspondence. The mean bias is positive in both cases— 3.9 Mm^{-1} for AEC_{LR} and 6.4 Mm^{-1} for AEC_{AOD} —which is consistent with the expectation that AEC exceeds ASC due to aerosol absorption.

Backward trajectories initialized at 21 UTC at altitudes corresponding to the observed layer maxima (3.4

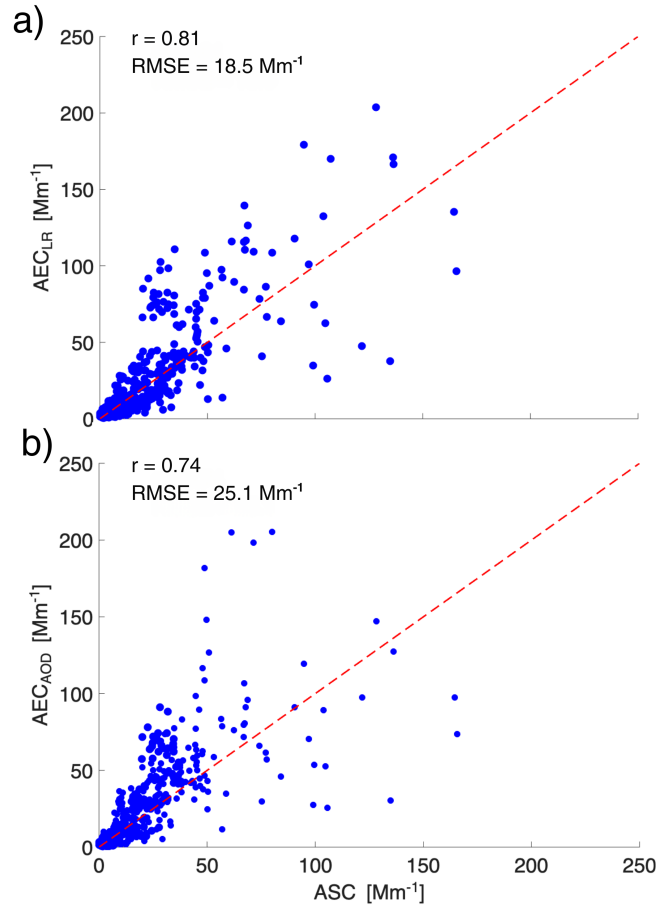


Figure 6. Scatter plots of aerosol optical coefficients averaged within 100 m vertical intervals. The x-axis shows the ASC at 525 nm retrieved from AeroSonde measurements, while the y-axis presents the AEC at 532 nm derived from lidar observations. Panel (a) displays AEC retrieved using the Klett LR approach (AEC_{LR}), and panel (b) shows AEC from Klett AOD (AEC_{AOD}). For each panel, the Pearson correlation coefficient (r) and the root mean square error (RMSE) are reported.

435 Figure 7 shows the distributions of differences between AEC and ASC for all available measurements, aggregated over all
campaigns. In the lowest layer (0.7–4.6 km, around 5.6 km, and near 102 km) indicate transport from Canada (Fig. 9a). Along
these trajectories, ICAP- AOD_{smoke} values were near zero prior to entering Canada, increased to up to ~ 3 over central and
eastern Canada, and decreased to approximately 0.2 upon arrival over Poland (Fig. 7a,b), both retrieval approaches exhibit a positive
bias, which is larger for the AOD-constrained method ($BIAS = 18.2 \text{ Mm}^{-1}$, $RMSE = 33.0 \text{ Mm}^{-1}$) compared to the LR-based
440 approach ($BIAS = 12.5 \text{ Mm}^{-1}$, $RMSE = 20.9 \text{ Mm}^{-1}$). The mean ASC in this layer is 20.5 Mm^{-1} , while the AEC is 33.0
 Mm^{-1} and 38.7 Mm^{-1} , respectively, for the approach based on LR and AOD.

In the 2–5 km range (Fig. 9b,c). Consistently, AERONET observations at 17:33 UTC reported $AOD_{500} = 0.45$, $AE_{440-870} = 1.47$
(long-term mean: 1.49) (Fig. 7c,d), the distributions become broader for both lidar methods, indicating larger variability in AEC–ASC

445 differences, with higher BIAS and RMSE for the AOD-based retrieval ($\text{BIAS} = 12.7 \text{ Mm}^{-1}$, $\text{RMSE} = 52.8 \text{ Mm}^{-1}$) than for the LR-based approach ($\text{BIAS} = 8.0 \text{ Mm}^{-1}$, $\text{RMSE} = 30.7 \text{ Mm}^{-1}$). In this layer the highest values of ASC (34.0 Mm^{-1}) and AEC (42.0 and $\text{SSA}_{440} = 0.97$ (Table 4) 46.7 Mm^{-1}) are observed, indicating long-range transport of aerosols above the PBL.

450 On 10 June, AeroSonde measurements were conducted between approximately 16:15 and 18:00 UTC under cloudy conditions. At higher altitudes (5–8 km) (Fig. B2). The cloud base descended from about 5 km to approximately 3 km during the measurement period, and cloud-contaminated parts of the lidar profiles were replaced using linear interpolation between adjacent cloud-free layers. The lidar signal indicates a stratified aerosol structure and suggests that the measurements were performed near the end of the BB aerosol influx, when only a single, substantially diluted layer remained. 7e,f), both methods show near-zero bias and narrower, more symmetric distributions, with $\text{BIAS} = -1.9$ and -0.6 Mm^{-1} and $\text{RMSE} = 6.9$ and 7.9 Mm^{-1} for the LR and AOD approaches, respectively. The slightly negative bias is somewhat unexpected, as AEC is generally expected to exceed ASC; however, the magnitude of this effect remains small. The mean ASC in this case is similar to mean between 0.7 and 2 km.

460 Backward trajectories for layers between 2 and 4 km a. s.l. observed at 16 UTC on the following day again indicate transport over Canada. Above 8 km (Fig. 10a). Along these trajectories, $\text{AOD}_{\text{smoke}}$ increased to up to 1.4 over central and eastern Canada before decreasing to approximately 0.22 over Poland (Fig. 10b,c). The closest AERONET observation, at 12:18 UTC, reported $\text{AOD}_{500} = 0.46$ with $\text{AE}_{440-870} = 1.50$, while SSA_{440} was not available (Table 4) 7g,h) both approaches also exhibit minimal bias ($\text{BIAS} = 0.6$ and 0.5 Mm^{-1}) and low RMSE (5.2 and 5.8 Mm^{-1}). In this case, the mean ASC is 8.0 Mm^{-1} , while AEC is 8.5 Mm^{-1} and 9.4 Mm^{-1} , respectively, for LR and AOD method.

7 August

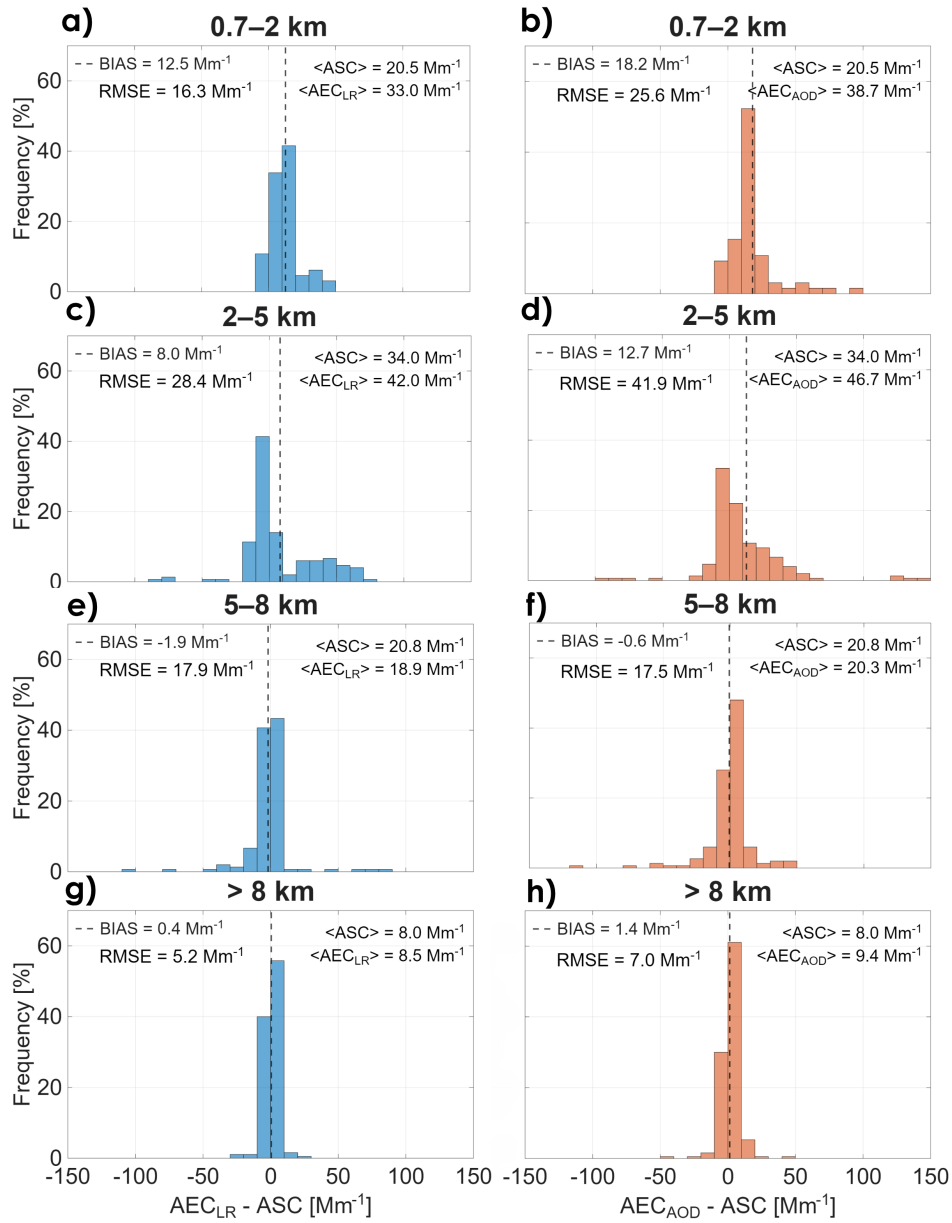


Figure 7. Frequency distributions of differences between aerosol extinction coefficients (AEC) at 532 nm derived from lidar and aerosol scattering coefficient (ASC) at 525 nm obtained from AeroSonde measurements for four altitude ranges: 0.7–2 km (a, b), 2–5 km (c, d), 5–8 km (e, f), and > 8 km (g, h) for all data collected during measurement campaigns. Left column (blue) shows differences between extinction derived using the lidar ratio approach ($AEC_{LR} - ASC$), while the right column (orange) shows differences based on AOD-constrained lidar retrievals ($AEC_{AOD} - ASC$). The dashed vertical line indicates the mean bias (BIAS), and the root-mean-square error (RMSE) is reported in each panel.

4.1 Case Studies of Aerosol Vertical Profiles for Different Aerosol Types

465 To highlight the versatility of the AeroSonde system, we examine in detail two representative events, one dominated by BB aerosols and the other by mineral dust, showing how the system captures distinct vertical profiles.

4.1.1 Biomass burning aerosol

The first case covers measurements performed on 7 August were similar to those in June, with the high-pressure centre located directly over the measurement region, resulting in lower subsidence inversions at approximately 1.2–1.3 km (Fig. 8c,d August 2025 at 15:20 UTC (Tab. 3). Under the prevailing westerly circulationprevailing westerly flow, the ICAP forecast (Fig. C2) indicated a BB aerosol transport event beginning on from 7 August and persisting until to 11 August (Fig. C2a). On 7 August, AOD_{smoke} was predicted to exceed 0.1 and to contribute 61 % of the total AOD, with total AOD estimated to reach approximately 0.3 at the event peak see Fig. S3a in the Supplement). A high-pressure system over the measurement region led to subsidence inversions at 1.2–1.3 km (Fig. C2b).

475 Aerosol S4), which limited vertical mixing and favored the persistence of elevated aerosol layers above the boundary layer. As a result, aerosol layers were present throughout the day (Fig. C1S5), with distinct layers observed between approximately well-defined structures between 4 and 11 km observed from 02:00 UTC onward. During the morning measurement period, the vertical structure remained relatively stable. After the AeroSonde reached about 12 km, low-level clouds developed at 1–2 km until around 11:30 UTC, while high-level clouds were present from approximately 09:30 to 13:00 UTC. The afternoon period was cloud-free; however, the aerosol layers exhibited pronounced downward displacement. In the afternoon, under cloud-free conditions, as confirmed by whole sky camera observation, these layers descended and were primarily located between 3 and 8 km a.g.l.

All LAGRANTO backtrajectories for this day, computed LAGRANTO back-trajectories initialized within the observed aerosol layers (except for the lowest ones (at around 1 km) ; indicate transport of BB aerosol confirm long-range transport from Canada (Fig. 11, 12). The trajectories were relatively straight and consistent follow consistent pathways across central Canada and the Atlantic, without strong curvature, spanning altitudes between 4 and 9 km a.s.l. in the morning and between of 2 and 8 km a. s.l. in the afternoon. Backtrajectories further show that initially clean. Along these pathways, air masses encountered regions with high AOD_{smoke} over central Canada , reaching values of 7.3 for the 07:00 UTC case and 4.5 for the 15:00 UTC case. Elevated AOD_{smoke} values persisted along the transport pathways over the Atlantic Ocean and gradually decreased as the air masses approached Europe, resulting in values of approximately 0.15 over Poland. AERONET observations reported AOD values ranging from 0.23 to 0.27, accompanied by relatively high $AE_{470-870}$ (1.66–1.67) and reduced SSA_{440} with high AOD_{smoke} (0.95) (Table 4). Over the course of the day, AOD decreased from 0.27 at 07 UTC to 0.23 at 15 UTC.

29 August

495 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. Two inversion layers were present, the first at approximately 0.7 km

and the second in the mid-troposphere at around 5.5 km (Fig. 8e), the latter being characteristic of subtropical air masses and associated with large-scale subsidence in the descending branch of the Hadley cell (Barreto et al., 2022). Consistent with this synoptic setting, the ICAP forecast for 28 August–2 September (Fig. D2) indicated a dust aerosol influx, with the main episode occurring between 29 and 30 August, during which AOD_{dust} up to 4.5), which gradually decreased toward Europe. Over Poland, AOD_{dustsmoke} was predicted to exceed 0.1 (Fig. D2a). The maximum dust load was forecast for around 06:00 UTC on 29 August, with AOD_{dust} exceeding 0.25 and contributing approximately 58 % to , accounting for 61 % of the total AOD ; which was estimated to range between 0.3 and 0.4 (Fig. D2b).

On that day, aerosol layers were detected by the lidar throughout its entire operation period (00:00–17:00 UTC) . The aerosol load was observed above approximately 1–1.5 km a.g.l., extending up to about 4–5 km (0.3) (Fig. D1). Dust clouds were present above these layers but dissipated shortly after 15:00 UTC, resulting in cloud-free conditions during the AeroSonde measurements. During the observation period , the dust layers were relatively stable: the aerosol load between 1.5 and 2.5 km showed a gradual ascent, while layers above 3 km remained stationary.

The three lowest LAGRANTO backtrajectories (with starting points between 1 and 2.3 km a.s.l.) originated from the north, bringing clean air. The remaining trajectories (starting points between 2.6 and 5.3 km a.s.l.) indicate that the air masses traveled over the northern part of Africa, resulting in dust transport (Fig. 17a). The ICAP model reports AOD_{dust} values of up to 1.16 over the northwestern part of Africa on 25–26 August (Fig. 17b) and approximately 0.17 over the Poland area. On 29 August at 15:20 UTC, when Saharan dust layers were observed, AERONET reported AOD₅₀₀ = 0.30 (0.19 long-term mean for August) with AE_{470–870} = 0.40 (1.55 long-term mean for August S3b). For the analyzed period AERONET observations reported an AOD₅₀₀ of 0.23, with high AE_{470–870} (1.66) and SSA₄₄₀ = 0.93. It should be noted that on 7 and 29 August, the quality criterion for the AERONET inversion product (AOD₄₄₀ > 0.4) is not satisfied; therefore, the retrieved SSA is associated with larger uncertainties. For example, for AOD₄₄₀ = 0.2 the uncertainty of SSA is 0.07 (Zhang et al., 2025)₄₄₀ (0.996) (Table 4).

