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# VERTICAL PROFILES OF AEROSOL OPTICAL AND MICROPHYSICAL PROPERTIES DURING A RARE CASE OF LONG-RANGE TRANSPORT OF MIXED BIOMASS BURNING-POLLUTED DUST AEROSOLS FROM THE RUSSIAN FEDERATION-KAZAKHSTAN TO ATHENS, GREECE

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## ABSTRACT

Multi-wavelength aerosol Raman lidar measurements with elastic depolarization at 532 nm were combined with sun photometry during the HYGRA-CD campaign over Athens, Greece, on May-June 2014. We retrieved the aerosol optical [3 aerosol backscatter profiles ($b_{aer}$) at 355-532-1064 nm, 2 aerosol extinction ($a_{aer}$) profiles at 355-532 nm and the aerosol linear depolarization ratio ($\delta$) at 532 nm] and microphysical properties [effective radius ($r_{eff}$), complex refractive index ($m$), single scattering albedo ($\omega$)]. We present a case study of a long distance transport (~3.500-4.000 km) of biomass burning particles mixed with dust from the Russian Federation-Kazakhstan regions arriving over Athens on 21-23 May 2014 (1.7-3.5 km height). On 23 May, between 2-2.75 km we measured mean lidar ratios (LR) of 35 sr (355 nm) and 42 sr (532 nm), while the mean Ångström exponent (AE) aerosol backscatter-related values (355nm/532nm and 532nm/1064nm) were 2.05 and 1.22, respectively; the mean value of δ at 532 nm was measured to be 9%. For that day the retrieved mean aerosol microphysical properties at 2-2.75 km height were: $r_{eff}$=0.26 μm (fine mode), $r_{eff}$=2.15 μm (coarse mode), $m$=1.36+0.00024i, $\omega$=0.999 (355 nm, fine mode), $\omega$=0.992(355 nm, coarse mode), $\omega$=0.997 (532 nm, fine mode), and $\omega$=0.980 (532 nm, coarse mode).

## 1. INTRODUCTION

The HygrA-CD campaign was an international field campaign which took place in Athens, Greece between 15 May and 22 June 2014, within the Initial Training on Atmospheric Remote Sensing-ITARS project (www.itars.net). HYGRA-CD (http://hygracd.impworks.gr) brought together a suite of different instruments and expertise aiming to enhance our understanding on the impact of aerosols and clouds on weather and climate. It was based on the synergy between remote sensing and in-situ instrumentation, making also use of numerical weather prediction and atmospheric modeling.

Tropospheric aerosols play a crucial role in climate change through scattering (cooling effect) and absorbing (warming effect) incoming solar and outgoing thermal radiation [1]. Despite recent progress documented in the latest Intergovernmental Panel for Climate Change (IPCC) [1], the uncertainty about the current level of radiative forcing due to aerosols (0.5 $Wm^{-2}$) is still relatively large compared to that of global warming (greenhouse) gases (0.25 $Wm^{-2}$).

In order to clarify the mechanisms of aerosol radiative forcing and reduce the respective uncertainties, detailed knowledge of the vertical profiles of the particle optical ($b_{aer}$, $a_{aer}$, AE and LR) together with microphysical ($r_{eff}$, $m$, $\omega$) and chemical properties (water content, dry chemical composition), as well as their mass concentration

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are required [1-3]. Raman lidars have proven to be the most adapted tools in aerosol characterization experiments since they can provide the vertical profiles of $b_{aer}$ and $a_{aer}$ with very high spatial and temporal resolution [3 and references therein].

## 2. METHODOLOGY

In this study a synergy of a multi-wavelength Raman lidar, a 532 nm depolarization lidar and a sun photometer was used to derive the aerosol optical and microphysical properties aloft. The Raman lidar system (EOLE) [4] together with the mobile single-wavelength depolarization lidar (AIAS) are part of the ARIADNE Greek lidar network [5]. EOLE and AIAS are based in the Laser Remote Sensing Unit (LRSU) of the National Technical University of Athens (NTUA) (37.9ºN, 23.6ºE, 200 m a.s.l.). The data processing was based on the Single Calculus Chain (SCC) developed within EARLINET.

The AERONET CIMEL sun photometer located at the National Observatory of Athens (NOA) (www.aeronet.gsfc.nasa.gov) was used to derive the daytime evolution of the columnar aerosol optical properties, like the aerosol optical depth (AOD), the Ångström exponent (AE) at 440 nm/870 nm and the aerosol size distribution. The microphysical particle properties inside specific atmospheric layers were retrieved using the inversion code provided by Böckmann et al. 2005 [6] and Osterloh et al., 2013 [7].

