Aged and fresh wildfire smoke from different sources in Europe and North America: Long-term lidar observations over Cyprus in the Eastern Mediterranean

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Abstract: Uncontrolled fires, mainly in rural areas, can be considered as wildfires. They are a natural part of many ecosystems, but climate change has notably influenced their frequency and heightened risk. Climate, air quality and visibility can be easily affected by wildfire smoke, so it is of great importance to investigate and improve our current knowledge of smoke particles' properties. During the period 2021-2023, intense wildfires affected many regions worldwide and especially North America and southern Europe. In this study we analyze the optical properties of smoke particles observed in the free troposphere of Limassol, Cyprus, during this period. Based on Hysplit model and VIIRS data we determined the origin and the source of the air masses. Utilizing a multiwavelength polarization Raman lidar, Polly, we investigated the behavior of lidar and particle depolarization ratio at 355 nm and 532 nm at different smoke aging levels.

1. Introduction

Climate change, leading to increased heat, extended drought, and decreased fuel (e.g. trees or forest debris) moisture, has amplified the risk and extent of wildfires worldwide. Moreover, future projections show an increase in the likelihood of fire events in many regions around the globe, even in areas with less fire activity historically [1]. Extended wildfire seasons and heightened frequency have already been spotted in US [2, 3], while studies show escalating wildfire threats in Southern Europe that can be attributed to climate warming [4]. It is well known that smoke particles play an important role in the climate system, impacting it both directly and indirectly. They absorb solar radiation affecting the Earth's radiation budget and influence the evolution of clouds by serving as cloud condensation nuclei (CCN) and ice-nucleating particles (INPs) [5, 6]. These impacts necessitate further study on the properties and behavior of smoke particles.

The fire seasons spanning 2021 to 2023 greatly affected many regions of the Northern Hemisphere with British Columbia (Canada) and southern Europe experiencing a high frequency of extreme fire events [7]. In this study emphasis is given to the intense activity of wildfires in Turkey's Mediterranean Region in July and August 2021 as well as in the major wildfire event in the Evros region of northeastern Greece, close to the Turkish border, that started on 19 August 2023 and lasted for about 15 days. These events led to tragic human losses, evacuations and devastating ecological, environmental, and economic disasters. Additionally, smoke plumes originating from wildfires in North America during this period and reaching Cyprus atmosphere at higher altitudes, are also investigated. These events motivated us to perform a statistical analysis of the smoke particle optical properties detected in the free troposphere above Limassol to investigate the potential changes in the lidar ratio and depolarization ratio of smoke particles at 355 and 532 nm at different aging levels, determined by their travelling times at the area under study. Potential differences in these properties attributed to different origins of the smoke plume will be also studied.

2. Instrumentation

This study was performed utilizing data from the multiwavelength polarization Raman lidar, Polly (POrtabLe Lidar sYstem) [8], which is operated at the Cyprus Atmospheric Remote Sensing Observatory (CARO) of the Eratosthenes Centre of Excellence at Limassol (34.677˚N, 33.0375˚E). It belongs to the third generation of Polly^{XT}s systems and is housed in a container. This system runs autonomously, and it is operated 24/7 with a diode-pumped laser that emits the first (1064nm), second (532 nm) and third (355 nm) harmonic frequency of linear polarization light with a pulse repetition rate of 100 Hz [9]. It enables the retrieval of vertically-height resolved profiles of the particle backscatter coefficient β at 355, 532 and 1064 nm, the particle extinction coefficient α at 355 and 532 nm, the corresponding extinction-to-backscatter ratios (lidar ratios, L), and the volume and particle linear depolarization ratios δ at 355 and 532 nm. The system also includes a water-vapor Raman channel (407 nm) and a second near-range receiver with four channels (355, 387, 532, and 607 nm). Now the full overlap of the overall system is at 120 m height above lidar, and more precise measurements can be made.

3. Data and Methodology

To characterize the aerosol layers in the atmosphere above Limassol, Cyprus, we initially relied on the information given from the quicklooks of the calibrated attenuated backscatter coefficient at 1064 nm and the volume depolarization ratio at 532 nm. Our first indication of smoke particles presence resulted from relatively increased backscatter coefficient values, suggesting the appearance of aerosols, across with low depolarization ratios. Previous research [10], has shown that the depolarization ratio of smoke can vary across different height levels, with lower values dominating in the lower and middle troposphere and higher ratios appearing in the upper troposphere and lower stratosphere, indicative of non-spherical particle shapes. Our analysis focuses on the geometrical and optical properties of smoke particles in the free troposphere, hence our assumption of low depolarization ratios of smoke.