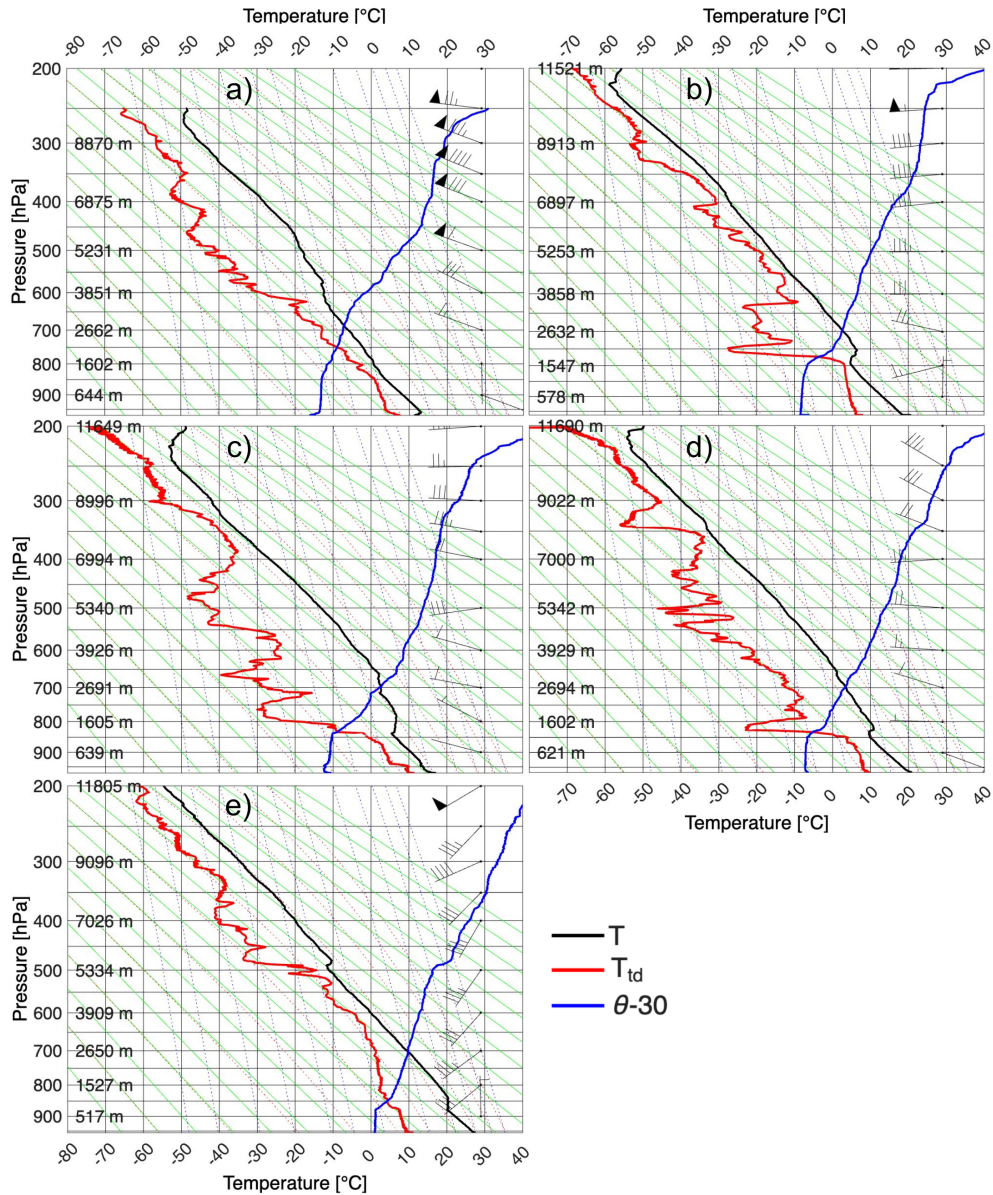


Figure 8. Stüve diagrams showing the vertical thermodynamic structure of the atmosphere based on soundings observations, plotted using temperature (°C) on the horizontal axis and pressure (hPa) on the vertical axis, with corresponding height (m) indicated. The thick black line represents the atmospheric temperature profile (T), the thick red line shows the dew-point temperature (T_{td}) profile, and the blue line depicts the potential temperature (θ), shifted by -30 °C for improved visibility. Diagram features include horizontal isobars (solid black lines), vertical isotherms (solid black lines), dry adiabats curving upward to the left (solid green lines), moist adiabats curving upward to the right (dashed dark-red lines), and mixing-ratio lines (blue dashed lines), expressed in g kg^{-1} . Wind barbs along the right margin depict wind speed [m/s] and direction at the corresponding pressure levels. Respective panels show diagrams for 9 July (a), 10 July (b), 7 August (c: 07 UTC, d: 15 UTC), and 29 August (e). Data were collected by the AeroSonde, except for 9 July, when observations from the WMO station in Tarnów were used.

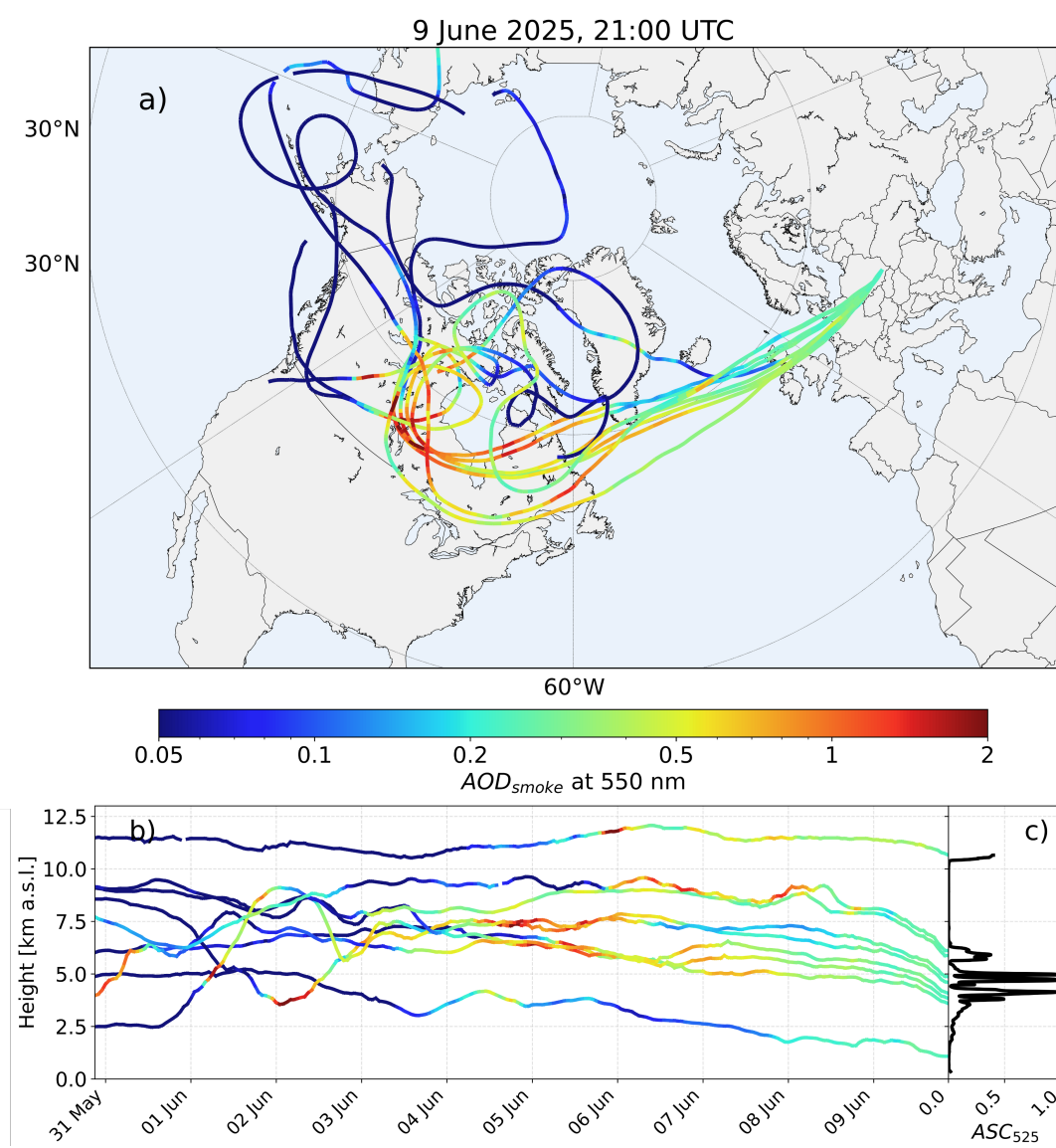


Figure 9. LAGRANTO 10-day backtrajectories starting on 9 June 2025 at 21:00 UTC. Panels (a) and (b) show the geographical distribution and the vertical cross-section of the selected trajectories, respectively. Line colours represent ICAP AOD_{smoke} at 550 nm. Panel (c) shows the normalised profile of ASC₅₂₅ measured by the AeroSonde.

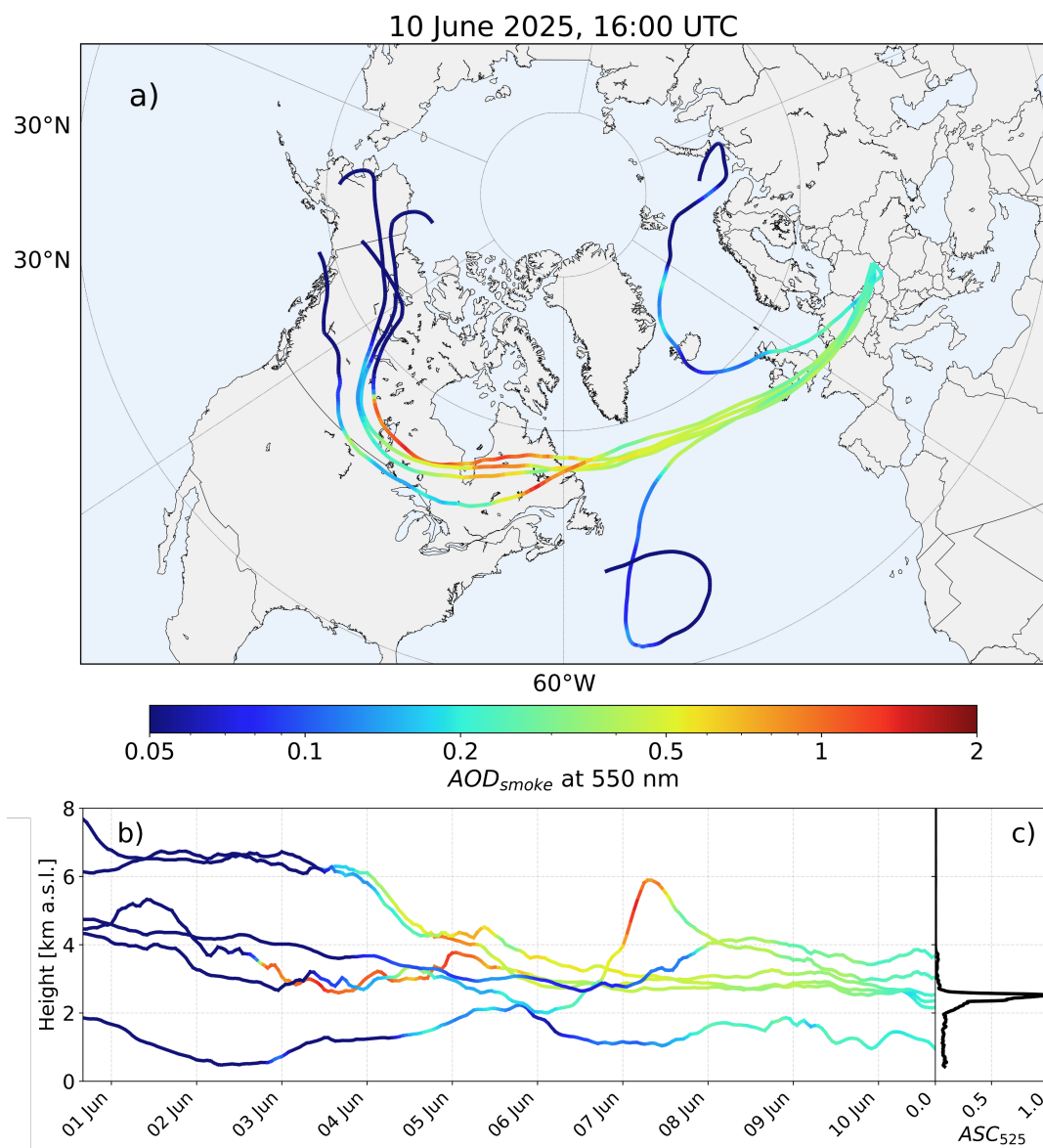


Figure 10. LAGRANTO 10-day backtrajectories starting on 10 June 2025 at 16:00 UTC. Panels (a) and (b) show the geographical distribution and the vertical cross-section of the selected trajectories, respectively. Line colours represent ICAP AOD_{smoke} at 550 nm. Panel (c) shows the normalised profile of ASC_{525} measured by the AeroSonde.

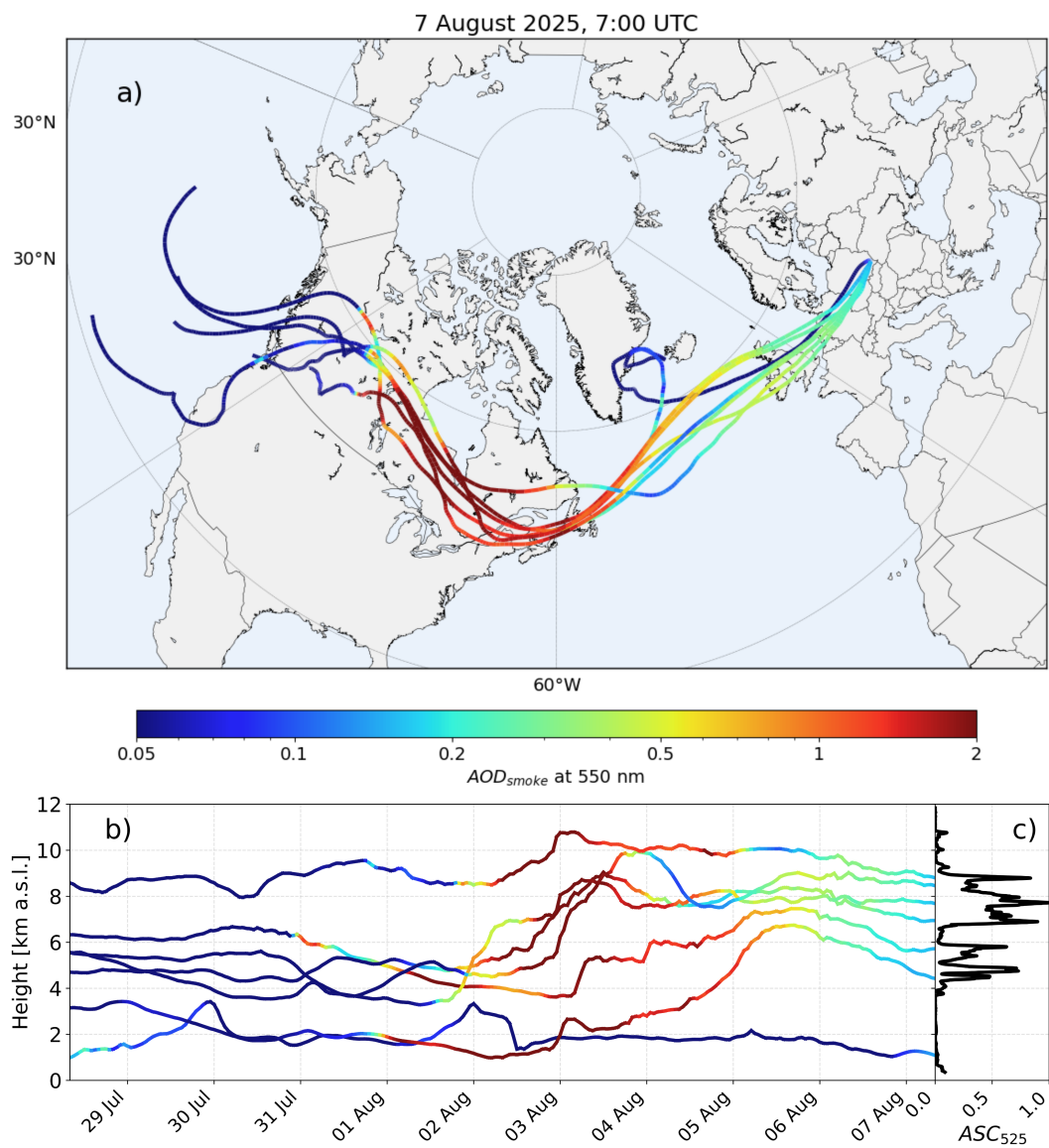


Figure 11. LAGRANTO 10-day backward trajectories starting on 7 August 2025 at 07:00 UTC. Panels (a) and (b) show the geographical distribution and the vertical cross-section of the selected trajectories, respectively. Line colours represent ICAP AOD_{smoke} at 550 nm. Panel (c) shows the normalised profile of ASC₅₂₅ measured by the AeroSonde.

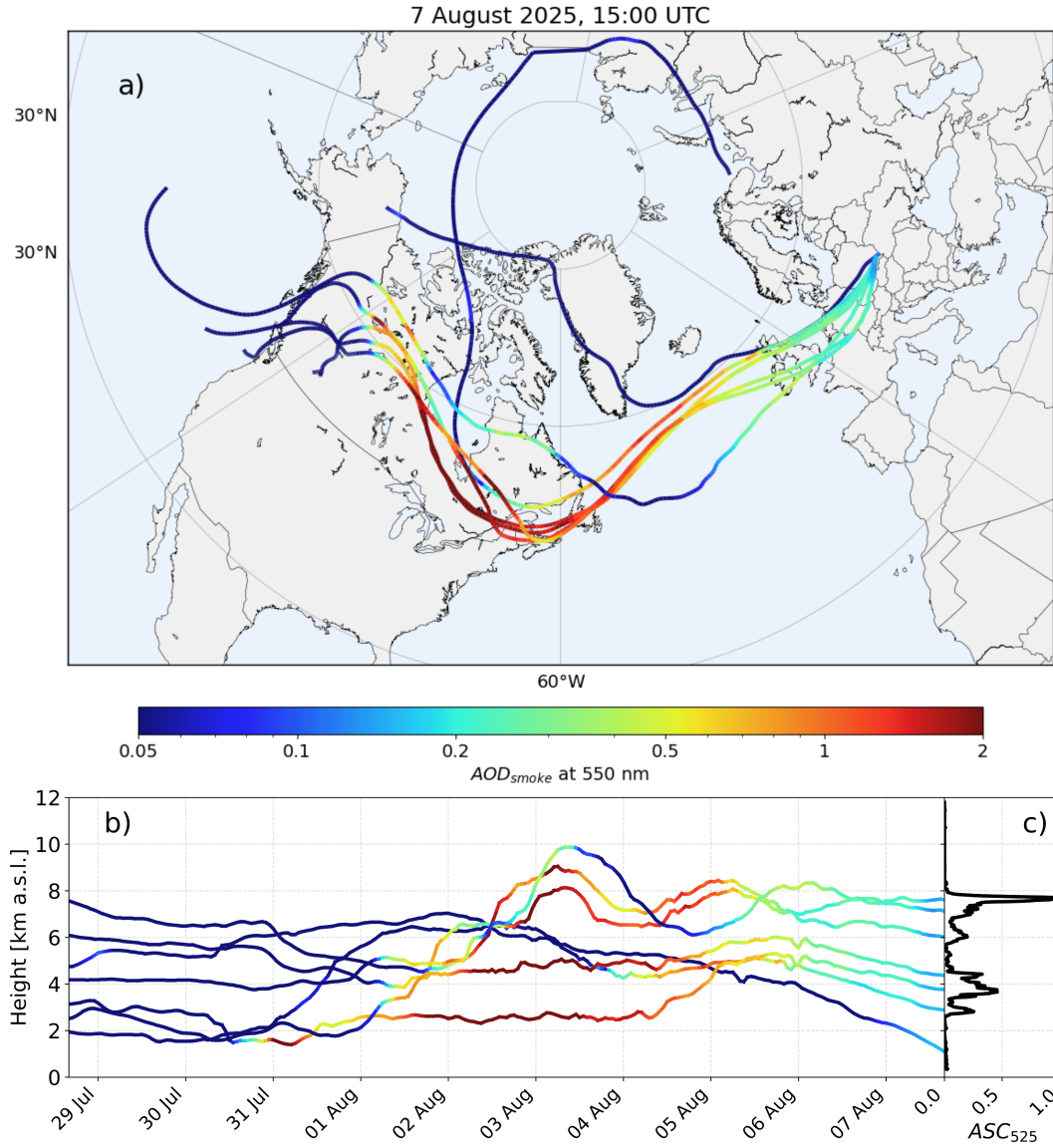


Figure 12. LAGRANTO 10-day backtrajectories starting on 7 August 2025 at 15:00 UTC. Panels (a) and (b) show the geographical distribution and the vertical cross-section of the selected trajectories, respectively. Line colours represent ICAP AOD_{smoke} at 550 nm. Panel (c) shows the normalised profile of ASC₅₂₅ measured by the AeroSonde.

