Investigating smoke optical properties in Eastern Mediterranean: Lidar observations in Cyprus.

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Introduction

Wildfires are large, uncontrolled fires that often occur in rural or sparsely populated areas. The main causes of wildfires can be attributed to either human activity or natural factors. When key conditions such as heat, drought, and fuel availability reach critical thresholds, wildfires can ignite or become more intense. Climate change affects these parameters by lowering the critical values required for fire activity to occur [1]. The IPCC (AR6) states with medium confidence that weather conditions favoring wildfires have become more probable in southern Europe, northern Eurasia, the USA, and Australia over the last century [2]. Smoke particles play a significant role in the climate system, affecting it directly by absorbing solar radiation and indirectly by influencing cloud formation as cloud condensation nuclei (CCN) and ice-nucleating particles (INPs) [3]. They also impact air quality, visibility, and pose health risks. Studying their optical properties is essential for understanding their role in the climate system and improving weather and climate models.

The Mediterranean region is a key area for atmospheric studies due to the diverse aerosol types it experiences. Cyprus, the third-largest island in the Mediterranean, provides a strategic location for investigating the vertical distribution of aerosols, including marine particles, desert dust, smoke, and anthropogenic particles. Hence, this is a great opportunity to study the behavior of smoke in such aerosol mixtures. This study emphasizes on the intense activity of wildfires in Turkey's Mediterranean Region in July and August 2021, and the corresponding smoke layers that were observed above Limassol site.

Methodology

Observations were performed using the multiwavelength polarization Ramam lidar, PollyXT (POrtabLe Lidar sYstem) [4], operated in Limassol (34.677° N, 33.0375° E) as part of the Cyprus Atmospheric Remote Sensing Observatory National Facility (CARO NF) of the Eratosthenes Centre of Excellence (ECoE). This lidar system operates continuously, 24/7, with a diode-pumped laser that emits the first (1064nm), second (532 nm) and third (355 nm) harmonic frequency with a pulse repetition rate of 100 Hz. In the present configuration the lidar can measure the backscatter coefficient profiles at three wavelengths (355, 532 and 1064 nm), and the extinction coefficient profiles and the depolarization ratio at two wavelengths (355 and 532 nm). Four near-field channels (355, 387, 532, and 607 nm) extend the vertical range of the lidar towards lower altitudes and a water-vapor Raman channel at 407 nm is also included.

To identify atmospheric particle layers, we relied on the temporal evolution of the calibrated attenuated backscatter coefficient at 1064 nm and the volume depolarization ratio at 532 nm. Relatively high backscatter coefficient values, indicating considerable aerosol loading, along with low depolarization ratio values, which are typical signatures of smoke at tropospheric levels [5-8], suggested the presence of smoke particles. To confirm the origin of the particles, we examined the backward trajectories from HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory model) simulations [9] together with VIIRS (Visible Infrared Imaging Radiometer Suite) fire and thermal anomalies data [10], available from the joint NASA/NOAA Suomi National Polar orbiting Partnership satellite. For the statistical analysis of the particles' optical properties we used nighttime measurements to which the Raman method could be applied [11]. In the cases presented here, vertical profiles of the optical properties were retrieved from nighttime observations, with a temporal averaging window of 60–70 minutes, typically between 18:00 and

00:00 UTC, and a vertical smoothing of 500 m. For each case, the mean depolarization and lidar ratios within the detected aerosol layers were calculated.

To assess the impact of fires along Turkey's south coast, we estimated the fire radiative power (FRP) at three key clusters where wildfire hotspots were identified. These areas were selected based on fire activity during the period under study. FRP values were calculated using the VIIRS 375 m active fire product from the Suomi NPP satellite, which offers improved nighttime performance and a better response over small fire areas. Only FRP values with high or nominal detection confidence level were used. To characterize the vegetation burned, we referred to the CORINE Land Cover (CLC) product [12], which provides land cover and land use data across Europe.

