



Technical note: comparison of manually and automatically evaluated profiles of a PollyXT multiwavelength polarization Raman lidar

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Abstract. This technical note presents a comprehensive comparison of manually and automatically analyzed lidar profiles of aerosol optical properties retrieved from an 18-month measurement campaign with a continuously measuring, automated PollyXT multiwavelength polarization Raman lidar in Dushanbe, Tajikistan. The manual analysis was performed using a custom software (known as *Verlauf*) in multiple analyses steps based on visual inspection of the lidar signals. Its results serve as the reference dataset. The automatic analysis was performed using the PollyNET Processing Chain (PPC) (version 4.0). Retrieval parameters, derived layer-mean values, and seasonal mean and median profiles of aerosol optical properties (backscatter and extinction coefficients, particle depolarization and lidar ratios, and backscatter- and extinction-related Ångström exponents) of the two datasets were compared. The absolute values of the percentage differences of the seasonal mean and median backscatter coefficient profiles at 1.5 km height are largely below 10 %, except at 532 nm in winter and at 1064 nm in spring and winter. The absolute values of the percentage differences of the seasonal mean and median extinction coefficient profiles at 1.5 km height are largely less than 5 %. The absolute values of the percentage differences of the seasonal mean and median particle depolarization ratios at 1.5 km are largely below 20 % at 355 and below 10 % at 532 nm wavelength. For the most part, these discrepancies are within the measurement uncertainties of the considered quantities despite challenges in the automatic retrieval such as reference height detection, depolarization calibration, and cloud screening. This supports the conclusion that the automatically analyzed profiles of aerosol optical properties are utilizable for common applications, such as extinction statistics, aerosol typing, and retrieval of microphysical and cloud-relevant aerosol properties. However, caution should be exercised when using the particle depolarization ratio at 355 nm and backscatter-related Ångström exponents, which showed enhanced discrepancies.



The results will assist further improvements of the PPC and the implementation of additional features (e.g., optimal estimation methods, retrievals of microphysics). Together with the growing network of PollyXT lidars, the automatic processing chain will remain under constant development with the goal of dissemination of near real-time data on product level with high quality to users and scientific databases.

1 Introduction

Lidar is an indispensable tool in observing fundamental atmospheric parameters at high temporal and vertical resolution, such as wind, cloud and aerosol properties, which are playing a vital role in weather and climate (Baker et al., 2014; Bühl et al., 2017). Performing aerosol-cloud-interaction studies is one way to investigate this crucial role (e.g., Jimenez et al., 2020a, b; Alexandri et al., 2024). These studies are enabled by vast coordinated ground-based lidar observations (e.g., WMO, 2007) as well as space-borne missions carrying lidars like CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations; Winker et al., 2009), Aeolus (Stoffelen et al., 2005), Atmospheric Environment Monitoring Satellite (DQ-1/2; Dai et al., 2024) and most recently EarthCARE (Earth Cloud, Aerosol and Radiation Explorer; Wehr et al., 2023).

To retrieve profiles of physical quantities such as backscatter and extinction coefficients from raw lidar signals, a sequence of data analysis steps has to be performed (e.g., Weitkamp, 2005). These steps consist, among others, of the choice of reference heights and reference values for performing a Rayleigh-fit calibration procedure (Freudenthaler, 2009), depolarization calibration (Freudenthaler, 2016), averaging time selection, and thus cloud filtering (Mattis et al., 2016). Particularly, when using regular but limited observations (e.g., Bösenberg et al., 2003), parts or all of these steps have been often carried out manually by visual inspection of the lidar signals.

Due to this rather laborious procedure, such manual analyses of a limited number of individual profiles are at most practicable for multi-week campaigns like SAMUM (Saharan Mineral Dust Experiment; e.g., Ansmann et al., 2011) or SALTRACE (Saharan Aerosol Long-range Transport and Aerosol-Cloud-Interaction Experiment; e.g., Haarig et al., 2017) to multi-season campaigns like INDOEX (Indian Ocean Experiment; e.g., Franke et al., 2001) or observations during the wet and dry season in the Amazon Basin presented in Baars et al. (2011, 2012). The latter campaign was the first long-term deployment of a PollyXT portable multiwavelength polarization Raman lidar (Althausen et al., 2009; Engelmann et al., 2016), after an earlier prototype version of the system has been deployed to different locations in China (Ansmann et al., 2005; Tesche et al., 2007), and after continuous operation at its home base in Leipzig, Germany, including for automatic monitoring of the planetary boundary layer height (Baars et al., 2008).

As nowadays PollyXT lidars become more frequently and numerously used for worldwide long-term observations (recently, e.g., Radenz et al., 2021, 2024; Wieder et al., 2022; Seidel et al., 2025; Ohneiser et al., 2025; Malollari et al., 2025) as well as permanent deployments (e.g., Szczepanik et al., 2023; Rogozovsky et al., 2025; Gebauer et al., 2026; Müller et al., 2026), the amount of data acquired within the network of PollyXT-type systems (PollyNET; Baars et al., 2016) is strongly increasing. This is illustrated in Fig. 1, showing the accumulated lidar observation time since the establishment of PollyNET.

One of the goals of PollyNET is to automatically process these globally and constantly accruing data in near real-time in a



common way and data structure, making use of the technical similarity of PollyXT-type systems (main optical layout, data acquisition, and data format; Baars et al., 2016; Engelmann et al., 2016), to promptly provide results to the PollyXT operators and community. The benefit of automatic data processing is rapid provision of standardized products in an easily traceable and reproducible way, while shortcomings are related to rigid settings like vertical resolution (smoothing), minimum averaging time periods and signal-to-noise ratios (SNR). Such issues were reported for stations with frequent low clouds, e.g., at the Mindelo site (Cabo Verde, tropical Atlantic; Gebauer et al., 2024, 2026), which leads to cloud-contaminated or missing profiles. This includes missing backscatter-related products, which would be retrievable even at shorter averaging time periods. In contrast to automatic data processing, manual retrievals offer a lot of flexibility with respect to settings and different atmospheric scenarios, like cloud situation or complex aerosol layering. Visual inspection of the lidar signals usually allows easy cloud filtering, while temporally averaging over stable, continuous aerosol situations leads to a more representative vertical average. Performing such an analysis also allows to consider different smoothing lengths to resolve the targeted features, which is optimal for detailed case study analyses. The shortcomings are that this is time-consuming and, to a certain degree, offers room for arbitrariness. The need for a robust automatic data processing scheme for a growing global network like PollyNET is therefore undeniable. Whereas performing comprehensive manual analyses for specific occasions, like case studies or quality control after major upgrades or relocation of PollyXT systems, will remain a crucial acquirement.

In addition, the automatically retrieved profile products can be uploaded in near real-time to the database of PollyNET's parent network EARLINET (European Research Lidar Network; Pappalardo et al., 2014), which is part of ACTRIS (Aerosol, Clouds and Trace gases Research Infrastructure; Laj et al., 2024), as a complement to processing PollyNET raw data in the framework of the Single Calculus Chain (SCC; D'Amico et al., 2015, 2016; Mattis et al., 2016), a versatile software able to analyze data of all EARLINET lidars. However, the SCC currently neither calculates water vapor profiles nor allows custom dead time correction and cannot take into account all the calibration procedures for the PollyXT design. Furthermore, it is much less flexible in changing settings, due to its duty to serve as operational database for ACTRIS. Moreover, it is not at all designed to retrieve cloud properties. Thus, more flexible tools to exploit the full capabilities of the Polly lidars are needed.

These databases allow climatological analyses (Matthias et al., 2004), model validation (Biniotoglou et al., 2015), large-scale monitoring of extreme events (e.g., Tsekeri et al., 2023; Papanikolaou et al., 2024), and facilitate extended satellite-validation efforts (e.g., Pappalardo et al., 2010; Papagiannopoulos et al., 2016; Proestakis et al., 2019; Michailidis et al., 2023; Baars et al., 2026). Furthermore, making used data openly available, for example in such databases, became a common necessity of most peer-reviewed journals and is therefore a prerequisite of publishing scientific findings obtained from these observations.

Along with quality assurance and control measures on the instrument level (e.g., ACTRIS/CARS, 2024), also the automated data analysis and production of profiles of physical quantities have to undergo testing, examination, and comparison, and eventually improvement. Particularly, since removing noisy profile parts and cloudy profile sections or time periods, due to insufficient cloud-screening procedures, often still needs manual inspection and intervention to provide profiles that can be easily and correctly interpreted by humans and machines. Having experienced strict quality assurance and additionally possessing corresponding metadata, e.g., certain height information with regard to cloud filtering, signal or product noise, and overlap characteristics, manually analyzed datasets offer an optimal evaluation opportunity for coinciding automatically ana-



lyzed datasets.

Such a manually analyzed dataset was acquired from the 18-month Central Asian Dust Experiment (CADEX 2015–2016, Hofer et al., 2017, 2020a, b) and is used in this technical note for various comparisons with a dataset automatically produced by the PollyNET software routines (Baars et al., 2016; Yin et al., 2020; Klamt et al., 2024). The results will help to gain insights in the performance of the software with respect to the different optical properties and atmospheric scenarios.

The paper is structured as follows: In Sect. 2, the used manually (Sect. 2.1) and automatically retrieved lidar profiles (Sect. 2.2), and the method how these two datasets were linked (Sect. 2.3) are introduced. In Sect. 3, comparisons of retrieval parameters (Sect. 3.1), layer means of aerosol optical properties (Sect. 3.2), and seasonal-mean vertical profiles of aerosol optical properties (Sect. 3.4) are presented. Finally, in Sect. 4, the findings are summarized and an outlook is provided.

2 Data and methods

2.1 Manually analyzed lidar profiles

Lidar data from the CADEX campaign in Dushanbe, Tajikistan (Hofer et al., 2017) are used for the comparison in this study. During the CADEX campaign from 17 March 2015 to 31 August 2016, a multiwavelength polarization Raman lidar PollyXT (Engelmann et al., 2016) was operated at a field site of the National Academy of Sciences of Tajikistan (38°33′34″ N, 68°51′22″ E, 864 m a.s.l). A LabVIEW analysis software (known as *Verlauf*), developed at TROPOS (Baars et al., 2016) and frequently used within the PollyNET community (e.g., Janicka et al., 2023), was used to manually retrieve individual profiles of aerosol optical properties from the lidar data acquired during the CADEX campaign. Hereby, the manual retrieval process consists of several steps performed by the *Verlauf*-software operator. The most relevant steps are based on visual inspection of the lidar signals or SNR, such as the choice of the averaging time period and the reference height range.

The resulting dataset, which serves as the reference dataset in this study, was initially described and analyzed in Hofer et al. (2020a, b) and partly used in Proestakis et al. (2019), Floutsi et al. (2023), and Shang et al. (2026). It is therefore only briefly described here. The basis of this study are 276 individual night-time profiles of aerosol optical properties over Dushanbe. The retrievable aerosol optical properties are the backscatter coefficient at 355, 532, and 1064 nm, the extinction coefficient at 355 and 532 nm, and the particle depolarization ratio at 355 and 532 nm wavelength. From those directly retrieved aerosol optical properties, the lidar ratio at 355 and 532 nm wavelength and the extinction- and backscatter-related Ångström exponents can be derived. These profiles were evaluated for each night during CADEX at which it was possible (i.e., no low-level clouds or fog) to apply the Raman retrieval technique (Ansmann et al., 1990, 1992a, b) and to retrieve extinction-related aerosol optical properties. To achieve this, sufficient temporal averaging of the raw signals is required, which ranges from 16 to 359 min with a mean of 130 min and a median of 119 min. For additional 52 profiles, only the backscatter-related optical properties could be determined. So, there is a superset of 328 profiles (328-superset) and a subset of 276 profiles (276-subset). In this study, the backscatter and particle depolarization ratio profile comparisons could be done on the superset, whereas the extinction profile comparisons were done just on the subset. All profiles have the same vertical smoothing length of 742.5 m. For all profiles, a number of additional information were collected by visual inspection of each individual profile. These metadata consist mainly



120 of geometrical information (i.e., height levels) and derived layer-mean values, which are described in the following.

To illustrate the procedure of applying these metadata to the individual profiles, an example comparison of a manually and an automatically analyzed profile is presented in Fig. 2, which is further described in Sect. 2.3. In a first step, cut-off heights of the backscatter coefficients were defined to discard cloud-containing profile segments if clouds occurred below 11 km height. In the example case in Fig. 2a, this step was not required due to cloud-free conditions. Necessarily, all height ranges explained
125 next are set below or equal to this initial cloud-filtering cut-off height. The extinction coefficient profiles were used to calculate the aerosol optical thickness by integration. For this purpose, a maximum integration height was set to avoid integration of too noisy sections of the extinction coefficient profiles. In the example case in Fig. 2b, this height was set at 8.6 km for both wavelengths. Accurate and smooth, i.e., noise-free, particle depolarization ratio profiles are essential to retrieve microphysical and cloud-relevant aerosol properties by using the POLIPHON method (Polarization Lidar Photometer Networking method;
130 e.g., Mamouri and Ansmann, 2016). So, additional maximum heights were defined up to which the particle depolarization ratio profiles were noise-free. In the example case in Fig. 2e, this height was set at 7.4 km for both wavelengths. In a last step, a height range was defined (violet dashed lines in Fig. 2) in which layer-mean values of the aerosol optical properties were determined (mean, minimum, maximum, and standard deviation). In the example case in Fig. 2, this height range was set to 1.5–2.8 km. For for legibility reasons only, noisy profile segments of the lidar ratio (Fig. 2c) and extinction- and backscatter-
135 related Ångström exponents (Fig. 2d) are cut above 5 km and 7 km, respectively, in this very example case. Furthermore, backscatter-related (extinction-related) optical properties are cut below 0.37 (1) km due to the overlap region.

The manual analysis of the CADEX dataset in such a way did not aim at the comparison presented here but at very specific scientific achievements, namely the provision of aerosol extinction, particle mass, cloud condensation nuclei, and ice-nucleating particle statistics over Central Asia (Hofer et al., 2020a) and of optical properties of Central Asian aerosol relevant for space-
140 borne lidar applications and aerosol typing (Hofer et al., 2020b). Therefore, the manual analysis was designed to meet the requirements to answer those scientific questions. Furthermore, at the time of the CADEX campaign and its data analysis, only predecessor software far from the current automatic analysis capabilities was available, which is described in Baars et al. (2016).