4.2 Vertical profiles

In this paragraph, we discuss the results of vertical atmospheric profiling, bearing in mind that the balloon also undergoes horizontal displacement; in all cases, the balloon exhibited pronounced horizontal drift, increasing with altitude as a result of

Table 4. Values of AOD₅₀₀ and AE_{440–870} obtained from AERONET level 1.5 for selected measurement times (given in parentheses), as well as SSA₄₄₀ and R_{eff} derived from the AERONET Almucantar Inversion product (level 1.5) for the corresponding inversion times (given in parentheses). In addition, the contributions of smoke AOD (AOD_{smoke}) and mineral dust AOD (AOD_{dust}) to the total AOD at 550 nm from ICAP are provided for the times closest available times, with a maximum temporal offset of ±3h relative to the measurements(max. 3h).

Date	AERONET				ICAP	
	AOD ₅₀₀	AE _{440–870}	SSA ₄₄₀	R _{eff}	AOD _{smoke} /AOD	AOD _{dust} /AOD
09 Jun 2025	0.45 (17:33)	1.47 (17:33)	0.974 (17:08)	0.249 (17:08)	0.47	0.06
10 Jun 2025	0.46 (12:18)	1.50 (12:18)	N.A.	N.A.	0.53	0.06
07 Aug 2025	0.27 (07:06)	1.67 (07:06)	0.953 (07:07)	0.221 (07:07)	0.61	0.02
07 Aug 2025	0.23 (15:25)	1.66 (15:25)	0.996 (12:40)	0.310 (12:40)	0.61	0.02
29 Aug 2025	0.28 (15:30)	0.40 (15:30)	0.927 (15:21)	0.734 (15:21)	0.11	0.58

~~strong winds in the upper troposphere (see Appendix B, C and D for more details). According to the raw (not calibrated) data obtained from Aerosonde (Fig. 14), the identified aerosol layers are dominated by fine-mode particles, as PM₁ closely follows PM₁₀ throughout the profile (Fig. 14a). Several layers with elevated PM₁ and PM₁₀ concentrations, relative to near-surface values, are observed between approximately 2 and 8 km.~~

4.1.1 Biomass burning aerosol (case 1)

9-June 2025

AeroSonde measurements, whose results are shown in Fig. 13b, reveal several distinct and thin layers that can be identified. Their thickness ranged from about 100 to 400 m, and they were mainly located between 3.3 km and 4.8 km, with extreme ASC values around 200 Mm^{−1} observed at 3.8, 4.4, and 4.6 km. Above these sharp layers, a broader and more diffuse structure, about 600 m thick, was observed between 5.3 km and 6 km. For the layers found between 3 and 6 km a.g.l., the uncertainty in the ASC retrieval was approximately 40 % of the reported ASC value. Due to the balloon leakage, the upper part of the layer near 10 km a.g.l. was not captured. The BB aerosol layers are found between 3.5 and 6 km a.g.l. accounted for 52.6 % of the total AOD retrieved from the Aerosonde ASC profiles, and for approximately 51.2 % of the total AOD derived using the Klett LR applied to the lidar data, and 44.7 % of the total AOD when the Klett AOD approach was used.

Examination of Fig. B4 shows that the layers between 3.7 and 6 km were relatively dry. The observed temperature inversion near the surface explains the enhanced ASC values close to the ground and the subsequent decrease in ASC as the inversion weakens with height. The thermodynamic profile also indicates that the uppermost aerosol layer could be constrained below the tropopause, leaving the stratosphere unaffected.

~~The correlation coefficient between the AEC~~ This is further supported by the particle number concentrations, where contributions from size bins larger than 1 μm remain negligible across the entire profile (Fig. 13a) and ASC (Fig. 13b) profiles was 0.72 when

540 AEC was retrieved with the Klett LR algorithm, and 0.7 when constrained by the AOD value from 17:30 (14b). Additionally, the coarse-to-fine mass ratio (Fig. 13a). The Klett AOD retrieval yielded slightly lower AEC values (not exceeding 125 Mm^{-1} , with a maximum around 180 Mm^{-1} at 4.25 km) (14d) remains low, generally below 0.12, while the Klett LR case produced values up to 250 Mm^{-1} at the same height. For the layers found between 3 and 7 km, the Klett LR exhibited values of AEC approximately $50\text{--}80 \text{ Mm}^{-1}$ higher than Klett AOD. The uncertainty of the AEC within aerosol layers was on the order of 18 % of the AEC magnitude for the Klett LR retrieval and about relative contribution of particles larger than $1 \mu\text{m}$ (Fig. 14e) does not exceed 2 % for the Klett AOD approach within the aerosol layer.

For the layers located between 4 and 5 km a.g.l., the profiles show an increase in R_{eff} accompanied by a corresponding decrease in SAE. Within the identified aerosol layers, the TPS profile (Fig. 13e). Below 4 km, SAE remains comparatively higher while R_{eff} stays relatively low. The uppermost layer exhibits the largest particles, reflected by elevated R_{eff} values and the lowest SAE values within the profile. Overall, the trend indicates that R_{eff} generally increases with altitude, whereas SAE decreases, with minor deviations linked to the presence of individual aerosol layers.

10 June 2025

The AeroSonde reached altitudes up to 21 km, with an average vertical resolution of 6.8 ± 2.1 (14c) shows relatively limited variability, with values confined to the range of $0.45\text{--}0.55 \mu\text{m}$. An increase in TPS is observed near the upper boundary of the main aerosol layer (below 8 km), coinciding with an increase in the coarse-to-fine mass ratio and the contribution of particles larger than $1 \mu\text{m}$. Its increasing horizontal displacement with height was consistent with the observed wind profile (Fig. 8b), which featured light southerly winds near the surface that shifted to stronger westerlies aloft. These winds intensified with altitude, reaching 27.5 ms^{-1} at 10 km a.g.l.

A single distinct layer was observed during this day (Fig. ??b). Values exceeding 60 Mm^{-1} were recorded between 1.6 km and 2.3 km, with a maximum ASC of about 150 Mm^{-1} at 2.15 km. The uncertainty of the ASC values for aerosol found between 1.6 km and 2.3 km was approximately 37.5 % of the reported ASC value. This layer contributed 30.8 % to the total AOD as estimated from the AeroSonde ASC profiles, 28.5 % when derived from lidar data assuming a constant LR, and 37.8 % when obtained using the AOD-based lidar approach. As shown in Fig. B5, the aerosol layer formed above the PBL, and the air within the layer was considerably drier than in the underlying atmosphere. The potential temperature profile indicates that the layer was well-mixed.

The correlation coefficients between the AEC (Fig. ??a) and ASC profiles (Fig. ??b) were 0.87 for both Klett retrievals. The Klett AOD algorithm (AOD value from 12:18) yielded a peak AEC of about 485 Mm^{-1} at 2.1 km, while the Klett LR retrieval gave approximately 220 Mm^{-1} at the same altitude. Between 1.6 km and 1.9 km, AEC values from the Klett AOD solution were about 100 Mm^{-1} higher than in the Klett LR case. The uncertainty of the AEC retrieved with the Klett LR method was approximately 35 % of the reported AEC value, whereas for the Klett AOD retrieval, the corresponding uncertainty was about 18.5 %.

For the single aerosol layer located between 1.6 and 2.3 km number concentration. Above 10 km, the coarse-to-fine ratio exhibits increased variability; however, this behaviour is not reflected in the TPS profile, the SAE exhibits a decrease relative to the surrounding atmosphere, while the corresponding R_{eff} shows a slight increase in the centre of the layer. This indicates the

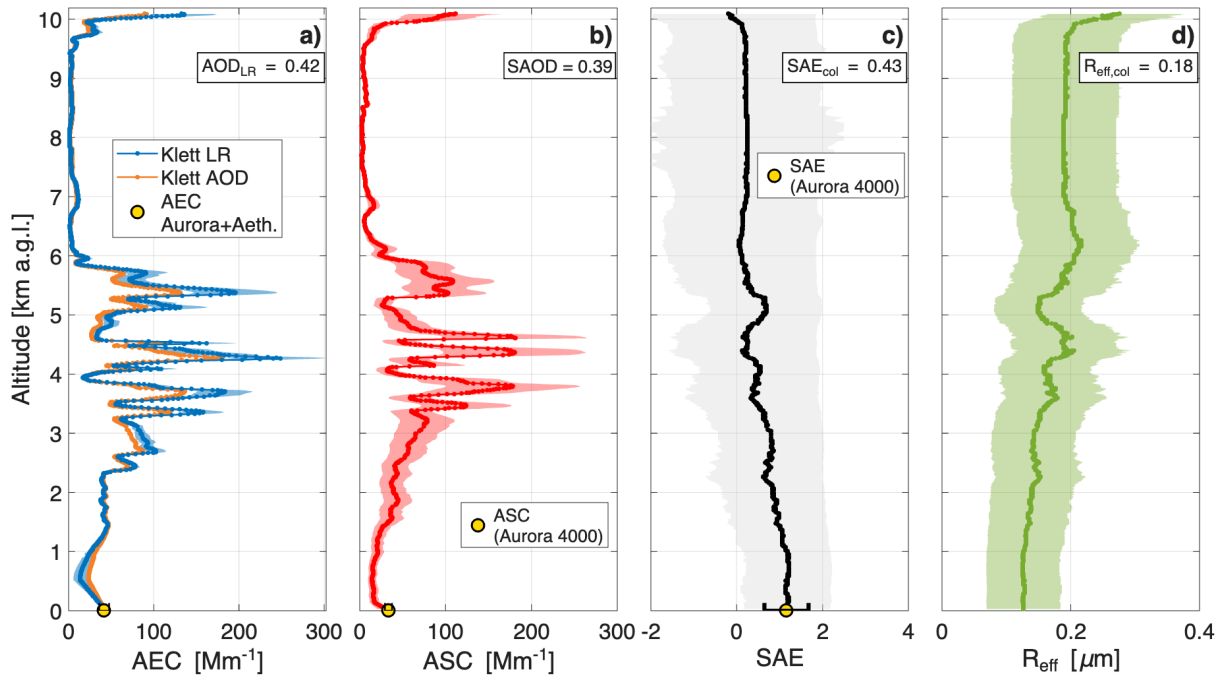


Figure 13. Results of the measurements on 9th June 2025, 21:00–21:40 UTC. Subfigure (a) shows aerosol extinction coefficient at 532 nm (AEC) profiles retrieved from the lidar signal from Raymetrics LB10-V-D200 lidar system using the Klett LR algorithm, assuming either a constant LR (blue line) or an AOD constraint (red line). The AEC is temporally and vertically collocated with the AeroSonde ascent. The yellow marker outlined in black represents the near-surface AEC derived from in situ measurements as the sum of the aerosol scattering coefficient (ASC) measured by the Aurora 4000 nephelometer and the aerosol absorption coefficient (AAC) measured by the AE31 aethalometer. The box in the upper right corner shows the AOD value calculated as the vertical integral of the AEC profile retrieved with the Klett LR method over the altitude range presented. Subfigure (b) presents the ASC at 525 nm profile obtained from data collected by the SPS30 particulate matter sensor, with the yellow marker indicating the near-surface value measured by the Aurora 4000 nephelometer. The box in the upper right corner shows the scattering aerosol optical depth (SAOD), calculated as the vertical integral of the ASC profile over the altitude range presented. Subfigure (c) shows the scattering Ångström exponent (SAE) profile derived from SPS30 data, with the yellow marker denoting the near-surface value obtained from nephelometer data. The box in the upper right corner presents the columnar SAE (SAE_{col}) derived using Eq. A7. Subfigure (d) depicts the effective radius (R_{eff}) profile derived from SPS30 data. The box in the upper right corner presents the columnar R_{eff} ($R_{eff,col}$). In all subfigures, the yellow marker outlined in black is shown together with its associated measurement uncertainty. The extinction profiles shown in subfigure (a) were derived from lidar measurements acquired with the Raymetrics LB10-V-D200 system, whereas the ASC, SAE, and R_{eff} profiles were obtained from data collected by the SPS30 particulate matter sensor.

575 ~~presence of larger particles within the layer compared with those found above and below it~~which remains relatively smooth.
This may indicate the influence of the retrieval algorithm, which likely reduces sensitivity to noise in this parameter. It should
be emphasized that aerosol concentrations above 8 km are very low, and therefore TPS measurements in this range are likely
associated with significant uncertainties.

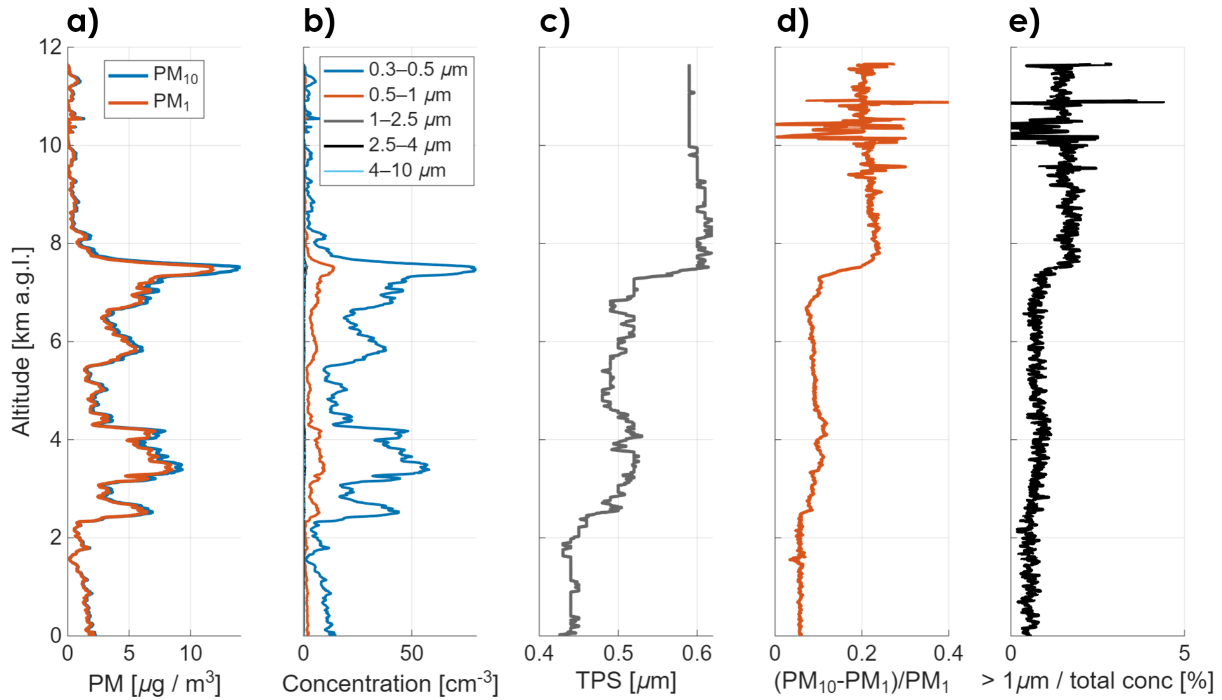


Figure 14. Results Vertical profiles of the raw data obtained by AeroSonde during measurements on 10th June 7th August 2025, 16:15–17:15 20-16:30 UTC. Same variables Panel (a) shows mass concentrations of PM_{10} and PM_1 . Panel (b) presents particle number concentrations for selected size ranges (0.3–0.5, 0.5–1, 1–2.5, 2.5–4, and 4–10 μm). Panel (c) shows the typical particles size parameter (TPS). Panel (d) displays the coarse-to-fine mass ratio expressed as in Fig($PM_{10} - PM_1$)/ PM_1 . Panel (e) presents the contribution of particles larger than 1 μm to the total number concentration.¹³

4.1.1 Biomass-burning aerosol (case 2)

On 7 August 2025, measurements were performed at two times: in the morning (07:00 UTC–9:00 UTC) and in the afternoon (15:20 UTC–17:00 UTC). On this day, clouds started forming shortly after 08:00 UTC but dissipated by 14:00 UTC (see Fig. C1). The range-corrected lidar signal indicates that aerosol layers were present throughout the entire day. During the initial measurement period, the layers remained relatively stable, exhibiting little temporal evolution. In contrast, during the afternoon measurement period, the layers began to descend and exhibited more rapid evolution.