Then, backward trajectories, generated with the HYSPLIT model, were used to confirm the origin of the particles in the observed layers, and to estimate their arrival time in Limassol. VIIRS (Visible Infrared Imaging Radiometer Suite) data, available from the joint NASA/NOAA Suomi National Polar orbiting Partnership (Suomi NPP) satellite, were also utilized to ascertain the presence of active fire hotspots within the areas crossed by the air masses, according to HYSPLIT outputs. In the case of North America wildfires, smoke particles travelled many days to reach Limassol site. To identify these aged smoke particles, we primarily relied on the layers' respective higher altitudes, placing less emphasis on the depolarization ratio values. We then confirmed the particles' origin utilizing the HYSPLIT model and the VIIRS data.

The retrieval of the lidar ratio and the depolarization ratio at 355 nm and 532 nm was based on nighttime observations with a temporal range of 60-90 minutes. In most cases we selected nighttime measurements for the intervals of 20:00 and 21:00, 01:00 and 02:30, for which the Raman lidar method [11], was applied. For each case we calculated the mean values of the aforementioned optical properties for each observed layer and investigated their behavior and the potential differences among different aging levels of smoke.

4. Results

During the summer periods of 2021-2023 more than 20 cases of smoke layers above Cyprus were related to wildfires in southern Europe and Eastern Mediterranean and more than 10 events linked to wildfires in North America. Smoke layers above Limassol were predominantly found between 1 and 5 km height for the case of the wildfires occurred in the first two regions and in the case of Canadian wildfires most of the respective smoke layers were observed in higher altitudes, between 5 and 11 km. Figure 1 presents a characteristic example of smoke layers observed above Limassol on 07/07/2021, 0100-0230 UTC. That day two smoke layers in Limassol's atmosphere were detected, with the first one at heights between 1-2.5 km and the second one at approximately 11 km. According to the backward trajectories, the lower wildfire smoke layer was advected from Turkey on that period and the higher layer is an indicative example of smoke particles originating from the Canadian wildfires. In Figure 2 the vertical profiles of the lidar ratio (left) and the particle depolarization ratio (right) at 355 nm (blue curve) and 532 nm (green curve) for the lower layer of the same day are presented.

The 355 nm mean lidar ratio and depolarization ratio for the lower smoke layer (1-2.5 km) were equal to 62.30 ± 4.44 sr and 5 ± 0.2 %, respectively. The respective values at 532 nm were found to be 48.83 ± 11.81 sr and 8 ± 0.4 %. These values of lidar ratio (LR355 > LR532) indicate the presence of quite fresh smoke [12]. Also, particle depolarization ratios at both wavelengths are low, suggesting the predominance of spherical particles. The higher value at 532 nm points to the impact of irregularly shaped soil dust particles in the aerosol mixture [10].

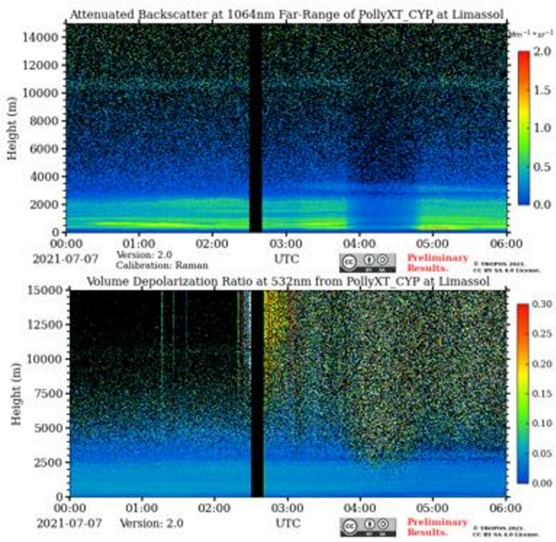

Figure 1. Quicklooks for the attenuated backscatter coefficient at 1064 nm (top) and volume depolarization ratio at 532 nm (bottom) (07/07/2021).

