STRATOSPHERIC SMOKE PROPERTIES BASED ON LIDAR OBSERVATIONS IN AUTUMN 2017 OVER WARSAW

Dongxiang Wang[1] and Iwona S. Stachlewska[1*]

[1] University of Warsaw, Faculty of Physics, Warsaw, 02-093, Poland
**Email: iwona.stachlewska@fuw.edu.pl*

ABSTRACT

Smoke layers in the stratosphere were observed during autumn 2017 using PollyXT-UW Raman lidar at the European Aerosol Research Lidar Network in the frame of the Aerosol Cloud and Trace Gases Research Infrastructure, i.e. the EARLINET-ACTRIS site in Warsaw, Poland. The analysis was focused on discriminating very weak signatures of smoke layers in the stratosphere and investigating their optical properties. Preliminary results are presented and discussed. A decrease of the lidar-derived stratospheric aerosol optical depth contribution to the total optical depth was detected after the stratospheric smoke particles circled Northern Hemisphere.

1. INTRODUCTION

The role of the stratospheric aerosol burden in climate variability and global radiative budget causes increasing attention in recent years [1], [2]. Due to its variability, it is essential to perform long-term observations of stratospheric aerosol over the world [3]. While measurements from space are performed with a large diversity of techniques, also long-term ground-based observations of stratosphere are highly valuable, as they ensure continuity and coherence of the stratospheric aerosol record [4, 5].

In summer of 2017, the unusually hot and dry environment led to a wide spread of wildfires in western Canada and United States of America. The smoke aerosol traveled over the North Atlantic, Europe, northern Asia, and circled the globe within less than 20 days [6]. In August 2017, these Canadian wildfire smoke events were observed not only in the troposphere but also in the lower stratosphere (12-26 km) by several European lidar sites [7-10]. However, once injected into the stratosphere, the traces of the stratospheric smoke are likely to be observed for several months after the major summer event. Therefore, this paper focus was set on nighttime observations of any stratospheric aerosol signatures detected in September and October 2017 over Warsaw. Profiles obtained at the elastic total and polarized channels both at 355 and 532 nm were evaluated in search for any aerosol load at an altitude range of 12-30 km a.g.l. The corresponding optical properties of stratospheric smoke layers were derived and analyzed. A comparative study of this stratospheric smoke at several sites was recently published [11].

2. LIDAR INSTRUMENT

Since July 2013, quasi-continuous atmospheric observations are performed using PollyXT-UW lidar at the Remote Sensing Laboratory (RS-Lab, *http://www.igf.fuw.edu.pl/en/instruments*), at the Faculty of Physics of the University of Warsaw. Lidar observations in the frame of the ACTRIS-Poland activities are conducted at the European EARLINET (*www.earlinet.org*, [12]), the worldwide Polly.NET (*http://polly.tropos.de*, [13]) and Polish Aerosol Research Network PolandAOD-NET (*www.polandaod.pl*, [14]).

The next generation PollyXT-UW lidar [15,16], emits vertically to the atmosphere high-energy laser pulses (180 mJ at 1064 nm, 110 mJ at 532 nm, and 60 mJ at 355 nm) with a repetition rate of 20 Hz. The laser beam is characterized by a low divergence of 0.2 mrad. The signals are received by the narrow field of view (1 mrad) telescope of 300 mm diameter. The detection is performed at 8-channels (so-called $2\alpha + 3\beta + 2\delta$ + WV) enabling determination of the total and particle extinction and backscatter coefficient, the volume and particle linear depolarization ratio, and the water vapor mixing ratio profiles.

The lidar signals are recorded up to 48 km. The initial signals at all channels are acquired with a 7.5 m vertical resolution in temporal steps of 30 s.

3. METHODOLOGY OF EVALUATION

Study was focused on search for the smoke aerosol loading in the stratosphere. The data in the daytime were not used due to too high background light level affecting signals in stratosphere. All available lidar data for the overnight time period from 18:00 to 04:00 UTC were analyzed. In September and October 2017, for 20 days there were no observations due to malfunction of the lidar laser cooling system. 10 days were not analyzed because they provided less than 8 hours of observations in the given period. 24 days were excluded from analyses due to the evidence of thick impenetrable low and mid-level clouds in the signals. Finally, 7 days for the case study analysis were chosen. As it is challenging to identify the weak stratospheric smoke layers in the time-height matrix plots of the background and range corrected lidar signals, for each of the 7 cases a single average profile from 18:00 to 04:00 UTC was obtained. Stratospheric aerosol signatures can be seen in these averaged, background corrected, smoothed and range-corrected vertical profiles.

