Response to Reviewer Report #1 by Wang et al. on 31 March 2019

Dear Reviewer, Dear Editor,

We are grateful to Reviewer for all comments and suggestions that helped us to improve this manuscript. In the following, answers to Reviewer's comments are reported below each comment and modifications of the initial manuscript as well as additions are reported in color highlight in the revised manuscript.

Interactive comment on "Interrelations between surface, boundary layer, and columnar aerosol

properties over a continental urban site" by Dongxiang Wang et al.

Anonymous Referee #1

Received and published: 4 January 2019

This manuscript presents a statistical analysis of optical products derived from lidar data and its interrelation with boundary layer height and aerosol optical depth at an urban site in central Europe. Overall, the manuscript is clear and data is well presented. Some of the interrelations described have statistical significance, while others do not seems to have relation. The manuscript appears scientifically sound to merit publication. However, in its current form, it requires some revisions.

Authors' response: Thank you very much for the kind words, we believe that we have fulfilled all of the required changes in the final version of the manuscript.

A main concern in this study is the comparison with AOD. It is stated that a percentage of the total AOD (obtained from CIMEL and/or MFR7 at some specific wavelengths) is within the boundary layer (calculated integrating the extinction profile from the ground to the ABLH at different wavelengths). This is not very precise since, a priori, you do not know if the integration of the entire profile (from ground to let say... 20 km) matches the total AOD from the independent instruments (CIMEL and/or MFR7). Al least this is not stated in the manuscript and it is a comparison worth having for, at least those 33 cases.

Authors' response: The CIMEL and MFR-7 instruments collect data only at daytime. Thus, the particle extinction coefficient profiles from lidar chosen for comparison were also derived at daytime (33 cases coinciding in time profiles between 04:00 and 16:00 UTC). During the daytime, the lidar signal to noise ratio is affected by the background sky radiation. Therefore the profiles of the particle extinction coefficient derived by the Raman approach from daytime lidar signals are limited, in our case up to ~3.5 km. So, it is not possible to calculate lidar-derived columnar AOD that will correspond to the CIMEL and MFR-7 columnar AOD. Therefore, we restricted the analyses and calculated the AOD from lidar only within ABL dynamically found for 3 elastic backscatter signals. Then the AOD in the free troposphere is defined as equal to AOD_{CL}-AOD_{ABL}.

Also, wavelengths should be the same. Since AE is available, using the Angstrom law the AOD at 355 nm and AOD at 532 nm can be calculated from CIMEL and MFR7. The wavelength dependence of the AOD is important, and the comparison should be made at the same wavelength.

Authors' response: Following this suggestion, the AOD values of CIMEL and MFR-7 were scaled to the lidar wavelengths 355 nm and 532 nm using Angstrom law (Angstrom, 1929, Iqbal, 1983) with equation:

$AOD_2 = \exp[\ln(AOD_1) - \ln(\lambda_2/\lambda_1) * AE]$, where λ_1 is original wavelength, λ_2 is the wavelength to which we scale. AOD_2 is the AOD values of CIMEL (or MFR-7) at 355 (or 532 nm) after it is scaled from initial value. AOD_1 is original AOD, i.e. for CIMEL (380 and 500 nm) and for MFR-7 (415 and 500 nm). AE is the AE(380/500) and AE(415/500) obtained from CIMEL and MFR-7, respectively.

All new AOD_{CL} and AE_{CL} values derived by CIMEL and MFR-7 and related statement are added to manuscript. The scaled data of both radiometers show the same values in the given range of the standard deviations. The fit with the lidar data is better. The lidar values within ABL and twice lower than columnar values, which is due to significant aerosol load in free troposphere.

Moreover, I added the following references to manuscript:

Angstrom, A.: On the atmospheric transmission of sun radiation and on dust in the air, Geogr. Ann., 12, 156–166, 1929.

Iqbal, M.: An introduction to solar radiation, Acadamec Press, Ontario, 1983.

Also, the CIMEL is at some distance from the lidar. Is it at the same altitude approximately? There are other comments and I'll enumerate indicating page (P) and line (L) or Figure. Some of them just typos, but others are important changes to be considered:

Authors' response: Thank you, indeed this was not specified in the manuscript. The altitude of CIMEL in Belsk is 190m (a.g.l.) and lidar in Warsaw is 112m (a.g.l.), respectively. Between the two sites there is flatland, with peri-urban character. The two sites and passive and active sensors are not expected to deliver perfectly comparable results; therefore we used for comparisons additionally the MFR data as measured directly at the lidar site. Agreement of the CIMEL and MFR AODs is high, and both compare better also to lidar AOD due to performing the scaling to the lidar wavelengths. We added this information to the text.

