Anonymous Referee #1

We would like to thank the reviewer for his / her useful comments.

GENERAL COMMENTS

The authors have applied the BOREAS retrieval algorithm to obtain vertical profiles of aerosol extinction for a substantial data set of two different MAX-DOAS instruments in the Vienna area. They assessed the quality of these retrievals by comparing the profiles, the integrated AOD and the near-surface values with extinction profiles derived from a ceilometer, AERONET measurements and PM10 measurements respectively. The data set was large enough to be able to differentiate between the seasons. In addition they demonstrate that the two MAXDOAS instruments can be used to study the spatial variability of NO2 and aerosol over Vienna.

The paper is very well structured and clearly written. This is the first assessment of the BOREAS aerosol retrieval method with a large dataset (two instruments, and almost two years of data), and with multiple colocated comparison instruments, making it an important study.

What is missing is a discussion of the issues of this particular retrieval method found in earlier studies (Boesch et al, 2018, Tirpitz et al, 2021, Friess et al, 2019): are these issues solved, can they be confirmed or disproven?

We have now added a discussion in the new section 2.2.1 (Vertical sensitivity, information content, and sources of errors) about issues of BOREAS highlighted in recent studies (see Page 9, Line 14-21).

I am disappointed about the sole use of linear correlation coefficients to determine the quality of the retrievals, see specific comments below.

We have now introduced absolute and relative differences, in addition to the correlation coefficients (see answer to specific comments below).

SPECIFIC COMMENTS

The use of a linear correlation coefficient to compare vertical profiles is not obvious to me. Correlation coefficients are typically used to assess a possible linear relationship between two datasets. Do we expect a linear relationship? And if so, between what and what? It is unclear how the corellation coefficient for vertical profiles is defined in this paper. Is it defined with respect to the average profile? And are relative or absolute differences used? Do all altitudes have equal weight in this definition? Please clarify how to interpret the correlation coefficient for vertical profiles.

We agree that the sole use of a linear correlation coefficient to compare vertical profiles is not the optimal way. In our study, we have defined the correlation coefficient for vertical profiles with respect to the average MAX-DOAS/ceilometer profiles, where all altitudes have equal weight (see Page 15, Line 18-21).

In order to provide more statistics for the comparison between vertical profiles (MAX-DOAS vs. Ceilometer), we have now computed absolute and relative differences of vertical aerosol profiles and presented these differences in additional figures (see Fig. 7 and 8) as well as in the text (see Page 16, Line 11-30 and Page 17, Line 1-2).

A more common, and more informative way to compare profiles is to look at the absolute and relative difference profiles, and quantify the differences for certain altitude ranges. Please add this to your study.

As mentioned in the answer to the comment above, we have now computed absolute and relative differences and presented these differences in additional figures (see Fig. 7 and 8) as well as in the text (see Page 16, Line 24-30 and Page 17, Line 1-15).

Please clarify the differences in sensitivity and averaging kernels between the BOREAS retrievals on one hand and the ceilometer retrievals on the other hand, and whether these differences are expected to influence the comparison.

In this study, we focus on vertical profiles within the planetary boundary layer and more generally between the station altitude and 4 km altitude. MAX-DOAS generally shows high sensitivity to lowermost layers of the troposphere. With respect to the profile retrieval algorithm BOREAS, vertical sensitivity is described by averaging kernels (AVKs). We have now introduced vertical sensitivity, information content (AVKs), and error sources in section 2.2.1.

We assume that the sensitivity of the ceilometer retrievals is more or less constant above the minimum altitude. For a better comparison of the vertical profiles from MAX-DOAS and ceilometer instruments, we have now convoluted the ceilometer data to the MAX-DOAS vertical resolution by applying the BOREAS averaging kernels (see Page 8, Line 24-27 and Page 9, Line 1-21).

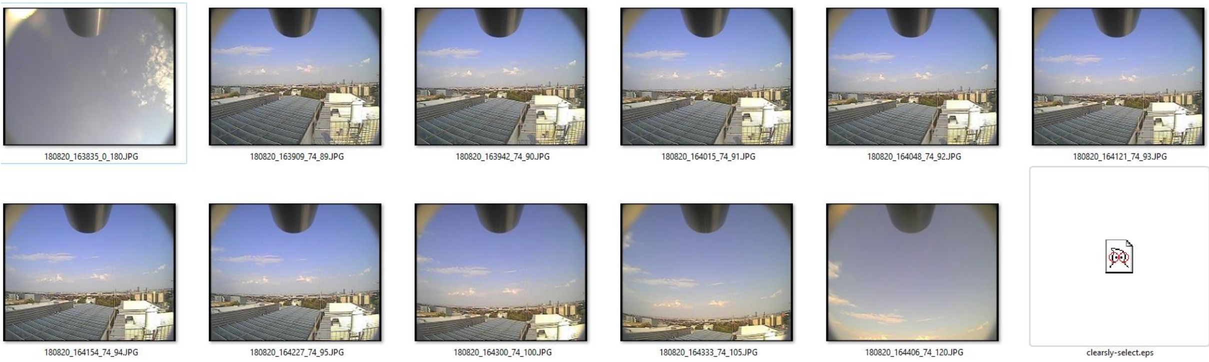
It is interesting to see that the observed average profiles often show an increase towards the lowest point, both for MAXDOAS and for Ceilometer (e.g. Fig. 2, fall, 10-16UTC, spring 8-14 UTC, and even summer 8-16 UTC). Please check if there is not an intrinsic different treatment for the lowest altitude (e.g. other vertical extent, or different interpolation). If not, can you elaborate on the possible reason why this is so often seen?

