Interactive comment on «First validation of GOME-2/MetOp Absorbing Aerosol Height using EARLINET lidar observations» by Konstantinos Michailidis et al.
RC1: 'Review', Anonymous Referee #2,
Received and published: 11 Jul 2020

We would like to thank the Reviewer #2 for his/her fruitful comments that led to the improvement of the manuscript. In the revised version the reviewer's comments have been taken into account, by improving the discussion of many sections (i.e., algorithm description, comparison among the different stations, adding new figures and tables) and by further improving the figures. Below we report the changes included in the revised manuscript as a response to the comments of the reviewer.
General remark: The figure numbers and the page numbers in the referee comments and in our replies correspond to the original manuscript.

General comments:
In this study, the authors evaluate geometrical features of lofted aerosol layers derived by the Level 2 absorbing aerosol height product of Global Ozone Monitoring Experiment-2 (GOME-2) aboard the Meteorological Operational satellite programme (MetOp) platforms, using collocated ground-based lidar observations from 13 European Aerosol Research Lidar Network (EARLINET) stations. The research has scientific merit and therefore, it is worth being published under the special issue "EARLINET aerosol profiling: contributions to atmospheric and climate research" of the Atmospheric Chemistry and Physics journal. However, I would kindly suggest the authors to take into account the following recommendations in order to improve the manuscript. I would advise the authors to reorder some parts of the manuscript, e.g results, in which the order of figures doesn't correspond to the order of their appearance in the text.

For example, the authors discuss Figure 13 before introducing figures 10 to 12. This is quite confusing. Also, I would recommend checking and improving the language usage. There are a few places in the text where the combination of long sentences and language makes it hard to follow. From the scientific point of view, it wasn't clear to me whether GOME-2/MetOp should only be used to fill a gap compared to other space-based observations (active or passive) or if it is as reliable and under which occasions?

REPLY:
Aerosol vertical distributions are either described by aerosol profiles or columnar aerosol layer heights. Detailed profile of attenuated backscatter can be probed by active remote sensing techniques using lidar, such as the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) (Winker et al., 2009). However, the spatial coverage of CALIOP measurements suffers from its narrow swath. Although they provide great details in the vertical direction, lidar measured profiles are subjected to limited spatial and temporal coverage. Besides the presence of clouds or optically dense aerosol layers may attenuate the lidar signal, resulting in large uncertainties or missing data in the measured profiles. By contrast, passive remote sensing techniques provide adequate spatial coverage but poor vertical resolution and have been mainly used to retrieve columnar aerosol quantities in cloud-free scenes have been developed to retrieve limited but useful information of aerosol altitude (Xu et al., 2017).

While not achieving the same level of accuracy as a lidar, passive techniques can add an important augmentation due to the better spatial coverage. To achieve a good agreement between retrieved aerosol height from O2A band measurements and LIDAR measurements is challenging and depends on some assumptions (Sanders et al., 2015). Aerosol layer height retrievals from passive sensor measurements are only applicable under certain conditions (e.g. elevated aerosol layers, dark/bright surfaces, clouds etc) and different ALH algorithms are existed. GOME-2 instrument has a global coverage in 1.5 days, which makes it also quite suitable for the detection and daily monitoring of forest fires and volcanic eruptions. Events with high aerosol loading, aerosols may have a dominant effect, especially for almost cloud free scenes and for these cases are preferred to GOME-2 AAH retrievals. The Absorbing Aerosol Index (AAI) is an indicator for the aerosol loading. We should always look at the AAI values in combination with cloud products from FRESCO algorithm (Wang et al., 2012). The thresholds about the reliability of the AAI product, are used in the following way:

- AAI<2: No AAH available (there is little absorbing aerosol)
- 2<AAH<4: There is absorbing aerosol, but the reliability is low
- AAH>4: The AAH is supposed to have high reliability.

References:

Nelson, D. L., Garay M. J., Kahn R. A., and Dunst B. A.: Stereoscopic Height and Wind Retrievals for Aerosol Plumes with the MISR INteractive eXplorer (MINX), Remote Sens., 5, 4593– 4628, doi:10.3390/rs5094593, 2013.

Sanders, A. F. J., de Haan, J. F., Sneep, M., Apituley, A., Stammes, P., Vieitez, M. O., Tilstra, L. G., Tuinder, O. N. E., Koning, C. E., and Veefkind, J. P.: Evaluation of the operational Aerosol Layer Height retrieval algorithm for Sentinel-5 Precursor: application to O2 A band observations from GOME-2A, Atmos. Meas. Tech., 8, 4947–4977, https://doi.org/10.5194/amt-8-4947-2015 , 2015.

Xu, X., J. Wang, Y. Wang, J. Zeng,O. Torres, Y. Yang, A. Marshak, J. Reid, and S Miller (2017), Passive remote sensing of altitude and optical depth of dust plumes using the oxygen A and B bands: First results from EPIC/DSCOVRat Lagrange-1 point, Geophys. Res. Lett., 44, 7544–7554, doi:10.1002/2017GL073939.

