

VARIABILITY OF SMOKE OPTICAL PROPERTIES IN EASTERN MEDITERRANEAN

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ABSTRACT

Wildfires can be considered as a natural part of many ecosystems, but their frequency and heightened risk have been notably influenced by climate change. This amplified threat poses a significant concern that necessitates further study on the properties and behavior of smoke particles. The 2023 was a year of intense wildfires worldwide with Greece experiencing the largest wildfire in European history. A record-breaking forest fire activity was spotted in the Evros region, of northeastern Greece during August. The smoke plume reached different regions leading to an international concern. In this work, we focus on the study of optical properties related to the smoke particles observed in the atmosphere of Limassol, Cyprus, during the recent forest fires as retrieved by the PollyXT of the ERATOSTHENES CoE. In addition, measurements provided by the THELISYS lidar system in Thessaloniki are used synergistically to confirm the transport of smoke above the Limassol region.

Index Terms— wildfires, remote sensing, lidar, optical properties

1. INTRODUCTION

Extended drought, increased heat, and the lack of moisture in fuels, such as trees or forest debris, are factors inextricably connected with climate change that amplify the risk and extent of wildfires worldwide. US already experiences extended wildfire seasons and heightened frequency [1,2], while studies show that climate warming has resulted in escalating wildfire threats in Southern Europe [3]. Smoke particles can strongly affect the climate system by absorbing solar radiation and by influencing the evolution of clouds through their behavior as cloud condensation nuclei (CCN) and ice-nucleating particles (INPs) [4,5]. The investigation

and the improvement of our current understanding of smoke particles' properties is therefore of great importance.

In this study, we focus on 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, burning more than 96,000 hectares. The consequences were devastating, leading to tragic human losses, evacuations and devastating ecological, environmental, and economic disasters. According to Copernicus Atmosphere Monitoring Service (CAMS) [6] this devastating wildfire was the largest ever recorded in Europe with the smoke plume traveling kilometers away, over central Greece and onwards towards Crete and southern Italy affecting the air quality of many regions. Thessaloniki, Greece, and Limassol, Cyprus, are areas that were affected by this wildfire event but in different time periods and with different severity levels. In particular, the plume initially reached the atmosphere of Thessaloniki, four days after the forest fire activity began in the Evros region. However, when smoke particles were observed in the atmosphere of Cyprus, eight days after the onset of this event, the plume had become more dispersed compared to its earlier intensity in Thessaloniki. Additionally, according to the HYSPLIT model, the air masses traveled over the ocean for several days before reaching the Limassol site. Our study presents a comprehensive analysis of the geometrical and optical properties of smoke particles at tropospheric heights above Limassol, focusing on the lidar and particle depolarization ratio retrieved by PollyXT-CYP observations. Moreover, lidar measurements obtained from the Thessaloniki's lidar station are used in a synergistic way to ascertain the origin of the particles observed in Limassol's atmosphere.

2. INSTRUMENTATION

Observations in Limassol were performed with a multiwavelength polarization Raman lidar, PollyXT

(POrtabLe Lidar sYstem) [7], situated at the Cyprus Atmospheric Remote Sensing Observatory (CARO) of the Eratosthenes Centre of Excellence at Limassol (34.677° N, 33.0375° E). This lidar system runs autonomously and it is operated 24/7 with a diode-pumped laser that emits the first (1064nm), second (532nm) and third (355nm) harmonic frequency with a pulse repetition rate of 100 Hz [8]. The PollyXT instrument used, enables the measurement of vertically-height resolved profiles of the particle backscatter coefficient (β_{aer}) at 355, 532, and 1064nm, the particle extinction coefficient (α_{aer}) at 355 and 532nm, the corresponding lidar ratios (LR), as well as the volume (δv) and particle (δp) linear depolarization ratios at 355 and 532nm. It also includes a water-vapor Raman channel (407 nm) and a second near-range receiver with four channels (355, 387, 532, and 607nm). The THEssaloniki's Lidar SYStem (THELISYS) is operating at the Laboratory of Atmospheric Physics (40.5°N, 22.9°E, LAP-AUTH) in Aristotle University of Thessaloniki as a multiwavelength Raman lidar (at 355, 532, 1064nm) with depolarization capabilities as well (at 532nm).