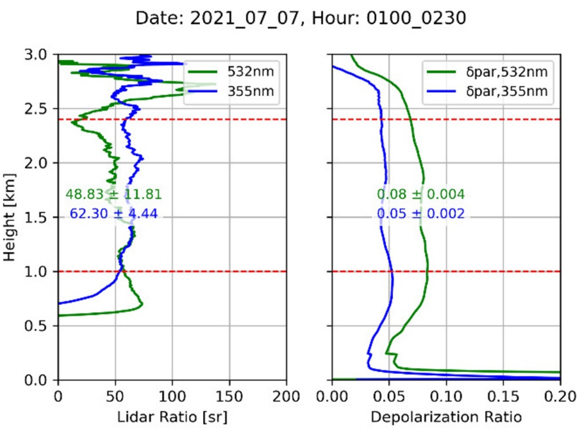

Figure 2. Vertical profiles of the lidar ratio (left) and particle depolarization ratio (right).

The statistical analysis for the overall period under study related to the wildfires events occurred in Europe and Eastern Mediterranean led to a 355 nm mean lidar ratio and particle depolarization ratio of 61.86 ± 13.51 sr and 6.54 ± 3 %, respectively. At 532 nm the mean lidar ratio was equal to 52.42 ± 10.22 sr and the depolarization ratio equal to 9.51 ± 4 %. The potential variability of the smoke particles' optical properties among different aging levels will be investigated, as well as their behavior in higher altitudes observed in the case of Canadian fires.

Figures 3 and 4 present a case study of aged smoke originating from wildfires in North America. These smoke measurements performed with the Polly instrument in Cyprus on 17/06/2023. Based on the quicklooks of the attenuated backscatter coefficient at 1064 nm and the volume depolarization ratio at 532 nm (Figure 3), an aerosol layer was observed above Limassol's site between 6-7 km. According to backward trajectories, this layer was attributed to the 8-9 days long-range transport of wildfire smoke from North America to the Eastern Mediterranean.

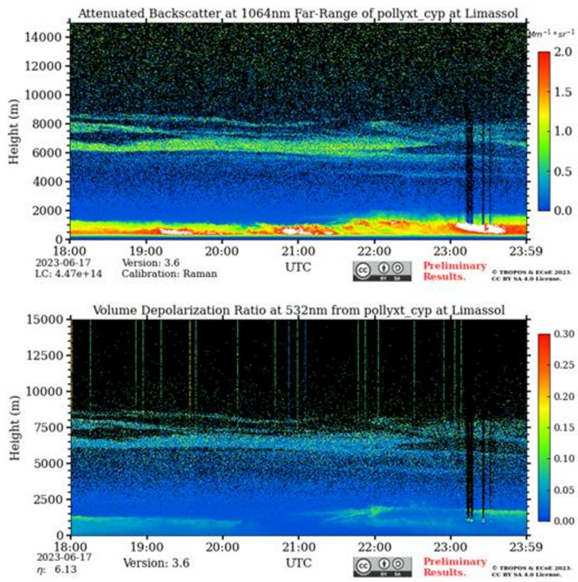

Figure 3. Quicklooks for the attenuated backscatter coefficient at 1064 nm (top) and volume depolarization ratio at 532 nm (bottom) (17/06/2023).

In Figure 4 the vertical profiles of the lidar ratio and the particle depolarization ratio at both wavelengths for the period from 19:00 to 22:00 UTC are presented. The mean lidar ratio and depolarization ratio for the lofted smoke layer

(6-7 km) at 355 nm were found to be 45.70 ± 3.55 sr and 8 ± 0. 3 %. The respective values at 532 nm were equal to 65.60 ± 5.68 sr and 4 ± 0. 2 %. At this case, the higher value of the lidar ratio at 532 nm is indicative of the presence of aged smoke [10].

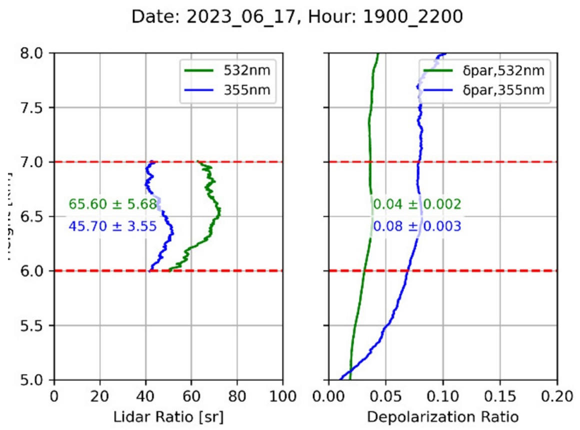

Figure 4. Vertical profiles of the lidar ratio (left) and particle depolarization ratio (right).

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