Results

A series of wildfires affected a large part of Turkey's Mediterranean region in July and August 2021. The fires began in July 2021 and continued until August 12, 2021. To study the fire radiative power, we divided the southern coast of Turkey into three major clusters based on the temporal evolution of the hotspots observed with FIRMS data. Some fire pixels in these regions displayed high values reaching 300 MW but most of them ranged between 50-100 MW. Based on the CORINE product, the burned areas were primarily characterized by coniferous vegetation (51%) and transitional woodland-shrub (23%). Studies showed that the 2021 wildfires resulted in the largest area loss in the history of forest fires in Turkey [13].

The daily distribution of FRP values for July and August 2020 and 2021 was also estimated, across all three clusters. These two years were used for comparison to assess the intensity of wildfire events in 2021. It was observed that during the period 28 July-12 August 2021, FRP values were considerably higher compared to the corresponding period in 2020. Elevated FRP values were also recorded on 15 July 2021, coinciding with another wildfire event along the southern coast of Turkey. Throughout the study period, the wide range of boxplot values indicated significant variability, with maximum FRP values approaching 100 MW. Continuous vertically resolved aerosol measurements performed by the PollyXT instrument in CARO station, combined with HYSPLIT trajectory analysis, confirmed the transport of smoke plumes from intense wildfires to the Limassol region within 12 hours. This rapid northward transport was driven by the Etesian winds, a persistent and well-known regional wind system in the eastern Mediterranean [14].

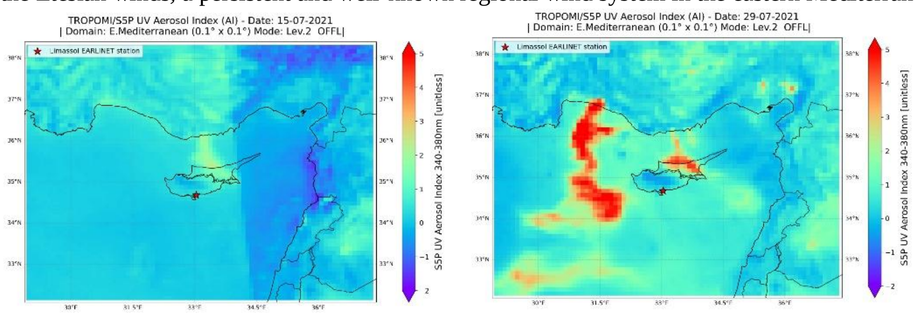

Figure 1. Spatial distribution of gridded UV Aerosol Index measurements obtained by the TROPOMI/Sentinel-5p on 15.07.2021 (left) and 29.07.2021 (right). The location of CARO station is marked by red stars.

In this study we present two case studies - 15.07.2021 and 29.07.2021 – during which FRP values reached their highest levels, according to the daily distribution estimations. The spatial dispersion of emitted smoke particles from southern Turkey towards Cyprus during this period is highlighted by the UV Aerosol Index (UVAI), captured by the TROPOMI (Tropospheric Monitoring Instrument) onboard the Sentinel-5P satellite [15]. The data were gridded to a 0.1˚x 0.1˚ (latitude x longitude) grid covering an extended area of E. Mediterranean, from 29˚E to 37˚E and from 32˚N to 38˚N. As shown in Figure 1, the high positive values reveal the significant load of absorbing aerosols, for both case studies, clearly illustrating that the smoke emitted from the occurred fires was transported southward to Cyprus.

Figure 2 (left) presents the temporal evolution of the attenuated volume backscatter signal at 1064nm, obtained by the PollyXT system on 15 July 2021 between 18:10-19:20 UTC. The vertical profiles of the optical properties for the same time interval, are also presented (Fig. 2, right). An intense smoke layer was detected between 1.8 and 2.8 km. Lidar signals averaged over 1 hour to retrieve the lidar and particle depolarization ratios vertical profiles. The mean lidar ratios were 72.31 ± 9.42 sr at 355 nm and 44.45 ± 3.51 sr at 532 nm, within the observed layer height, values typical of fresh smoke [5-8, 16]. The retrieved values are also in agreement with the typical behavior of fresh smoke, where the lidar ratio at 355 nm is generally higher than that at 532 nm. Mean particle depolarization ratios of 4 ± 0.6 % at 355 nm and 5 ± 1.3 % at 532 nm align with typical values observed for tropospheric smoke [5-8]. The Ångström exponents indicated the presence of fine-mode particles [17].