Winker, D. M., Vaughan, M. A., Omar, A., Hu, Y., Powell, K. A., Liu, Z., Hunt, W. H., and Young, S. A.: Overview of the CALIPSO Mission and CALIOP Data Processing Algorithms, J. Atmos. Ocean. Tech., 26, 2310–2323, https://doi.org/10.1175/2009JTECHA1281.1, 2009.

Could the authors also comment regarding the performance of the different MetOp instruments? Do they perform equally?

REPLY:

Iinstrument degradation is a serious problem, which strongly affects the Earth reflectance measurements performed by GOME-2 in the UV wavelength range (Tilstra et al., 2012). As a result, it also has an impact on the AAI products retrieved from the GOME-2 instruments (Tilstra et al., 2010). For this reason, correction factors are applied to the Earth reflectances

GOME-2 Level1 products, especially for GOME-2A. There are no indications from our study that the quality of ALH differs between the three instruments.

Another point that wasn't clearly mentioned is whether the findings apply to all aerosol types or a specific category (e.g absorbing ones)? This needs to be stated clearly in the manuscript.

REPLY:

The findings of the present study refer to the presence of absorbing particles in the atmosphere. This is mentioned in detail in our main text. The UV Aerosol Index is an indicator for the presence of aerosol in the atmosphere. The aerosol types that are mostly seen in the GOME-2 AAI data are the desert dust, volcanic ash and biomass burning smoke aerosols. A positive value of AAI indicates the presence of absorbing aerosols, whereas negative or non-zero values imply non-absorbing aerosols or clouds. In this study, we use only the pixels containing positive AAI values and especially only values greater (or equal) than 2.0. As discussed in the ATDB (Tilstra et al, 2019), observation pixels with AAI values below 2.0 correspond to scenes with too low amount levels of aerosol to result in a reliable AAH retrieval.

The following sentences have been added in the revised manuscript:

"The Aerosol Index is an indicator for the presence of aerosol in the atmosphere. A positive value of AAI indicates the presence of absorbing aerosols, whereas negative or non-zero values imply non-absorbing aerosols or clouds. In this study, we use only the pixels containing positive AAI values and especially only values greater (or equal) than 2.0. According to Tilstra et al. (2019) (ATBD), observation pixels with AAI values below 2.0 correspond to scenes with too low amount levels of aerosol to result in a reliable AAH retrieval. This threshold, does not apply to every passive satellite instrument which retrieve the aerosol layer height product. For example, the TROPOMI ALH is only retrieved for pixels with UV AI (calculated by 354-388nm wavelength pair) larger than 1."

References:

Tilstra, L. G., Tuinder, O., Wang, P. and Stammes, P.: ALGORITHM THEORETICAL BASIS DOCUMENT GOME-2 Absorbing Aerosol Height, SAF/AC//KNMI/ATBD/005, 1.4, Royal Netherlands Meteorological Institute, de Bilt, 32 pp., 2019, https://acsaf.org/docs/atbd/Algorithm_Theoretical_Basis_Document_AAH_Apr_2019.pdf, last access: 15 October 2020.

Tilstra, L. G., Tuinder, O., Wang, P. and Stammes, P.: PRODUCT USER MANUAL GOME-2 Absorbing Aerosol Height, SAF/AC/KNMI/PUM/006, 1.1, Royal Netherlands Meteorological Institute, de Bilt, 28 pp., 2020, https://acsaf.org/docs/pum/Product_User_Manual_AAH_Aug_2020.pdf, last access: 15 October 2020.

Furthermore, what is the advantage of using GOME-2/MetOp instead of other passive sensors or CALIPSO for the geometrical boundaries of aerosols? Do the results presented here have a difference with similar studies for other space-borne sensors? Should we use AAH product or not, under which conditions these retrievals are reliable? A bit more discussion should be included in the manuscript.

REPLY:

Passive satellite remote sensing of aerosol layer height can by far not provide the same details as active remote sensing but adds an important extension compared to active remote sensing in terms of spatial coverage. The GOME-2 absorption aerosol layer height (AAH) is a new product, not yet publicly accessible, but will be accessible soon in future. The retrieval depends on many factors for a reasonable retrieval. The AAH is very sensitive to cloud contamination. The presence and the location of clouds compared to aerosol layer is important. In order to distinguish whether the contribution of clouds is crucial, three situations about the reliability of the AAH product are used and the effective cloud fraction (CF). The AAH product can be used to monitor volcanic eruptions globally and provide the height of the ash layers (Balis et al., 2016). For more detailed algorithm description one can refer to Tilstra et al. (2019). CALIOP employs a much more comprehensive layer detection algorithm (SIBYL, Vaughan et al., 2009) where the magnitude of the threshold is adapted according to the characteristics of the signal (Winker et al., 2009). CALIOP measures the actual aerosol vertical distribution. But due to the presence of heavy clouds and aerosols, the lidar signal tends to attenuate, which may lead to missing data in the measure profiles. Also, employs a much more comprehensive layer detection algorithm (SIBYL, Vaughan et al., 2009). In general, uncertainties in satellite-based aerosol retrievals arise from many sources, e.g. cloud contamination, treatment of surface reflectance and instrumental issues. The above discussion has been added in the manuscript.