## 3. RESULTS

In this paper we will focus on a case study of long-range transport of mixed aerosols arriving over Athens on 21-23 May 2014 in the height range 1.7-3.5 km height a.s.l. The prevailing synoptic meteorological conditions and air mass trajectories based on WRF-FLEXPART model simulations [8] showed that during the studied period a low pressure system was established over the Balkans and a high pressure system north of the Caspian and Aral Seas. The relative position of these two synoptic systems was governing the air mass flow over the Eastern Europe and the Balkans. On 21 May the synoptic situation resulted in transportation of elevated smoke particles from the persisting fires in S. Russian Federation and Kazakhstan towards the Baltic Sea. Displacement of the trough axis towards the east on 22 May, resulted in wind convergence along the frontal area between the two systems and in the formation of a secondary smoke plume, this time over the Black Sea, together with transportation of Asian dust. On 23 May these particles merged with the older smoke particles coming from the North. According to our model, the establishment of a northern flow over Greece, mainly on 22-23 May, favored the transportation of smoke particles from Russia-Kazakhstan towards Athens, as seen in the model results (Fig. 1) where elevated smoke layers arrived between 3.5-8 km on 22 May, while on 23 May smoke should also be found near ground.

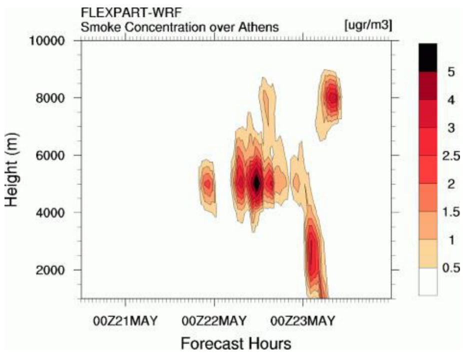


Figure 1. Time-height plot of smoke concentration (in μg m$^{-3}$) over Athens from 21 to 23 May 2014.

WRF-FLEXPART model simulations agree with the 8-day air mass back trajectories calculated by the HYSPLIT model. For instance on the evening of 23 May the air masses arriving over Athens between 2-2.75 km height originated from the southern Russian-northern Kazakhstan biomass burning regions and were mixed with desert dust during their overpass over central Kazakhstan and NW Iran desert areas, resulting in air masses with a mixture of dust and smoke particles.

The evolution of the columnar daily mean AOD values obtained at 340-500-1020 nm and the AE values at 440 nm/870 nm and 380nm/500nm, as derived by the NOA CIMEL sun photometer, are depicted in Fig. 2 (upper plot) for the period 21-23 May 2014. In that figure (lower plot) we show the respective columnar particle size distribution (in um). From Fig. 2 we can see that the AOD increases with the arrival of the air masses originating from the biomass (Russian-Kazakhstan) and desert (S. Kazakhstan-NW Iran)

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regions on 22 and 23 May, as previously explained. On 22 May (Fig. 2-lower plot) the fine ($r$=0.15 μm) particles (smoke) dominate (AE~1.7-1.85) while on 23 May the coarse ones ($r$=1-4 μm) (mostly mixed desert dust and smoke) dominate (AE~0.65-1.2).

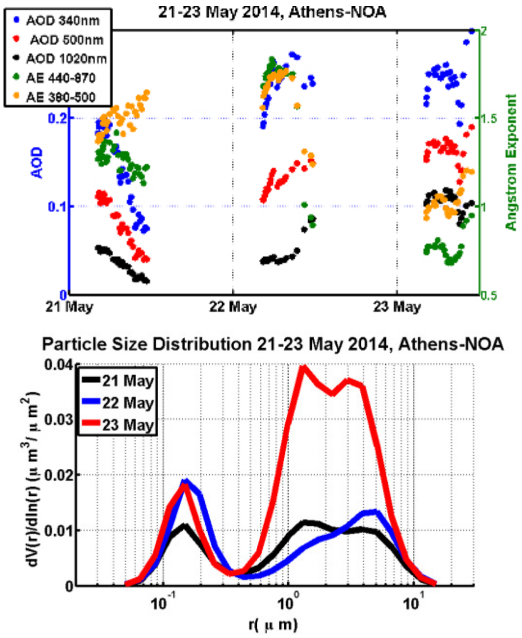


Figure 2. *upper plot:* Evolution of the columnar daily mean AOD obtained over Athens at 340-500-1020 nm and AE values at 440nm/870nm and 380nm/500nm, as derived by the NOA CIMEL sun photometer; *lower plot:* the particle size distribution (in μm) of the aerosol column (21-23 May 2014).

The corresponding EOLE Raman lidar measurements, expressed in terms of the temporal evolution of the range-corrected lidar signals (RCS) at 1064 nm, on 21-23 May (Fig. 3) showed discrete aerosol layers between 0.5-3.5 km heights over Athens, extending up to 3.5-4 km height. In Figure 4 we present the aerosol optical properties (backscatter and extinction coefficients, AE and Ångström backscatter and extinction-related exponent) retrieved by EOLE lidar between 1-5 km height on 23 May 2014 (20:30-21:40 UTC): $b_{aer}$ at 355-532-1064 nm, $a_{aer}$ and LR at 355-532 nm and Ångström backscatter (355nm/532nm and 532nm/1064nm) and extinction-related (355nm/532nm) exponents.