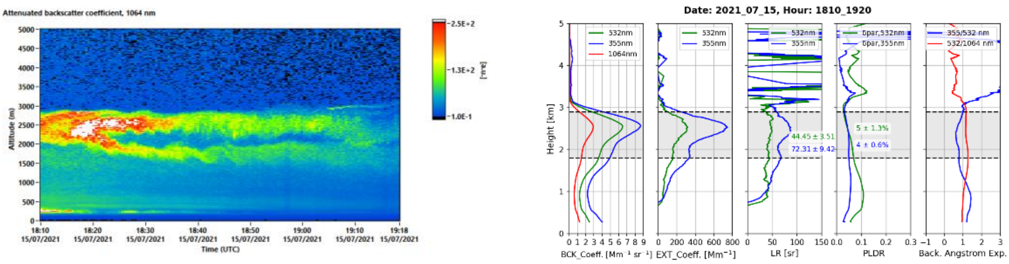

Figure 2. (left) Time–height display of the attenuated backscatter signal at 1064nm on 15.07.2021, 18:10-19:20 UTC, and (right) vertical profiles of intensive and extensive optical properties.

In late July 2021, the PollyXT lidar detected an intense smoke layer at 2.6–3.5 km altitude. The smoke, classified as fresh, reached Limassol in less than 12 hours. Figure 3 shows the time evolution of the attenuated backscatter coefficient at 1064 nm (23:00–23:59 UTC) and corresponding vertical profiles of the optical parameters. The backscatter and extinction coefficients at the detected layer were similar to those observed on 15.07.2021, though the aerosol index was notably higher on 29.07.2021 (Fig. 1). This may be attributed to meteorological factors and plume dispersion. Mean lidar ratios were 97.50 ± 14.54 sr (355 nm) and 66.38 ± 7.30 sr (532 nm), higher than in the previous fresh smoke case but still within typical values referred in the literature. The $LR_{532}/LR_{355} < 1$ pattern, characteristic of fresh smoke, was again observed. Mean particle depolarization ratios were 12 ± 1.0 % (355 nm) and 7 ± 0.5 % (532 nm), with values near 0.1 indicating possible influence of soil dust and dust injected during the fire into the aerosol mixture [18].

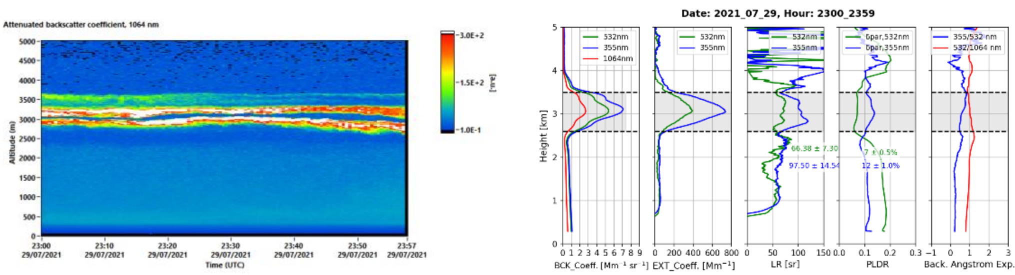

Figure 3. Same as Figure 2 but for 29.07.2021 and for 1-h average lidar signal between 23:00-23:59 UTC.

Conclusions

During July and August 2021, Turkey's Mediterranean Region experienced a series of wildfires that affected a large area, burning various types of vegetation. FRP values indicated intense wildfire activity in the clusters under study, compared to the previous year, making this wildfire season the worst on record in the country's history. Backward trajectories and satellite imagery indicated that smoke particles reached the Limassol site within 12 hours. The PollyXT lidar system detected these fresh smoke layers, and the analysis of the optical properties confirmed the presence of fresh smoke above Limassol. It also suggested the presence of soil dust and dust injected during the fire into the aerosol mixture. Further study will focus on comparing the optical properties of fresh smoke cases with those of background smoke observed in the subsequent days. Additionally, the hygroscopic growth of aerosol particles and the influence of humidity on the depolarization of smoke particles will be examined.

Acknowledgements

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