145 2.2 Automatically analyzed lidar profiles

Lidar-derived profiles of aerosol optical properties retrieved by the PollyNET Processing Chain (PPC; version 4.0; PollyNET, 2026; Baars et al., 2016; Yin et al., 2020; Klamt et al., 2024) were used for comparison with manually derived ones (Sect. 2.1). In contrast to the manual analysis, including its metadata, the PPC raw output cannot meet the full needs of detailed studies as presented in Hofer et al. (2020a, b) (see Sect. 2.1). The PPC repository (Klamt et al., 2024) contains Matlab codes for automatic
150 processing and visualization of data from PollyNET (Baars et al., 2016). Both Klett (Klett, 1981, 1985; Fernald, 1984; Sasano et al., 1985) and Raman retrievals are available, as well as further properties such as water vapor (Foth et al., 2015; Dai et al., 2018; Jakob et al., 2026), a target classification based on high-temporal-resolution products (Baars et al., 2017), and dust and non-dust backscatter coefficients derived via POLIPHON (Müller et al., 2026). Quicklooks of the retrieved lidar products are



available on the PollyNET website <https://polly.tropos.de/> (last access: 30 June 2026).

155 For the PPC, several parameters for the analysis of the optical aerosol parameters have to be pre-set. A full list of adjustable parameters including description is given on github (https://pollynet.github.io/Pollynet_Processing_Chain/modules/config.html, last access: 30 June 2026). Here, we list only the ones relevant for the optical properties and discuss the values used for the manual analysis, which is more flexible concerning those parameters (Tables A1 and A2). For the Dushanbe station, the PPC is set to retrieve profiles with an averaging time of 0.5–1.5 h. The output was almost 7000 (including daytime/Klett) automatically
160 analyzed profiles with the same vertical smoothing length as the manually analyzed profiles (742.5 m). Later in the manuscript, the automatically (manually) retrieved profiles will be simply called "automatic (manual) profiles".

It is important to mention that the automatic PPC retrieval is performed operationally and thus is independent of the above-mentioned manually analyzed dataset or its individual profiles (i.e., not a PPC-reprocessing of the very same lidar data in terms of e.g., chosen reference heights and averaging time periods). On the other hand, the manual analysis was not carried out for
165 the purpose of this comparison but for specific scientific purposes (see Sect. 2.1) with a different analysis strategy (e.g., longer averaging periods). Therefore, despite basing on the same raw data, these two datasets are not per se identical in the first place and therefore well suited for comparison to each other.

2.3 Linking automatic and manual lidar profiles

170 The automatic and manual profiles were linked to each other by comparing the profiles' middle times of the averaging period. For each manual profile, the temporally closest available automatic Raman profile was determined. A cut-off threshold of a maximum 2 h time gap between the middle times of the averaging periods was applied to discard temporally too distant automatic profiles. This is resulting in 244 (285) PPC profiles in the case of the 276-subset (328-superset) of the manually analyzed dataset. The difference (manual–automatic; mean (median) $\pm$ standard deviation) in averaging period duration is
175 78 (60) $\pm$ 58 min for the 276-subset and 74 (60) $\pm$ 58 min for the 328-superset. This means that the averaging duration of the manual analyses is usually 1 h longer than the one of the automatic analyses. The absolute temporal distance (mean (median) $\pm$ standard deviation) of the middle times of the averaging period is 17 (17) $\pm$ 13 min for both sub- and superset. This means that the averaging periods of the manual and automatic analyses overlap well despite the different durations of their averaging periods.

180 For each of the manual profiles of the 276-subset, the full set of optical properties is available. For the 328-superset, backscatter-related properties are available. However, the automatic retrieval yields individual results for each optical property and wavelength, respectively. Some optical properties might be not retrieved while others are, depending on the successful determination of parameters such as the reference height. For the 276-subset, e.g., all 244 automatic PPC profile files fulfilling the temporal proximity criterion contain a retrieved extinction coefficient at both 355 and 532 nm wavelength. For the backscatter coefficient, most corresponding retrievals are available at 532 (236), followed by 355 (233), and 1064 nm wavelength (187).
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Above-mentioned metadata (Sect. 2.1) are applied to the automatic profiles, which were linked to the manual ones. This means cutting the profiles at certain cut-off heights and applying layer-mean averaging. This procedure was applied to all available



linked profiles of optical properties and is illustrated as an example case in Fig. 2. In this case from 13 July 2015, the manual and automatic profiles have a similar averaging period and align rather well. The layer-mean values were determined between 1.5–2.8 km due to relatively constant particle depolarization and lidar ratios in this height range. Within that height range, the layer-mean backscatter coefficients of the automatic profiles are $0.03 \text{ Mm}^{-1} \text{ sr}^{-1}$ (2 %) larger (355 nm), $0.09 \text{ Mm}^{-1} \text{ sr}^{-1}$ (5 %) smaller (532 nm), and $0.22 \text{ Mm}^{-1} \text{ sr}^{-1}$ (18 %) smaller (1064 nm) than the ones from the manual profiles. The layer-mean extinction coefficients of the automatic profiles are 1.44 Mm^{-1} (2 %) smaller (355 nm) and 4.26 Mm^{-1} (9 %) smaller (532 nm) than the ones from the manual profiles. The layer-mean particle depolarization ratios of the automatic profiles are 0.014 (13 %) larger (355 nm) and 0.01 (5 %) larger (532 nm) than the ones from the manual profiles. Generally, a slightly different profile structure of the backscatter-related properties below about 1 km is obvious, which is likely caused by fast changing atmospheric conditions close to the ground during the two dissimilar averaging periods.

3 Results

3.1 Comparison of retrieval and calibration parameters

Basic parameters used to retrieve the backscatter coefficients and particle depolarization ratios are shown in Figs. 3 and 4, respectively. Figure 3 shows reference heights at all three wavelengths, as automatically retrieved by the PPC (Fig. 3a–c for all available profiles and Fig. 3d–f for the profiles linked to the manual ones) and the manual ones chosen by visual inspection of the signals (Fig. 3g–i), respectively.

The automatically determined reference height ranges are distributed mainly within 7–18 km (355 nm, Fig. 3a), 4–18 km (532 nm, Fig. 3b), and at 1064 nm, in a more variable way, roughly within 4–18 km (Fig. 3c). Predominantly during the autumn and winter months, also some lower reference heights starting from 1 km were determined. However, profiles with such low reference heights are mostly Klett profiles and therefore almost not linked to manual profiles (Fig. 3d–f). The manually determined reference heights are mostly equal for all three wavelengths and spread from about 5–14 km with some lower values starting from about 3 km in the autumn and winter months (Fig. 3g–i).

The reference values in the automatic analyses are fixed to $1 \times 10^{-5} \text{ km}^{-1} \text{ sr}^{-1}$ at both 355 and 532 nm, and $5 \times 10^{-6} \text{ km}^{-1} \text{ sr}^{-1}$ at 1064 nm wavelength. In the manual analyses, they are generally the same for all three wavelengths, namely $1 \times 10^{-5} \text{ km}^{-1} \text{ sr}^{-1}$, with a few exceptions such as extreme dust events or for profiles calibrated below clouds. Figure 4 shows the automatically and manually retrieved molecular depolarization ratio parameters ("parameter" in the sense of a settings parameter, not to be confused with the depolarization parameter used in scattering theory) δ_{mol} (e.g., Freudenthaler et al., 2016) used for the calculation of the particle depolarization ratios (Fig. 4a,b), and the depolarization-calibration constants η (Fig. 4c,d) determined from the $\Delta 90^\circ$ -calibration measurements (Freudenthaler, 2016) performed regularly (3 times a day) and autonomously by the PollyXT system (Engelmann et al., 2016).

The manually retrieved η values were determined at individually chosen height ranges usually between 2 and 3 km height, while the PPC determines the η values between 0.7 and 3.725 km in a 300-m window with requirements on the signal maximum and SNR. The η values used in the manual analyses are averages of periods of constant system configuration (Table A3).



The automatic analyses use the η value with the lowest standard deviation from a same-day $\Delta 90^\circ$ -calibration measurement.

In case of the manual analyses, δ_{mol} values are calculated individually for each profile from the volume depolarization ratio around the reference height region, i.e., an ideally nearly aerosol-free region. The PPC can be operated in two modes with respect to δ_{mol} . Either it is calculated from the volume depolarization ratio in the reference height range, too, or it is pre-set with a fixed default value. For the dataset described in this study, the former is the case. However, if no δ_{mol} values can be determined by the PPC, due to e.g., low SNR of the cross channel's signal in the reference height region, the default values are used as fallback (see Table A4, Fig. A1). The default value of the molecular depolarization ratio parameter has to be used rather often by the PPC, particularly at 532 nm wavelength (Fig. A1). This is an indication that the PPC, at times, struggles to identify sufficiently aerosol free height ranges, which might be exceptionally difficult in regions which are often dust-laden up to the upper troposphere, like Tajikistan.

The manually calculated η values scatter more (especially at 355 nm, Fig. 4c) and their mean and median values for the above-mentioned periods of constant system configuration are slightly larger than the ones of the automatically calculated η values (Table A3). The automatically retrieved δ_{mol} values at both wavelengths are on average slightly larger than the manually retrieved ones at almost all periods (Table A5).

3.2 Comparison of layer-mean optical properties

Layer-mean optical properties derived from the manual and automatic profiles (Sect. 2.3) are compared by calculating least-square linear regressions including coefficients of determination (R^2), root-mean-square errors (RMSE), mean absolute errors (MAE), and mean bias errors (MBE), and by plotting them against each other in scatter plots (Fig. 5) and in histograms of residuals (automatic—manual; only directly measured quantities, i.e., except lidar ratios and Ångström exponents; Fig. 6). Figure A2 shows the same data as the scatterplots in Fig. 5, but with the fit line forced through the origin, leading to different R^2 values. Additionally, the median instead the mean errors are provided in Fig. A2. For better visualization, showing the same data as Fig. 5, a zoomed-in view to the lower backscatter and extinction coefficient values is provided in the scatterplots in Fig. A3.

3.2.1 Comparison of layer-mean backscatter coefficients

Regarding the layer means of the backscatter coefficients (Figs. 5a–c and 6a–c), R^2 (RMSE; MAE; MBE) values of 0.965 (0.45; 0.26; 0.06 $\text{Mm}^{-1} \text{sr}^{-1}$) at 355, 0.968 (0.54; 0.21; $-0.12 \text{ Mm}^{-1} \text{sr}^{-1}$) at 532, and 0.885 (0.45; 0.25; $-0.07 \text{ Mm}^{-1} \text{sr}^{-1}$) at 1064 nm are found. At 355 nm wavelength, the lower layer-mean values are evenly distributed around the identity line (Fig. 5a). Only for a few of the largest values, the layer means of the manual profiles tend to be lower. The residuals lay largely between -0.5 and $0.6 \text{ Mm}^{-1} \text{sr}^{-1}$ with a peak at -0.1 to $0 \text{ Mm}^{-1} \text{sr}^{-1}$ (Fig. 6a). At 532 nm wavelength, many of the layer-mean values aggregate above the identity line (Fig. 5b). This is more pronounced for most of the higher values. The residuals lay largely between -0.4 and $1 \text{ Mm}^{-1} \text{sr}^{-1}$ with a peak at 0 to $0.1 \text{ Mm}^{-1} \text{sr}^{-1}$ (Fig. 6b). At 1064 nm wavelength, the layer-mean values scatter more and exhibit the lowest R^2 of the backscatter layer means (Fig. 5c). From the lower values,



it is apparent that many of the layer-mean values lay above the identity line. The residuals lay largely between -0.4 and $0.8 \text{ Mm}^{-1} \text{ sr}^{-1}$ with a peak, however, at -0.1 to $0 \text{ Mm}^{-1} \text{ sr}^{-1}$ (Fig. 6c).

255 3.2.2 Comparison of layer-mean Ångström exponents

The layer means of the Ångström exponents (Fig. 5d–f) scatter significantly, which leads to mediocre correlations with resulting R^2 (RMSE; MAE; MBE) values of 0.877 (0.31; 0.18; -0.05) for the extinction-related Ångström exponents, 0.579 (0.61; 0.40; 0.21) and 0.389 (0.36; 0.27; 0.01) for the backscatter-related Ångström exponents of the 355/532 and 532/1064 nm wavelength pairs, respectively. Nevertheless, the values scatter evenly, distributed around the identity line for the layer means of
260 the extinction-related Ångström exponents (Fig. 5d). The scatter is more diffuse for the backscatter-related Ångström exponent of the 355/532 (Fig. 5e) and the 532/1064 nm wavelength pairs (Fig. 5f) and the value ranges of the automatic layer means are more extended compared to the manual layer means.

3.2.3 Comparison of layer-mean particle depolarization ratios

Regarding the layer means of the particle depolarization ratios (Figs. 5g,h and 6d,e), R^2 (RMSE; MAE; MBE) values of
265 0.881 (0.04; 0.02; -0.02) at 355 and 0.965 (0.02; 0.02; -0.01) at 532 nm wavelength are found. The layer-mean particle depolarization ratios at 355 nm assemble often above the identity line (Fig. 5g). This deviation becomes more pronounced for larger values. The layer-mean particle depolarization ratios at 532 nm predominantly lay above the identity line (Fig. 5h), too. That deviation, however, does not clearly change depending of the magnitude of the values. The residuals of the layer-mean particle depolarization ratios at 355 nm lay mostly between -0.03 and 0.01 and peak at 0.02 to 0.03 (Fig. 6d). At 532 nm, they
270 lay largely between -0.04 and 0.8 and peak at 0 to 0.01 (Fig. 6e).

3.2.4 Comparison of layer-mean extinction coefficients

Regarding the layer means of the extinction coefficients (Figs. 5i,j and 6f,g), R^2 (RMSE; MAE; MBE) values of 0.996 (10; 4.5; -0.1 Mm^{-1}) at 355 and 0.965 (19; 5.0; -1.1 Mm^{-1}) at 532 nm wavelength are found. The layer-mean extinction coefficients are distributed narrowly around the identity line for both wavelengths. Only a few low values (at both wavelengths) and one
275 very high value at 532 nm deviate clearly. The residuals of the layer-mean extinction coefficients at 355 nm lay mostly between -10 and 14 Mm^{-1} and peak at 0 to 2 Mm^{-1} (Fig. 6f). At 532 nm, they lay largely between -12 and 16 Mm^{-1} and peak also at 0 to 2 Mm^{-1} (Fig. 6g). The histograms of the residuals of both wavelengths do not show a clear skew.