The particle backscatter coefficient profiles at 532 and 355 nm were computed by solving the elastic lidar equation (second order Bernouli equation solution for mathematically ill-posed problem) [17] with an assumption of the height-independent particle lidar ratio (LR). The choice of lidar ratio values (31 sr at 355 nm and 55 sr at 532 nm) was based on the sensitivity study, i.e. defined as the lowermost lidar ratio that, if applied, guarantee no negative values in the derived vertical profile of the particle backscatter coefficient. The selection of the calibration range (CR) was set at a range free of any aerosol signatures. Proposed in [17] forward and backward inversions were used respectively above and below the aerosol-free calibration range. The particle extinction coefficient profiles were estimated by multiplying the particle backscatter coefficient profiles with the constant lidar ratio (values as specified above). Similar methodology was used in [11] for Warsaw data.

The volume linear depolarization ratio (VDR) at 355 and 532 nm, defined as the ratio of the polarized-to-total elastic backscatter signal), were calculated with the mean calibration constants of V_{355} of $2.10*10^{-1}\pm3.79*10^{-2}$ and V_{532} of $5.37*10^{-2}\pm5.95*10^{-3}$, as in [14].

The aerosol optical depth (AOD) at 355 and 532 nm was derived by integrating the particle extinction coefficient profile for different height ranges: within the aerosol boundary layer, in the free troposphere, and in the lower stratosphere, as in [18]. The aerosol boundary layer (ABL) height and the tropopause (TRP) height were obtained using the wavelet covariance transform method (WCT), as in [19]. The advantage of the WCT method is that it is less affected by the signal noise than the other classical methods, such as the gradient method [20]. The WCT with the dilation of 30 m was applied on the three average overnight elastic signals, and the average height is marked as ABL/TRP height.

4. RESULTS

Figure 1 depicts the wavelength-dependent VDR of stratospheric smoke layers detected over several days in September and October 2017 in Warsaw. The smoke signatures mainly distribute within the range 14-22 km. Lack of data on many days is not that there was no layer; it was not possible to evaluate lidar data e.g. due to low clouds. The mean background (bluish) VDR values outside the layers were of 0.015±0.03 at 355 nm and 0.018±0.01 532 nm. The mean VDR values of stratospheric smoke layers was 0.031±0.04 (maximum 0.049) at 355 nm and 0.033±0.01 (maximum 0.059) at 532 nm. The uncertainty of the VDR values at 355 and 532 nm is < 10%.

This indicates that stratospheric smoke particles over were almost spherical in shape during observed cases in Warsaw. Ansmann [7] reported for Leipzig (the closest EARLINET site, around 700 km, SW off Warsaw), that on 21-22 August 2017 the VDR for the extreme smoke layer in the lower stratosphere was mostly between 0.1-0.2 at height from 12 to 16 km at 532 nm, indicating aspherical particles.

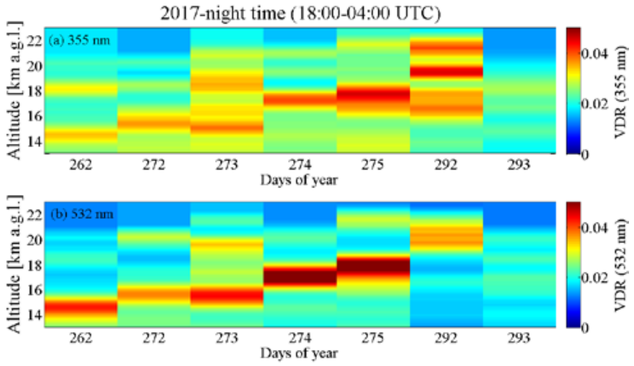

Figure 1. PollyXT-UW lidar-derived volume depolarization ratio (VDR) at 355 (a) and 532 nm (b) for stratospheric smoke layers on several nights in autumn 2017 over Warsaw.