During the 07:00 UTC measurements, smoke layers were observed between 4.1–5.6 km and 6.5–8.7 km (Fig. 15b). At 15:00 UTC, the lower layers descended to 2.4–4.2 km, while the upper layer became more pronounced, with the highest values between 6.8 km and 7.6 km, and the upper layer (5.5–7.8 km a.g.l.), with peak values between 6.7 and 7.7 km (Fig. 16b). In the morning, Retrieved ASC exceeded 40 Mm^{-1} within the developing layers, reaching maxima of about 60 Mm^{-1} at 7.5 km, 6.7 km, and 8.5 km, and the associated ASC uncertainty was approximately 38% of the reported values. In the afternoon, the layers again exceeded 40, reaching a maximum of

70 Mm^{-1} , with the peak near 7.5 km reaching approximately 70 Mm^{-1} with the uncertainty in ASC $\sim$ with an uncertainty of approximately 35 % of the retrieved ASC values. For the morning case, two aerosol layers were identified. The lower layer (4.00–5.75 km a.g.l.) contributed 24.0 % to the total AOD based on the AeroSonde ASC profiles, compared to 18.8 % and 17.5 % derived from lidar data using the Klett LR and Klett AOD approaches, respectively. The upper layer (6.40–8.85 km a.g.l.) dominated the column, contributing 41.3 % according to the AeroSonde ASC profiles and 44.2 %–48.6 % based on the two lidar retrieval methods. In the afternoon, the aerosol layer terminates at an altitude of approximately 8 km, which is associated with a noticeable change in the temperature gradient (isothermal layer) and a sharp decrease in dew point temperature at this height (Fig. S4).

In this case, the lower layer (2.26–4.30 km a.g.l.) accounted for contributed 32.1 % of % to the total AOD from the derived from AeroSonde ASC profiles, while lidar estimates ranged from compared to 27.6 % to 30.1 % from lidar. The upper layer (5.45–7.75 km a.g.l.) contributed accounted for 36.3 % according to the AeroSonde data and 34.1 %–38.8 % from the lidar-based methods % from lidar retrievals.

Examination of the atmospheric thermodynamic profiles (Fig. C3, C4) shows that during the morning, the lower aerosol layers (4.1–5.6 km) were characterised by dry conditions, whereas the higher layers were relatively more humid. Non-zero ASC values above 11 km indicate the possibility of the presence of aerosol in the stratosphere, as this altitude is where the temperature inversion occurs. In the afternoon, the lower aerosol layers were a little less dry than in the morning, although dry conditions still prevailed. The upper layer exhibited the highest humidity at its top, while becoming progressively drier towards its lower boundary of this layer. During the afternoon, ASC values sharply decreased at the temperature inversion associated with the stratosphere, suggesting the stratosphere was free from aerosol load there.

During the morning measurements, the correlation coefficients between the The correlation between AEC (Fig. 15a) and ASC profiles (Fig. 15b) were 0.85–16b) profiles was 0.75 for the Klett LR retrieval and 0.87 for the Klett AOD retrieval. In the afternoon, the corresponding values were 0.76 and 0.74, respectively.

For the morning case, the maximum AEC retrieved with the Klett LR algorithm reached 70 Mm^{-1} at 8.6 km, and both the lower and upper layers showed values exceeding 20 Mm^{-1} (Fig. 15a). The Klett AOD retrieval, the AEC values reached up to 95 Mm^{-1} , approaching this value at peak at 8.6 km. Both the Klett LR and the Klett AOD profiles show a pronounced peak at 8.6 km, while the ASC profile from the AeroSonde indicates comparable values at this altitude and in the layers below (7.5 km and 6.7 km). The differences between the two Klett retrievals reach around 15 Mm^{-1} in the upper layers (above 6 km), and rise to around 925 Mm^{-1} at the peak, while lower layers (below 6 km) are retrieved with comparable values for both Klett algorithms. The uncertainty associated with the Klett LR retrieval in the aerosol layers was about 17 % of the retrieved AEC, whereas for the Klett AOD retrieval it was approximately 3 %.

For the afternoon case, the Klett LR retrieval (Fig. 16a) showed, The Klett LR method yielded a peak AEC of about 41 Mm^{-1} at 7.2 km, whereas the Klett AOD retrieval yielded a more distinct peak reaching above approach produced a more pronounced maximum exceeding 75 Mm^{-1} , showing the largest difference between the two methods within this profile Mm^{-1} , representing the largest discrepancy between the methods. In other layers, AEC from the Klett LR algorithm produced AEC values lower by approximately retrieval was typically lower by 15–25 Mm^{-1} , depending on the layer and its

vertical structure. The Klett LR profile is characterized by Mm^{-1} . The LR-based profile shows layers between 2.5 and 4.2 km in altitude, with maximum AEC values around with maxima of 20–30 Mm^{-1} . The layers Mm^{-1} , and values above 10 Mm^{-1} above 5.5 km exceeded 10 Mm^{-1} . For. In contrast, the Klett AOD profile, AEC values in the lower layers exceeded exceeds 25 Mm^{-1} Mm^{-1} in both lower and upper layers, reaching up to 50 Mm^{-1} at an altitude of Mm^{-1} at 3.3 km, while the higher layers also exceeded 25 Mm^{-1} . For this case, the. The uncertainty of the Klett LR retrieval in the aerosol layers was approximately 24 % of the retrieved AEC, whereas for the Klett AOD retrieval it remained close to % within aerosol layers, compared to around 3 %.

Examination of the morning profiles of SAE (Fig. 15c) and R_{eff} (Fig. 15d) indicates a general pattern in which the R_{eff} increases with altitude, accompanied by a corresponding decrease in SAE. A localized deviation from this tendency is observed at the base of the upper aerosol layer, where a temporary reduction in R_{eff} coincides with an increase in SAE. Above this point, both quantities resume their typical vertical behaviour. In the upper layer, these two parameters show almost no variability, staying relatively constant. In the lower layer, there is a slight increase with altitude in R_{eff} while SAE slowly grows. In the afternoon case % for the AOD-constrained method.

R_{eff} remains nearly constant (Fig. 16c,d), R_{eff} remains nearly constant throughout most of the lower and middle troposphere. A change appears near the upper part of the highest distinct change occurs near the top of the main aerosol layer, where an increase in R_{eff} is accompanied by a corresponding decrease in SAE. Above this altitude level, both parameters are again nearly constant, but at these altitudes, stabilize, although the aerosol load becomes sparse.

4.1.1 Dust aerosol

On The second case covers measurements made on 29 August 2025, measurements were conducted from 15:00 to 17:00 UTC. The range-corrected lidar signal 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. Consistent with this synoptic setting, the ICAP forecast for 28 August–2 September indicated a dust aerosol influx, with a peak event on 29–30 August (Fig. D1) indicates S6a). Two thermal inversion layers were present on that day: a lower one at 0.7 km and a mid-tropospheric one at 5.5 km (Fig. S7), the latter being characteristic of subtropical air masses and associated with large-scale subsidence (Barreto et al., 2022), thereby limiting vertical mixing and contributing to the stratified structure of the observed aerosol layers.

Lidar observations confirmed the presence of an aerosol layer above from aerosol layers, extended from 1 to 2–1.5 km up to 4–5 km a.g.l. and located below a cloud layer observed between (Fig. S8). Whole sky camera shows that clouds present above these layers dissipated after 15:00 UTC, resulting in cloud-free conditions during the AeroSonde measurements. The dust layers remained relatively stable, with a gradual ascent of the lower layer (1.5–2.5 km) and little variability above 3 and 6 km.

LAGRANTO back-trajectories indicate two distinct air-mass origins. The lowest trajectories (1–2.3 km a.s.l.) originated from the north and transported relatively clean air, whereas higher-altitude trajectories (2.6–5.3 km a.g.s.l. At the time of the measurements, the sky became cloud-free, allowing the observations to be carried out without cloud interference. The analysis

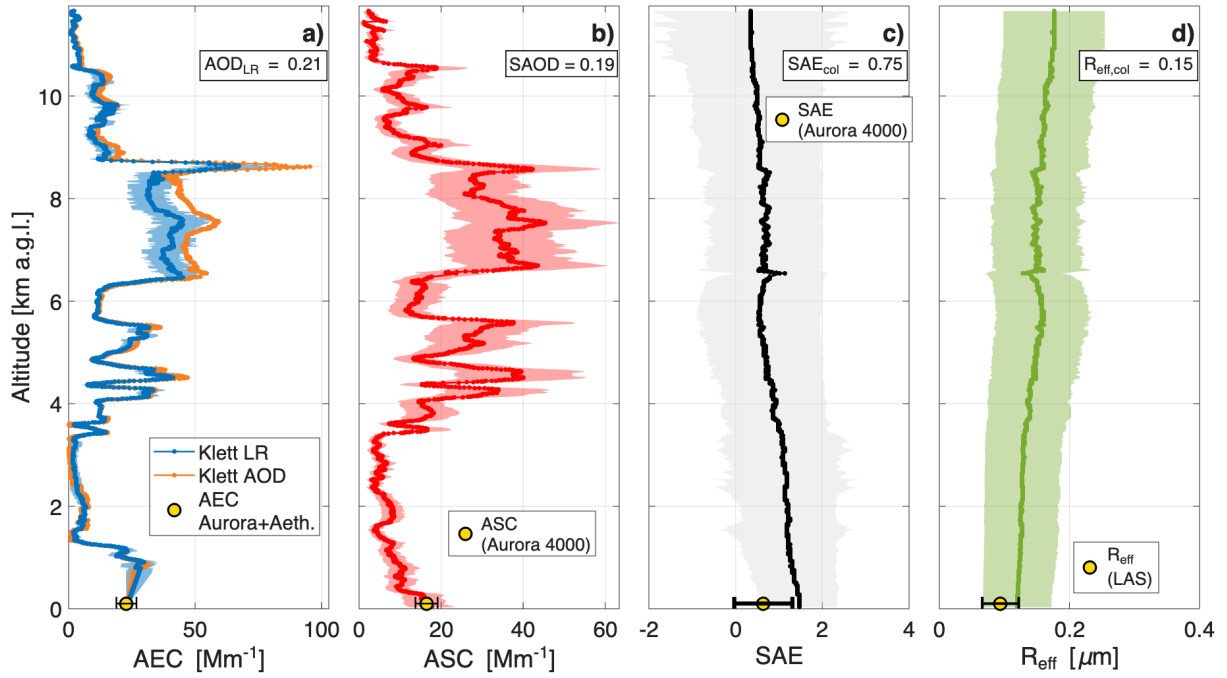


Figure 15. Results of the measurements on 7th August 2025, 07:00–08:15 UTC. Same variables as in Fig. 13. In subfigure (d), the yellow marker denotes the near-surface value of R_{eff} obtained from LAS.

660 of the lidar signal shows the layer was relatively stable with little lower values of signal between 11 and 14) passed over northern Africa, confirming Saharan dust transport (Fig. 17a). Consistently, the ICAP model shows AOD_{dust} values of up to 1.16 over northwestern Africa and 0.17 over Poland (Fig. 17b), with dust contributing 58 % to the total AOD (0.3–0.4) over Poland (Fig. S6b).

At 15:30 UTC. Quick-look of the lidar signal shows that the aerosol layer was relatively stable, with slightly reduced signal intensities observed earlier in the day, between 11:20 UTC on 29 August, AERONET reported AOD_{500} of 0.30 (August mean: 0.19), with low $\text{AE}_{470-870}$ (0.40) and SSA_{440} of 0.93, consistent with coarse-mode dust dominance. It should be noted that the AERONET inversion quality criterion ($\text{AOD}_{440} > 0.4$) was not met, implying increased uncertainty in SSA retrievals; for example, at $\text{AOD}_{440} = 0.2$, SSA uncertainty is approximately 0.07 (Zhang et al., 2025).

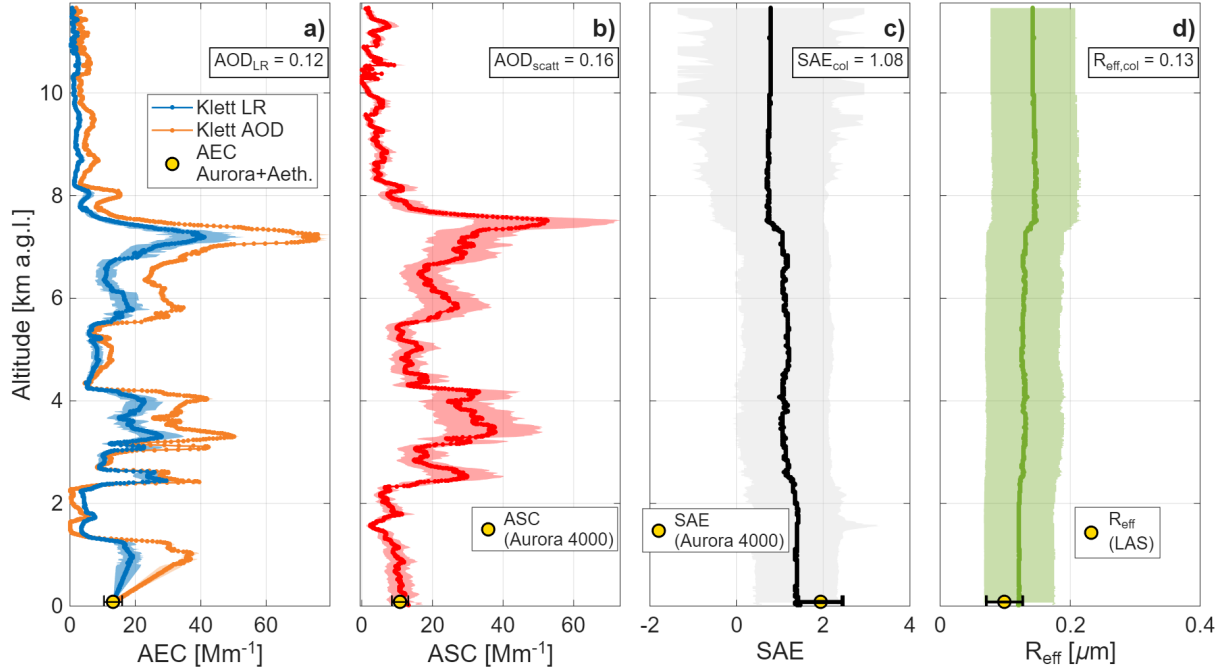


Figure 16. Results of the measurements on 7th August 2025, 15:20-16:30 UTC. **Same variables** Subfigure (a) shows aerosol extinction coefficient at 532 nm (AEC) profiles retrieved from the lidar signal from the Raymetrics LB10-V-D200 lidar system using the Klett LR algorithm, assuming either a constant LR (blue line) or an AOD constraint (red line). The AEC is temporally and vertically collocated with the AeroSonde ascent. The yellow marker outlined in black represents the near-surface AEC derived from in situ measurements as the sum of the aerosol scattering coefficient (ASC) measured by the Aurora 4000 nephelometer and the aerosol absorption coefficient (AAC) measured by the AE31 aethalometer. The box in the upper right corner shows the AOD value calculated as the vertical integral of the AEC profile retrieved with the Klett LR method over the altitude range presented. Subfigure (b) presents the ASC at 525 nm profile obtained from data collected by the SPS30 particulate matter sensor, with the yellow marker indicating the near-surface value measured by the Aurora 4000 nephelometer. The box in the upper right corner shows the scattering aerosol optical depth (SAOD), calculated as the vertical integral of the ASC profile over the altitude range presented. Subfigure (c) shows the scattering Ångström exponent (SAE) profile derived from SPS30 data, with the yellow marker denoting the near-surface value obtained from nephelometer data. The box in the upper right corner presents the columnar SAE (SAE_{col}) derived using Eq. A7. Subfigure (d) depicts the effective radius (R_{eff}) profile derived from SPS30 data. The box in the upper right corner presents the columnar R_{eff} ($R_{eff,col}$). In all subfigures, the yellow marker outlined in black is shown together with its associated measurement uncertainty. In the subfigure (d), the yellow marker denotes the near-surface value of R_{eff} obtained from LAS.

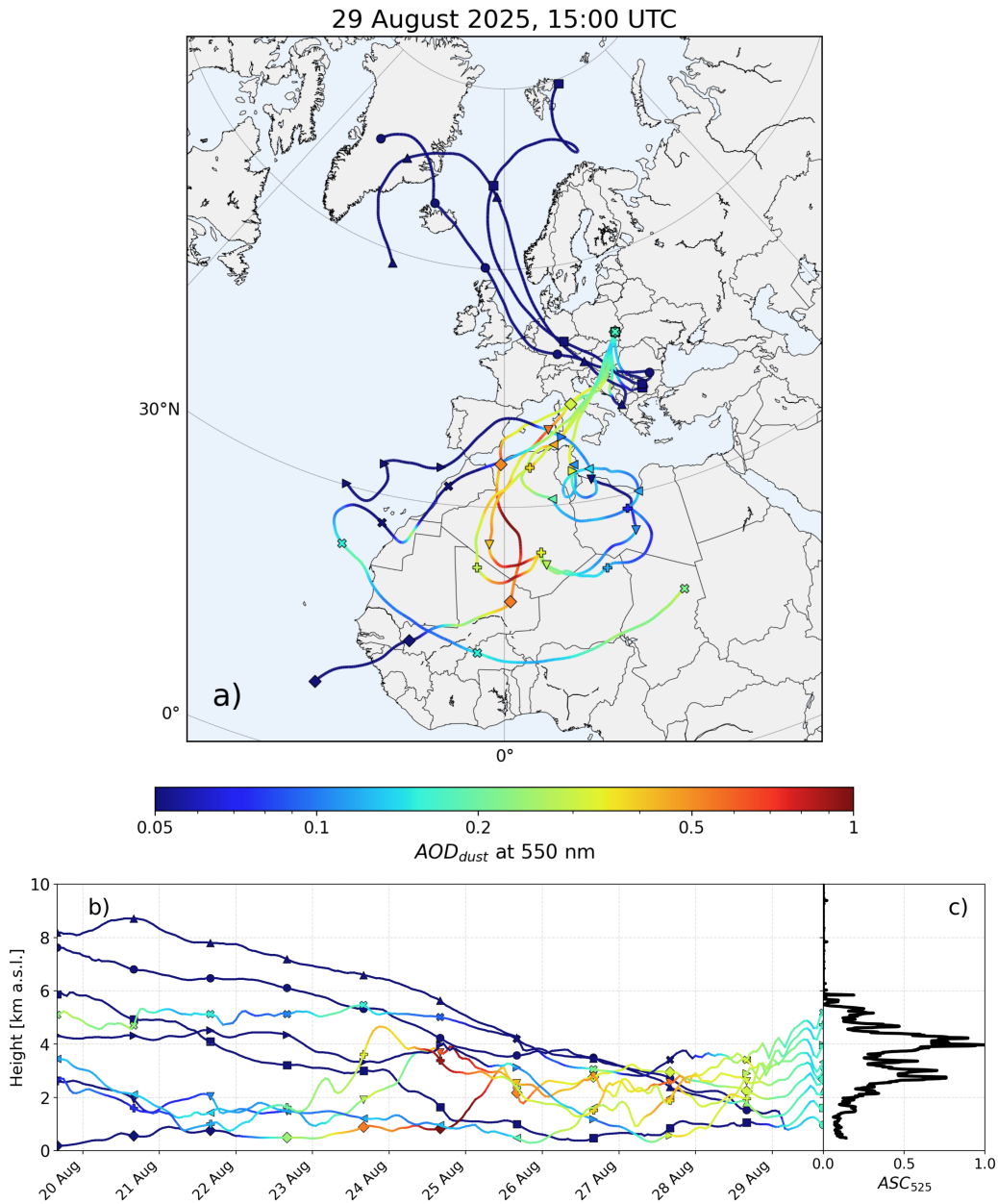


Figure 17. LAGRANTO 10-day backtrajectories starting on 29 August 2025 at 15:00 UTC. Panels (a) and (b) show the geographical distribution and the vertical cross-section of the selected trajectories, respectively. Line colours represent ICAP AOD_{dust} at 550 nm, and, for clarity, each trajectory is marked with distinct symbols. Panel (c) shows the normalised profile of ASC_{525} measured by the AeroSonde.