3.2.5 Comparison of layer-mean lidar ratios

Regarding the layer means of the lidar ratio (Fig. 5k,s), R^2 (RMSE; MAE; MBE) values of 0.522 (7.6; 5.3; -1.3 sr) at 355 and
280 0.8 (4.8; 3.5; 1.7 sr) at 532 nm wavelength are found. The layer-mean lidar ratios at 355 nm scatter notably but, still, are rather evenly distributed around the identity line (Fig. 5k). However, the correlation is mediocre and the value range of the automatic layer means at 355 nm is clearly extended compared to the manual layer means. This is mainly a consequence of the enhanced



scatter in the layer means of the backscatter coefficient at 355 nm (larger MAE at 355 than 532 nm; Fig. 5a,b), while the layer means of the extinction coefficient agree similarly well at both wavelengths (similar MAE; Fig. 5i,j). The layer-mean lidar ratios at 532 nm scatter significantly, too, but the correlation is better and the value ranges of the automatic and manual layer means are more similar than at 355 nm wavelength (Fig. 5k). While both the layer means of the backscatter and extinction coefficients at 532 nm lay partly above the identity line (Fig. 5b,j), the layer-mean lidar ratio values at 532 nm tend to aggregate partly below the identity line, however, in a scattered way (Fig. 5l).

3.3 Seasonal comparison of layer-mean intensive optical properties

To assess the seasonal distribution of the layer-mean optical properties, the intensive, i.e., concentration-independent quantities (lidar and particle depolarization ratio, and backscatter- and extinction-related Ångström exponents), were also plotted seasonally resolved in boxplots (Fig. 7). The corresponding seasonal mean, median, and standard deviation values are listed in Table 1.

3.3.1 Seasonal comparison of layer-mean particle depolarization ratios

The seasonal distribution of the layer-mean particle depolarization ratios (Fig. 7a) shows that the automatic values at 355 nm, compared to the manual ones, are shifted towards larger values and have a larger spread (interquartile range and whiskers) in all seasons. In spring, the mean, and in winter, the mean and median of the automatic layer means lay outside of the interquartile range of the manual layer means. The difference of the seasonal means (automatic–manual) is 0.02 in most seasons, except in spring (0.03), while the difference of the seasonal medians is 0.01 in all seasons (Table 1). The interquartile ranges of the layer-mean particle depolarization ratios at 532 nm are more congruent and do not show a clear tendency towards higher or lower values of the automatic layer-mean values throughout the seasons. The difference of the seasonal means is 0.01 in all seasons. The differences of the seasonal medians are 0.02 in spring and summer, 0.00 in autumn, and –0.02 in winter (Table 1).

3.3.2 Seasonal comparison of layer-mean lidar ratios

The seasonal distribution of the layer-mean lidar ratios (Fig. 7b) shows that the automatic and manual values at 355 nm agree well in all seasons. The automatic layer means have a larger spread (interquartile range and whiskers) in all seasons, which is most pronounced in spring. The mean and median values agree well within the interquartile ranges in all seasons. At 532 nm, the automatic layer-mean lidar ratios are shifted towards lower values in all seasons. The median and mean values agree within the interquartile ranges in all seasons, but only barely for the median in spring. However, in spring, the medians of the automatic and manual layer-mean lidar ratios deviate clearly (difference of –3.4 sr). In winter, both the means (difference of –4.7 sr) and the medians (difference of –7.3 sr) deviate significantly (Table 1).



3.3.3 Seasonal comparison of layer-mean Ångström exponents

The seasonal distribution of the layer-mean extinction- and backscatter-related Ångström exponents is illustrated in Fig. 7c. The mean and median values of the layer-mean extinction-related Ångström exponents agree well within the interquartile ranges. In spring, at large spread of both automatic and manual layer means, the mean values deviate with a difference of 0.11.

315 In winter, the interquartile range of the automatic layer means is shifted towards higher values and the median values deviate with a difference of 0.10 (Table 1).

The automatic layer means of the backscatter-related Ångström exponents of the 355/532 nm wavelength pair are shifted towards lower values in all seasons. This is most pronounced in winter, where the interquartile ranges are nearly disjoint and the means (medians) deviate with a difference of 0.65 (−0.45) (Table 1).

320 For the automatic layer means of the backscatter-related Ångström exponents of the 532/1064 nm wavelength pair, there is no clear picture throughout the seasons. While the automatic layer-mean values are moderately shifted towards larger values in summer and autumn, the opposite is the case in spring and winter, only more so. This is again most pronounced in winter, where the interquartile ranges only slightly overlap and the means (medians) deviate with a difference of −0.28 (−0.20) (Table 1).

3.4 Comparison of profile-mean optical properties

325 The vertical structure of the backscatter coefficients (Fig. 8), particle depolarization ratios (Fig. 9a–h), and extinction coefficients (Fig. 9i–p) are compared by plotting seasonal means, medians, and standard deviations of all linked manual and automatic profiles (see Sect. 2.3). For better visualization, the same backscatter coefficient profiles as in Fig. 8 are also shown with logarithmic x-axes in Fig. A4. Additionally, the differences of the seasonal mean and median values of the automatic and manual profiles at 1.5 km height are provided in Table A6. Comparison at 1.5 km height was chosen because it is well above

330 the overlap region, most optical property profiles are at or close to their maximum magnitude, and the impact of fast-changing atmospheric conditions very close to the ground could be limited (see e.g., Fig. 2). In contrast to layer-mean values, entire automatic profiles are more likely to contain cloud contamination despite the application of above-described cut-off heights (Sects. 2.1 and 2.3), which, however, might not be fully appropriate to discard all potential cloud segments from the automatic profiles that were evaluated with different parameters (reference height and value, molecular depolarization ratio parameter,

335 depolarization-calibration constant) and primarily at different time periods. The PPC's current cloud detection module relies on signal gradients and is very sensitive to signal noise and to the threshold for maximum signal gradient (Klamt et al., 2024; Gebauer et al., 2024). Still, PPC-retrieved profiles occasionally contain cloud segments. Nevertheless, no further cloud filtering was applied on the cut automatic backscatter and extinction coefficient profiles (Figs. 8 and 9i–p) in a postprocessing like e.g., Müller et al. (2026) did by applying a backscatter coefficient threshold. In case of the automatic particle depolarization ratio

340 profiles, values >0.4 and <-0.1 at both wavelengths were removed for denoising (Fig. 9a–h).



3.4.1 Comparison of profile-mean backscatter coefficients

The manual and automatic seasonal mean and median profiles of the backscatter coefficient at 355 nm reveal discrepancies in the mean between about 1–1.5 km height in spring (Fig. 8a). This is likely due to cloud contamination in a few automatic profiles since the median is less affected. In summer, the manual mean and median profiles are slightly higher and have a higher standard deviation than the automatic ones below 2.5 km (Fig. 8b). In autumn and winter, the automatic profiles are clearly larger than the manual ones at heights below about 1 km (Fig. 8c,d). In autumn, at heights above 1 km, the manual mean profile is larger than the automatic one (Fig. 8c), though. The differences at 1.5 km height (automatic–manual and percentage change ((automatic–manual)/manual); mean (median); spring, summer, autumn, and winter) are 0.04 (0.01), –0.15 (–0.09), –0.10 (–0.09), and 0.02 (–0.01) $\text{Mm}^{-1} \text{sr}^{-1}$, and 2.8 (0.8), –5.9 (–4.6), –6.3 (–5.7), and 2.3 (–1.6) %, respectively.

The manual and automatic seasonal mean and median profiles of the backscatter coefficient at 532 nm, at 1–1.5 km, show the same behavior in spring as at 355 nm, but the automatic profiles remain slightly higher than the manual ones throughout the profile (Fig. 8e). In summer, however, the automatic profiles, particularly the mean profiles, are slightly higher and have a higher standard deviation than the manual ones (Fig. 8f). In autumn and winter, again, the automatic profiles are clearly larger than the manual ones at heights below about 1 km and stay slightly larger throughout the profile (Fig. 8g,h). The differences at 1.5 km height are 0.09 (0.09), 0.10 (0.01), 0.12 (0.01), and 0.07 (0.06) $\text{Mm}^{-1} \text{sr}^{-1}$, and 8.5 (10.2), 4.1 (0.6), 8.5 (0.7), and 13.2 (16.7) %, respectively.

The manual and automatic seasonal mean and median profiles of the backscatter coefficient at 1064 nm show that the automatic profiles are higher than the manual ones at all heights in spring (Fig. 8e) but not as cloud-contaminated as at 355 and 532 nm. In summer, the automatic and manual mean profiles agree well, while the manual median profile is slightly larger than the automatic one at heights below 3 km (Fig. 8f). In autumn and winter, again, the automatic mean profiles are larger and become increasingly larger than the manual ones towards lower heights (Fig. 8g,h). The median profiles in autumn and partly also in winter agree better, except once more in the lowermost 1 km. The differences at 1.5 km height are 0.15 (0.14), 0.00 (–0.13), 0.09 (0.00), and 0.07 (0.01) $\text{Mm}^{-1} \text{sr}^{-1}$, and 22.1 (25.9), 0.0 (–9.7), 8.7 (0.0), and 25.9 (4.5) %, respectively.

In summary, the automatic mean and median backscatter coefficient profiles are consistently higher than the manual ones in the lowermost 1 km height in autumn and winter. The absolute values of the percentage differences at 1.5 km height are largely below 10 %, except for some indicators (i.e., mean and/or median) in spring and winter at 532 and 1064 nm wavelength. These larger discrepancies can be caused by a combination of the different reference values (5×10^{-6} (automatic) and $1 \times 10^{-5} \text{ km}^{-1} \text{sr}^{-1}$ (manual); Sect. 3.1) and reference heights at 1064 nm, as the automatic reference height is often, but not always, higher than the manual one (Fig. 3).

3.4.2 Comparison of profile-mean extinction coefficients

The manual and automatic seasonal mean and median profiles of the extinction coefficient of both wavelengths generally agree well at all heights and seasons. In spring, the automatic mean profiles are slightly larger than the manual ones in the very lowest heights (1–1.3 km) (Fig. 9a,e). In summer, the impact of a single extreme dust event on 14 July 2016 (see also Hofer



et al., 2017) becomes visible. The corresponding automatic profile is only available up to 1.6 km height, which causes the obvious discrepancies of the mean and median profiles in Fig. 9b,f. In winter, the automatic mean profiles between about 1–1.5 km height are slightly larger than the manual ones (Fig. 9d,h). For the profiles at 355 nm, the differences at 1.5 km height are 0.7 (1.6), –0.5 (–0.5), –0.5 (2.4), and 2.6 (–1.7) Mm^{-1} , and 1.1 (3.0), –0.5 (–0.7), –0.6 (3.4), and 3.4 (–4.5) %, respectively. For the profiles at 532 nm, the differences at 1.5 km height are 0.5 (1.9), 2.2 (2.9), –1.5 (–0.2), and 1.6 (–0.3) Mm^{-1} , and 0.8 (3.6), 2.4 (5.7), –3.0 (0.4), and 3.3 (–1.1) %, respectively, for the profiles at 532 nm wavelength.

In summary, the absolute values of the percentage differences between manual and automatic seasonal mean and median extinction coefficients at 1.5 km height are generally below 5 %, except for the median in summer at 532 nm wavelength, which can be explained by the rather noisy median extinction profiles.

3.4.3 Comparison of profile-mean particle depolarization ratios

The automatic seasonal mean profiles of the particle depolarization ratio at 355 nm are generally higher than the manual ones up to about 5 km in spring and summer (Fig. 9i,j), 3.5 km in autumn (Fig. 9k), and 3 km in winter (Fig. 9l). Above those heights, i.e., outside of the main aerosol layer (see also Hofer et al., 2020a), the mean profiles agree better. The automatic median profiles are consistently higher than the manual ones, too, but approach 0 at lower heights, which is most pronounced in spring (Fig. 9i). The differences at 1.5 km height are 0.013 (0.006), 0.018 (0.014), 0.016 (0.022), and 0.007 (0.007), and 16.7 (7.8), 13.3 (11.1), 17.8 (22.9), and 17.1 (17.5) %, respectively.

The manual and automatic seasonal mean and median profiles of the particle depolarization ratio at 532 nm are shown in Fig. 9m–p. Again, the automatic median profiles approach 0 at lower heights than the manual ones at all seasons. In spring, the automatic and manual profiles roughly agree between 1–3 km, while the manual profiles are clearly higher than the automatic ones at heights above that (Fig. 9m). In summer, the automatic mean and median profiles are larger than the manual ones up to about 5 km (Fig. 9n). Above that height, the mean profiles agree better, while the automatic median profile becomes smaller than the manual one. In autumn, the automatic and manual mean profiles agree well up to about 3 km (Fig. 9o), with the automatic mean profile having a slightly larger standard deviation. At higher heights, the automatic mean profile is smaller than the manual one. The automatic median profile is lower than the manual one at most heights, however. In winter, the profiles are noisy. Up to about 3 km, the automatic mean profile is higher than the manual one, and vice versa above 3 km. Median profiles are similar but variable up to 2.7 km, and from there upwards, the manual one becomes larger than the automatic one (Fig. 9o). The differences at 1.5 km height are –0.001 (–0.001), 0.014 (0.020), 0.00 (–0.02), and 0.005 (–0.016), and –0.6 (0.7), 6.0 (8.9), 0.0 (–10.3), and 5.7 (–17.4) %, respectively.

In summary, the absolute values of the percentage differences between manual and automatic seasonal mean and median particle depolarization ratios at 1.5 km are largely below 20 % at 355 and 10 % at 532 nm wavelength, respectively. Exceptions are the medians at both wavelengths in autumn and the median at 532 nm in winter. Thus, the mean and median particle depolarization ratios generally agree better at 532 than at 355 nm. Furthermore, particle depolarization ratio profiles at 532 nm do not have the tendency towards higher values throughout the seasons and heights that the ones at 355 nm wavelength have.