3. DATA AND METHODOLOGY

To identify the atmospheric particle layers at Limassol's site, we utilized the daily timeseries of the calibrated attenuated backscatter coefficient at 1064nm and the volume depolarization ratio at 532nm. We assumed the presence of smoke particles in the atmosphere when the backscatter coefficient values were relatively high, indicating the presence of aerosols, along with low depolarization ratios, which are indicative of smoke particles at tropospheric heights [9]. Backward trajectories, generated with HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory model) simulations [10], combined with VIIRS (Visible Infrared Imaging Radiometer Suite) fire and thermal anomalies data [11], available from the joint NASA/NOAA Suomi National Polar orbiting Partnership (Suomi NPP) satellite, were used to confirm the origin of the air masses at the time and the height altitude of the identified aerosol layers.

The vertical profiles of the lidar ratio and the particle depolarization ratio at 355nm and 532nm, concerning lidar measurements at Limassol's site, were retrieved based on nighttime observations with a temporal average of 90-120 minutes. For the cases presented here, we selected nighttime measurements during the interval of 00:00 to 02:00 UTC, for which the Raman lidar method [12] was applied. Lidar measurements over Thessaloniki regarding the detection of smoke layers and the retrieval of aerosol optical properties refer exclusively to daylight measurements. The strong presence of low clouds prevented night observations. The temporal average was approximately 60 minutes in the interval time from 09:00 to 13:00 UTC.

4. RESULTS

At the end of August 2023, the THELISYS lidar system at the Thessaloniki station detected a thick and intense particle layer at heights above 3.5km. Backward trajectories generated with the HYSPLIT model, along with VIIRS data, indicated that the detected air masses had previously crossed the area of northeastern Greece, where the extreme wildfire event occurred. The particle depolarization ratio at 532nm and the backscatter-related Ångström exponent values confirmed the presence of spherical, fine-mode, absorbing particles, characteristics displayed by smoke particles. The CIMEL sun/sky photometer operating at LAP-AUTH in the framework of Aerosol Robotic Network (AERONET), recorded extreme aerosol optical depth values (AOD), approximately up to 3.5 in the UV wavelength range. These values significantly exceed the climatological mean (~0.45 in August). Additionally, the size distribution measurements showed the predominance of fine-mode particles supporting the indication that the observed atmospheric layer consists of smoke particles.

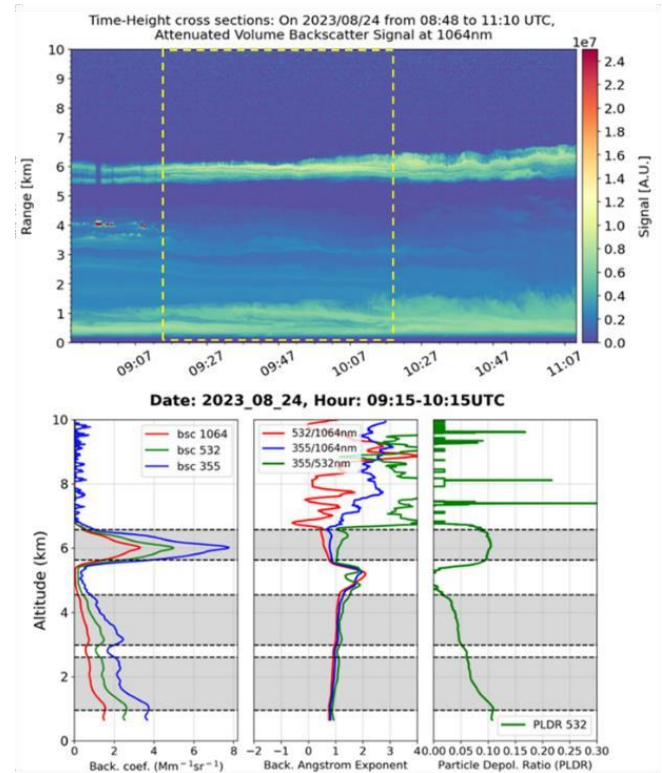


Figure 1. (top) Temporal evolution of the attenuated volume backscatter signal at 1064nm from the THELISYS lidar system on 24/08/2023, 08:48-11:10 UTC, and (bottom) vertical profiles of the particle backscatter coefficients at 355, 532, 1064nm, backscatter Ångström exponents (red: 532–1064nm spectrum, blue: 355–1064nm, and green: 355–532nm), and particle linear depolarization ratio at 532nm.

