

# A long-range smoke transport from Canadian forest fires to the Eastern Mediterranean during August 2023

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**Abstract:** In the summer of 2023, huge wildfires in Canada led to the injection of a remarkably high concentration of biomass burning aerosol in the atmosphere. These aerosol masses reached the city of Thessaloniki (Greece) at the end of August 2023, where they were detected with use of the Thessaloniki Lidar system (THELISYS) capable of measuring at 355, 532, and 1064 nm and interpreted with available information from the AERONET columnar products. On 31<sup>st</sup> of August 2023, a thick smoke layer was observed in the troposphere between 6-10 km over Thessaloniki. Our results confirmed the main typical features of aged Biomass Burning (BB) particles, i.e., the decreased Ångström exponent after long-range transport, enhanced depolarization ratio ( $\delta_{p532}$ ), in accordance with previous reported studies. These observations are indicative of almost aspherical smoke particles, probably because of aging processes. Our findings highlight the effectiveness of multiwavelength lidar observations, in offering a robust understanding of aerosol characteristics.

## 1. Introduction

In the summer period 2023, a series of wildfires took place in Northern America resulting in thousands of square kilometers of boreal forest being burned and emitting massive amounts of smoke to enter the atmosphere affecting the air quality. The 2023 wildfire season had the most area burned in Canada's recorded history. From August 27 to 31 August 2023, extended smoke plumes crossed the Atlantic, reaching Europe and Mediterranean Basin from Iberian to Greece. In the context of this study, we focus on a case study where a long-range transported biomass burning (BB) smoke originated from Canadian fires, reached and was observed over Thessaloniki on 31 August 2023. Mean optical aerosol properties of long-range transported BB particles and mixtures are documented by the lidar data set of multiwavelength Raman lidar data, obtained by the Thessaloniki Lidar system (THELISYS) over the city of Thessaloniki, Greece. The event was observed, among others, by the collocated Cimel sun-photometer operating within the AERONET Network.

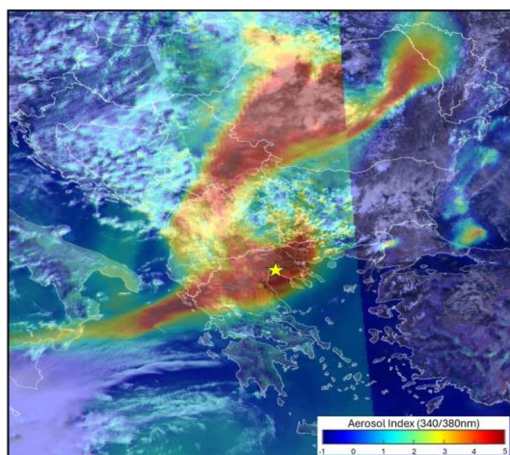
## 2. Instrumentation and Datasets

A synergistic use of a multiwavelength-depolarization lidar, a sun photometer along with trajectory model and satellite data, were used to derive the aerosol optical properties aloft, during BB event observed over Thessaloniki on 31 August 2023. Lidar observations were performed by the THELISYS lidar system which is located at the Laboratory of Atmospheric Physics (LAP; 40.5°N, 22.9°E, 50 m asl) on the roof of the Department of Physics in Aristotle University of Thessaloniki (AUTH). THELISYS has been in operation since 2000 and is part of the European Aerosol Lidar Network (EARLINET) [1]. THELISYS is able to perform independent measurements of the vertical profiles extensive aerosol properties, namely three  $\beta_{\text{aer}}$  (355, 532, 1064 nm) and two  $\alpha_{\text{aer}}$  (355, 532 nm) as well as aerosol intensive properties namely the backscatter and extinction related Ångström exponents ( $\text{AE}_{\text{b-355/532}}$ ,  $\text{AE}_{\text{b-355/1064}}$ ,  $\text{AE}_{\text{b-532/1064}}$ nm), the lidar ratio (SR), and additionally the linear volume ( $\delta_{v532}$ ) and particle depolarization ratio ( $\delta_{p532}$ ). Moreover, sun-photometric

observations were also used, performed by a co-located Cimel sun-sky radiometer, which is part of the Aerosol Robotic Network (AERONET) Global Network [2].