4 Summary, conclusion, and outlook

Manually and automatically analyzed profiles of aerosol optical properties, which were retrieved from an 18-month measure-
410 ment campaign with a PollyXT multiwavelength polarization Raman lidar in Dushanbe, Tajikistan were compared for the first
time. The manual analysis was conducted by visual inspection of the lidar signals and applying standard retrieval techniques
and algorithms on the campaign's raw lidar data. The automatic analysis was conducted by running the PollyNET Processing
Chain (PPC) on the same raw data. For the comparison, the individual profiles of the two datasets were linked based on a tem-
poral proximity criterion. Basic lidar retrieval parameters from both datasets like reference heights and values, depolarization-
415 calibration constants, and molecular depolarization ratio parameters were compared. Layer-mean values of backscatter and
extinction coefficients, particle depolarization and lidar ratios, and extinction- and backscatter-related Ångström exponents of
the linked manually and automatically retrieved profiles were compared in bulk and seasonally resolved. Lastly, seasonal mean
and median profiles of backscatter and extinction coefficients and particle depolarization ratio of the linked automatically ana-
lyzed profiles were compared to the manually analyzed ones.

420 Mean absolute errors in the order of $0.25 \text{ Mm}^{-1} \text{ sr}^{-1}$ in the comparison of automatic and manual layer-mean backscatter co-
efficients at 355, 532, and 1064 nm are found. The absolute values of the percentage differences of the manual and automatic
seasonal mean and median backscatter coefficient profiles at 1.5 km height are largely less than 10 % at 355 and 532 nm. At
1064 nm, however, absolute values of the percentage differences of up to 25 % in winter and spring are found. These larger
discrepancies can be caused by a combination of the differences in reference values and reference heights. Furthermore, the
425 backscatter coefficient at 1064 nm was often not retrieved at all by the PPC.

Mean absolute errors in the order of 5 Mm^{-1} in the comparison of layer-mean extinction coefficients at 355 and 532 nm are
found. The absolute values of the percentage differences of the manual and automatic seasonal mean and median extinction
coefficient profiles at 1.5 km height are largely less than 5 %.

Mean absolute errors of 0.02 in the comparison of layer-mean particle depolarization ratios at 355 and 532 nm are found.
430 The absolute values of the percentage differences between manual and automatic seasonal mean and median particle depo-
larization ratios at 1.5 km height are largely below 20 % at 355 and below 10 % at 532 nm wavelength, respectively. These
differences in the particle depolarization ratio profiles can be caused by differences in the backscatter coefficient profiles, the
depolarization-calibration constant, and the molecular depolarization ratio parameter. For the used raw data from a strongly
dust-laden location, the PPC often fails to retrieve molecular depolarization ratio parameters in an ideally aerosol-free height
435 range, and therefore needs to fall back to default values.

The derived aerosol optical properties, i.e., the lidar ratios at 355 and 532 nm, and the extinction- and backscatter-related
Ångström exponents, were only compared by layer means. Mean absolute errors of 5.3 and 3.5 sr, respectively, in the compar-
ison of layer-mean lidar ratios at 355 and 532 nm are found. Mean absolute errors of 0.18 in the case of the extinction-related,
and 0.4 and 0.27, respectively, in case of the backscatter-related Ångström exponents of the 355/532 and 532/1064 nm wave-
440 length pairs were found.

The results of the comparison presented in this study lead to the conclusion that the PPC products are well suitable for the



common fields of applications of lidar-derived aerosol optical property profiles. The extinction coefficient profiles retrieved by the PPC can be used for instance for extinction statistics (e.g., Baars et al., 2012; Hofer et al., 2020a) as discrepancies between automatic and manual extinction coefficient profiles are well within the measurement uncertainties of Raman-retrieved extinction coefficient profiles (e.g., 5–10 Mm^{-1} caused by the uncertainty the atmospheric input parameters, i.e., temperature and pressure profiles; Ansmann et al., 1992a). Caution has to be taken at extreme events, where discontinuities in the automatic extinction coefficient profiles could lead to distortions of for example seasonal mean and median profiles. The discrepancies found between manual and automatic particle depolarization ratio and backscatter coefficient profiles, which are largely within the measurement uncertainties and particularly small at 532 nm, suggest that the PPC profiles offer sufficient accuracy for POLIPHON retrievals of estimates of microphysical and cloud-relevant aerosol properties, while the larger discrepancies of the particle depolarization ratios at 355 nm would need to be considered in the enhanced uncertainties using that wavelength (Mamouri and Ansmann, 2017). However, the automatic particle depolarization ratio profiles at both wavelengths needed significant trimming to denoise them at the level of seasonal means. This might obstruct such retrievals and would make manual interventions or postprocessing necessary. The discrepancies of the automatic and manual layer-mean values of lidar and particle depolarization ratios, again particularly at 532 nm, and extinction-related Ångström exponents are sufficiently small, i.e., within the measurement uncertainties (e.g., Hofer et al., 2017), for aerosol typing efforts (e.g., Groß et al., 2025). However, the elevated discrepancies between automatic and manual particle depolarization ratios at 355 nm and in particular backscatter-related Ångström exponents, if used at all in aerosol typing (e.g., Gómez Maqueo Anaya et al., 2025), need to be considered in the uncertainties of a typing.

Cloud contamination in the automatic profiles played only a minor role in the comparisons in this study, because only automatic profiles or sections of these profiles (i.e., layer means) were used that were evaluated temporally close to the carefully cloud-filtered manual profiles. This led to an implicit cloud filtering of the automatic profiles. Nevertheless, some cloud contamination affected the seasonal-mean automatic profiles. Tuning the current gradient-based cloud-filtering method to be more strict or applying threshold-based methods in a postprocessing (e.g., Müller et al., 2026) could be options to reduce cloud contamination.

The PPC can also retrieve near-range profiles of backscatter and extinction coefficients using PollyXT's near-range channels, which usually consist of 355 and 532 nm and their corresponding Raman channels (Engelmann et al., 2016). Further comparisons regarding those retrievals will be needed, which this study could not provide since the PollyXT system used during CADEX (specifically, PollyXT_TROPOS; Baars et al., 2016), at that time, did not have near-range capability, which was only added later (e.g., Heese et al., 2022).

The most recent and major change of the PPC is transferring the code from proprietary Matlab to open-source Python (<https://github.com/PollyNET/PicassoPy>, last access: 30 June 2026) to enable a broader community to participate in the development. The Python-based version is envisaged to become operational in the near future, after implementing and testing all the features of the yet operational Matlab-based version. A product already recently added to the PPC are retrievals of microphysical and cloud-relevant aerosol properties via POLIPHON (https://github.com/PollyNET/Pollynet_Processing_Chain, last access: 30 June 2026) using 355, 532, and, if available, 1064 nm parameters and corresponding, novel conversion fac-



480 tors (Ansmann et al., 2026; Hofer et al., 2026a). Further planned extensions to the PPC — foreseen for the rather distant future — are implementing a more intuitive and interactive user interface, optimal estimation methods for Raman extinction retrieval (Povey et al., 2014) and aerosol typing (Floutsi et al., 2024), advanced 1064 nm backscatter coefficient calibration techniques, system condition monitoring including ACTRIS-conform quality assurance outputs (e.g., ACTRIS/CARS, 2024), and polarization-dual-field-of-view (Jimenez et al., 2020a, b, 2026) and fluorescence lidar products (e.g., Gast et al., 2025).



Acknowledgements. The CADEX project was funded by the German Federal Ministry of Education and Research (BMBF), now German Federal Ministry of Research, Technology and Space (BMFTR), in the context of "Partnerships for sustainable problem solving in emerging and developing countries" under the grant number 01DK14014. The construction of a new lidar for permanent observations in Tajikistan was funded by the BMBF (now BMFTR) under the grant number 01LK1603A. We would like to thank the National Academy of Sciences of Tajikistan for the helpful support of any kind during all stages of the CADEX campaign. This research has been supported by the BMBF (now BMFTR) under the FONA Strategy "Research for Sustainability" (grant no. 01LK2001A and 01LK2002A). This activity has received funding from the European Union's Horizon 2020 research and innovation programme through the ATMO-ACCESS Integrating Activity under grant agreement No 101008004.

Code and data availability The used datasets are available at Zenodo (Hofer et al., 2026b). Furthermore, the manually analyzed profiles are available via ACTRIS services at <https://data.earlinet.org/> (last access: 30 June 2026). The code of the PollyNET Processing Chain is available at Zenodo (Klamt et al., 2024).

Author contributions. JH performed the manual analysis of the CADEX data and drafted the manuscript. HoB, ZY, AK, MR, LK, AAF, CJ, BG, NS, JN, HâB, and MH were involved in the development of PPC. JB provided the analysis of the accumulated measurement time within PollyNET. UW, AA, DA, RE, SFA, and ANM were essential in conducting the CADEX campaign and its data analysis. All authors jointly contributed to the paper and the technical discussion.

Competing interests. At least one of the (co-)authors is a member of the editorial board of Atmospheric Measurement Techniques.



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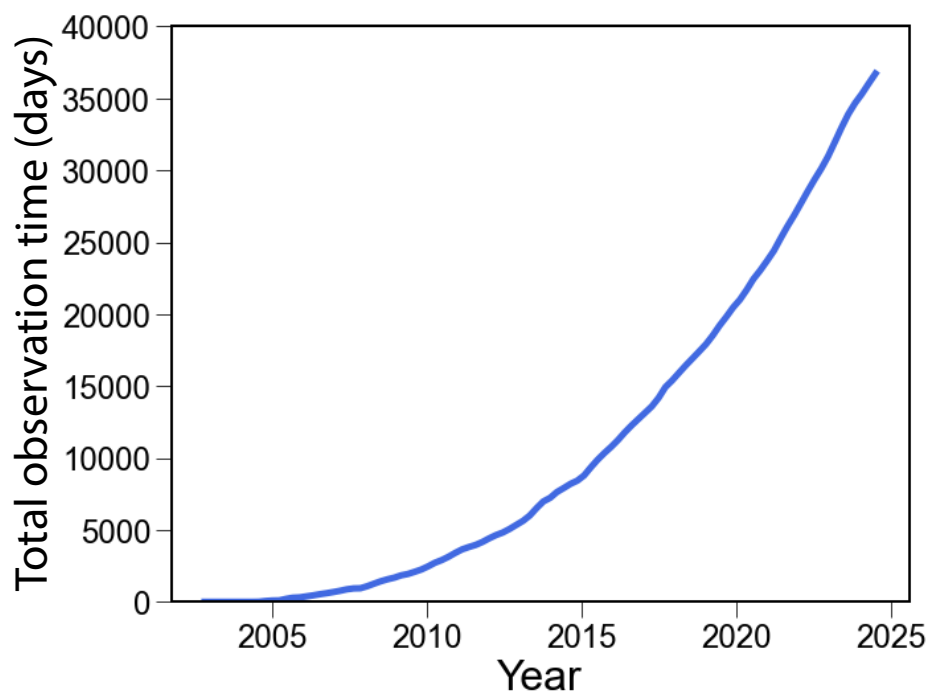


Figure 1. Accumulated lidar observation time since the establishment of PollyNET.

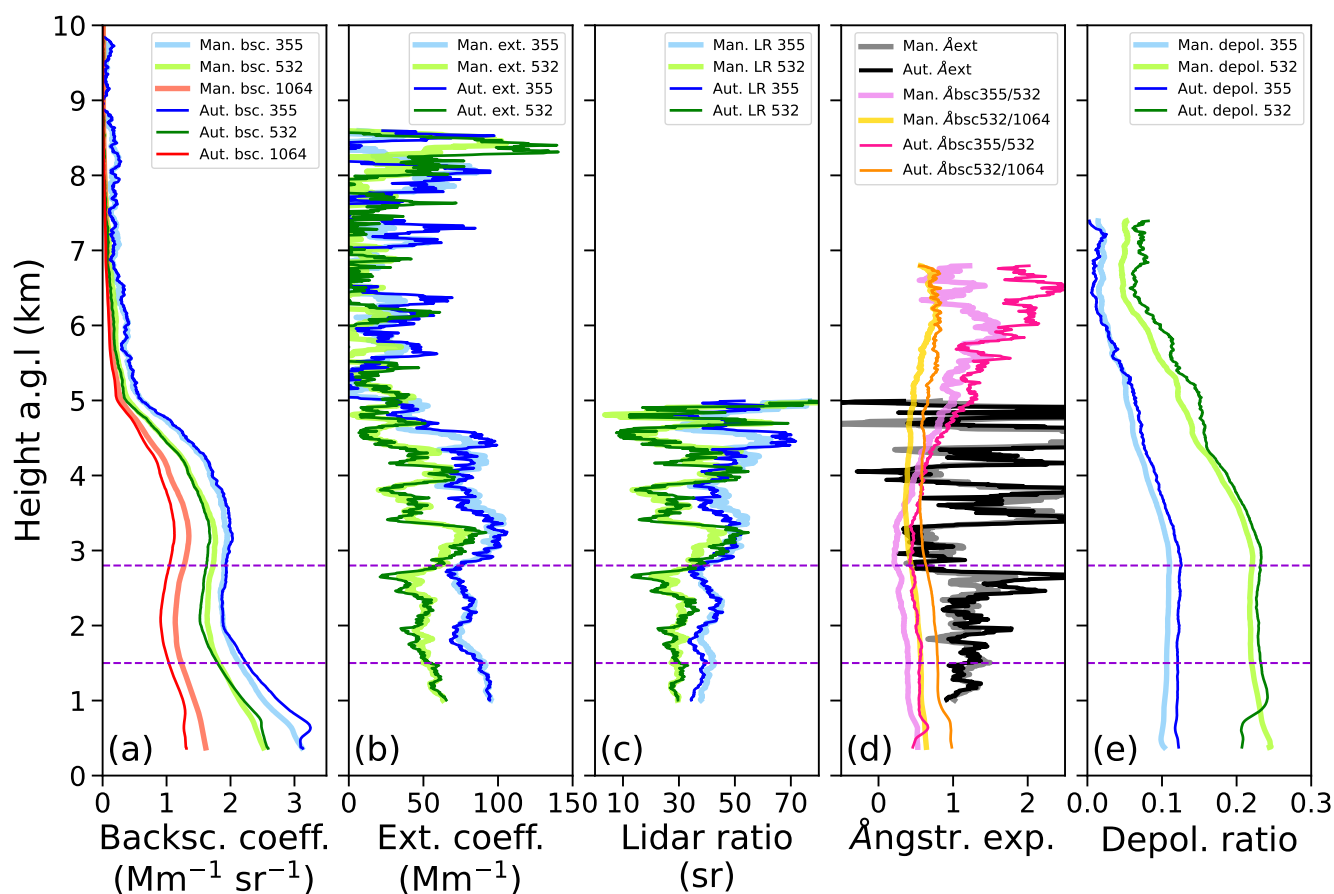


Figure 2. Profiles of aerosol optical properties at Dushanbe measured by PollyXT on 13 July 2015. Backscatter coefficient (a), extinction coefficient (b), lidar ratio (c), extinction- and backscatter-related Ångström exponents (d), and particle depolarization ratio (e) manually analyzed from 16:00–17:38 UTC (lighter colors, thicker lines) and automatically analyzed from 16:18–17:17 UTC (darker colors, thinner lines) with a vertical smoothing length of 742.5 m are shown. The heights at which the profiles are cut are described in Sect. 2.1. Horizontal violet dashed lines indicate the averaging height range used to retrieve the layer-mean values. The uncertainties of the aerosol optical properties are 5–10 (backscatter coefficient), 10–20 (extinction coefficient), 11–22 (lidar ratio), 7–11 (particle depolarization ratio), and 14–28 and 7–11 %, respectively, (extinction- and backscatter-related Ångström exponents) (Hofer et al., 2017).

