Long-range smoke transport from North America: Optical characterization of smoke layers over the Eastern Mediterranean by means of Polly^{XT} lidar

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Abstract: Increased heat and prolonged drought -parameters strongly connected with climate change- have been the key drivers in amplifying wildfire risk worldwide. Understanding how smoke particles influence the atmospheric system and climate is essential for improving their representation in atmospheric models and climate projections. North America has experienced frequent, intense, and long-lasting wildfire events with transboundary environmental effects, as smoke is transported to distant regions, including Europe. This study focuses on aged smoke aerosol layers transported from North American wildfires and observed in the free troposphere over the Eastern Mediterranean. The layers were detected by the Polly^{XT}-CYP lidar system operated in Limassol, Cyprus. A statistical analysis of the optical and geometrical properties from 2020 to 2025 is conducted, with particular emphasis on the behavior of lidar ratio and particle depolarization ratio at 355 and 532 nm.

1. Introduction

Higher latitudes of the Northern Hemisphere have experienced an increasing trend in wildfire activity in recent years, driven by more frequent heatwaves and droughts [1]. North America is one of the regions most affected, with rising fire activity in the northwestern United States and Canada. The extent and duration of the wildfire season in Northwest America have increased due to climate-change-related factors, while human activities -including land-use changes and land management policies- also contribute to this trend [2]. In recent years, Canada has likewise experienced severe wildfire events, with the typical fire season occurring during the summer months in boreal forest regions. Weather systems play a significant role in wildfire behavior and in the long-range transport of smoke plumes [1].

Cross-oceanic transport of North American smoke to distant regions, such as Europe, and its transboundary effects have been reported in various studies. Ansmann et al. (2018) reported the stratospheric smoke layers over Leipzig, Germany, resulting from the long-range transport of smoke produced by the record-breaking 2017 Canadian wildfires [3]. The smoke travelled across the entire Northern Hemisphere, with 28 European lidar stations capturing this stratospheric perturbation and illustrating the significant impact of long-range smoke transport on the atmosphere [4]. Smoke particles can strongly influence the climate system, as they absorb solar radiation and affect cloud formation [5]. A characteristic case of heterogeneous ice nucleation induced by aged smoke particles was observed at the CARO station in Limassol, Cyprus [6] following the long-range smoke transport from the 2020 North American wildfire events. These findings motivated us to study the smoke layers observed in the free troposphere above Limassol during 2020-2025, originating from North American wildfires. A statistical analysis of their optical and geometrical properties is performed based on Polly^{XT} lidar measurements.

2. Instrumentation

Multiwavelength polarization Raman lidar measurements were performed using the Polly^{XT}-CYP lidar system [7], operating at the Cyprus Atmospheric Remote Sensing Observatory National Facility (CARO NF) of the Eratosthenes Centre of Excellence (ECoE). The system has a 3β+2α+2δ+w configuration enabling the vertically-height resolved retrievals of backscatter coefficient at three wavelengths (355, 532 and 1064 nm); extinction coefficients at 355 and 532 nm; volume and particle linear depolarization ratios (PLDR) at 355 and 532 nm; and the water vapor mixing ratio at 407 nm. Continuous and automated measurements offer the opportunity to monitor the atmosphere in an aerosol-complex environment such as the eastern Mediterranean.

3. Methodology

North American smoke particle layers were detected after conducting HYSPLIT (Hybris Single-Particle Lagrangian Integrated Trajectory model) [8] backward-trajectory analysis and examining VIIRS (Visible Infrared Imaging Radiometer Suite) fire and thermal anomalies data [9]. This approach allowed us to assess the presence of active fire hotspots within the areas crossed by the air masses before reaching Limassol, as well as to determine their arrival time in the study area. It should be noted that we focused on higher-altitude layers based on previous studies for North American aerosol signatures over central Europe [10, 11] and on the climatology of the CARO station. At this site, North American layers are typically observed at altitudes between 3 and 8 km, but aged smoke has also been detected at heights of 10–12 km. However, the signal at these higher altitudes is weaker and cannot be easily analyzed.

Nighttime measurements were primarily used, and the data were processed with a temporal averaging window of 60-150 minutes and vertical smoothing of 500 m. Cases with weak lidar signal were excluded. For each detected layer, mean optical properties were estimated with emphasis on the behavior of aged-smoke lidar ratio and particle depolarization ratio under mixed-aerosol conditions in a climatically sensitive region.

4. First Results

Figure 1 presents a Canadian wildfire smoke measurement retrieved by the Polly^{XT}-CYP lidar at CARO station, on 19 June 2023. The smoke reached Limassol, Cyprus, after 6 days transport and it was detected at 5.3-7.4 km height. For this case, the lidar signal was processed for the period 2030-2258 UTC.

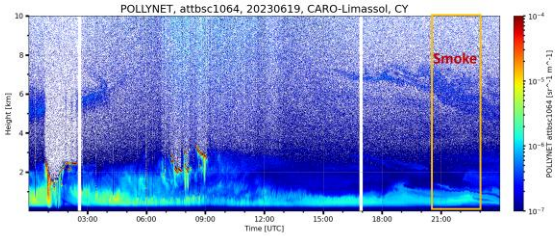

Figure 1. Temporal evolution of the attenuated backscatter signal at 1064 nm on 19.06.2023. The orange rectangle marks the temporal window (2030-2258 UTC) during which the lidar signal was analyzed.

The layer-mean lidar ratio (LR) was found to be equal to 54 ± 16 sr at 532 nm and 50 ± 14 sr at 355 nm, with LR532>LR355 suggesting the presence of aged smoke. However, the spectral difference was less pronounced than reported in previous studies. The particle depolarization ratios (PLDR) were 4 ± 0.4 % (532 nm) and 9 ± 0.5 % (355 nm), with the 355 nm (9%) value coming into contrast with existing findings for tropospheric aged smoke layers. Additionally, the mean backscatter-related Angstrom exponents near to 1.5 confirmed the presence of small particles such as smoke [12, 13]. The vertical profiles of the optical properties are shown in Figure 2.