On 29 August 2025, sounding was conducted from 15:00 to 17:00 UTC. In contrast to the BB case, the identified aerosol layer exhibits a substantial contribution from coarse-mode particles (Fig. 18). This is reflected in the divergence between

PM₁ and PM₁₀ (Fig. 18a), particularly within the main layer between 3 and 4 km, where PM₁₀ significantly exceeds PM₁. This behaviour is further supported by the particle number concentrations (Fig. 18b), which show noticeable contributions from size bin 1–2.5 μm within the same altitude range. Additionally, the coarse-to-fine mass ratio (Fig. 18d) increases markedly within the layer, reaching values above 2–3, while the relative contribution of particles larger than 1 μm (Fig. 18e) rises up to 20 % where the aerosol load peaks.

The TPS profile (Fig. 18c) shows pronounced variability, with values increasing up to 1.0 μm within the main aerosol layer. The vertical structure of TPS generally follows that of the coarse-to-fine ratio and the contribution of particles larger than 1 μm , although it does not reproduce the sharp peaks observed in these profiles. This behaviour may indicate the influence of the retrieval algorithm, which likely smooths the TPS profile. At the same time, TPS responds to the presence of larger particles, increasing within the aerosol layer where the coarse-mode contribution is enhanced, while remaining relatively constant above the layer.

During this day

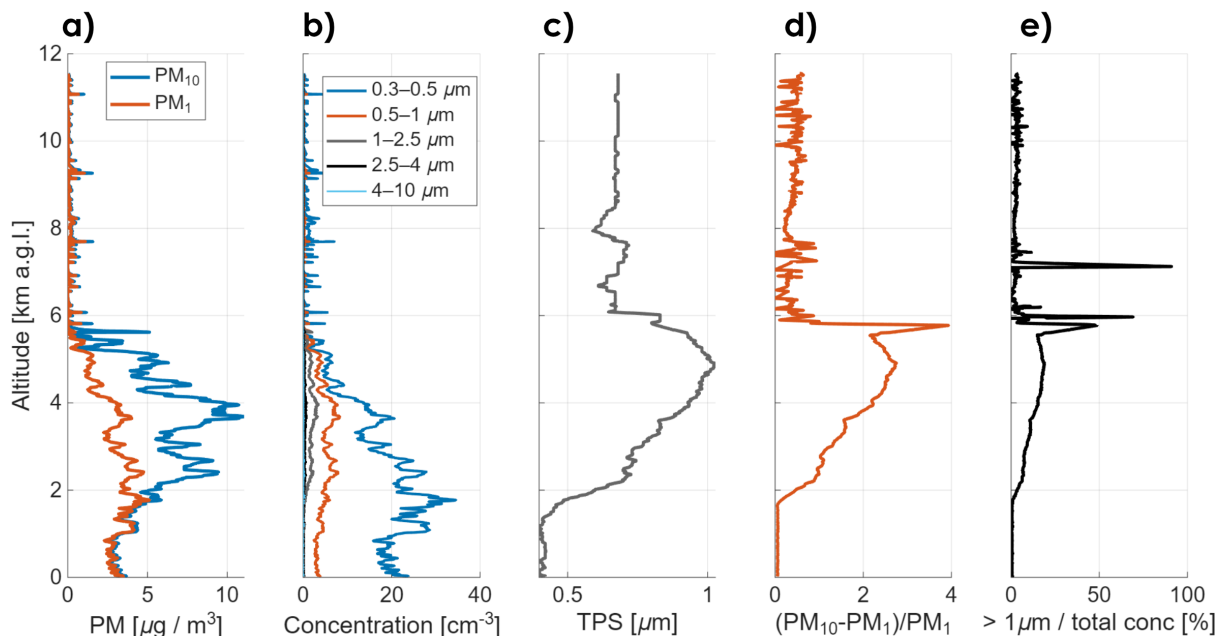


Figure 18. Vertical profiles of raw data obtained by AeroSonde during measurements on 29th August 2025, 15:20-16:30 UTC. Same variables as in Fig. 14

During this sounding, a single aerosol layer was observed in which, with elevated ASC values (above $>15 \text{ Mm}^{-1}$) persisted extending from the surface up to the peak at around a peak at approximately 3.7 km, reaching approximately 40 Mm^{-1} (Fig. 19b). The highest values within this layer (exceeding $>30 \text{ Mm}^{-1}$) were recorded between 2.25 km occurred between 2.3 and 4 km, where the uncertainty of the ASC estimate was approximately with an associated uncertainty of around 43 % of the reported value. Above about %. Above 5.8 km, ASC values became minimal, fluctuating around the background level. The

aerosol load contained within this layer (1.5–5.2 km a.g.l.) accounted for a substantial fraction of the total AOD: 43.1 % as estimated from the AeroSonde ASC profiles, 39.3 % when derived from Klett LR, and 33.1 % when using the Klett AOD approach.

Examination of the thermodynamic conditions during this measurement series decreased to near-background levels. Thermodynamic profiles (Fig. D3) indicate that the aerosol load layer was located above the PBL, with the highest humidity found in the middle of the dust aerosol layer, at approximately maximum humidity in its middle part (3–4 km. The upper boundary of the main aerosol layer). Its upper boundary coincides with a temperature inversion at around 5.5 km; however, aerosol presence, although a small fraction of aerosol extends above this inversion, accounting for approximately level, contributing 7–8 % of % to the total AOD and likely representing background free tropospheric aerosol. Aerosol found between 1.5–5.2 km a.g.l. contributed substantially to the total AOD: 43.1 % from AeroSonde ASC profiles, compared to 39.3 % and 33.1 % from the Klett LR and Klett AOD retrievals, respectively.

The correlation coefficients between the between AEC (Fig. 19a) and ASC (Fig. 19b) profiles were was 0.85 for both Klett retrievals. For both Klett profiles, Both AEC profiles show a distinct layer became apparent from approximately above 1.4 km upward, which was, which is less pronounced in the ASC profile. The Klett LR retrieval again indicated yields slightly higher AEC values, reaching nearly with a peak of 107 Mm^{-1} at the peak around Mm^{-1} at 3.5 km. Another peak, and a secondary maximum of 35 Mm^{-1} near 5 km reached almost 35 Mm^{-1} , and its value was comparable to the value of AEC in the boundary layer. On average, within. Within the 1.5–4 km layer, AEC values from the Klett LR profile were about method exceeds the AOD-constrained retrieval by 5–15 Mm^{-1} higher than those from the Klett AOD retrieval, with the difference at the 5 km peak being approximately Mm^{-1} , with differences of up to 20 Mm^{-1} . For the dust aerosol layer (2.4–4.25 km), the uncertainty of the AEC retrieved with the Klett LR method was approximately Mm^{-1} near 5 km. The uncertainty is around 10 % of the AEC value, whereas the AOD-constrained retrieval yielded an uncertainty of about % for the LR retrieval and 2.5 % % for the AOD-constrained approach.

Examination of the vertical profiles Vertical profiles of microphysical parameters (Fig. 19c,d) shows show that R_{eff} increases with altitude within the main aerosol layer, reaching its a maximum near the height of peak aerosol loading, and then decreases above this level. At higher altitudes, R_{eff} stabilises and exhibits weaker variability, stabilizes. In contrast, SAE remains nearly constant in the lowest part of the profile (within the PBL) and then begins to decrease with altitude above PBL, reaching its minimum at the height and decreases above it, reaching a minimum where R_{eff} attains its maximum. Above this point, SAE increases again, eventually approaching at is highest, before increasing again toward 5 km a.g.l. values close to those near the beginning of the dust aerosol layer km. At higher altitudes, if SAE varies, it follows the structure of the R_{eff} profile SAE variability follows that of R_{eff} , with lower SAE values associated with slightly larger particles. Above 8.5 km a.g.l. km, both parameters become nearly constant.

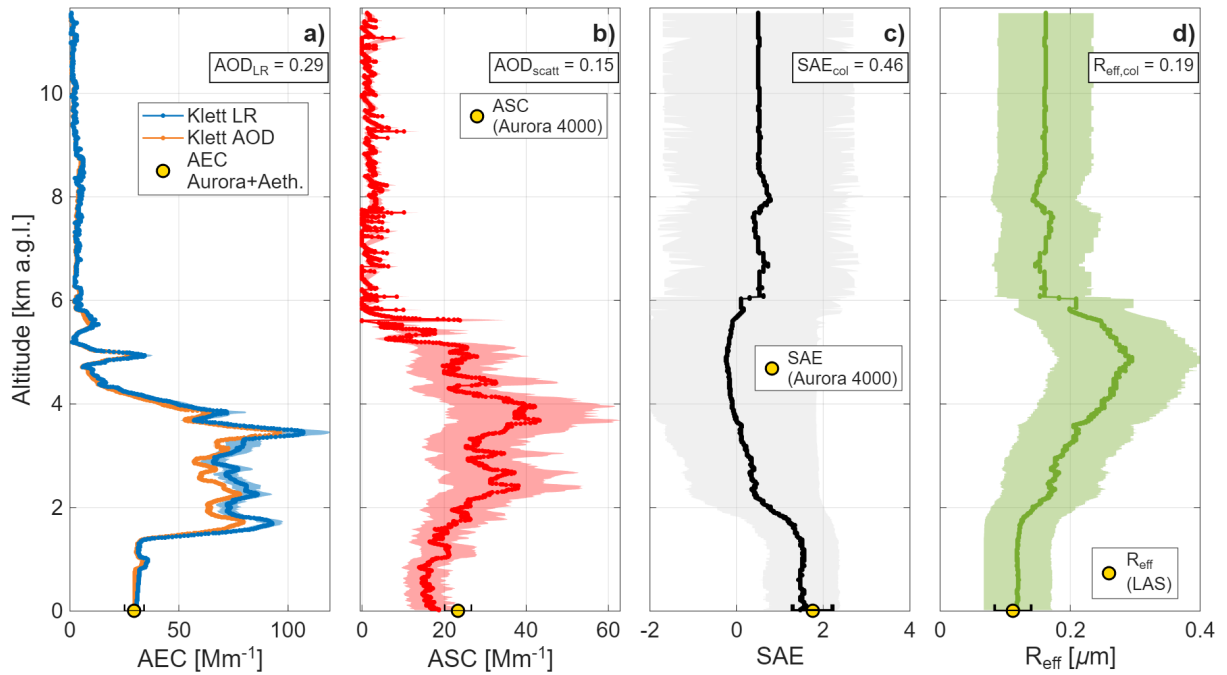


Figure 19. Results of the measurements on 29th August 2025, 15:20-16:30 UTC. Same variables as in Fig.1316. In the subfigure (d), the yellow marker denotes the near-surface value of R_{eff} obtained from LAS.

5 Discussion

720 Comparisons between ASC retrieved from AeroSonde measurements and aerosol extinction coefficients (AEC) derived from
 lidar using the Klett LR method (AEC_{LR} ; Fig. 20a) and the Klett AOD approach (AEC_{AOD} ; Fig. 20b) were performed using
 100 m vertical averages. For AEC_{LR} , ASC exhibits a Pearson correlation of $r = 0.81$ with an RMSE of 18.5 Mm^{-1} , while for
 725 AEC_{AOD} , vertical profiles obtained using the AeroSonde and lidar show a similar aerosol layer structure in both qualitative
 and quantitative terms. Some differences in the values of optical parameters are evident and arise from several factors. First,
 they result from the different physical quantities measured by the two instruments (ASC versus AEC). Second, they are related
 to the measurement limitations of the SPS30 sensor and the correlation is slightly lower ($r = 0.74$) with a higher RMSE of
 25.1 Mm^{-1} . Both lidar retrievals show good agreement with AeroSonde-derived ASC, with the Klett LR method providing the
 closest correspondence. The mean bias is positive in both cases—3.9 Mm^{-1} for AEC_{LR} and 6.4 Mm^{-1} for AEC_{AOD} —which
 is consistent with the expectation that AEC exceeds ASC due to aerosol absorption.
 730 Figs. B4, B5, C3, C4, D3 shows inversion methods applied to lidar data in the elastic 532 nm channel. Third, they stem
 from the fact that the balloon-borne sonde does not follow a purely vertical path, and atmospheric conditions vary along its
 trajectory. Figs. 16 and 19 show that the altitudes of layers with maximum values can differ by up to 100 m between AeroSonde
 and lidar measurements. Averaging over 100 m vertical intervals mitigates discrepancies arising from the differing sampling

strategies of the two systems, with lidar probing a fixed vertical column and the AeroSonde following a slanted ascent profile.

735 The assumption of horizontal homogeneity of the wind field, applied to enable lidar–sonde comparisons (Appendix A2), is a simplification of real atmospheric conditions and may introduce additional pointwise differences between AEC and ASC at individual altitudes. It should be noted that previous studies primarily focused on the validation of lidar-derived aerosol properties (backscattering coefficient) using in situ measurements ((Brunamonti et al., 2021)). Therefore, in the present work, lidar observations cannot be treated as an absolute reference, but rather as an independent dataset for comparison.

740 The vertical profiles of ASC obtained from the AeroSonde enable estimation of SAOD, columnar SAE, and, when combined with AERONET single-scattering albedo (SSA) data, also AOD. Table 6 compares these quantities with measurements from the sun photometer. The AOD comparison shows excellent agreement on 9 June (bias 0.01), moderate discrepancies on 7 August (0.05), and the largest difference on 29 August (0.12). During the Saharan dust intrusion, both AOD and ASC measured by the AeroSonde were significantly underestimated relative to AERONET and lidar-derived AEC.

Table 5. Values of AOD_{532} calculated using Eq. A3, and SSA_{532} obtained by linear interpolation between SSA at 440 nm and 675 nm, based on AERONET data (level 1.5). The scattering Angström exponent $SAE_{440-675}$ is computed from AERONET AOD and SSA using Eq. A11. SAOD denotes the integrated ASC from the AeroSonde measurements, while AOD represents the AOD retrieved from the AeroSonde profile using Eq. A10. Additionally, the column includes the columnar SAE_{col} derived from AeroSonde data using Eq. A7.

Date	AERONET			AeroSonde		
	AOD_{532}	SSA_{532}	$SAE_{440-675}$	SAOD	AOD	SAE_{col}
09 Jun 2025	0.41 (17:33)	0.974 (17:08)	1.27	0.39	0.40	0.39
10 Jun 2025	0.42 (12:18)	N.A.	N.A.	0.21	N.A.	1.17
07 Aug 2025	0.24 (07:06)	0.952 (07:07)	1.86	0.19	0.20	0.75
07 Aug 2025	0.21 (15:25)	0.996 (12:40)	1.54	0.16	0.16	1.08
29 Aug 2025	0.27 (15:30)	0.939 (15:21)	0.26	0.15	0.16	0.48

745 Several factors contribute to these discrepancies. First, mineral dust can substantially increase AEC due to absorption (Müller et al., 2009), 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. Second, the use of only elastic lidar channels limits retrieval accuracy; Raman channels would provide more precise characterization (Ansmann et al., 1992), but were not available during these measurements. Third, particle nonsphericity and differing measurement geometries affect the comparisons: the SPS30 measures at a scattering angle of approximately 90°, whereas the lidar detects backscatter at 180°. For mineral dust, the scattering phase function reaches a minimum near 90°, causing the SPS30 to potentially underestimate ASC (Podgorny et al., 2000). It should also be noted that no depolarization measurements were available, as the lidar system operated at a single wavelength without polarization capability.

750

755 [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.](#)

Previous studies indicate that the SPS30 performance decreases in the presence of coarse, dust-like aerosols, particularly for PM₁₀ ([Kuula et al., 2020; Nevrlý et al., 2024](#)) ([Nevrlý et al., 2024; Kuula et al., 2020](#)). Field observations during Saharan dust events show that PM₁₀ is often underestimated relative to reference instruments, reflecting the sensor's design, which is better suited for fine-mode aerosols ([Nevrlý et al., 2024](#)). Laboratory and intercomparison studies further demonstrate limited size selectivity in low-cost optical sensors, including the SPS30, with coarse particles ($> 5 \mu\text{m}$) prone to misclassification or undercounting due to restricted bin resolution and reliance on optical scattering principles ([Kuula et al., 2020](#)). Moreover, laboratory experiments with monodisperse aerosols reveal that the SPS30 response depends on particle size and material properties, with increasing deviations for larger particles ([Nothhelfer et al., 2025](#)). Consistent with these findings, sensor performance varies with aerosol type, and correlations with reference instruments are generally stronger for PM_{2.5} than PM₁₀, particularly under coarse-particle-dominated conditions ([Tryner et al., 2020; Kuula et al., 2020; AQMD, 2021](#)) ([AQMD, 2021; Kuula et al., 2020](#)), ([Tryner et al., 2020](#)).