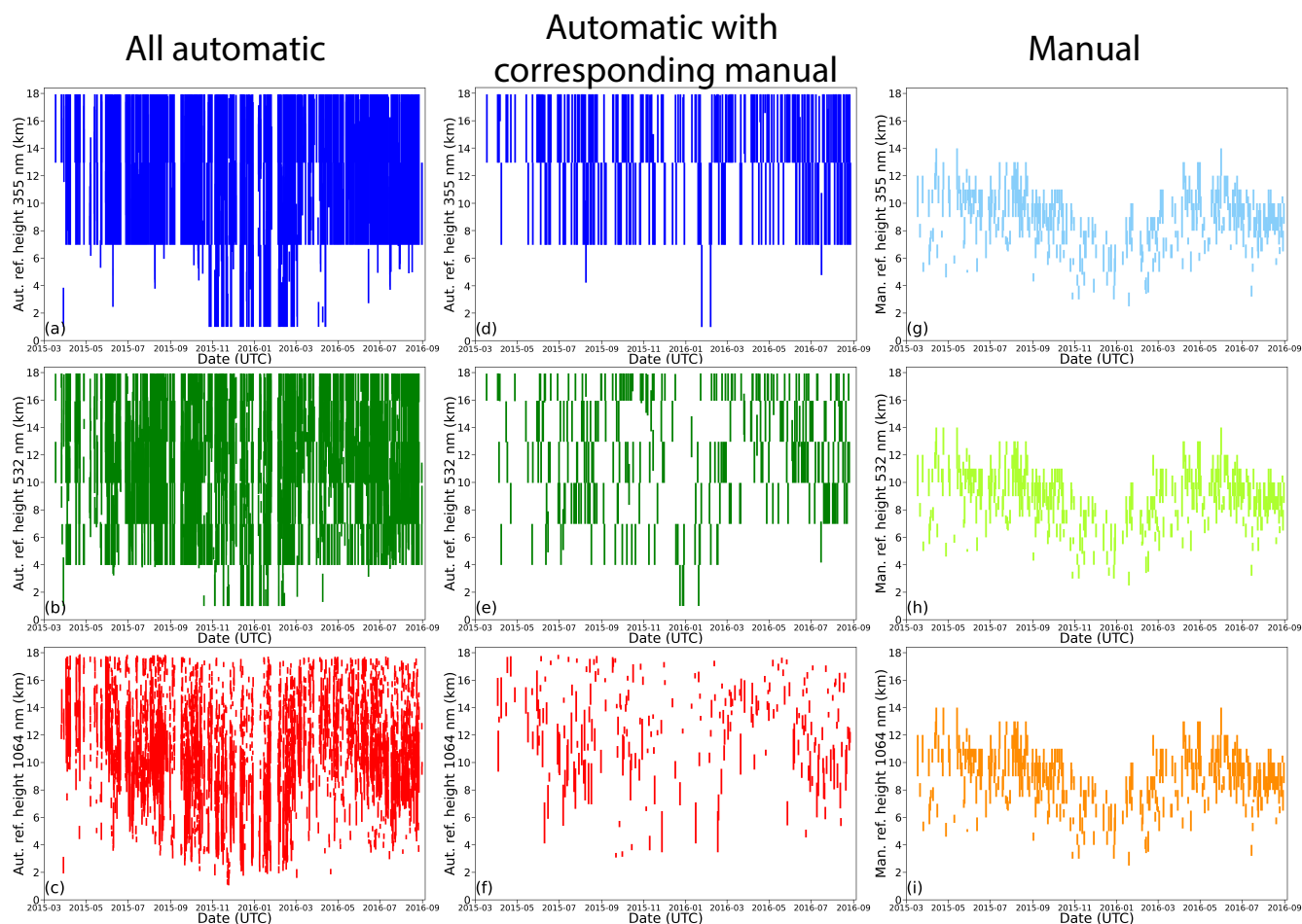


Figure 3. Time series of reference heights (in km a.g.l.) displayed as vertical bars. The reference heights for all available automatic profiles are shown on the left-hand side for 355 (a), 532 (b), and 1064 nm wavelength. The reference heights of the automatic profiles linked to corresponding manual profiles (time gap between the middle times of the averaging periods < 2 h) used for the comparisons of the layer-mean values (Sects. 3.2) and the backscatter coefficient and particle depolarization ratio profiles (Sect. 3.4) are shown in the center for 355 (d), 532 (e), and 1064 nm wavelength (f). The reference heights of the manual profiles are shown on the right-hand side for 355 (g), 532 (h), and 1064 nm wavelength (i).

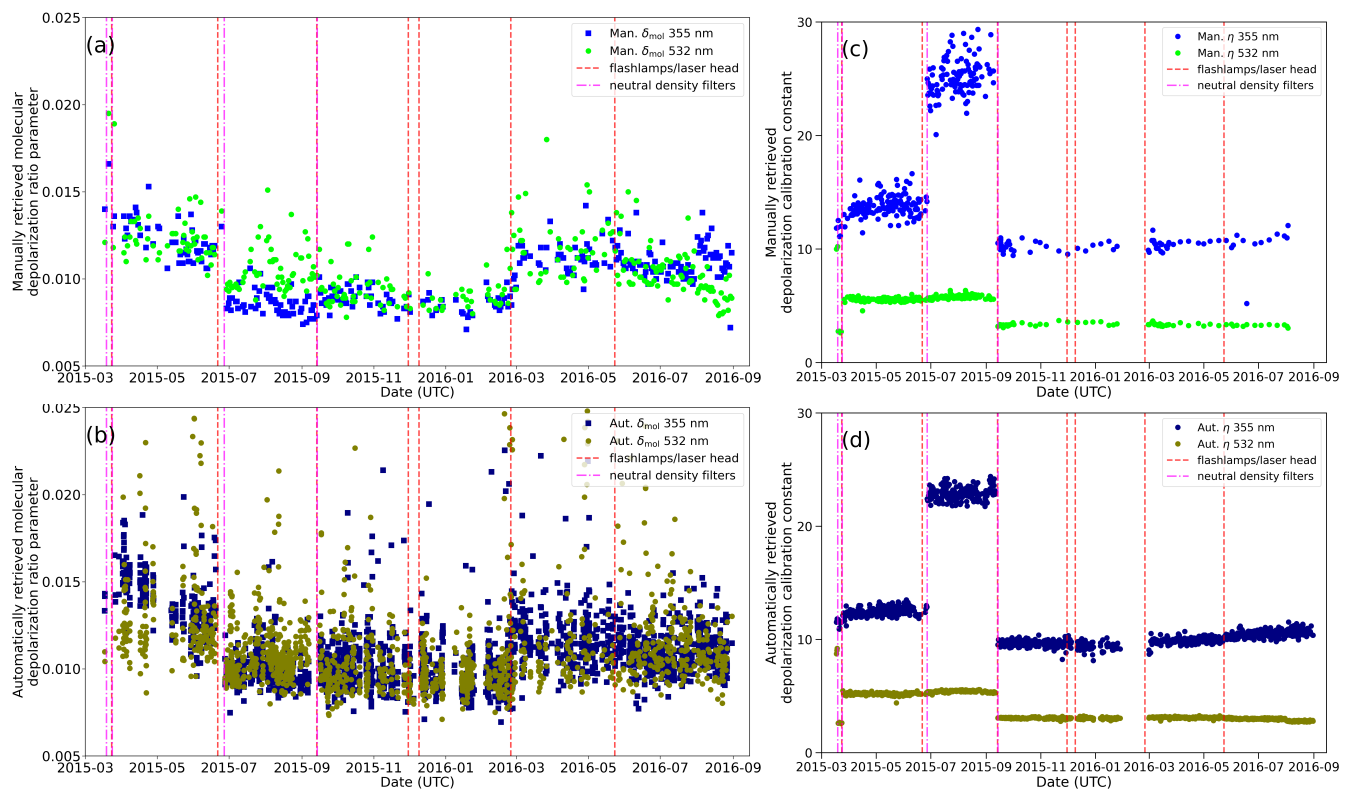


Figure 4. Time series of the molecular depolarization ratio parameter δ_{mol} averaged around the chosen reference heights (see Fig. 3) used in the manual profiles for 355 (blue) and 532 nm (lime) (a), and automatically retrieved for all available automatic profiles for 355 (navy) and 532 nm wavelength (olive) (b). Time series of depolarization-calibration constants η manually retrieved from $\Delta 90^\circ$ -calibration measurements for 355 (blue) and 532 nm wavelength (lime) (c), and automatically retrieved for all automatic profiles for 355 (navy) and 532 nm wavelength (olive) (d). Times of laser head removals and flashlamp exchanges are indicated with red dashed vertical lines. Times of neutral density filter changes are indicated with magenta dash-dotted vertical lines. Default δ_{mol} and η values (see Table A4 and Fig. A1) were excluded in (b,d).

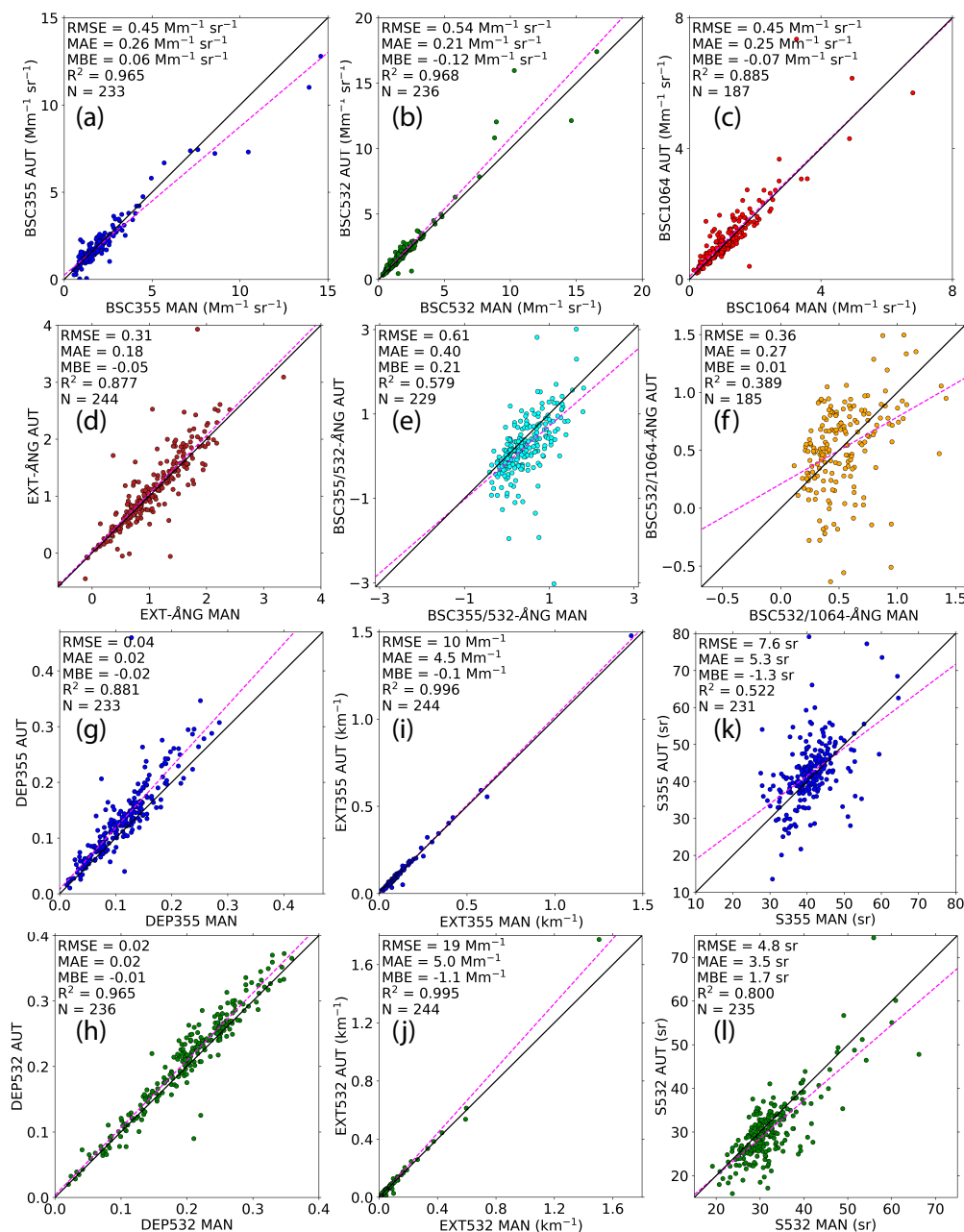


Figure 5. Scatterplots of layer-mean aerosol optical properties of the automatic versus manual profiles. Shown are the scatterplots for the backscatter coefficients at 355 (a), 532 (b), and 1064 nm (c) wavelength, the Ångström exponents for the 355/532 extinction (d), 355/532 backscatter (e), and 532/1064 nm backscatter wavelength pairs (f), the particle depolarization ratios at 355 (g) and 532 nm wavelength (h), the extinction coefficients at 355 (i) and 532 nm (j), and the lidar ratios at 355 (k) and 532 nm wavelength (l). N denotes the number of layer means. The least-square regression line (dashed magenta), the coefficient of determination (R^2), the root-mean-square error (RMSE), the mean absolute error (MAE), the mean bias error (MBE), and the identity line (solid black) are given. In (a), (b) and (k), one case, and in (l), two cases of negative automatic layer means are removed. In (k) and (l), one case of an automatic lidar ratio >100 sr is removed.