Figure 1 (top) presents the temporal evolution of the attenuated volume backscatter signal at 1064nm, obtained by the THELISYS system on 24 August 2023 between 08:48-11:10 UTC. The vertical profiles of the backscatter coefficients, the backscatter-related Ångström exponents and the particle depolarization ratio for the time interval of 09:15 to 10:15 UTC, are also presented (Fig. 1, bottom). According to Fig.1, an intense elevated aerosol layer was detected at heights from 5.5km to 6.2km, with the backscatter coefficient showing maximum value of almost $8 \text{ Mm}^{-1} \text{ sr}^{-1}$ at 355nm. The particle depolarization ratio exhibited low values, around 0.1, indicating the predominance of spherical particles. Meanwhile, the backscatter-related Ångström exponents averaged close to 1, suggesting the presence of fine mode particles. These values, combined with the HYSPLIT trajectories, point to smoke particles [8, 13], originating from the plume that traveled to Thessaloniki from the extreme wildfire event in the Evros region.

The extreme wildfires occurred in the northeast of Greece near Alexandroupolis created a significant plume of smoke that extended hundreds of miles southwest, reaching toward Italy. As can be seen in Figure 2, this event was well-captured during August 22 (left) and 23 (right), 2023, by the VIIRS on the Suomi NPP satellite. The smoke was dispersed widely due to the influence of the strong north-northeast "meltemi" winds, which are characteristic of the Aegean Sea during the summer [14]. These winds pattern blow from northerly directions in the central-eastern Aegean and played a crucial role in spreading the smoke plume hundreds of miles. The satellite imagery highlights the extensive reach and impact of the smoke plume, demonstrating the severity of the fire and its potential transboundary environmental effects.

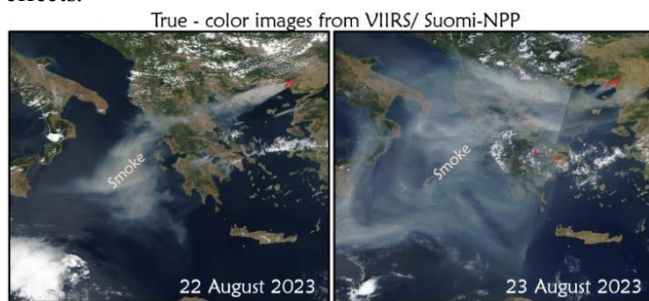


Figure 2. True-color images captured by VIIRS on board Suomi NPP during 22-23 August 2023 (source: NASA Worldview Snapshots, <https://wvs.earthdata.nasa.gov/>).

Continuous vertically resolved aerosol measurements performed by the PollyXT instrument in Limassol, combined with HYSPLIT trajectories, showed that after 27 August 2023, smoke particles could have been transported to the Limassol site from south of Italy, where the dispersed plume was detected in the previous days. In this study we chose to present the case of 29 August 2023 when an intense aerosol structure was observed over Limassol. In Figure 3, HYSPLIT

trajectories confirm that the air masses passed over the burning areas and the regions where the plume was dispersed before reaching the Limassol station. The origin of the observed particles is verified by lidar measurements in Thessaloniki, where a dominant smoke layer was present in the days before the air masses reached Limassol, as previously mentioned (see Fig. 1). The heights at which the smoke was detected above Thessaloniki are in good agreement with the HYSPLIT model findings (see the color of the circles and color bar in Fig. 3).

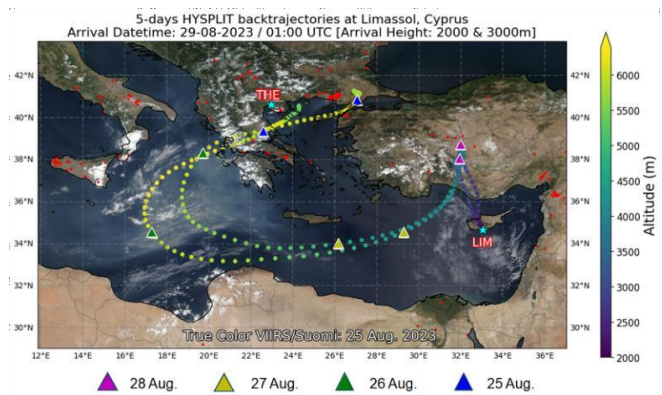


Figure 3. HYSPLIT 5-d back-trajectories arriving at 2000m and 3000m over Limassol, Cyprus, on 29 August 2023, 01:00 UTC. The colored triangles represent the start and end of each day during which the air masses travelled towards Cyprus. The locations of the Thessaloniki and the Limassol lidar stations are marked by blue stars. The overlaid true color image is taken from VIIRS on Suomi-NPP platform.