Specific Comments:

- A list of acronyms would be good. There are a lot of acronyms within the manuscript starting on the abstract and sometimes is hard to follow. Also revise the acronyms used in figure axis, sometimes they do not match the text.

Authors' response: Thank you, we looked throughout manuscript, revised them, and defined as in following list, the we added this list to Appendix.

List of symbols and physical quantities:

Aerosol boundary layer (derived by lidar)	-- ABL
Aerosol boundary layer height (derived by lidar)	-- ABLH
Particle extinction coefficient (within aerosol boundary layer)	-- α_{ABL}
Particle backscatter coefficient (within aerosol boundary layer)	-- β_{ABL}
Aerosol optical depth (within aerosol boundary layer, derived by lidar)	-- $AOD_{ABL}(\lambda)$
Aerosol optical depth (columnar, derived by sun-photometer or radiometer)	-- $AOD_{CL}(\lambda)$
Lidar ratio (within aerosol boundary layer)	-- $LR_{ABL}(\lambda)$
Particle linear depolarization ratio (within aerosol boundary layer)	-- $\delta_{ABL}(\lambda)$
Ångstrom exponent (within aerosol boundary layer, derived by lidar)	-- $ÅE_{ABL}(\lambda_1/\lambda_2)$
Ångstrom exponent (columnar, derived by sun-photometer or radiometer)	-- $ÅE_{CL}(\lambda_1/\lambda_2)$
Water vapor mixing ratio (within aerosol boundary layer)	-- WV_{ABL}
Relative humidity (at the near-surface)	-- RH
Particulate matter with diameter <10 μm; <2.5 μm	-- PM_{10}; $PM_{2.5}$

Fine to coarse mass ratio	-- FCMR
Wavelength	-- λ

- Please avoid the use of exclamations within the manuscript.

Authors' response: Thank you, we corrected in the manuscript.

- P4L6: The Tropos website should be http://polly.tropos.de/ instead of www.polly.tropos.de/.

Authors' response: Thank you, we corrected it in the manuscript.

- P4L16-17: I do not understand the incomplete overlap issue sentence. What does it mean?

Authors' response: Wording incomplete is indeed unfortunate here. Thus, we added the following sentences to text: "In winter, the atmospheric boundary layer height derived at noon and midnight from the radiosonding profiles can be found below the complete lidar's overlap range (i.e. the range in which the lidar laser beam is fully received by the field of view of the lidar telescope), and therefore the detection go the boundary layer height from lidar data is limited in winter. In contrast, in summer and early-autumn, the boundary layer height is always above the complete lidar's overlap range, and thus not affecting the profiles. Therefore, we restricted the analyses of the optical properties within boundary layer the latter seasons. "

- P5L5: A map of the different locations would be good. The CIMEL is 25 km away from the lidar, the air quality monitoring site is also at a different location. It would be good to have a sense of the locations visually.

Authors' response: Thank you for your suggestion, can add the following map (Figure 1 in the final manuscript).