In Fig. 4 we observe a strong aerosol layer between 2.2-3 km extending up to nearly 3.5-4 km height. In the 2-2.75 km height region we measured mean LR values of 35 sr (355 nm) and 42 sr (532 nm), with mean particle linear depolarization ratio of 9% (532 nm), and AE aerosol backscattered-related values (355nm /532nm and 532nm/1064nm) of 1.22 and 2.05, respectively; these values are higher than the 0.95-1.2 measured at the end of the day by CIMEL in the atmospheric column. The columnar microphysical properties from CIMEL for 21-23 May were: $r_{eff}$=0.32-0.59 μm, $m$=(1.48-1.51)+(0.0018-0.0080)i, $\omega$=0.93-0.96. These columnar values are compared with the retrieved mean aerosol microphysical properties from EOLE data on 23 May (2-2.75 km asl.): $r_{eff}$=0.26 μm (fine mode), $r_{eff}$=2.15 μm (coarse mode), $m$=1.36+0.00024i, $\omega$=0.999 (355 nm, fine mode), $\omega$=0.992 (355 nm, coarse mode), $\omega$=0.997 (532 nm, fine mode), $\omega$=0.980(532 nm, coarse mode).

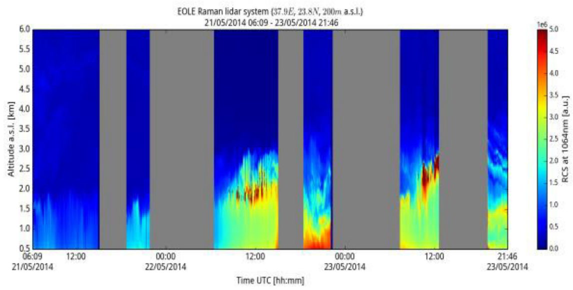


Figure 3. Spatio-temporal evolution of the range-corrected backscattered lidar signals (RCS) obtained by the EOLE lidar over Athens at 1064 nm between 21 (07:06 UTC) and 23 (21:45 UTC) May 2014.

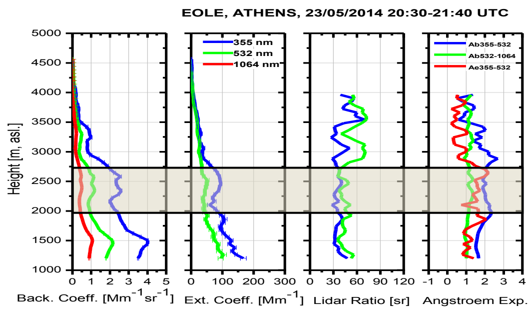


Figure 4. Vertical profiles of the aerosol optical parameters (extinction and backscatter coefficients, LR, AE) retrieved from the EOLE Raman lidar measurements on 23 May 2014 (20:30–21:40 UTC).

All these aerosol microphysical values compare well with those measured under similar atmospheric conditions regarding mixed smoke aerosols with polluted dust [9,10]. Finally, in Fig. 5 we present the forward FLEXPART simulations of the fire smoke integrated column (μg/m$^2$) for 23 May 2014 (21:00 and 22:00 UTC).

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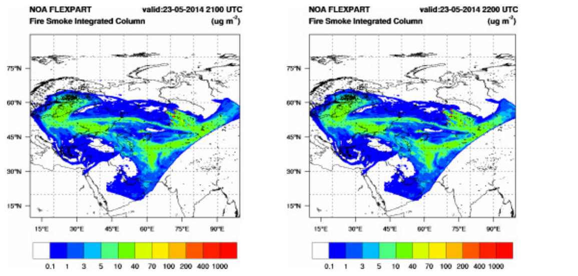


Figure 5. Forward FLEXPART simulations of the fire smoke integrated column (μg/m$^2$) for 23 May 2014 (*left:* 21:00 UTC and *right:* 22:00 UTC).

## 4. CONCLUSIONS

In this paper we presented a rare case of long-range transport of mixed aerosols (biomass burning particles mixed with dust) arriving from the S. Russian-Kazakhstan-NW Iran regions over Athens on 21-23 May 2014. In the 2-2.75 km height region we measured on 23 May mean LRs of 35 sr (355 nm) and 42 sr (532 nm) and mean AE aerosol backscatter-related values (355nm/532nm and 532nm/1064 nm) of 2.05 and 1.22, respectively; the mean value of δ at 532 nm was 9%. In this height region the mean retrieved aerosol microphysical properties $r_{eff}$=0.26 μm (fine mode), $r_{eff}$=2.15 μm (coarse mode), $m$=1.36+0.00024i, $\omega$=0.999 (355 nm, fine mode) $\omega$=0.992 (355 nm, coarse mode), $\omega$=0.997 (532 nm, fine mode), $\omega$=0.980(532 nm, coarse mode) are compared with the columnar microphysical properties from CIMEL for 21-23 May: $r_{eff}$=0.32-0.59 μm, $m$=(1.48-1.51)+(0.0018-0.0080)i and $\omega$=0.93-0.96.

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