Direct comparison of VDR values in the extreme smoke layer in the lower stratosphere is not possible due to laser failure in Warsaw in August 2017. Thus, the reason for the strong VDR contrast in August 2017 values in Leipzig and September-October values in Warsaw is due to both, the difference in each site location and the difference in observation period. The smoke aerosol can circle the globe within less than 20 days [7, 11], therefore during its transport smoke layers are expected to dilute and either dry and decrease their size or take up water – both will lower the VDR. Figure 2 depicts an example of the wavelength dependent mean vertical profiles of the particle extinction coefficient (α_p) averaged over the period from 18:00 UTC on 18 September to 04:00 UTC on 19 September 2017. The ABL height (separating the aerosol boundary layer and free troposphere) marks the red line and the TRP height (separating the troposphere and the stratosphere) the black line. The uncertainty in the derived particle extinction coefficient and the AOD values was less 20%. The variation of α_p profiles showed weak aerosol layers at 14-20 km, being indicative of an existence of the stratospheric smoke. In lower troposphere, at 6-10 km the aerosol load was significantly enhanced and the free troposphere AOD_{FT} was slightly higher than within aerosol boundary layer AOD_{ABL}, which indicates aerosol advection in the free troposphere (not of interest to this paper). The total aerosol optical depth (AOD_{TO}) was of 0.30 (355 nm) and 0.27 (532 nm). In lower stratosphere AOD_{STR} was of 0.06 and 0.02, contributing with 20% and 7% to AOD_{TO} at 355 and 532 nm, respectively. For the extreme smoke observed in August 2017 in Leipzig, the 532 nm smoke related AOD_{TR} was of 0.08 and as high as 0.2-0.25 for AOD_{STR} [7]. This is indicating a significant dilution of the stratospheric smoke aerosol load over Warsaw.

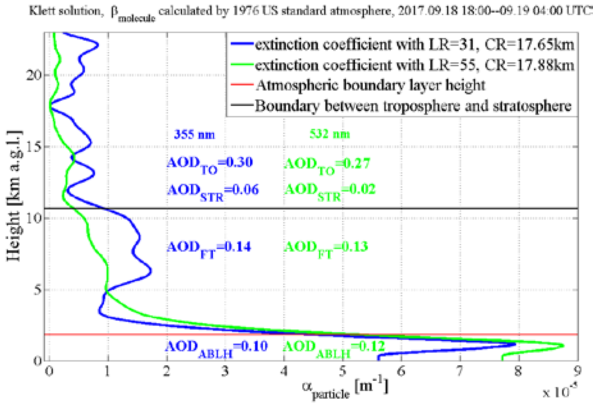

Figure 2. PollyXT-UW lidar-derived vertical profiles of particle extinction coefficient (α_p) at 355 nm and 532 nm, calculated as a mean of 18:00-4:00 UTC on 18/19 September 2017 in Warsaw. Aerosol optical depth within aerosol boundary layer (AOD_{ABL}), free troposphere (AOD_{FT}), stratosphere (AOD_{STR}) and total (AOD_{TO}) are given.

5. CONCLUSIONS

Well documented wildfires originating over North America in August of 2017 with smoke aerosol layers detected in the troposphere and stratosphere after long range transport over the globe, were explored in this study in view of the assessment of the change of their optical properties 2-3 months after the event.

The stratospheric smoke aerosol layers observed over Warsaw in September and October of 2017 were discussed in terms of the volume depolarization ratio (VDR) and aerosol optical depth (AOD). The VDR values of stratospheric smoke layers were in the range from 0.020 to 0.049 at 355 nm and from 0.020 to 0.059 at 532 nm. The AOD of the smoke layers in stratosphere contributed with 0.06 (20%) and 0.02 (7%) to the total AOD at 355 and 532 nm, respectively. The comparison of these results implies that the circulation of the smoke particles related to the biomass burning injection of North American wildfires smoke aerosol into the atmosphere in August 2017 [7] caused significant (10 times) dilution of the aerosol optical depth and indicate significant decrease of the volume depolarization ratio, which can be explained either by strong ageing (decreasing size and drying of particles) or by water uptake of the stratospheric aerosol.