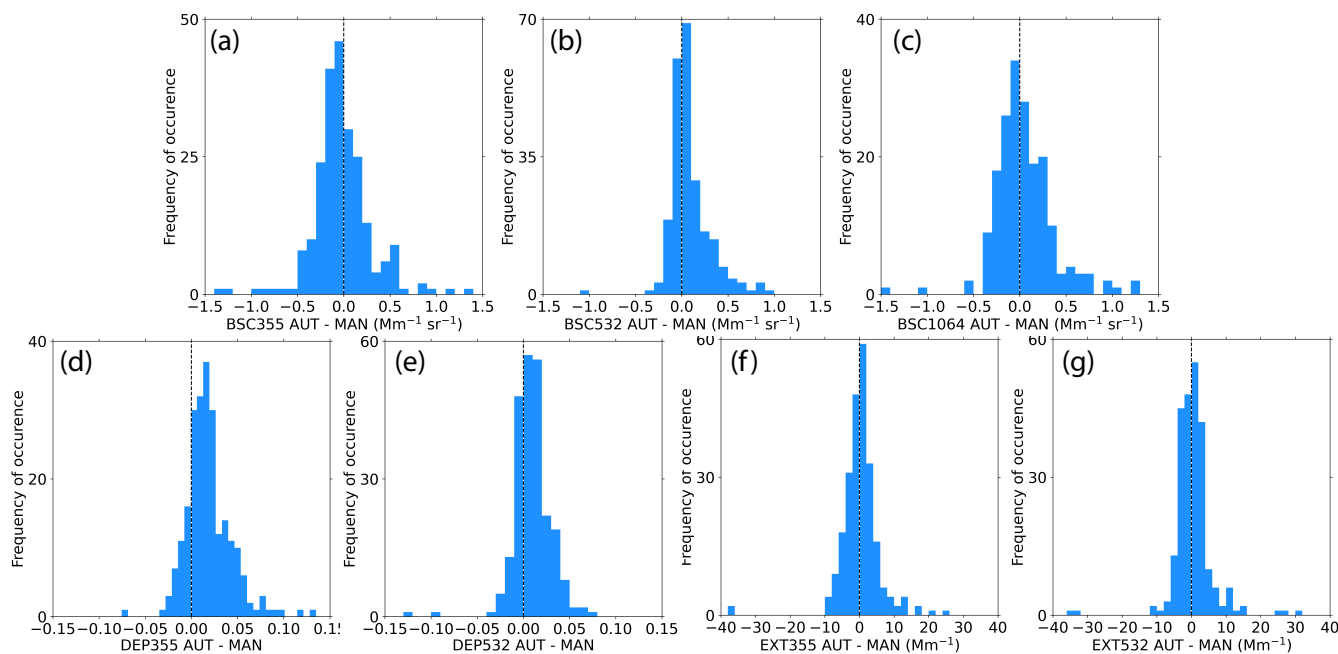


Figure 6. Histograms of residuals of layer-mean aerosol optical properties of the automatic and manual profiles (automatic–manual). The residuals of the layer-mean backscatter coefficients at 355 (a), 532 (b), and 1064 nm (c) wavelength ($2 \text{ Mm}^{-1} \text{sr}^{-1}$ binwidth), the particle depolarization ratios at 355 (d) and 532 nm wavelength (e) (0.01 binwidth), and the extinction coefficients at 355 (f) and 532 nm wavelength (g) (2 Mm^{-1} binwidth) are shown. Not the full data range, but a zoom around the zero residual line (black-white dashed vertical line) is shown.

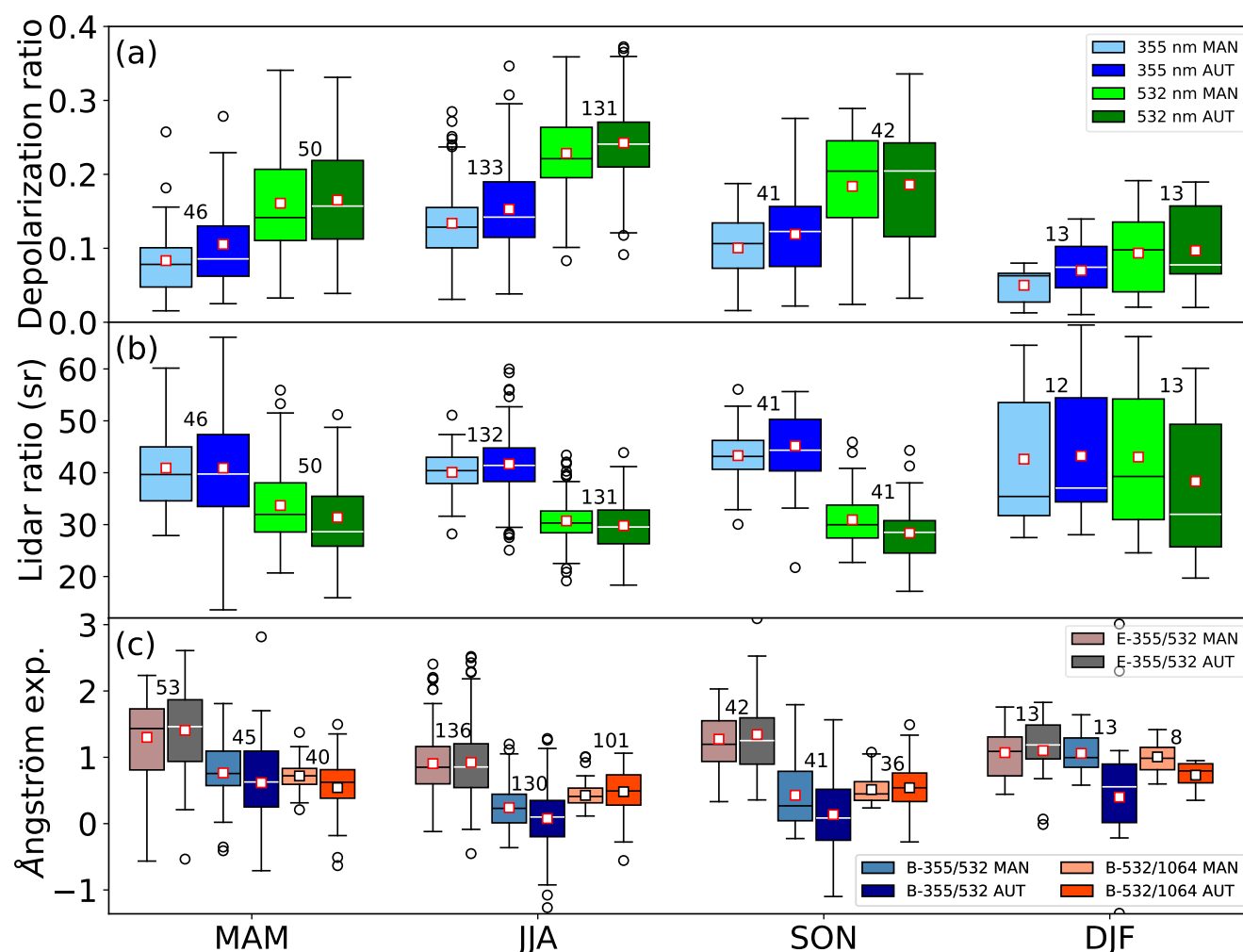


Figure 7. Boxplots of layer-mean particle depolarization ratio (a), lidar ratio at 355 (manual: light blue; automatic: blue) and 532 nm wavelength (manual: lime; automatic: green) (b), and extinction-related Ångström exponent (manual: brown, automatic: grey), and backscatter-related Ångström exponent for the 355/532 (manual: light blue; automatic: dark blue) and 532/1064 nm wavelength pair (manual: salmon; automatic: orange) (c) per season. The seasons spring (MAM; March, April, May), summer (JJA; June, July, August), autumn (SON; September, October, November), and winter (DJF; December, January, February) are indicated. The number of profiles per season are given on top of the boxes for each optical property and wavelength (pair). The boxes extend from the lower to the upper quartile values of the data with a line at the median. White squares are the mean. The whiskers extend 1.5 times the interquartile range from the boxes and the fliers (circles) are values outside the whiskers.

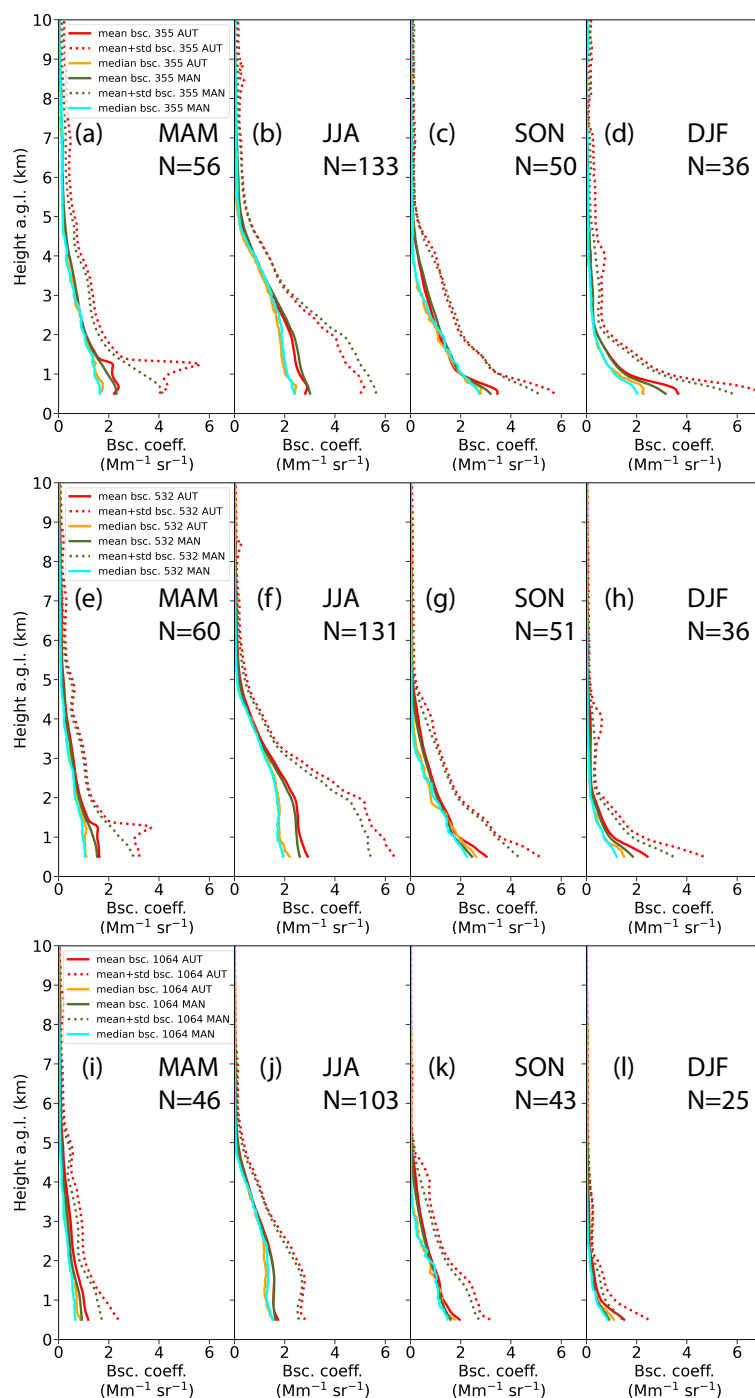


Figure 8. Profiles of median, mean, and mean plus standard deviation (dashed lines) of manual and automatic retrievals of backscatter coefficients at 355 (a–d), 532 (e–h), and 1064 nm wavelength (i–l) for the seasons spring (MAM), summer (JJA), autumn (SON), and winter (DJF). The automatic (manual) median profiles are depicted in orange (cyan). The automatic (manual) mean and mean plus standard deviation profiles are depicted in red (olive).

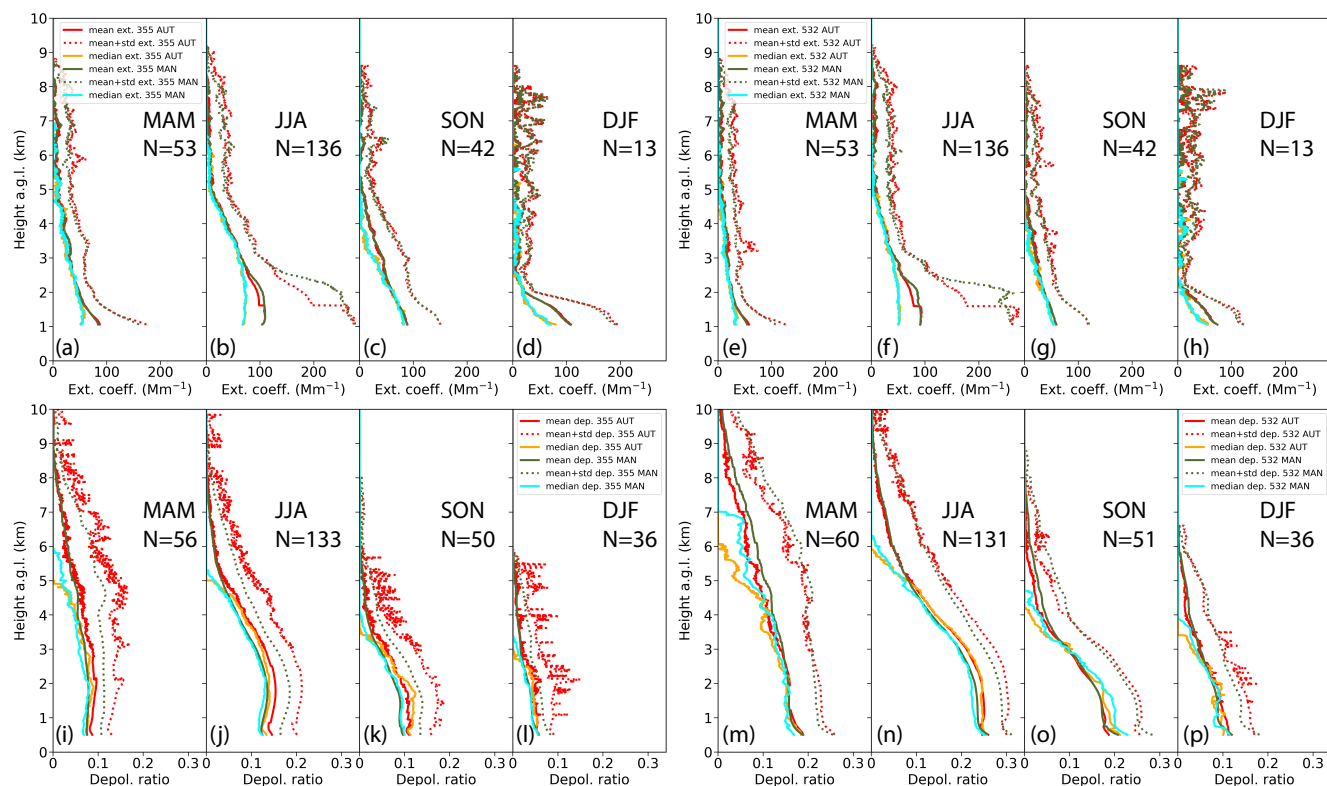


Figure 9. Profiles of median, mean, and mean plus standard deviation (dashed lines) of manual and automatic extinction coefficient at 355 (a–d) and 532 nm wavelength (e–h), and particle depolarization ratio at 355 (i–l) and 532 nm wavelength (m–p) for the seasons spring (MAM), summer (JJA), autumn (SON), and winter (DJF). The color scheme is the same as in Fig. 8. The extinction profiles are cut below 1.05 km and the particle depolarization ratio profiles below 0.5 km due to the overlap region. Particle depolarization ratio values of the automatic profiles >0.4 and <-0.1 were removed for denoising. The jump in the mean and median of the automatic extinction coefficient profiles in summer (b,f) is caused by a single extreme dust event on 14 July 2016, where the automatic extinction coefficient profiles (18:09–19:09 UTC) only reach up to 1.6 km.