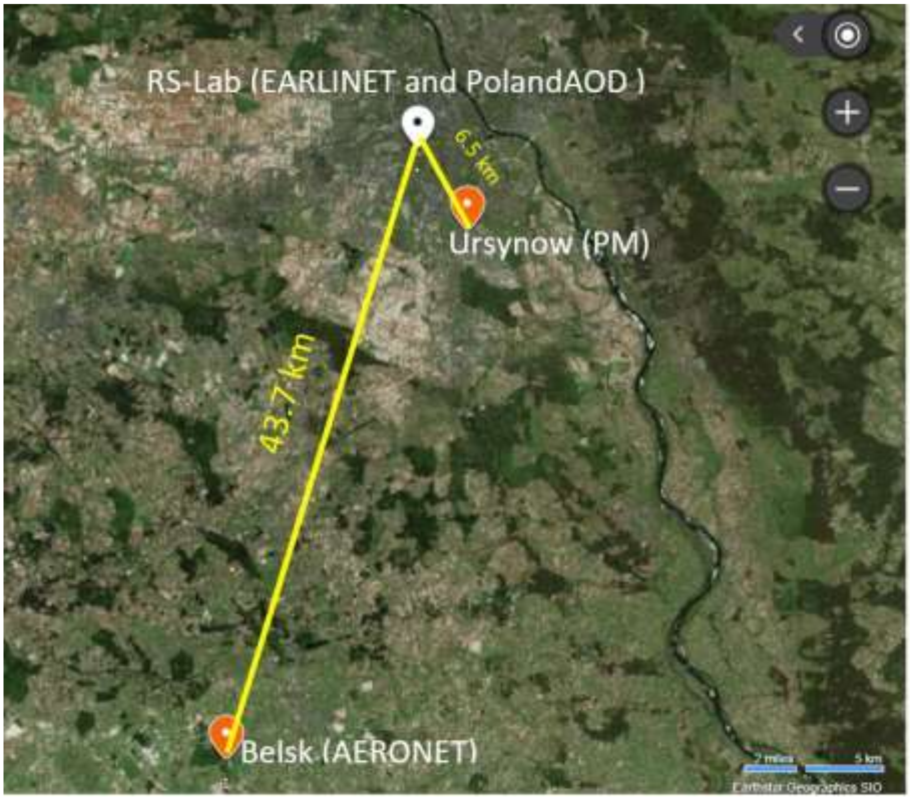

Figure 1. The location of RS-Lab in Warsaw, IGF-PAN observatory in Belsk and WIOS in Ursynow. Source: Microsoft Map (March 2019).

- P6L29: Why the water vapor mixing ratio profiles are extrapolated from 100 m?

Authors' response: We clarified this in the text with following sentences:

The water vapor mixing ratio profile is calculated using the ratio of two signals at 407 and 387 nm Raman channel. The overlap term of those two is close in spectral range (only 20nm) signal channels practically cancel when calculating their ratio. Similarly, the particle depolarization ratio is the ratio of cross channel and corresponding total channel at the same wavelength; also here the overlap term cancels. Therefore, water vapor mixing ratio profile (so as the linear particle depolarization ratio profile) can be obtained almost down to the ground.

- P7L8: It is clear that the LR is wavelength dependent. What is the wavelength of the LR described for aerosol typing?

Authors' response: Thank you for this comment. To clarify this sentence, we added the following descriptions to text: A review of aerosol types include in the classification scheme values reported by Groß et al., 2013, 2015, based on which LR for the marine particles is varying from 16-30sr at 355 nm and 18-26sr at 532 nm, the biomass burning varying from 50-95sr at 355 nm and 60-90sr at 532 nm, the mineral dust varying from 50-70sr at 355 nm and 45-65sr at 532 nm, the pollution varying from 50-65sr at 355 nm and 50-60sr at 532 nm.

Moreover, two new references were added to manuscript:

Groß, S., Esselborn, M., Weinzierl, B., Wirth, M., Fix, A., and Petzold, A.: Aerosol classification by airborne high spectral resolution lidar observations, Atmos. Chem. Phys., 13, 2487–2505, doi:10.5194/acp-13-2487-2013, 2013.

Groß, S., Freudenthaler, V., Schepanski, K., Toledano, C., Schäfler, A., Ansmann, A., and Weinzierl, B.: Optical properties of longrange transported Saharan dust over Barbados as measured by dual-wavelength depolarization Raman lidar measurements, Atmos. Chem. Phys., 15, 11067–11080, doi:10.5194/acp-1511067-2015, 2015.

- P7L13: Values in range of 4-8 is correct?

Authors' response: Thank you, it was a typo, it should read 0.04 -0.08.. We have corrected it in the text

- P9L8: is it possible to have marine aerosol at the surface in Warsaw? It is a continental location hundreds of kilometers away from the sea.

Authors' response: Thank you for your question. Indeed the nomenclature used as marine aerosol is unfortunate here. What is meant is the aerosol that is transported to Warsaw directly from Arctic. We clarified this in the text as following sentences:

In current study, for several cases LR_{ABL} in the range of 25-30 sr at both wavelengths was obtained (Figure.2). This is interpreted as likely due to transport of the clean air mass arctic marine particles into the boundary layer in Warsaw during the analyzed period. Such cold air masses can be transported from Arctic to Eastern Europe (Costa-Surós et al. 2015).

Moreover, we added new reference to manuscript:

Costa-Surós M., I.S. Stachlewska, A. Nemuc, C. Talianu, B. Heese, and R. Engelmann, 2015: Study case of air-mass modification over Poland and Romania observed by the means of multiwavelength Raman depolarization lidars, International Laser Radar Conference (ILRC 27th), 5-10 July 2015, New York, USA, Paper ID: 315.

- P10L9: The numbers given for MFR7 are not the same shown on Table 2.