### 3. Results

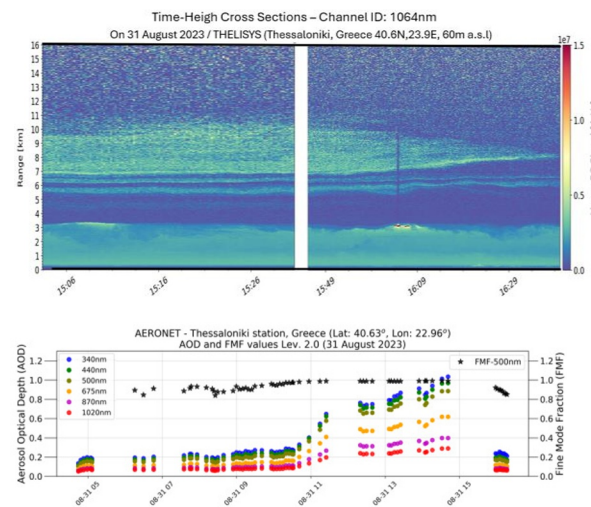
According to satellite observations, as the smoke plume was transported along the Mediterranean detected over Greece on 31 August, attributed to the Canadian fire activities. The smoke plumes can be clearly seen in the earth's true color image (Fig.1) captured by the Visible Infrared Imaging Radiometer Suite (VIIRS) overlaid with the UV aerosol index from TROPOMI [3] observations. The smoke plumes are highlighted by large positive values of UVAI, related to the presence of absorbing aerosols.



**Figure 1.** Spatial distribution of TROPOMI UVAI (340/380 nm) on 31 August 2023, over Eastern Europe during the smoke plume transport. The yellow star denotes the Thessaloniki-LAP site.

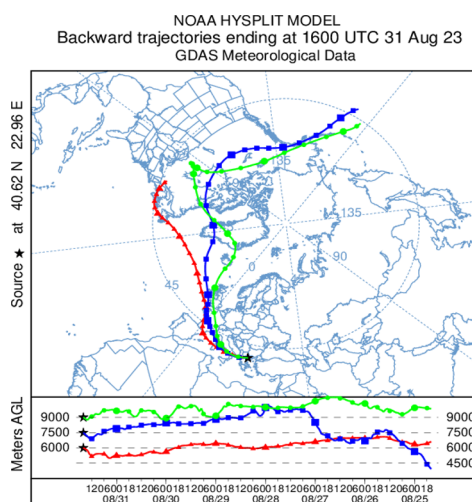
Figure 2 (Top) shows the spatio-temporal development of the range-corrected signal (RCS) at 1064 nm (15:00-16:40UTC) obtained by THELISYS. Aerosol layers at about 6 and 10 km are clearly visible. Moreover, the bottom panel illustrates the spectral temporal variation of aerosol optical depth (AOD) and Fine-Mode-Fraction (FMF) at 500nm on this day, measured by the Cimel sun-photometer. Figure 2 indicates that the aerosol optical depth increases significantly on early afternoon on this day, when the smoke plumes arrived over Thessaloniki. The highest aerosol optical depth is registered on 14:30 with a value of 1.08 (340 nm), along with increased

FMF levels close to 1, highlighting the dominance of fine particles in the atmospheric column.

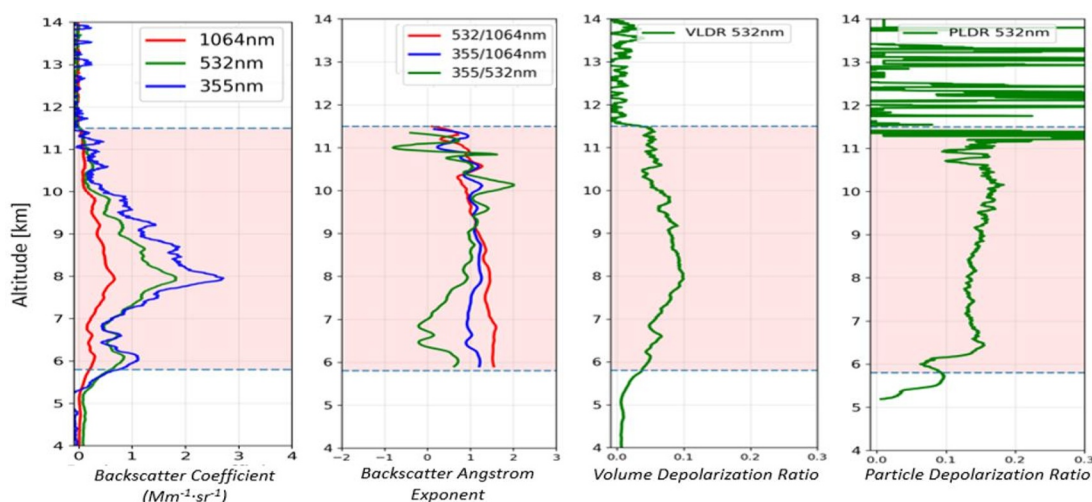


**Figure 2.** (Top) Range-corrected signal at 1064 nm between 15:00-16:40UTC and (Bottom) variation in spectral aerosol optical depth and fine-Mode-Fraction (FMF) at 500 nm on 31 August 2023.