Figure 4 presents the temporal evolution of the attenuated backscatter at 1064nm between 00:00 and 05:59 UTC (top) and the vertical profiles of the optical properties (bottom) for the period from 00:00 to 02:00 UTC. The lidar signal was averaged in a 2-h time-window (yellow dashed-box) to estimate the mean values of the lidar ratio and the particle depolarization ratio within the detected layer. The mean lidar ratios at both wavelengths were 55 sr and specifically $55.13 \pm 3.33 \text{ sr}$ at 355nm and $55.02 \pm 4.89 \text{ sr}$ at 532nm. The mean particle depolarization ratios were equal to $5 \pm 0.7 \%$ (355nm) and $10 \pm 1.5 \%$ (532nm), respectively. These values indicated primarily the presence of spherical particles. The values of the backscatter-related Ångström exponents averaged close to 1 confirming the predominance of fine mode particles. Lidar ratio and depolarization ratio estimates found relevant to values from the literature [15, 16, 17, 18]. It should also be noted that, due to the dispersion area of the smoke plume (Fig. 2) and the air masses pathways reaching Limassol (Fig. 3), the potential impact of dust particles contribution in the aerosol mixture cannot be excluded.

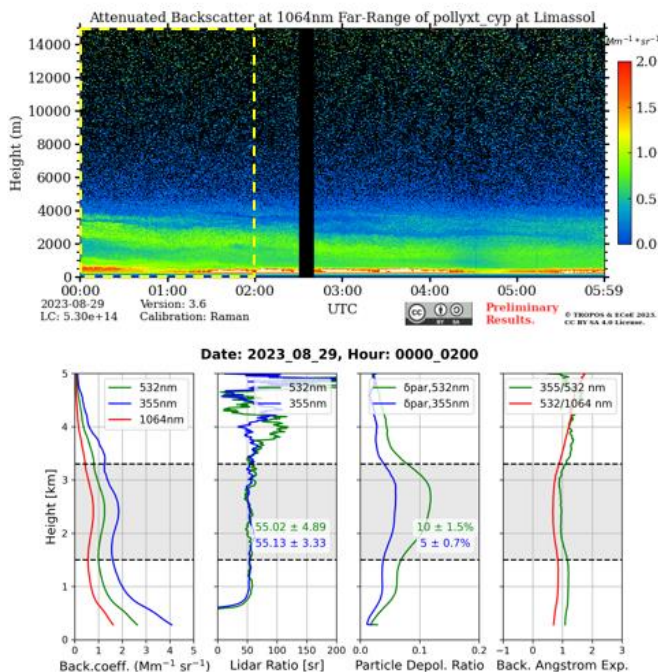


Figure 4. (top) Temporal evolution of the attenuated volume backscatter signal at 1064nm from the PollyXT lidar system on 29/08/2023, 00:00-05:59 UTC, and (bottom) vertical profiles of the particle backscatter coefficients at 355, 532, 1064nm, lidar ratios at 355 and 532nm, particle linear depolarization ratios at 355 and 532nm, and backscatter Ångström exponents (red: 532–1064nm spectrum, and green: 355–532nm).

5. CONCLUSIONS

During the second half of August 2023, Greece experienced a series of wildfires that burned a large area in the Evros region. The smoke plume impacted various regions. The Thessaloniki lidar station detected a smoke layer four days after the onset of the event, while the Limassol lidar station observed it nearly eight days later. In Limassol, the situation appeared more complex, but the particle optical properties suggested the presence of smoke in the aerosol mixture. The transfer of smoke particles to Cyprus is further confirmed by the HYSPLIT trajectories, that indicate passage from Thessaloniki, where the THELISYS system detected the smoke layer.

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