Authors' response: Thank you, the values of CE318 and MFR-7 were scaled to 355 and 532 nm using Angstrom law in Table 2, we also changed these values in the text for consistency.

- P10L15: Having only 33 profiles, it is easy to see if there is free troposphere aerosol by looking directly at the profiles. Also, according to the very first comment, if the AOD is calculated for the entire profile (integrating the entire profile) a percentage of AOD outside the boundary layer could be given. The statement indicating that AOD_ABL is 3-4 times lower than the AOD_CL could change if the AOD considerations from above are taking into account.

Authors' response: Thank you for your suggestion; to follow it I made a plot of the 33 lidar-derived particle extinction coefficient profiles at 355 and 532 nm, so as obtained from the EARLINET-ACTRIS Data Base. The derived aerosol boundary layer heights of these 33 cases ranged from 1.5 to 2.6 km. The maximum height of particle extinction coefficient profiles is limited to 3.5 km (profiles derived at daytime: 04:00 to 16:00 UTC) by Raman approach. *Note that obtaining daytime Raman profile up to this height at daytime is itself - an achievement.* Thus, aerosol layers in the free troposphere > 3.5 km were not derived. 33 profiles can only indicate the aerosol conditions below 3.5 km. This is why we mainly focused on study optical properties of ABL in this paper, as for the very first comment.

We modified the statement as following in the text: "The obtained results of the mean values of the AOD_{ABL} being 2 times lower than the mean values of AOD_{CL}."

The most important change is that for the new manuscript, we re-extrapolated extinction coefficient of all profiles, and then new 44 profiles are added to analyses. Therefore, all available 246 profiles (2α + 3β +

2δ) during 2013, 2015 and 2016 were obtained. New comparisons and discussions were based on 246 profiles in entire time, 96 profiles in nocturnal time and 93 profiles in sunrise and sunset time.

- P10L22-25: Consider the same comment regarding the AOD calculations and wavelength of AOD for this statement.

Authors' response: Thank you, we modified this sentence as following in the text:

Clearly this very rough approximation for the Warsaw urban continental site would be rather of AOD_{ABL} (Warsaw) ≈ 75% AOD_{CL}.

- P11L13: The reference Stachlewska at al. 2017 is not clear. There are 2 references for the same year. They should be called 2017a and 2017b in the manuscript and reference list.

Authors' response: Thank you, here it should be Stachlewska at al. (2017b), we corrected it in the text.

- Table 2: This Table should chance if the wavelength change from CIMEL and MFR7 to lidar wavelength is taking into account.

Authors' response: Thank you. According to the suggestion, the initial values of the AOD_{CL} and AE_{CL} of CE318 and MFR-7 were scaled to 355 and 532 nm using Angstrom law. We added following Table 2 to manuscript.

Table 2. Mean aerosol optical depth (AOD) and Ångstrom exponent (ÅE) with standard deviations derived within boundary layer at 355 and 532 nm from PollyXT lidar at the EARLINET site in Warsaw, and in atmospheric column measured by CE318 CIMEL (380 and 500nm) at the AERONET site in Belsk and MFR-7 radiometer (415 and 500nm) at the PolandAOD-NET site in Warsaw. AOD_{CL} at CE318 and MFR-7 were scaled to 355 and 532 nm using Angstrom law. Average is obtained for July September of 2013, 2015, 2016 for cases when all instruments operated simultaneously (33 cases). In brackets, the mean values derived for cases of no long-range transport in the free-troposphere, as given in EARLINET/ACTRIS Data Base. 0

	AOD_{ABL}(355)	AOD_{CL}(355)	AOD_{ABL}(532)	AOD_{CL}(532)	ÅE
AERONET		0.46±0.19 (0.32±0.07)		0.25±0.13 (0.13±0.03)	1.48±0.23 (1.67±0.06)
PolandAOD		0.52±0.22 (0.28±0.07)		0.30±0.16 (0.16±0.03)	1.56±0.21 (1.74±0.04)
EARLINET	0.22±0.08 (0.20±0.06)		0.14±0.05 (0.12±0.03)		1.42±0.33 (1.28±0.28)

- Figure 2: This Figure should change if AOD consideration from above are taking into account as well. On the Figure caption 2016 is a LEAP year (not lap).

Authors' response: Thank you, we corrected the typo, then modified the figure (i.e. only scaled AOD values are plotted) and replaced with the new plot (now, Figure 3) in the final manuscript.