These results highlight the need for aerosol-type-dependent calibration and careful interpretation of SPS30-derived PM₁₀ data, particularly when relying on factory calibration in dust-influenced environments ([Tryner et al., 2020; AQMD, 2021](#)), ([Nothhelfer et al., 2025](#)) ([Nothhelfer et al., 2025; AQMD, 2021; Tryner et al., 2020](#)). To address this limitation, the SPS30 should be calibrated against the Aurora 4000 under a range of aerosol conditions, capturing the variability in the conversion between particle mass (as reported by the SPS30) and optical properties arising from differences in chemical composition and particle size. Accordingly, Eq. 1 should be revised to explicitly account for the relationship between reported mass concentration and ASC.

775 Differences in measurement geometry may also contribute to discrepancies between AeroSonde, lidar, and sun photometer columnar properties. During the Saharan dust event, the balloon-borne sonde travelled northeast, the lidar performed vertical profiling, and the sun photometer measured AOD along a westward slanted column. Given the strong spatial and temporal variability during this event, these differing measurement geometries could have introduced substantial variability in the retrieved optical quantities ([Ryan et al., 2025](#)).

780 The uncertainty of AeroSonde-derived ASC ranges from 35–43 %, while lidar AEC uncertainties vary between 10–35 % (Klett LR) and 2–19 % (Klett AOD). Derived quantities such as SAE and R_{eff} exhibit larger uncertainties, particularly for clean layers with low ASC; these uncertainties amount to approximately ± 1.0 for SAE and range from $\pm 0.05 \mu\text{m}$ to $\pm 0.1 \mu\text{m}$ for R_{eff} . Columnar quantities (SAOD, SAE_{col} , $R_{\text{eff,col}}$) were evaluated assuming full correlation of uncertainties with altitude, yielding upper-limit uncertainties of 33–43 % for SAOD and ± 1.0 for SAE_{col} and $\pm 0.07 \mu\text{m}$ for $R_{\text{eff,col}}$. Comparisons with AERONET indicate that SAE retrievals from AeroSonde are less robust and should be interpreted cautiously.

A rigorous quantification of uncertainties in the column-integrated parameters (SAOD and SAE_{col}) remains challenging, as the vertical correlation of uncertainties in ASC and SAE is unknown. The maximum uncertainty in SAOD is estimated by assuming full correlation (correlation coefficient equal to 1) between ASC uncertainties at all altitude levels. Similarly, the upper-limit uncertainty of SAE_{col} is calculated under the assumption of full correlation between ASC and SAE uncertainties

Table 6. Values of AOD_{532} calculated using Eq. A3, and SSA_{532} obtained by linear interpolation between SSA at 440 nm and 675 nm, based on AERONET data (level 1.5). The scattering Angström exponent $SAE_{440-675}$ is computed from AERONET AOD and SSA using Eq. A11. SAOD denotes the integrated ASC from the AeroSonde measurements, while AOD represents the AOD retrieved from the AeroSonde profile using Eq. A10. Additionally, the column includes the columnar SAE_{col} derived from AeroSonde data using Eq. A7.

Date	AERONET			AeroSonde		
	AOD_{532}	SSA_{532}	$SAE_{440-675}$	SAOD	AOD	SAE_{col}
09 Jun 2025	0.41 (17:33)	0.974 (17:08)	1.27	0.39	0.40	0.39
10 Jun 2025	0.42 (12:18)	N.A.	N.A.	0.21	N.A.	1.17
07 Aug 2025	0.24 (07:06)	0.952 (07:07)	1.86	0.19	0.20	0.75
07 Aug 2025	0.21 (15:25)	0.996 (12:40)	1.54	0.16	0.16	1.08
29 Aug 2025	0.27 (15:30)	0.939 (15:21)	0.26	0.14	0.15	0.48

790 at each altitude. These estimates~~therefore~~, therefore, represent conservative upper bounds rather than precise uncertainty quantification, since a realistic characterization of vertical error correlations is not feasible in the present study. Under these assumptions, the upper limit of SAOD uncertainty ranges from 33 % to 43 %.

In contrast, uncertainties in SAE_{col} and $R_{eff,col}$ are substantially larger, exceeding ± 1.0 for SAE_{col} and $\pm 0.06\text{--}0.07\text{ }\mu\text{m}$ for $R_{eff,col}$. For AERONET $AE_{440-870}$, reported uncertainties are on the order of ± 0.3 at $AOD_{440} \sim 0.15$, increasing to ± 0.6 795 when AOD_{440} drops to ~ 0.08 , showing an approximate inverse dependence on AOD (Zhang et al., 2025). This comparison further indicates that SAE retrievals from AeroSonde data are less robust and should be interpreted with caution, particularly when used for aerosol-type classification.

AeroSonde measurements also enable estimation of the contribution of the planetary boundary layer (PBL) to total AOD. During the analysed long-range transport events, the ~~PBL-contribution~~contribution from aerosol found within PBL ranged from 800 approximately 1 % to 36 %, which is comparable to lidar-based estimates that varied between 1 % and 30 % for the Klett AOD retrieval and between 1 % and 39 % for the Klett LR method (Table 7). These findings are broadly consistent with CALIOP aerosol extinction data, indicating that roughly 69 % of tropospheric AOD originates within the boundary layer and 31 % in the free troposphere, with a similar day–night vertical distribution due to the persistence of a residual layer at night (Bourgeois et al., 2018). The free-tropospheric contribution is particularly significant in the tropics, where convective transport largely 805 controls aerosol vertical profiles. Regional lidar studies in Warsaw show that aerosols within the PBL contribute approximately 61 % of total AOD (Wang et al., 2019a). Unlike lidar measurements, the AeroSonde approach is not affected by limitations associated with PBL heights below the lidar overlap layer, enabling more reliable characterization of boundary-layer aerosol contributions.

Compared to UAV-based measurement platforms, the balloon-borne AeroSonde offers several distinct advantages that en- 810 hance its suitability for atmospheric aerosol studies. Its passive ascent, without active air intake, prevents flow-induced artefacts and avoids particle size–selective sampling that can result from propeller-induced turbulence in drones, enabling a more rep-

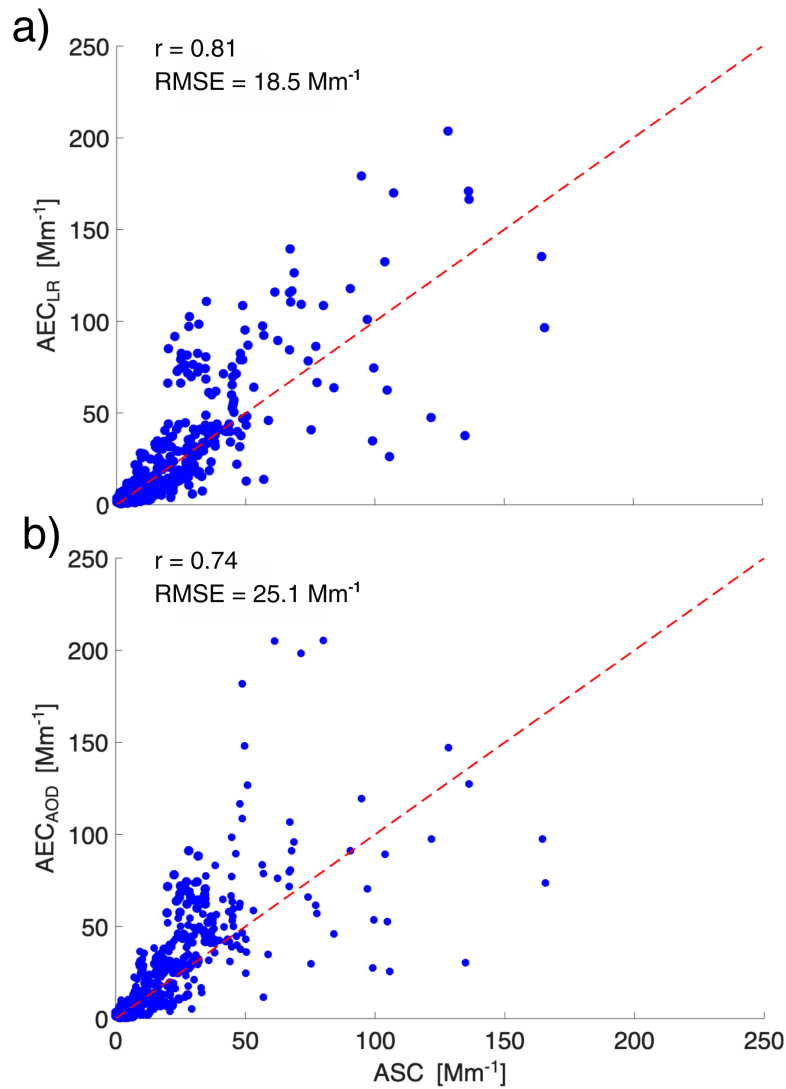


Figure 20. Scatter plots of aerosol optical coefficients averaged within 100 m vertical intervals. The x-axis shows the ASC at 525 nm retrieved from AeroSonde measurements, while the y-axis presents the AEC at 532 nm derived from lidar observations. Panel (a) displays AEC retrieved using the Klett LR approach (AEC_{LR}), and panel (b) shows AEC from Klett AOD (AEC_{AOD}). For each panel, the Pearson correlation coefficient (r) and the root mean square error (RMSE) are reported.

representative characterization of the ambient aerosol population. Additionally, the AeroSonde can reach altitudes extending into the stratosphere, making it particularly valuable for monitoring phenomena such as volcanic eruption plumes, whereas UAV platforms are generally restricted to the lower troposphere. A notable limitation of the AeroSonde, however, is its typical non-recoverability after launch. In contrast, UAV systems allow sensors to be reused, facilitating repeated flights at lower op-

Table 7. The planetary boundary layer (PBL) height and the corresponding contribution of AOD within the PBL to the total AOD. Values are derived from AeroSonde vertical profiles and lidar retrievals (Klett LR and Klett AOD methods).

Date	Hour	PBL height [km]	Contribution of AOD in PBL to total AOD [%]		
			AeroSonde	Klett AOD	Klett LR
9 Jun	21:00 UTC	0.12	0.7	1.3	1.1
10 Jun	16:15 UTC	1.60	35.8	33.0	39.2
7 Aug	7:00 UTC	0.25	2.1	2.4	2.8
7 Aug	15:20 UTC	1.20	7.6	16.1	16.8
29 Aug	15:20 UTC	0.71	8.1	8.2	7.7

erational cost. To ensure accurate measurements, each SPS30 sensor deployed on the AeroSonde must therefore be calibrated through colocated measurements with the Aurora 4000 across a wide range of aerosol conditions, capturing the full variability of both ASC and SAE.

Finally, the AeroSonde provides a valuable tool for validating vertical aerosol profiles from reanalysis and model products (e.g., CAMS, MERRA-2, NAAPS). Direct measurements of light scattering in the lower troposphere enable independent assessment of modelled aerosol profiles. Future work combining AeroSonde with Raman lidar will allow retrieval of AEC without assuming a fixed LR or relying solely on AOD, improving the quantitative accuracy of vertical aerosol characterization and enhancing closure studies.

6 Conclusions

This study presents and demonstrates a new balloon-borne measurement system (AeroSonde) designed to provide reliable, high-resolution, vertically resolved measurements-observations of aerosol optical properties, delivering profiles from the surface up to the upper troposphere or-even-the-lower-/middle-stratosphereand, in some cases, the lower stratosphere, with a vertical resolution of a few meters. The performance of the AeroSonde was evaluated across several-a limited number of case studies, confirming-that-these-measurements-enable-independent-estimates-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 provide-a-valuable tool-for-validating-show potential for supporting the evaluation of reanalysis products and satellite-based aerosol retrievals. The results show-indicate generally good agreement with lidar and AERONET observationsand-highlight-the-potential-of-, within the expected uncertainty range, and demonstrate that the SPS30 low-cost sensor to-capture-key-is capable of capturing the main features of aerosol vertical structure,-including-. In particular, the system allows the identification of boundary-layer contributions and elevated layers associated with long-range transportevents. However, parameters such as SAE and Reff should be interpreted with caution and are better suited for qualitative characterization. The most important findings are:

- 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.

- 840
- AOD derived from AeroSonde agrees with AERONET values, with biases ~~ranging from of 0.01 to 0.12 depending on the case study and aerosol type~~ –0.05 for BB and 0.11 for the dust case, which is consistent with the higher uncertainty associated with coarse-mode aerosol and its vertical variability.
 - Error analysis indicates that the AeroSonde is suitable for ~~qualitative estimation of ASC and for~~ quantitative estimation of ASC, while SAE and R_{eff} provide only a rough, qualitative characterization, particularly in terms of capturing vertical
- 845
- During long-range transport events, the contribution of AOD within the PBL does not exceed 33–39 %, and values derived independently from the AeroSonde and lidar remain mutually consistent, indicating that both measurement approaches capture a comparable vertical distribution of AOD.

Despite its limitations, the AeroSonde system demonstrates clear potential as a complementary tool to ground-based remote

850 sensing and traditional radiosonde observations. 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 ~~conditions, improved calibration strategies for coarse-mode particles, and integration with Raman lidar, which would allow~~ regimes would help to assess the robustness of the proposed approach. The

855 additional integration of the AeroSonde system with a Raman lidar would provide complementary information by enabling the retrieval of aerosol extinction profiles ~~to be retrieved~~ without assuming LR or AOD, ~~thereby enhancing closure studies~~ which are typically required when using conventional lidar alone. Raman lidar, in particular, enables the determination of AE, which can be compared with the data obtained from the AeroSonde, offering deeper insight into the particle size distribution. Moreover, combining Raman lidar’s AEC with the AeroSonde’s ASC would allow estimation of the single scattering albedo.

860 This combination would not only improve the accuracy of vertical aerosol profiles but also provide more reliable data for closure studies, as the dependence on assumptions such as LR and AOD would be minimized. These developments would further improve the quantitative capabilities of the AeroSonde system and broaden its applicability in atmospheric aerosol research.

Data availability. All data are available from the corresponding author upon request.

A1 Lidar data processing

The recursive relationship used in the Klett algorithm is given by

$$\beta_A(z-1) = \frac{S(z-1)\psi(z-1, z)}{\frac{S(z)}{\beta_R(z)+\beta_A(z)} + \frac{\Delta z}{R_A} [S(z) + S(z-1)\psi(z-1, z)]} - \beta_R(z-1), \quad (\text{A1})$$

where β_A and β_R are the aerosol and molecular backscatter coefficients, $S(z)$ is the range-corrected signal, Δz is the vertical
870 resolution, R_A is the inverse of the LR for aerosol scattering, and ψ is defined as

$$\psi(z-1, z) = \exp \left\{ \left(\frac{1}{R_A} - \frac{1}{R_R} \right) [\beta_R(z) + \beta_R(z-1)] \Delta z \right\}. \quad (\text{A2})$$

R_R is the inverse of the LR for molecular scattering.

The AOD₅₃₂ was derived from the 500 nm AOD (AOD₅₀₀) and the Ångström exponent (AE_{440–870}) calculated between
440 and 870 nm, according to

$$875 \quad \text{AOD}_{532} = \text{AOD}_{500} \left(\frac{532}{500} \right)^{-\text{AE}_{440-870}}. \quad (\text{A3})$$

A2 Meteorological data usage

~~Since the Klett inversion relies on the molecular optical properties of the atmosphere, which are calculated from meteorological
profiles, measurements of temperature and pressure obtained by the attached Vaisala radiosonde were used as primary input
data.~~

880 ~~An exception occurred on 9 June, when the AeroSonde only reached an altitude of approximately 10 km and did not cover
the full height range required for an accurate determination of the molecular scattering profile in the aerosol-free layer. In this
specific case, a radiosonde profile launched from Tarnów at 00:00 UTC on 10 June was used instead.~~

A2 Spatio-temporal adjustment of lidar profiles to AeroSonde observations

The procedure was as follows: for each AeroSonde measurement at altitude z , the horizontal distance d between the AeroSonde
885 position (θ_2, ϕ_2) and the lidar site (θ_1, ϕ_1) was computed using the haversine formula:

$$d = 2R \arcsin \left(\sqrt{\sin^2 \left(\frac{\Delta \theta}{2} \right) + \cos \theta_1 \cos \theta_2 \sin^2 \left(\frac{\Delta \phi}{2} \right)} \right), \quad (\text{A4})$$

where R is the Earth's radius, $\Delta \theta = \theta_2 - \theta_1$, and $\Delta \phi = \phi_2 - \phi_1$ (latitudes and longitudes expressed in radians).

Using this distance, the temporal offset Δt was calculated as

$$\Delta t = \frac{d}{u(z)}, \quad (\text{A5})$$

890 where $u(z)$ denotes the horizontal wind speed at altitude z . The time when the air parcel sampled by the AeroSonde was located above the lidar was then obtained as

$$t' = t - \Delta t, \quad (\text{A6})$$

where t is the AeroSonde timestamp.

For each altitude level z , the extinction coefficient $\alpha_{\text{ext}}(z, t')$ was extracted from the lidar profile corresponding to time t' .
895 In this way, a spatio-temporally matched extinction profile was reconstructed from the surface up to approximately 12 km.

The final profile was smoothed with a moving average using a five-point window. Given the typical AeroSonde vertical resolution of 5–9 m, this corresponds to an effective vertical averaging of approximately 25–45 m.