Table 1. Seasonal mean (median) $\pm$ standard deviation of automatic (Aut) and manual layer-mean values (Man) of the lidar ratio at 355 (S_{355}) and 532 (S_{532}), the particle depolarization ratio at 355 ($\delta_{p,355}$) and 532 nm wavelength ($\delta_{p,532}$), and the extinction-related ($\hat{A}_{E,355/532}$) and backscatter-related Ångström exponents of the 355/532 ($\hat{A}_{B,355/532}$) and 532/1064 nm ($\hat{A}_{B,532/1064}$) wavelength pairs as shown in the boxplots in Fig. 7.

Season	MAM	JJA	SON	DJF
Quantity				
Man S_{355} (sr)	40.9 (39.7) $\pm$ 7.7	40.1 (40.4) $\pm$ 3.8	43.3 (43.1) $\pm$ 5.0	42.6 (35.4) $\pm$ 13.5
Aut S_{355} (sr)	40.9 (39.7) $\pm$ 12.1	41.7 (41.4) $\pm$ 6.2	45.2 (44.3) $\pm$ 8.5	43.2 (37.0) $\pm$ 12.9
Man S_{532} (sr)	33.7 (32.0) $\pm$ 7.8	30.7 (30.3) $\pm$ 4.2	30.9 (30.0) $\pm$ 5.2	43.0 (39.3) $\pm$ 13.6
Aut S_{532} (sr)	31.4 (28.6) $\pm$ 9.9	29.8 (29.5) $\pm$ 4.7	28.4 (28.5) $\pm$ 5.7	38.3 (32.0) $\pm$ 14.0
Man $\delta_{p,355}$	0.08 (0.08) $\pm$ 0.04	0.13 (0.13) $\pm$ 0.05	0.10 (0.11) $\pm$ 0.04	0.05 (0.06) $\pm$ 0.02
Aut $\delta_{p,355}$	0.11 (0.09) $\pm$ 0.07	0.15 (0.14) $\pm$ 0.06	0.12 (0.12) $\pm$ 0.06	0.07 (0.07) $\pm$ 0.04
Man $\delta_{p,532}$	0.16 (0.14) $\pm$ 0.07	0.23 (0.22) $\pm$ 0.06	0.18 (0.20) $\pm$ 0.07	0.09 (0.10) $\pm$ 0.05
Aut $\delta_{p,532}$	0.17 (0.16) $\pm$ 0.07	0.24 (0.24) $\pm$ 0.06	0.19 (0.20) $\pm$ 0.08	0.10 (0.08) $\pm$ 0.06
Man $\hat{A}_{E,355/532}$	1.30 (1.43) $\pm$ 0.59	0.91 (0.85) $\pm$ 0.50	1.27 (1.20) $\pm$ 0.51	1.07 (1.09) $\pm$ 0.40
Aut $\hat{A}_{E,355/532}$	1.41 (1.46) $\pm$ 0.70	0.92 (0.85) $\pm$ 0.57	1.34 (1.25) $\pm$ 0.58	1.10 (1.19) $\pm$ 0.54
Man $\hat{A}_{B,355/532}$	0.76 (0.76) $\pm$ 0.46	0.24 (0.23) $\pm$ 0.32	0.42 (0.27) $\pm$ 0.50	1.05 (1.00) $\pm$ 0.32
Aut $\hat{A}_{B,355/532}$	0.62 (0.63) $\pm$ 0.76	0.08 (0.10) $\pm$ 0.48	0.14 (0.08) $\pm$ 0.65	0.40 (0.55) $\pm$ 1.44
Man $\hat{A}_{B,532/1064}$	0.72 (0.72) $\pm$ 0.23	0.43 (0.41) $\pm$ 0.16	0.51 (0.45) $\pm$ 0.22	1.01 (0.99) $\pm$ 0.26
Aut $\hat{A}_{B,532/1064}$	0.54 (0.62) $\pm$ 0.47	0.48 (0.49) $\pm$ 0.32	0.54 (0.54) $\pm$ 0.38	0.73 (0.79) $\pm$ 0.21



Appendix A: Appendix

770 Figure A1 shows the actually used molecular depolarization ratio parameter values in the PPC retrieval of the particle depolarization ratio profiles used in the comparison of layer-mean particle depolarization ratios (Sect. 3.2) and particle depolarization ratio profiles (Sect. 3.4), including the recurring default molecular depolarization ratio parameter values of 0.0115 at 355 (less often used) and of 0.0136 at 532 nm wavelength (more often used).

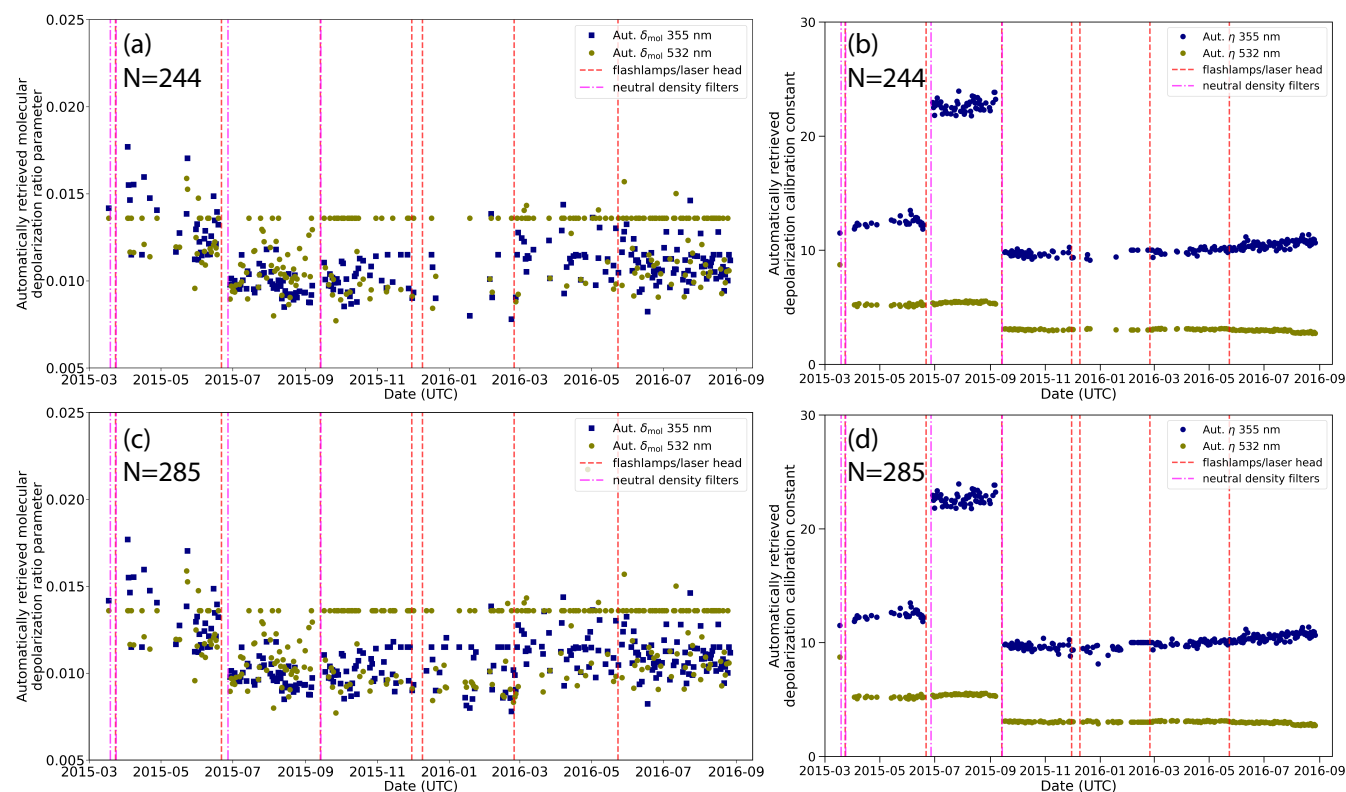


Figure A1. Same as Fig. 4b,d but of automatic profiles (time gap between the middle times of the averaging periods < 2 h) used in the comparison of layer-mean particle depolarization ratios (Sect. 3.2) and particle depolarization ratio profiles (Sect. 3.4), including default values.

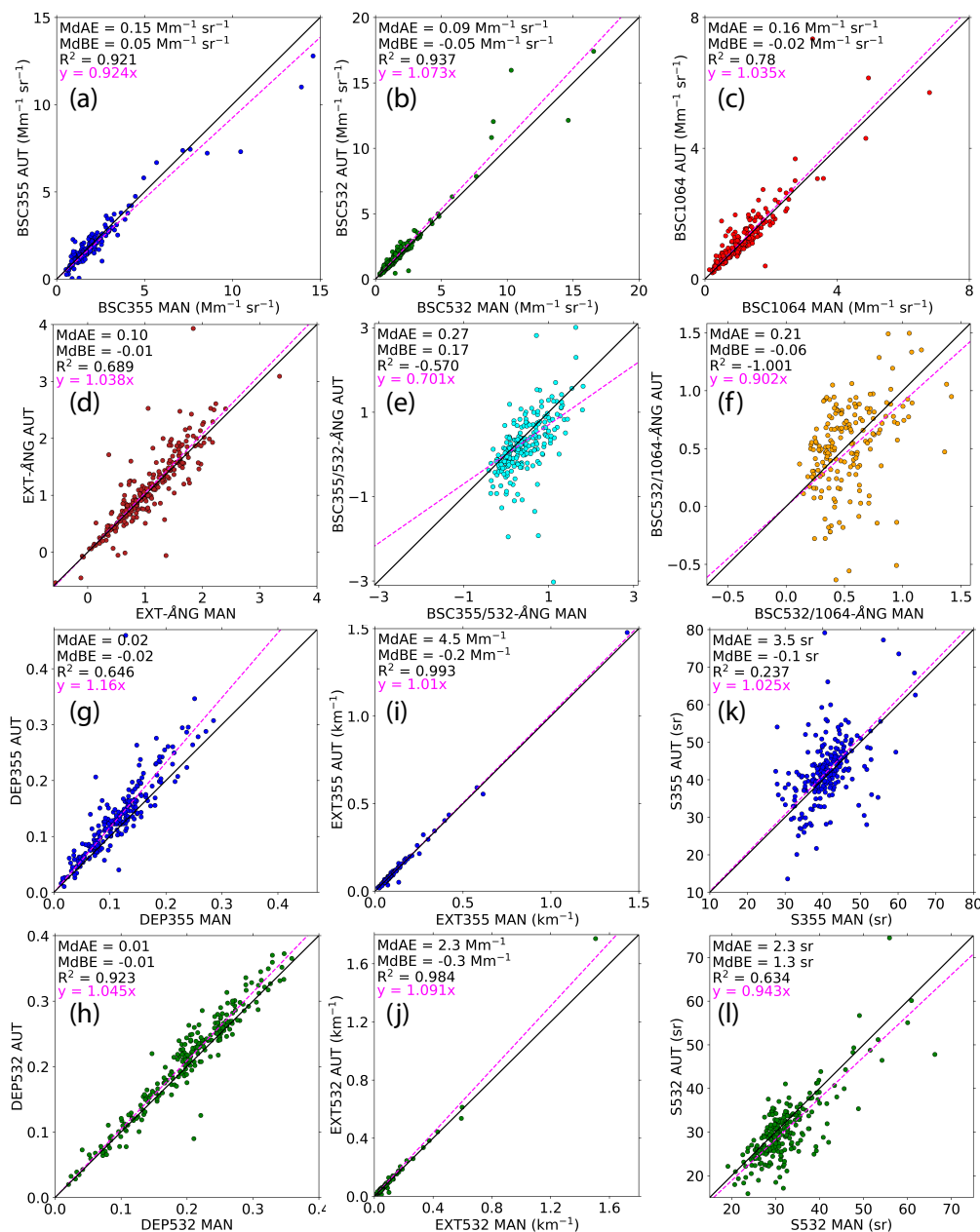


Figure A2. Same as Fig. 5 but forcing the linear regression through the origin, which leads to different coefficients of determination (R^2). Median absolute error (MdAE) and median bias error (MdBE) are provided (instead of mean errors in Fig. 5). The corresponding fit functions are given in magenta text.