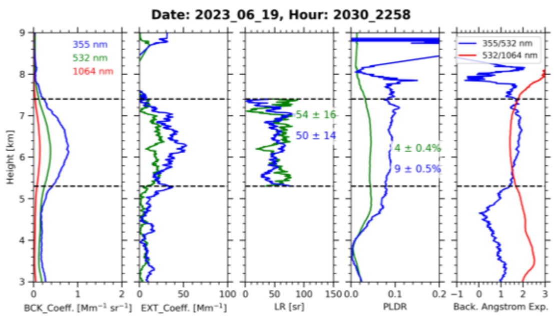

Figure 2. Vertical profiles of intensive and extensive optical properties for 19 June 2023, 2030-2258 UTC.

The first findings of our study showed that during the summer period of 2021-2023, thirteen Canadian smoke layers were detected above Limassol by the Polly^{XT}-CYP lidar. As shown in Figure 3, the lidar ratio exhibited values in the range of approximately 40–80 sr at both wavelengths, with mean values of 60 sr at 532 nm and 56 sr at 355 nm. The expected spectral dependence -typically a higher value at 532 nm than at 355 nm- was not evident in all cases. Nevertheless, the mean color ratio of the lidar ratio (CRLR) was 1.20 ± 0.50, pointing to the presence of aged smoke particles.

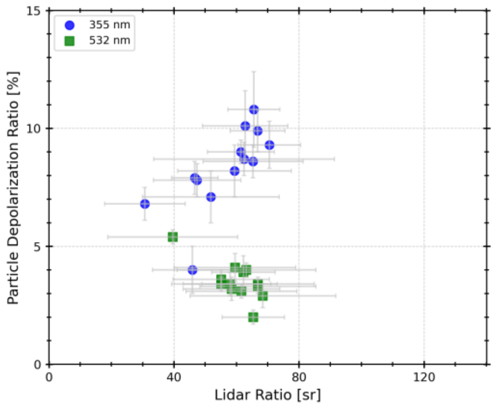

Figure 3. LR versus PLDR values for the observed Canadian smoke layers, measured at 355 nm (blue) and 532 nm (green).

Regarding the PLDR, values at 355 nm were consistently higher than those at 532 nm, with mean values of 8% and 3%, respectively, over the study period. This behavior is clearly presented in Figure 3. The mean backscatter-related Angstrom exponents were 1.81 ± 0.40 for the 355-532 nm spectrum and 1.30 ± 0.17 for the 532-1064 nm spectrum, while the extinction-related Angstrom exponent had a mean value of 1.67 ± 0.75. These values indicated the predominance of fine-mode particles. Table 1 summarizes the mean intensive optical properties for the thirteen smoke layers observed above Limassol after 6–7 days of transport from the Canadian wildfires.

Table 1. Mean intensive optical properties of aged Canadian wildfire smoke

Aged smoke (13 cases)	532 nm	355 nm
LR [sr]	60 ± 7	56 ± 11
PLDR [%]	3 ± 0.8	8 ± 1.7

With respect to the geometrical properties of the particle layers, Figure 4 illustrates the distribution of the layers' bottom and top heights for the thirteen aged smoke layers observed above Limassol. All layers were observed above 4 km, with the lowest bottom and top heights at 4 km and 5.3 km, respectively. The maximum bottom and top heights were 7.2 km and 9.6 km, respectively.

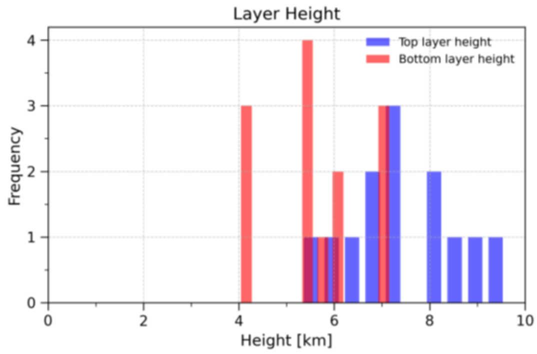

Figure 4. Histogram of the bottom and top heights of the Canadian smoke layers detected by the Polly^{XT}-CYP lidar.

The optical depth (top height minus bottom height) of the observed layers ranged from 1 to 3 km, with minimum and maximum values of 1.1 km and 2.6 km, respectively. Figure 5 shows the distribution of these values, with layer depths of 2–2.3 km being the most frequently observed.

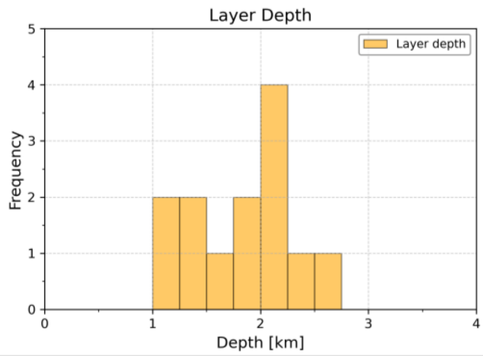

Figure 5. Histogram of layer depth.

To better understand the behavior of North American smoke over the Cyprus region and to support LR and PLDR observations for fresh and aged tropospheric smoke layers, we extended our analysis to the entire period 2020-2025, during which the Polly^{XT} lidar has been operating at the CARO station. Further insights into the behavior of intensive and extensive smoke parameters, as well as the geometrical characteristics of the aged smoke layers will be given.

Acknowledgments

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