It is important to note that we have used a single data point (50 m above instrument's location, which corresponds to a total altitude of 248 m asl, resulting from the instrument's altitude (198 m) + 50 m) for the lowest point of ceilometer data. This data point is assumed to be 'equal' to the lowest altitude of BOKU MAX-DOAS (260±50 m). The other data points of vertical ceilometer profiles with 10 m vertical resolution are averaged according to the 100 m vertical extent of MAX-DOAS vertical profiles (e.g. 60-140m, 150-240m, 250-340m, … etc). The different treatment of the lowest ceilometer point (using a single point instead of averaging 10 points) might explain these occasionally observed increases for the ceilometer. As we have now applied smoothing with the MAX-DOAS AVKs to the ceilometer vertical profiles, these increases disappear for the ceilometer (see Fig. 5).

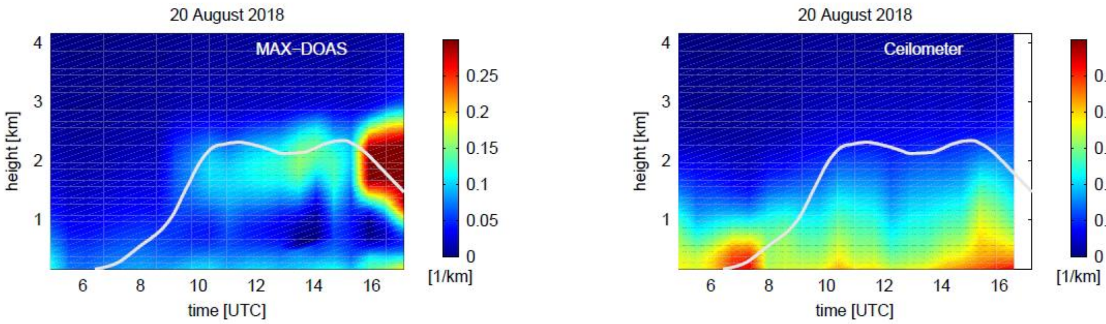
Several average MAXDOAS profiles in Figure 3 (visible) show elevated aerosol between approximately 2 and 3 km altitude, while this is not seen in the ceilometer profiles. In Figure 2 (UV) this is much less pronounced. Please give an explanation, and also how this effects the observed differences.

A possible explanation for the elevated aerosol between 2 and 3 km altitude, which particularly is found for the vertical AE profiles retrieved in the Vis channel might be explained by the presence of clouds within the viewing direction of MAX-DOAS.

The following digital images of a typical elevation sequence taken on 20 August 2018 between 16:38 and 16:44 UTC indicate the presence of clouds a few kilometers away from the location of the MAX-DOAS instrument. The clouds most probably affect the retrieval of AE profiles on this day, which was defined as a 'cloud-free' day.



This elevated 'aerosol', which can be nicely seen in the Vis contour plot below (left panel), seems to also affect the averaged profiles presented in Fig. 3 (which after revisions is Fig. 6). While the elevated aerosol is observed for the MAX-DOAS profiles, it is not found for the ceilometer profiles, most probably because of the fact that the clouds on that specific day where not present above the instrument but rather a few kilometers away. We have now added a short discussion also in the manuscript (see Page 15, Line 21-25). In order to reduce such influence of clouds, future studies could try to find a modified filtering, e.g. by also considering the color index.



The regression coefficients printed in Figures 2-6 have the wrong number of significant digits. The offsets have too many, and the slopes too few. Please use the number of significant digits that is justified by the uncertainty of the coefficients. Also do not print '+-', but rather '-'.

We have now changed the number of digits as well as '+-' into '-' in the relevant figures (see Fig. 5, 6, 9, 10, and 11).

Figures 7 and 8 are very difficult to assess. I recommend adding a more map-like display. For example a figure with four subpanels for NO2, AOD, and the near-surface values, where each subpanel represents the spatial area considered and the values from fig 7 and 8 can be shown as colored bars (or parts of a circle) in the respective viewing directions, where the length of the stripe is somewhat representative for the area observed by the MAXDOAS. The use of

We agree that Fig. 7 and Fig. 8 (which are Figs. 12 and 13 in the revised manuscript) are not very easy to assess. Using map-like figures instead is generally a good recommendation. However, as the differences of NO2, AOD and the respective near-surface values between the individual azimuthal directions are rather small, it is hard to assess these differences in a map-like figure (see unfinished example below, where the length, thickness, and color of the lines represent AOD, near-surface AE, and season, respectively).