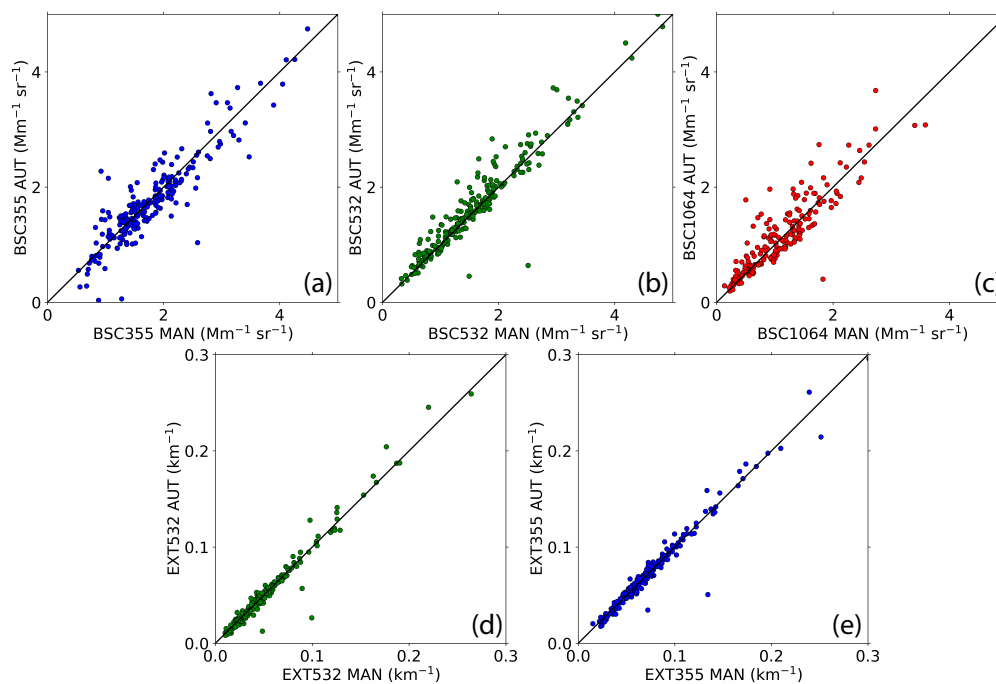


Figure A3. Same as Fig. 5a,b,c but zoomed-in to backscatter coefficient values of maximum $5 \text{ Mm}^{-1} \text{sr}^{-1}$ (a,b,c) and as Fig. 5i,j but zoomed-in to extinction coefficient values of maximum 0.3 km^{-1} (d,e), excluding the fit lines and statistical error parameters.

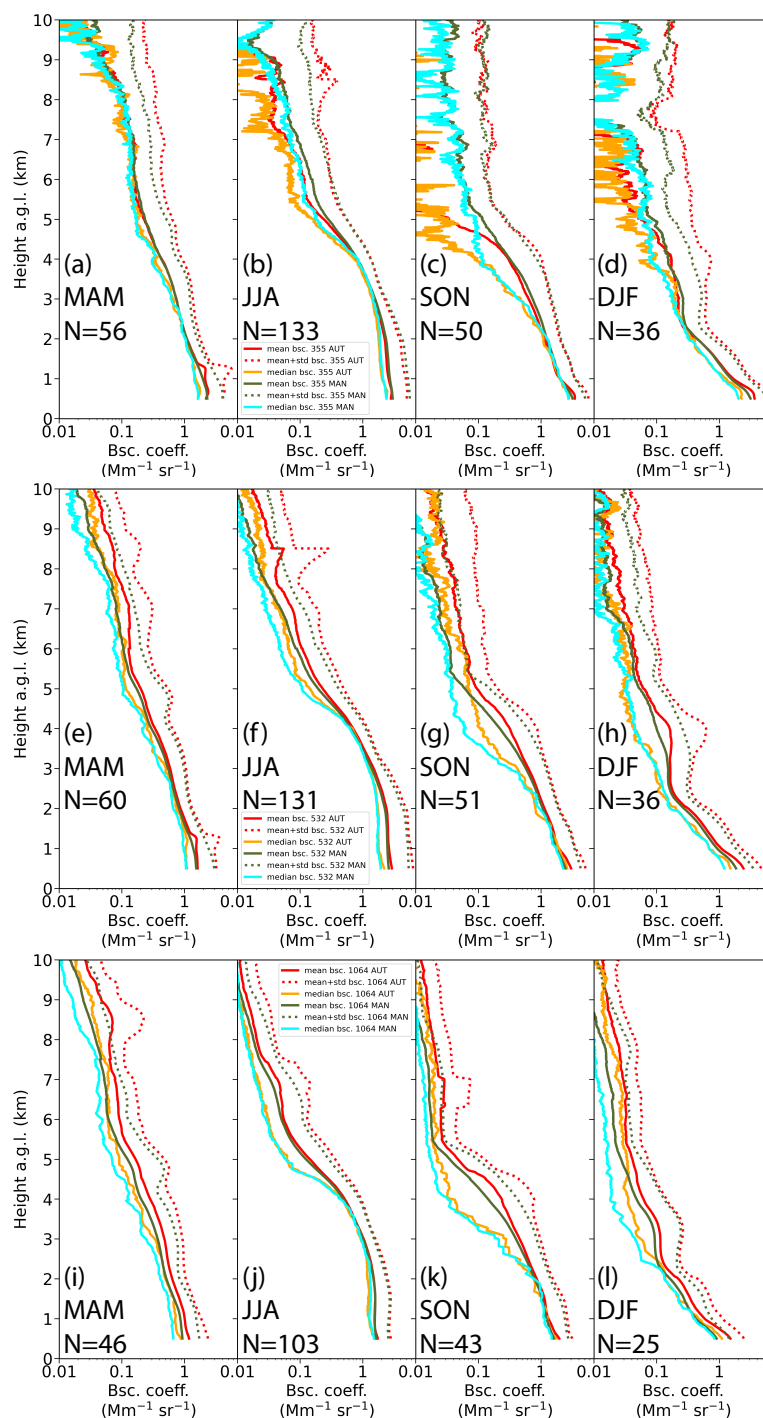


Figure A4. Same as Fig. 8 but with logarithmic x-axes.



Table A1. Pre-set configurations used for analyzing the datasets.

Parameter	Automatic	Manual
Ångström exponent	0	0
Overlap	No correction	No correction
Time period for optical profiles	30–90 min	16–359 min
Meteorological dataset	GDAS1 (GDAS, 2026)	GDAS1
First bin:	251	251
First height (m):	3.75	3.75
Deadtime	Polynomial (Engelmann et al., 2016)	Polynomial
Smoothing	99 bins (i.e., 742.5 m)	99 bins (i.e., 742.5 m)
Optical transmission correction*	Constant value below full overlap height	Constant value below 1 ± 0.1 km
Full overlap height (m):	900	900
Lidar ratio for Klett (sr)	40 at all wavelengths	n.a. (Raman only)

* For the retrieval of the Raman backscatter, the extinction profiles from the surface (instrument altitude) up the height region of choice is needed. This is done in the PPC by assuming a height-constant extinction profile from the height of full overlap (to be set in the configuration) down to the ground using the extinction value at the height of full overlap. For the manual analysis, this height region can be chosen individually, which was the case and given as mean ($\approx$ median) $\pm$ standard deviation, or the transmission correction for particles only can be neglected. Molecular transmission is always taken into account.

Table A2. Retrieval parameters used in the automatic and manual analyses. Aut stands for the automatic and Man for the manual analysis type.

Wavelength (nm)	355	355	532	532	1064	1064
Analysis type	Aut	Man	Aut	Man	Aut	Man
Maximum reference height (m)	18000	free	18000	free	18000	free
Reference height thickness (m)	1000–6000	free	600–3000	free	300–2000	free
Reference value ($\text{m}^{-1} \text{sr}^{-1}$)	1.00E-08	1.00E-08	1.00E-08	1.00E-08	5.00E-09	1.00E-08
Min. SNR Klett (elastic)	5	n.a.	3	n.a.	1	n.a.
Min. SNR Raman (elastic+inelastic)	5+3	~ 5	4+2	~ 5	0.5	~ 5

Table A3. Automatically (Aut) and manually determined (Man) depolarization-calibration constants (η ; mean (median) $\pm$ standard deviation) at 355 and 532 nm wavelength (subscript) for periods of constant system configuration.

Period	Aut η_{355}	Man η_{355}	Aut η_{532}	Man η_{532}
17–18 Mar. 2015	11.52*	11.87 (11.87) $\pm$ 0.03	8.74*	10.12 (10.12) $\pm$ 0.11
19–22 Mar. 2015	n.a.†	11.70 (11.59) $\pm$ 0.60	n.a.†	2.72 (2.74) $\pm$ 0.05
23 Mar.–26 Jun. 2015	12.41 (12.39) $\pm$ 0.37	13.90 (13.73) $\pm$ 1.30	5.19 (5.19) $\pm$ 0.10	5.54 (5.53) $\pm$ 0.15
27 Jun.–13 Sep. 2015	22.70 (22.64) $\pm$ 0.52	25.00 (24.92) $\pm$ 2.08	5.42 (5.44) $\pm$ 0.08	5.76 (5.77) $\pm$ 0.29
14 Sep. 2015–31 Aug. 2016	9.98 (9.90) $\pm$ 0.53	10.32 (10.41) $\pm$ 0.76	3.02 (3.03) $\pm$ 0.20	3.34 (3.32) $\pm$ 0.13

* During that period, only values from a single $\Delta 90^\circ$ -calibration measurement are available. Hence, no standard deviation and median is provided.

† During that period, no automatic profiles were retrieved by the PPC.



Table A4. Default values of the depolarization-calibration constant η and the molecular depolarization ratio parameter δ_{mol} . The numeric subscript indicates the wavelength in nm.

Parameter	Automatic	Manual
η_{355}	Last database entry (if too old, default value [*])	No default but mean value (see Fig. 4c and Table A3)
η_{532}	Last database entry (if too old, default value [†])	No default but mean value (see Fig. 4c and Table A3)
$\delta_{\text{mol},355}$	0.0115	No default but individual value (see Fig. 4a and Table A5; mean is not used but calculated for illustration here)
$\delta_{\text{mol},532}$	0.0136	No default but individual value (see Fig. 4a and Table A5; mean is not used but calculated for illustration here)

^{*} 10.02 (29 Jan. – 27 Feb. 2016) or 5.5 (else; only once used on 28 Feb. 2016, 12:22–13:19 UTC).

[†] 3.02 (29 Jan. – 27 Feb. 2016) or 14.6 (else; only once used on 28 Feb. 2016, 12:22–13:19 UTC).

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Table A5. Automatically (Aut) and manually determined (Man) molecular depolarization ratio parameters (δ_{mol} ; mean (median)±standard deviation) at 355 and 532 nm wavelength (subscript) for the same periods (five rows) of constant system configuration as in Table A3.

Aut $\delta_{\text{mol},355}$	Man $\delta_{\text{mol},355}$	Aut $\delta_{\text{mol},532}$	Man $\delta_{\text{mol},532}$
0.0139 (0.0142)±0.0004	0.0140 [*]	0.0107(0.0107)0.0003	0.0121 [*]
n.a. [†]	0.0166 [*]	n.a. [†]	0.0195 [*]
0.0157 (0.0137)±0.0175 [‡]	0.0122 (0.0121)±0.0010	0.0136 (0.0122)±0.0039	0.0124 (0.0121)±0.0013
0.0099 (0.0097)±0.0009	0.0086 (0.0085)±0.0008	0.0109 (0.0105)±0.0019	0.0106 (0.0102)±0.0013
0.0109 (0.0105)±0.0039	0.0102 (0.0104)±0.0014	0.0110 (0.0101)±0.0036	0.0102 (0.0098)±0.0016

^{*} During each of those periods, only one manual profile is available. Hence, no standard deviation and median is provided.

[†] During that period, no automatic profiles were retrieved by the PPC.

[‡] The large standard deviation is caused by a few outliers.

Table A6. Seasonal-mean (median) backscatter coefficient at 355 (β_{355}), 532 (β_{532}) and 1064 (β_{1064}), extinction coefficient at 355 (α_{355}) and 532 (α_{532}), particle depolarization ratio at 355 ($\delta_{\text{p},355}$) and 532 nm wavelength ($\delta_{\text{p},532}$) at 1.5 km height as in the profiles in Figs. 8 and 9.

Season	MAM	JJA	SON	DJF
Quantity				
Man β_{355} ($\text{Mm}^{-1} \text{sr}^{-1}$)	1.45 (1.32)	2.54 (1.96)	1.60 (1.58)	0.87 (0.63)
Aut β_{355} ($\text{Mm}^{-1} \text{sr}^{-1}$)	1.49 (1.33)	2.39 (1.87)	1.50 (1.49)	0.89 (0.62)
Man β_{532} ($\text{Mm}^{-1} \text{sr}^{-1}$)	1.06 (0.88)	2.42 (1.75)	1.41 (1.40)	0.53 (0.36)
Aut β_{532} ($\text{Mm}^{-1} \text{sr}^{-1}$)	1.15 (0.97)	2.52 (1.76)	1.53 (1.41)	0.60 (0.42)
Man β_{1064} ($\text{Mm}^{-1} \text{sr}^{-1}$)	0.68 (0.54)	1.58 (1.34)	1.04 (1.01)	0.27 (0.22)
Aut β_{1064} ($\text{Mm}^{-1} \text{sr}^{-1}$)	0.83 (0.68)	1.58 (1.21)	1.13 (1.01)	0.34 (0.23)
Man α_{355} (Mm^{-1})	63.6 (52.9)	108.9 (71.6)	77.5 (71.6)	76.7 (37.7)
Aut α_{355} (Mm^{-1})	64.3 (54.5)	108.4 (71.1)	77.0 (74.0)	79.3 (36.0)
Man α_{532} (Mm^{-1})	36.3 (28.9)	91.1 (50.4)	50.0 (45.8)	48.5 (26.8)
Aut α_{532} (Mm^{-1})	36.8 (30.6)	93.3 (53.3)	48.5 (45.6)	50.1 (26.5)
Man $\delta_{\text{p},355}$	0.078 (0.077)	0.135 (0.126)	0.090 (0.096)	0.041 (0.040)
Aut $\delta_{\text{p},355}$	0.091 (0.083)	0.153 (0.140)	0.106 (0.118)	0.048 (0.047)
Man $\delta_{\text{p},532}$	0.158 (0.150)	0.235 (0.224)	0.170 (0.194)	0.088 (0.092)
Aut $\delta_{\text{p},532}$	0.157 (0.149)	0.249 (0.244)	0.170 (0.174)	0.093 (0.076)