A3 AeroSonde data processing

Along with the retrieved aerosol extinction coefficient ~~profiles~~ (AEC) profiles, aerosol scattering coefficient profiles (ASC),
900 the scattering Ångström exponent (SAE), and the effective radius (R_{eff}) were also derived, following the procedure described in Sect. 3. The correlation coefficient (r) was calculated between the ASC profiles derived from the AeroSonde and the AEC profiles retrieved from the lidar. Moreover, the columnar scattering Ångström exponent (SAE_{col}) was calculated as

$$\text{SAE}_{\text{col}} = \frac{\sum_z \text{SAE}(z) \text{ASC}(z)}{\sum_z \text{ASC}(z)}, \quad (\text{A7})$$

and columnar effective radius ($R_{\text{eff,col}}$) as

$$905 \quad R_{\text{eff,col}} = \frac{\sum_z R_{\text{eff}}(z) \text{ASC}(z)}{\sum_z \text{ASC}(z)}. \quad (\text{A8})$$

Using the ASC profile, the scattering aerosol optical depth (SAOD) was calculated as follows:

$$\text{SAOD} = \sum_z \text{ASC}(z) \Delta z. \quad (\text{A9})$$

Using the calculated SAOD and the single scattering albedo (SSA) derived from AERONET, one can estimate AOD as:

$$\text{AOD} = \frac{\text{SAOD}}{\text{SSA}}. \quad (\text{A10})$$

910 Since AERONET does not provide SSA at 532 nm, the value was obtained by linear interpolation between SSA reported at 440 and 675 nm. The SAE from AERONET was calculated as:

$$\text{SAE} = - \frac{\ln \left(\frac{\text{AOD}_{440} \cdot \text{SSA}_{440}}{\text{AOD}_{675} \cdot \text{SSA}_{675}} \right)}{\ln \left(\frac{440}{675} \right)}, \quad (\text{A11})$$

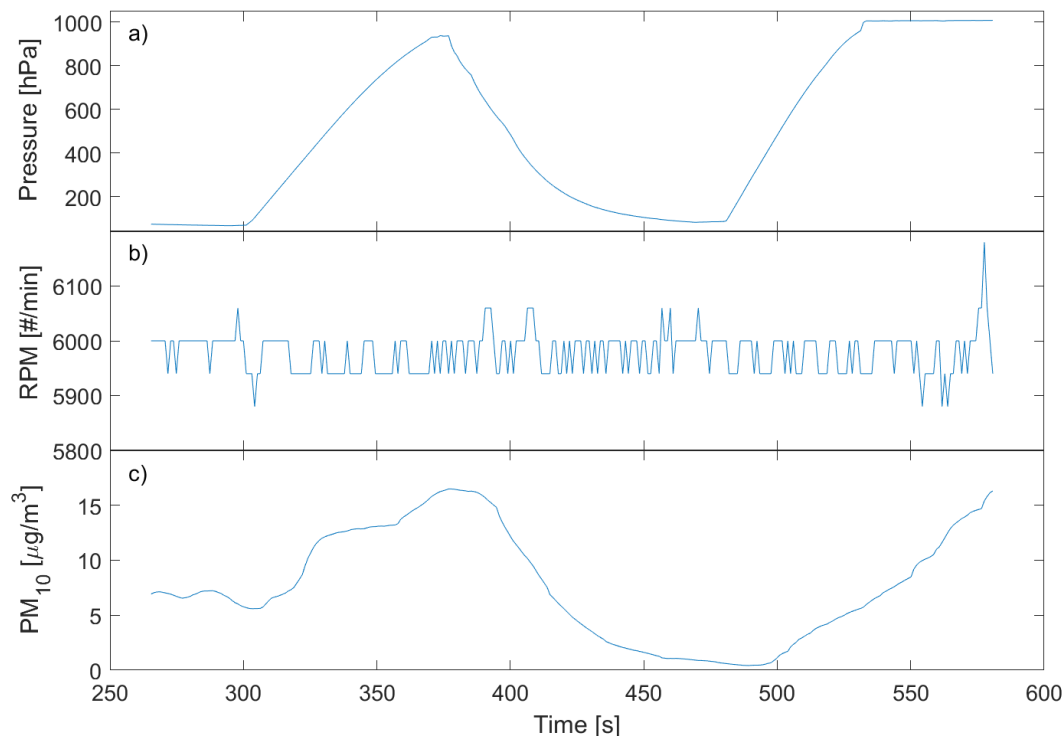


Figure A1. Temporal variability of (a) air pressure [hPa], (b) fan rotational speed (RPM) in SPS30, and (c) PM_{10} mass concentration during measurements in the vacuum chamber.

where AOD_{440} and AOD_{675} are AOD at 440 and 675 nm, respectively, and SSA_{440} and SSA_{675} are SSA at 440 and 675 nm, respectively.

915 The resulting values of AOD, SAE_{col} and $R_{eff,col}$ were compared with those obtained from AERONET.

Appendix B: Biomass burning aerosol (case 1)

9-June-2025

920 During measurements, the meteorological balloon began leaking at an altitude of around 10 km and started descending for unknown reasons. Later ascents confirmed that the balloon could reach higher altitudes. The mean vertical resolution of the AeroSonde data was 8.8 ± 3.7 m. During the ascent, the horizontal displacement was initially minimal: at 2 km a.g.l., the AeroSonde had drifted about 4 km from the station. However, it increased substantially with height, reaching about 10 km at 4 km altitude, 35 km at 7 km, and approximately 65 km at 10 km. Wind conditions drove this pattern: near the surface, wind speeds ranged from 4 to 6 $m s^{-1}$, blowing from the west ($260-275^\circ$). Above the surface, the wind shifted to northwesterly

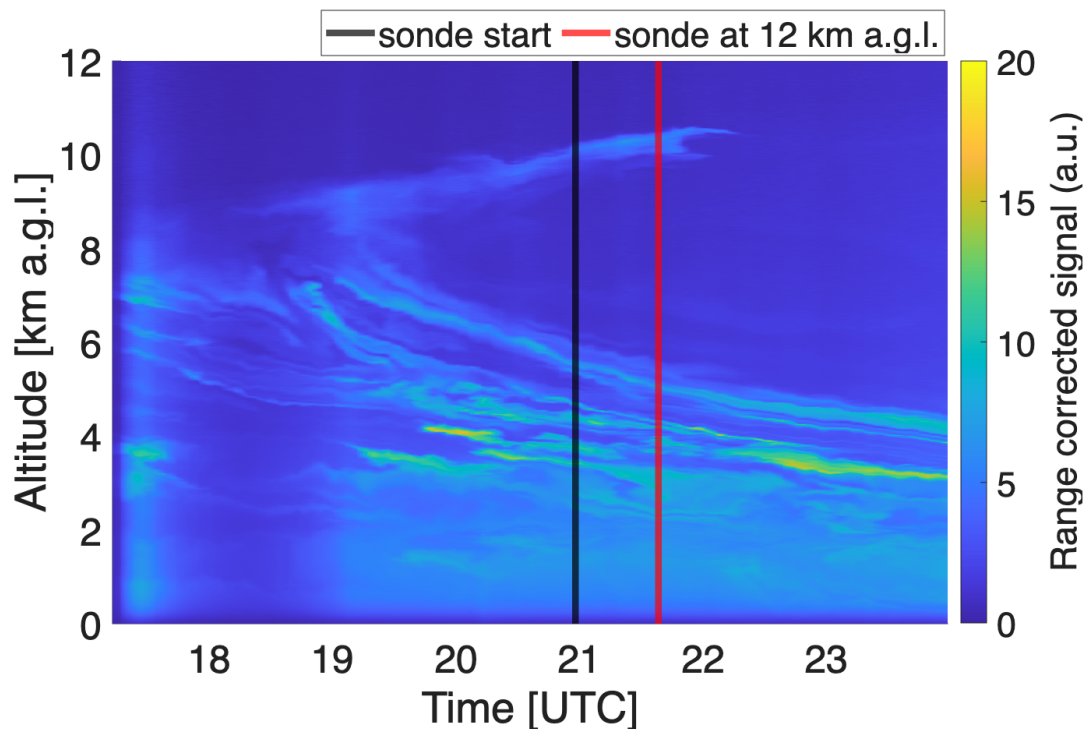


Figure B1. Lidar range corrected signal at 532 nm for 9 June 2025. The black line indicates the AeroSonde flight start, while the red line points to the time of reaching the 12 km a.g.l.

directions, with speeds increasing from approximately 5 m s^{-1} at $\sim 650 \text{ m a.g.l.}$ to about 35 m s^{-1} at 10 km.

925

10 June 2025

During these measurements, the maximum altitude from which the signal was received reached approximately 21 km after 1.5 hours of ascent (see Table 3). The mean vertical resolution of the AeroSonde data was $6.8 \pm 2.1 \text{ m}$. Similar to the previous day, at 2 km a.g.l. the AeroSonde was located about 4 km from the station, increasing to 11.5 km at 4 km, 30 km at 7 km, and 50 km at 10 km altitude. The wind profiles explain this behaviour (Fig. 8b): near-surface wind speeds were $5\text{--}7 \text{ m s}^{-1}$, blowing from the south ($160\text{--}170^\circ$), and this direction persisted up to roughly 600 m a.g.l. Above this height, the wind shifted to westerly directions, with a slight oscillation towards the south and north, and increased in magnitude to approximately 27.5 m s^{-1} at 10 km a.g.l.

930

Appendix C: Biomass burning aerosol (case 2)

During the AeroSonde launches at 07:00 UTC and 15:00 UTC, the maximum altitudes from which the signal was received were 25.3 km and 19.3 km, respectively (see Table 3). The mean vertical resolution of the AeroSonde data was $5.4 \pm 2.6 \text{ m}$

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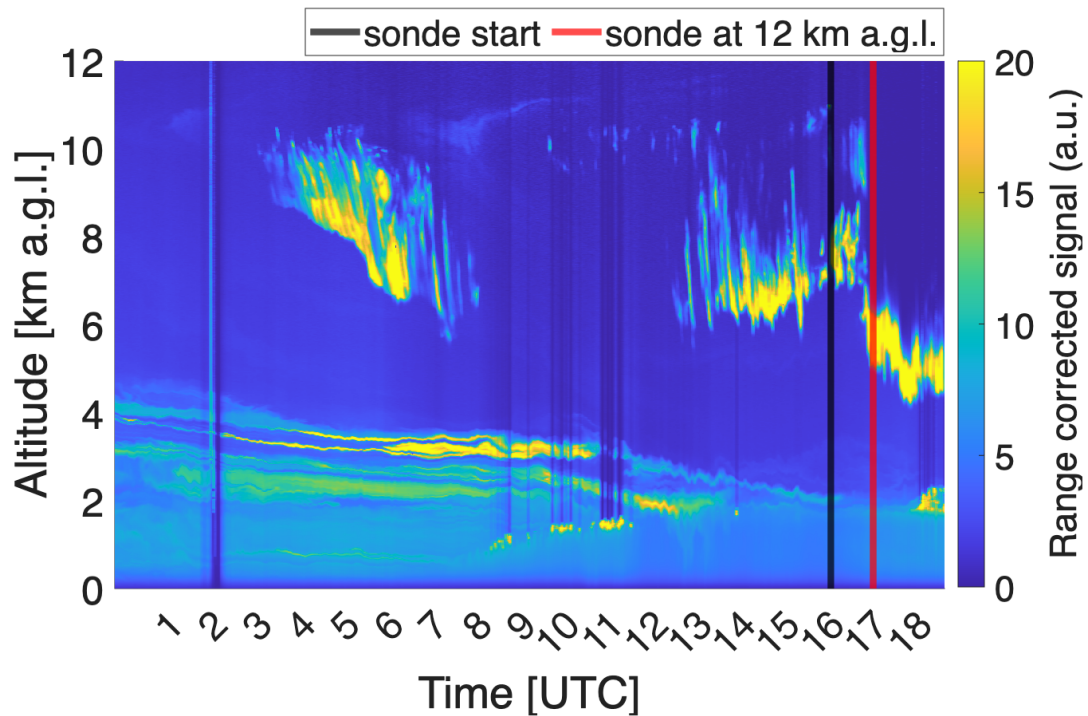


Figure B2. Lidar range corrected signal at 532 nm for 10 June 2025. The black line indicates the AeroSonde flight start, while the red line points to the time of reaching the 12 km a.g.l.

and 5.4 ± 2.4 m for the morning and afternoon ascents, respectively. During both ascents, the wind was weak. In the morning, the AeroSonde was less than 0.5 km from the station at 2 km a.g.l., about 7 km at 5 km, 18 km at 7 km, and approximately 35 km at 10 km. In the afternoon, it was within 1 km at 2 km, about 10 km at 5 km, and around 35 km at 10 km altitude. The wind profile measured by the meteorological sonde explains this horizontal displacement. During the morning ascent, wind speeds remained below 5 m s^{-1} up to 4 km a.g.l. and increased only above this level, reaching less than 20 m s^{-1} at 10 km. Throughout the morning, the wind was predominantly westerly. In the afternoon, a similar vertical structure of wind speed was observed, with speeds of approximately 7.5 m s^{-1} at 4 km and again remaining below 20 m s^{-1} at 10 km. Near the surface, the wind was from the southeast; however, already at around 1.5 km a.g.l. the flow shifted to a westerly direction, and above 7 km a southwesterly flow prevailed.

Appendix D: Dust aerosol

During these measurements, the maximum altitude from which data were received reached 26.8 km after 2.5 hours of ascent (see Table 3). The mean vertical resolution of the AeroSonde data was 5.3 ± 2.1 m. At 2 km a.g.l., the AeroSonde was already located about 10 km from the station, at 5 km the distance increased to 28 km, and at 10 km it reached approximately 65 km

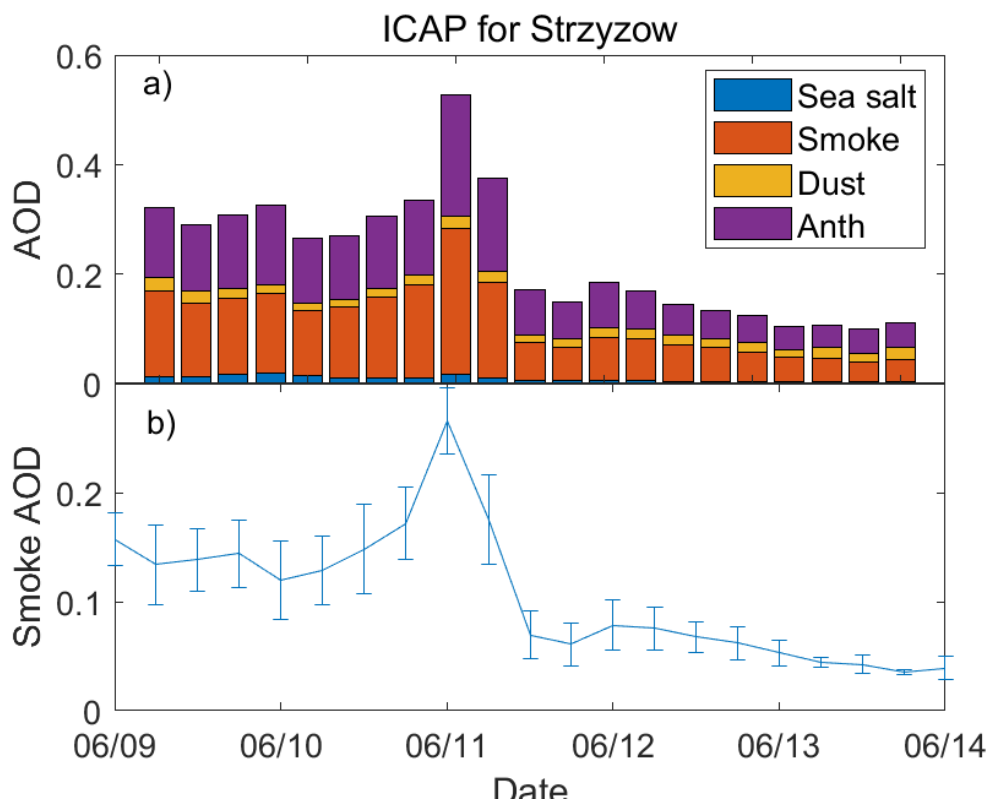


Figure B3. Total AOD with four categories distinguished (sea salt, smoke, dust, and anthropogenic) (a), and smoke AOD (b) at the Strzyżów site in the 9–14 June 2025 period. Values were retrieved from the ICAP model and are given at 550 nm.

950 from the station. Wind near ground level (500 m a.g.l.) was blowing from north with a speed of around 2.5 m s^{-1} . But at 1.5 km a.g.l. it started blowing from the southwest with a velocity minimum of 15 m s^{-1} , which persisted up to 12 km, where it reached 25 m s^{-1} .

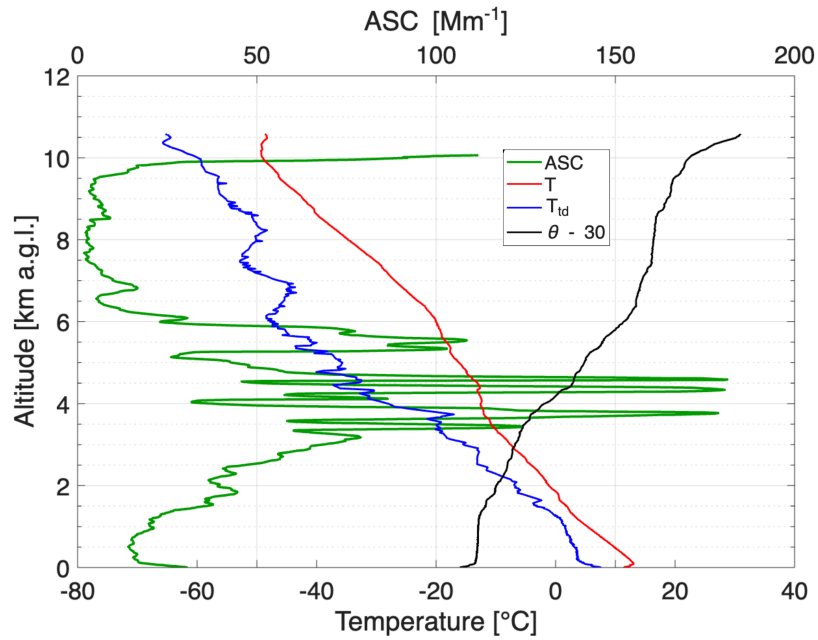


Figure B4. Vertical profiles of thermodynamic variables and aerosol scattering coefficient (ASC) obtained from the AeroSonde sounding on 10 June. The vertical axis represents height (km a.g.l.). Temperature is shown on the lower horizontal axis, while the ASC is shown on the upper horizontal axis (Mm^{-1}). The red line denotes the air temperature profile (T), the blue line represents the dew-point temperature (T_{id}), and the black line shows the potential temperature (θ), shifted by $-30\text{ }^{\circ}\text{C}$ for clarity. The green line corresponds to the vertical profile of the ASC.