At first, the lidar measurements were used to estimate altitudes of aerosol layers that could possibly contain BB aerosols. This information was used as an input to calculate air mass backward trajectories using the NOAA HYSPLIT [4] trajectory model. The trajectories were calculated for a mean arrival time, which is the time closest to the THELISYS Lidar observations and at altitude levels (6000, 7500 and 9000m) where elevated aerosol layers were detected.



**Figure 3.** Seven-days HYSPLIT backward arriving at Thessaloniki on 31st August 2023, for arrival height of 6500, 7500 and 9000m.



**Figure 4.** Mean vertical profiles of  $\beta_{\text{aer}}$ ,  $\text{AE}_b$  at 355, 532, 1064 nm and depolarization ratio at 532nm obtained by the THELISYS on 31 August 2023, [15:45-16:41UTC]. The red-shaded areas represent the detected smoke layer.

A 7-day back-trajectories analysis illustrated in Figure 3 supports the findings regarding the arrival of smoke aerosol above LAP on that day from north-western directions, where biomass burning events took place over Canada.

The 1-hour mean vertical profiles of the optical properties ( $\beta_{\text{aer}}$ ,  $\text{AE}_b$ ,  $\delta_v532$ ,  $\delta_p532$ ) for the period 15:45-16:41UTC are presented in Figure 4, having measured with the THELISYS in the afternoon of 31 August 2023. Moreover, signal smoothing was applied with window lengths of 200-500m. The results are slightly noisy (especially for 355nm affected by strong Rayleigh attenuation). The Fernald-Klett (FK) [5,6] method was applied to determine particle backscatter profiles at 355, 532 and 1064nm. Regarding climatological values, a lidar ratio of 70sr, 65sr, 60sr was approximated used for the 355 nm, 532nm and 1064nm, respectively. A pronounced elevated layer was detected in the altitude range of 6-11km, with maxima peaking at about 8km and backscatter values of 7.76, 4.97 and 3.30  $\text{Mm}^{-1}\text{sr}^{-1}$  at 355, 532 and 1064 nm, respectively. The mean values regarding the  $\text{AE}_b$  within the smoke layer were about approx. 1.2 (532/1064nm), 1.1 (355/1064nm) and 0.8 (355/532nm). The mean particle depolarization ratio of 0.13 at 532 nm suggests the predominance of non-depolarizing smoke particles. The enhanced particle depolarization ratio of about 0.15 are clear indications for aged smoke on the mid/upper

tropospheric altitudes, according to previous studies [7,8,9]. The lack of significant vertical variability of the  $\text{AE}_b$  and  $\delta_p532$  suggests the presence of aerosol of the same type within the detected layer. shows no significant vertical variations in the BB layer.

#### 4. Conclusions

The THELISYS lidar operating at LAP in Thessaloniki allowed for the detection of BB aerosols detected over Eastern Mediterranean on 31 August 2023 originated from Canadian wildfires. A detailed analysis of the geometrical and optical properties of the smoke layers allowed a thorough characterization of this event. The presented case study of long-range BB transport showed elevated layers in range of 6-11km a.s.l., with  $\text{PLDR} \approx 0.13$  and  $\text{AE}_b$  (355/532, 355/1064, 532/1064nm)  $\approx 1$ . Our findings are in good agreement regarding those reported in the literature concerning various biomass burning events observed by Raman lidars. As an outlook, we plan to also perform the retrieval of micro-physical properties of aerosols for characteristic layers found for this event. The presented case study demonstrates the unique potential of the upgraded THELISYS lidar to contribute on atmospheric aerosol research, highlighting the potential of combined use of data to study the horizontal, vertical, and temporal evolution of optical properties of aerosols. Such aerosol particles can not only be distributed in the troposphere but can even

reach the stratosphere above and influence the Earth's radiation budget and cloud cover over long periods.

## 5. Acknowledgements

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