We therefore would like to keep the original figures, which can be assessed in combination with Fig. 1, where we have now added the symbols to the azimuthal directions.

p2, l19: "widely documented": please give references here

We have now added a few more references (see Page 2, Line 25).

p6, l11: An elevation of 0 degree with a FOV of more than 0 will result in a vegetation signal. Is this measurement used in the retrieval?

The 0 degree elevation measurements are not used in the retrieval in our study. We have now added a sentence in the text to clarifying that measurements taken at 0° elevation angles are not used for the profile retrieval (see Page 6, Line 19-20).

section 2.2.1:

- second step to 'pre-select': what are the pre-selection criteria?

The pre-selection criteria are actually explained in the third step (see Page 13, Line 22).

- third step: this is very complex; please add a figure illustrating the procedure.

We have now added a figure illustrating the procedure (see Fig. 4).

- please explain what you mean by 'second-order difference'

This is a fixed term in mathematics: discrete equivalent of a "second derivative". https://stats.stackexchange.com/questions/351697/what-is-the-intuition-behind-second-order-differencing

We have now changed the first occurrence to: "second-order differences of the radiation time-series" (see Page 13, Line 26).

p10, l8: How large is the effect of using measured p,T-profiles instead of US standard profiles?

The effect of using p- and T-profiles instead of US standard profiles was estimated in the PhD thesis of Tim Bösch (https://media.suub.uni-bremen.de/handle/elib/1572, Page 183-186) for a single day (15 September 2016). Overall, larger (smaller) temperatures in the troposphere are directly linked to smaller (larger) O_4 values which will lead to an increase (decrease) in extinction for the aerosol profiles within the retrieval. More specifically, the use of US standard atmosphere led to negative relative differences, whereas the use of sonde profiles from this particular campaign day led to changes in surface extinction of up to 15% and altitude depending changes of up to 30%, in comparison to mean monthly sondes profiles used within Bösch et al., 2018. Even though the altitude depending changes due to more accurate pressure and temperature profiles might be large, the impact on mean values can be considered as small when using noon sondes profiles due to the averaging of profiles retrieved with smaller and higher temperatures, in the morning and afternoon, respectively.

Section 2.2.3: the profiles are scaled by the AOD: do you mean that the profiles are scaled so that the AOD derived from the profile matches the AERONET AOD at a specific wavelength? It is not clear to me why you need the intermediate step at 910nm

The scaling of profiles is performed by using the AERONET AOD, in accordance to the procedure described in Wagner et al., 2019, who have selected the AERONET AOD retrieved at the wavelength closest with the wavelength of the ceilometer for their scaling. This intermediate scaling in our study is performed with the average of AERONET AODs at 870 and 1020 nm, which is in good accordance with the 910 nm of the ceilometer instrument. The second scaling in our study is then performed with averages of AERONET AODs at 340 and 380 nm as well as averages of AERONET AODs at 440 and 500 nm to make the ceilometer profiles comparable to MAX-DOAS UV (360 nm) and Vis (477 nm) profiles, respectively.

Section 3.1 Only sucessful retrievals are evaluated here, which makes sense. However, it is also interesting to know how often the retrieval does not succeed (does not match the criteria). Please give numbers.

We have now calculated the percentage number of retrievals that match the criteria. The numbers are given in the text of the manuscript (see Page 16, Line 6-9).

p13, l15: I don't fully agree with this assessment. It seems that the visible retrieval tends to result in higher aerosol levels at higher altitudes, which might be the reason for the worse correlation.

After convolution of ceilometer profiles with BOREAS AVKs, correlation is better for the visible than for the UV channel. We therefore revoke the assessment (see Page 15, Line 21-22).

TECHNICAL CORRECTIONS

p2, l1: "Hile high correlation" should probably be "High correlation"?

Has been changed as suggested (see Page 2, Line 7).

p8, l11: "sza is taken from retrieved maxdoas data" is better changed to " sza is taken at the time of the maxdoas measurement"

Has been changed as suggested (see Page 13, Line 15-16).

p9, l29: is SCRIATRAN implemented in BOREAS or BOREAS in SCIATRAN?

BOREAS and SCIATRAN are linked in several ways: For the aerosol retrieval part, BOREAS uses an inversion function implemented in SCIATRAN. For the trace gas retrieval part, BOREAS calls SCIATRAN only for the RTM calculations, but not for the inversion (see Page 10, Line 24-27).

p12,l27: intervalls -> intervals

Has been changed as suggested (see Page 15, Line 20).

p14, l12-17: this sentence is too long, please split in two or three sentences.

This sentence is no longer present in the manuscript as we have deleted the discussion of ‘Saharan dust’ from our manuscript as this was not the main focus and rather a speculation, without enough additional data to prove.