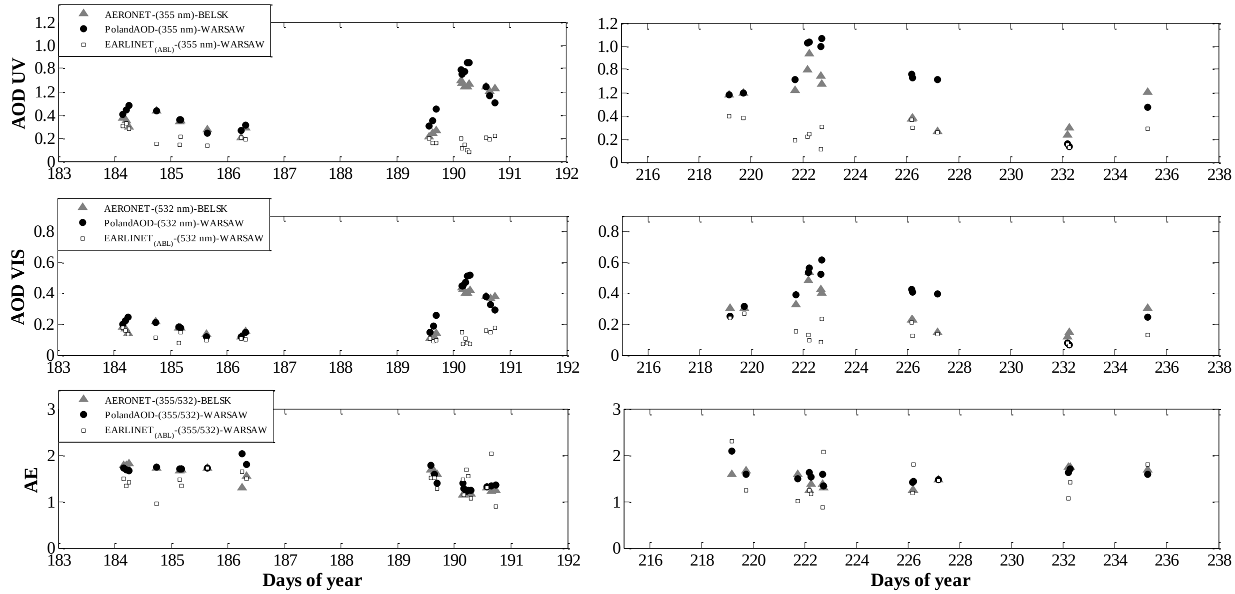

Figure 3. Hourly averages of aerosol optical depth (AOD) and Ångstrom exponent (ÅE) derived within boundary layer at 355 and 532 nm from PollyXT lidar at the EARLINET site in Warsaw (open circle/square), and in atmospheric column measured by CE318 CIMEL (380 and 500nm) at the AERONET site in Belsk (grey/triangle) and MFR-7 radiometer (415 and 500nm) at the PolandAOD-NET site in Warsaw (black /circle). AOD_{CL} at CE318 and MFR-7 were scaled to 355 and 532 nm using Angstrom law. Note, only data points for which all 3 measurements were available are plotted. For day of year 182-274, for all years (2013, 2015, 2016) we superimpose available data points (33 cases) on single plot (note 2016 was a leap year).

- Figure 4: For consistency, the Y label should be AOD_ABL instead of just AOD.

Authors' response: Thank you, we have corrected Y label in the plot.

- Figure 5: The horizontal lines on the first row graphs are not explained.

Authors' response: Thank you. We added the following sentence to the figure caption (now, Figure 6):

Thresholds of FCMR are marked as horizontal lines.

- Figure 6: The correlation between AE and FCMR is not explained well in the manuscript and conclusions. There should be a clear correlation since larger values of AE means predominance of smaller particles (fine mode dominates).

Authors' response: Thank you for your comment. In fact, it is rather intuitive that when the AE values increase, the FCMR values must also increase. However, it is not so strait forward the other way around, i.e. if FCMR values increase, the change trend of the AE values will depend on specific condition. When the particles with diameter < 1 µm will dominate (causing increase of FCMR), also the values of AE will increase. In contrast, when the particles with diameter between 1 µm and 2.5 µm dominate (causing increase of FCMR) the AE values shall not show any increasing trend.

- Figure 7: Same as Figure 4.

Authors' response: Thank you, we corrected Y label in the plot.

- Figure 8: Same as Figure 4.

Authors' response: Thank you, we corrected X and Y label in the plot.

- Figure 9: For consistency with the text, the Y axis label should be RH_

Authors' response: Thank you, we modified RH_0 to RH in the text, so that the Y-axis label in the plot is now consistent with the text.