ACKNOWLEDGEMENTS

The PollyXT lidar in Warsaw was developed in scientific collaboration of the Faculty of Physics, University of Warsaw (FUW) with the Institute of Tropospheric Research (TROPOS) financed by Polish Foundation of Science & Technology (519/FNITP/115/2010). We acknowledge work of colleagues of PollyXT Lidar Group lead by Dietrich Althausen.
The algorithms developed for this research were financed within the ESA-ESTEC Contract for Development of a European HSRL airborne facility (MULTIPLY) Contract No. 4000112373/14/NL/CT.

REFERENCES

[1] T. Deshler, et al. A review of global stratospheric aerosol: Measurements, importance, life cycle, and local stratospheric aerosol. Atmos. Res. 90, 223–232 (2008)

[2] S. Kremser, et al. Stratospheric aerosol – observations, processes, and impact on climate. Rev. Geophys. 54, 278–335 (2016)

[3] S. Solomon, et al. The Persistently Variable “Background” Stratospheric Aerosol Layer and Global Climate Change. Sci, 333, 866–870 (2011)

[4] Zuev, V. V, et al. 30-year lidar observations of the stratospheric aerosol layer state over Tomsk (Western Siberia, Russia). Atmos. Chem. Phys. 17, 3067-3081 (2017)

[5] S. Khaykin, et al. Variability and evolution of the midlatitude stratospheric aerosol budget from 22 years of ground-based lidar and satellite observations. Atmos. Chem. Phys. 17, 1829-1845 (2017)

[6] S. Khaykin, et al. Stratospheric Smoke With Unprecedentedly High Backscatter Observed by Lidars Above Southern France. Geophys. Res. Lett. 45, 1639–1646 (2018)

[7] A. Ansmann, et al. Extreme levels of Canadian wildfire smoke in the stratosphere over central Europe on 21–22 August 2017. Atmos. Chem. Phys. 18, 11831–11845 (2018)

[8] M. Haarig, et al. Depolarization and lidar ratio at 355, 532, and 1064 nm and microphysical properties of aged tropospheric and stratospheric Canadian wildfire smoke. Atmos. Chem. Phys. 18, 11847-11861 (2018)

[9] Q. Hu, et al. Long-range-transported Canadian smoke plumes in the lower stratosphere over northern France. Atmos. Chem. Phys. 19, 1173-1193 (2019)

[10] C Jimenez, et al. Polarization lidar: an extended three-signal calibration approach. Atmos. Meas. Tech. 12, 1077-1093 (2019)

[11] H. Baars, et al. The unprecedented 2017–2018 stratospheric smoke event: decay phase and aerosol properties observed with the EARLINET. Atmos. Chem. Phys. 19, 15183–15198 (2019)

[12] G. Pappalardo, et al. EARLINET: Towards an advanced sustainable European aerosol lidar network. Atmos. Meas. Tech. 7, 2389-2409 (2014)

[13] H. Baars, et al. An overview of the first decade of Polly NET: An emerging network of automated Raman-polarization lidars for continuous aerosol profiling. Atmos. Chem. Phys. 16, 5111-5137 (2016)

[14] K. Markowicz, et al. Study of aerosol optical properties during long-range transport of biomass burning from Canada to Central Europe in July 2013. J. Aeros. Sci. 101, 156-173 (2016)

[15] R. Engelmann, et al. The automated multiwavelength Raman polarization and water-vapor lidar PollyXT: The next generation. Atmos. Meas. Tech. 9, 1767-1784 (2016)

[16] I. S. Stachlewska, et al. Raman lidar water vapour profiling over Warsaw, Poland. Atmos. Res. 194, 258-267 (2017)

[17] J. D. Klett. Lidar inversion with variable backscatter/extinction ratios. Appl. Opt. 24, 1638–1643 (1985)

[18] I. S. Stachlewska, et al. Modification of local urban aerosol properties by long-range transport of biomass burning aerosol. Remote Sens. 10, 412 (2018)

[19] D. Wang, et al. Interrelations between surface, boundary layer, and columnar aerosol properties derived in summer and early autumn over a continental urban site in Warsaw, Poland, Atmos. Chem. Phys., 19, 13097–13128 (2019)

[20] I.M. Brooks. Finding boundary layer top: Application of a wavelet covariance transform to lidar backscatter profiles. J. Atmos. Ocean. Tech. 20, 1092-1105 (2003)