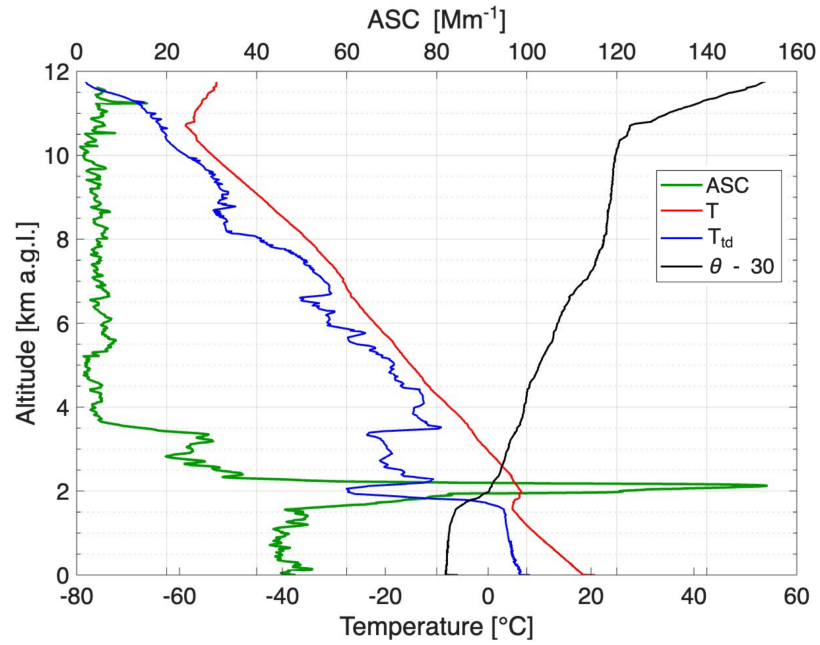


Figure B5. Vertical profiles of thermodynamic variables and aerosol scattering coefficient (ASC) obtained from the AeroSonde sounding on 10 June. The notation follows Fig. B4.

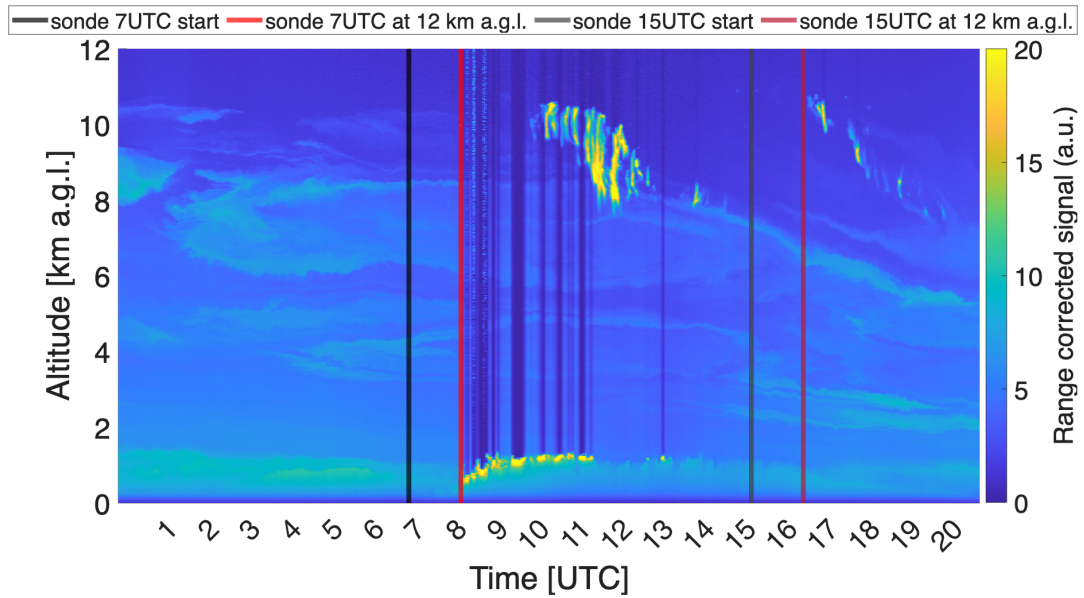


Figure C1. Lidar range corrected signal at 532 nm for 7 August 2025. The black line indicates the AeroSonde flight start, while the red line points to the time of reaching the 12 km a.g.l.

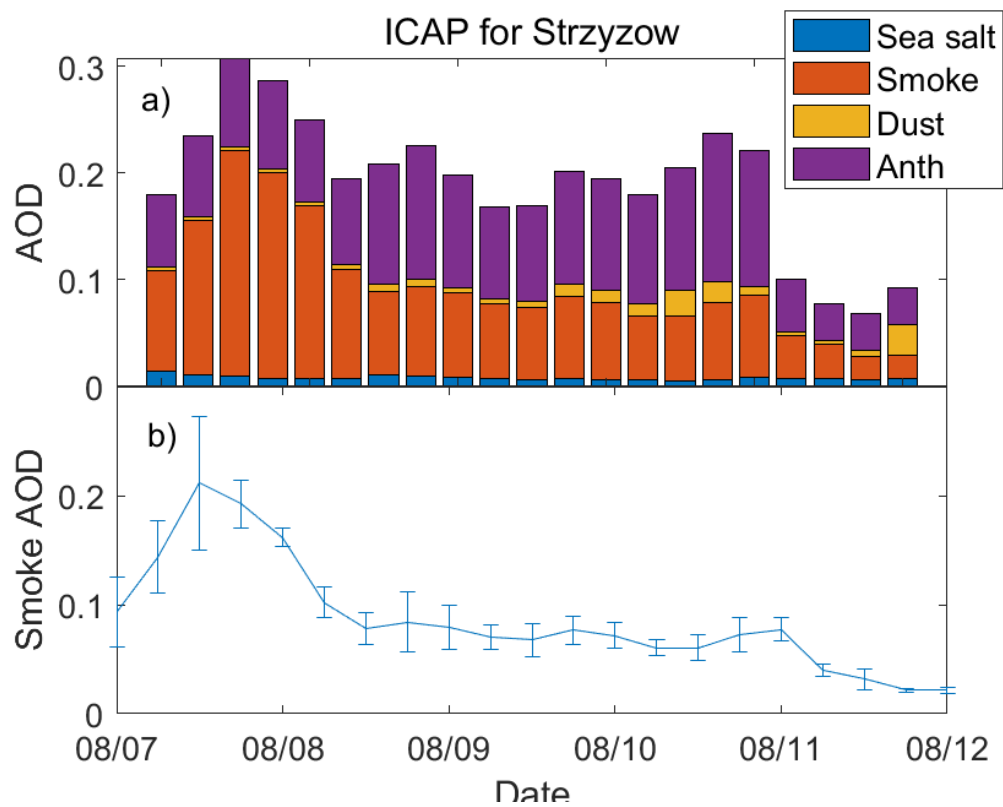


Figure C2. Total AOD with four categories distinguished (sea salt, smoke, dust, and anthropogenic) (a), and smoke AOD (b) at the Strzyżów site in the 7–12 August 2025 period. Values were retrieved from the ICAP model and are given at 550 nm.

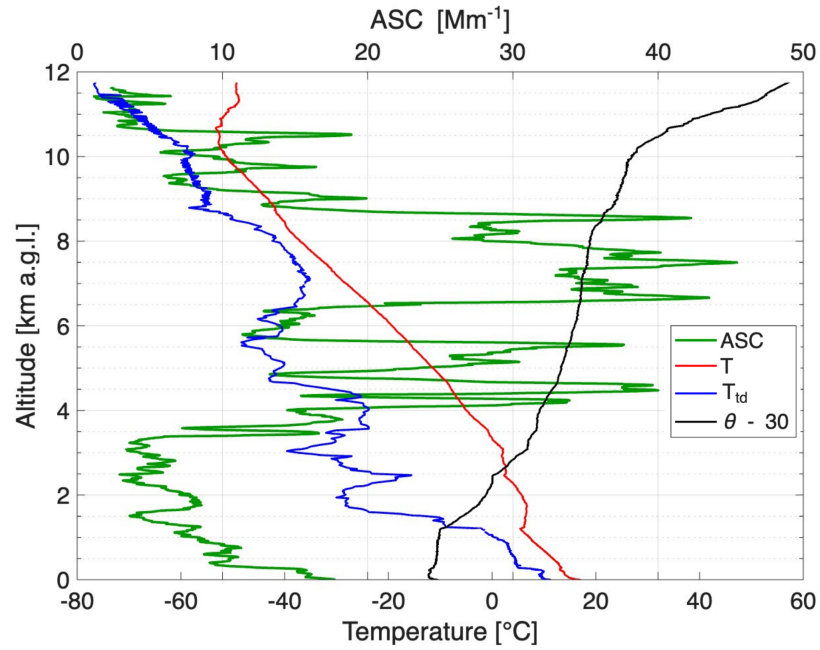


Figure C3. Vertical profiles of thermodynamic variables and aerosol scattering coefficient (ASC) obtained from the AeroSonde sounding on 7 August in the morning. The notation follows Fig. B4.

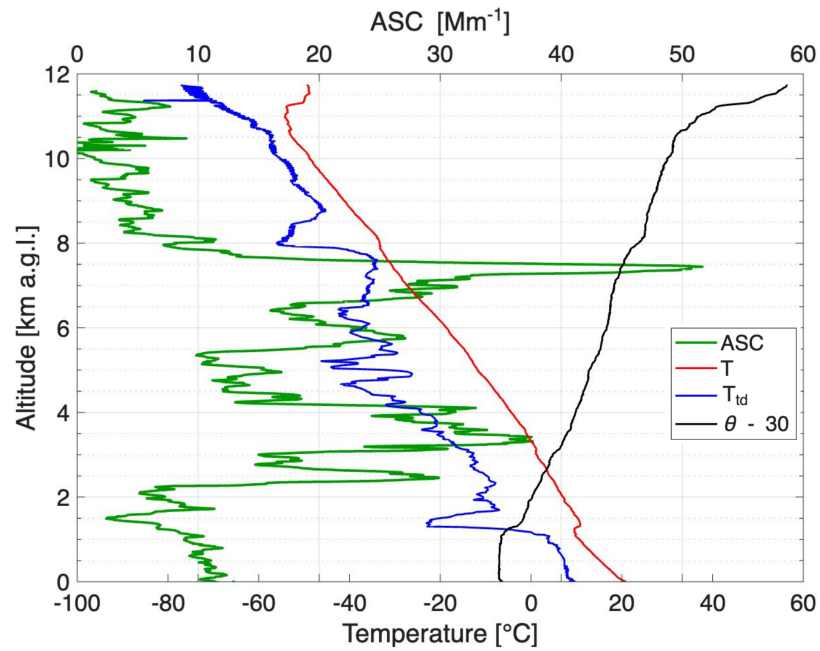


Figure C4. Vertical profiles of thermodynamic variables and aerosol scattering coefficient (ASC) obtained from the AeroSonde sounding on 7 August in the afternoon. The notation follows Fig. B4.

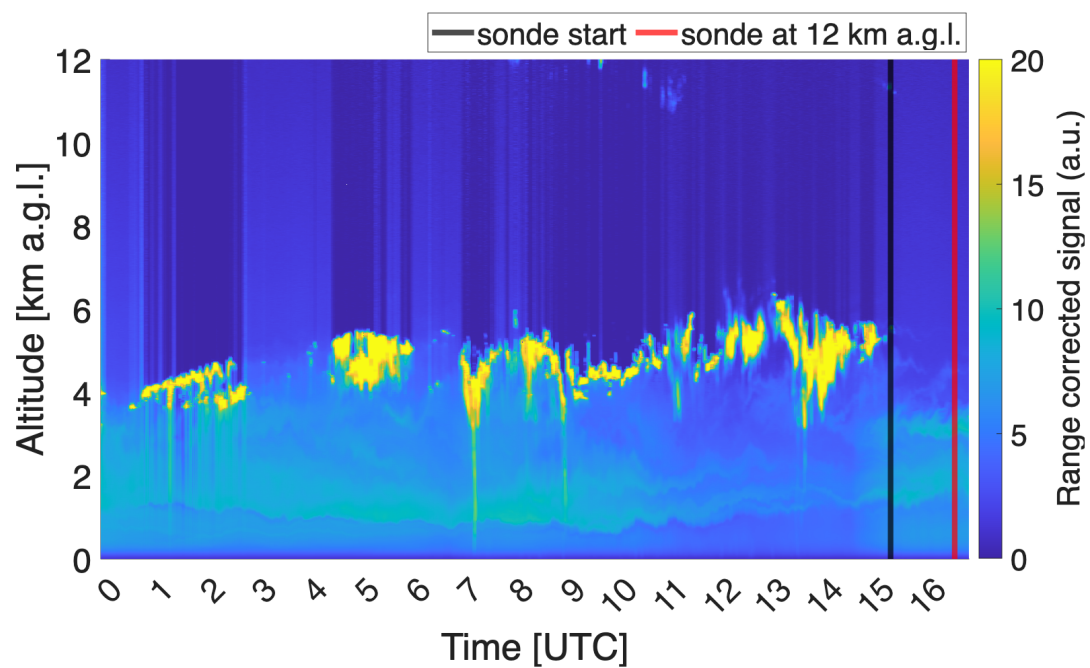


Figure D1. Lidar range corrected signal for 29 August 2025. The black line indicates the AeroSonde flight start, while the red line points to the time of reaching the 12 km a.g.l.

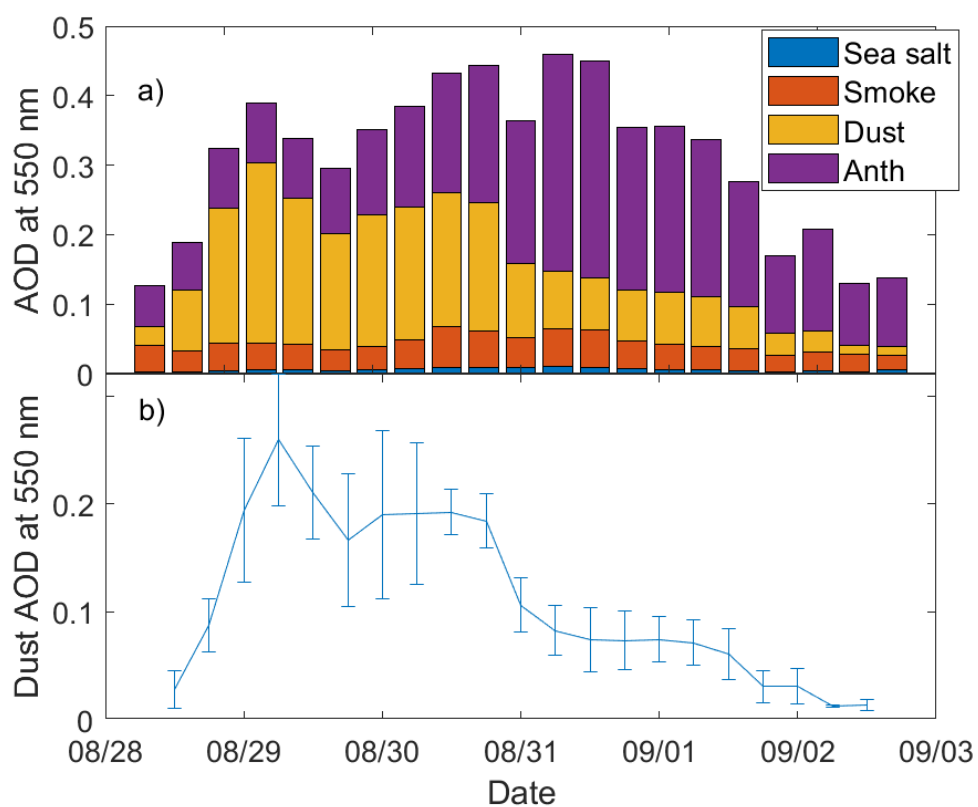


Figure D2. Total AOD with four categories distinguished (sea salt, smoke, dust, and anthropogenic) (a), and dust AOD (b) at the Strzyżów site in the 28 August–3 September 2025 period. Values were retrieved from the ICAP model and are given at 550 nm.

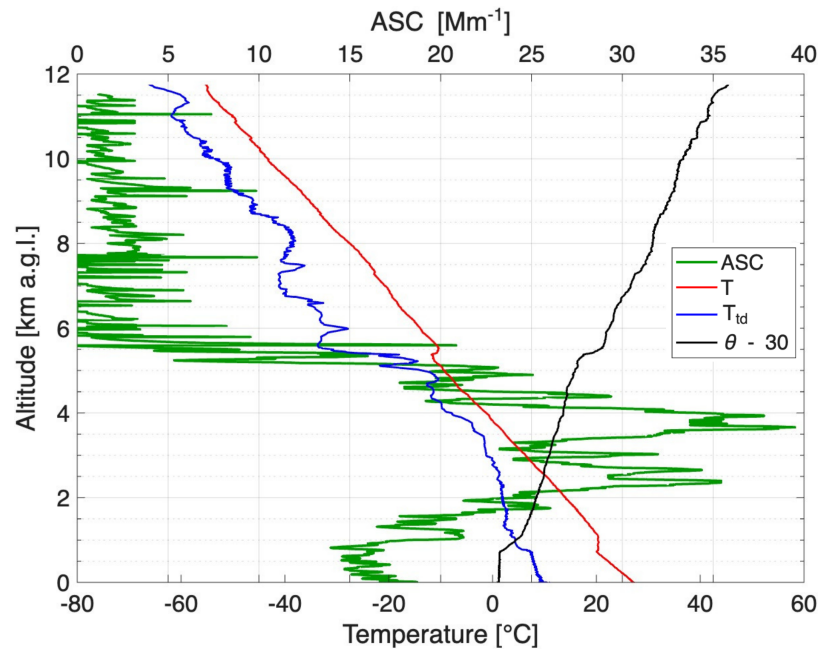


Figure D3. Vertical profiles of thermodynamic variables and aerosol scattering coefficient (ASC) obtained from the AeroSonde sounding on 29 August. The notation follows Fig. B4.

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Competing interests. The authors declare no conflicts of interest.

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