References:

Sanders, A. F. J., de Haan, J. F., Sneep, M., Apituley, A., Stammes, P., Vieitez, M. O., Tilstra, L. G., Tuinder, O. N. E., Koning, C. E., and Veefkind, J. P.: Evaluation of the operational Aerosol Layer Height retrieval algorithm for Sentinel-5 Precursor: application to O2 A band observations from GOME-2A, Atmos. Meas. Tech., 8, 4947–4977, https://doi.org/10.5194/amt-8-4947-2015, 2015.

Balis, D., Koukouli, M.-E., Siomos, N., Dimopoulos, S., Mona,L., Pappalardo, G., Marenco, F., Clarisse, L., Ventress, L. J.,Carboni, E., Grainger, R. G., Wang, P., Tilstra, G., van der A,R., Theys, N., and Zehner, C.: Validation of ash optical depthand layer height retrieved from passive satellite sensors using EARLINET and airborne lidar data: the case of the Eyjafjallajökull eruption, Atmos. Chem. Phys., 16, 5705–5720, https://doi.org/10.5194/acp-16-5705-2016 , 2016.

Vaughan, M., K. Powell, R. Kuehn, S. Young, D. Winker, C. Hostetler, W. Hunt, Z. Liu, M. McGill, and B. Getzewich, "Fully Automated Detection of Cloud and Aerosol Layers in the CALIPSO Lidar Measurements", J. Atmos. Oceanic Technol., vol 26, pp. 2034–2050, 2009.

Winker, D. M., Vaughan, M. A., Omar, A., Hu, Y., Powell, K. A., Liu, Z., Hunt, W. H., and Young, S. A.: Overview of the CALIPSO Mission and CALIOP Data Processing Algorithms, J. Atmos. Ocean. Tech., 26, 2310–2323, https://doi.org/10.1175/2009JTECHA1281.1, 2009.

Specific comments:

1. Introduction: I suggest the authors to improve the reasoning for the need of accurate spatial distribution of aerosols. Where this information can be used and what would improve (e.g Xu et al., 2017; Sun et al., 2019)? Currently, this information is more or less there but it is missing a sentence which would bring together and combine all the separate reasons mentioned in the first paragraph.

- Sun, J., Veefkind, P., Nanda, S., van Velthoven, P., and Levelt, P.: The role of aerosol layer height in quantifying aerosol absorption from ultraviolet satellite observations, Atmos. Meas. Tech., 12, 6319–6340, https://doi.org/10.5194/amt-12-6319-2019, 2019.

- Xu, X., J. Wang, Y. Wang, J. Zeng,O. Torres, Y. Yang, A. Marshak, J. Reid, and S Miller (2017), Passive remote sensing of altitude and optical depth of dust plumes using the oxygen A and B bands: First results from EPIC/DSCOVRat Lagrange-1 point, Geophys. Res. Lett., 44, 7544–7554, doi:10.1002/2017GL073939.

REPLY: The suggested references and discussion thereof has been included in the introduction.

Measurements of aerosol height distribution can provide insight into aerosol transport processes since elevated aerosols are typically being carried over long distances, whereas aerosols confined to the primary boundary layers usually stay near the source region. Active remote sensing instruments, such as lidar and radar techniques, have proofed to be useful tools in providing measurements of high spatial and temporal distributions of aerosol and clouds and their geometrical and optical properties. Although the aerosol layer information by the environment is limited, several previous studies were investigated including sensitivity results and methodology in the retrieved methodology. Some notable mentions of missions that retrieve ALH are the Multi-angle Imaging SpectroRadiometer (MISR) on board the NASA Terra satellite (Nelson et al., 2013), which measures aerosol height using geometric optics; the Deep Space Climate Observatory (DSCOVR) mission with its Earth Polychromatic Imaging Camera (EPIC) (Xu et al., 2017, 2019); the Ozone Monitoring Instrument (OMI) on board the NASA Aura satellite (Chimot et al., 2017, 2018); and currently the TROPOspheric Monitoring Instrument (TROPOMI) instrument on board the Sentinel-5 Precursor satellite (Veefkind et al., 2012). Xu et al. (2017, 2019) are the first studies to demonstrate that the diurnal cycle of aerosol height is retrievable. The next years, missions like the upcoming Multi-Angle Imager for Aerosols (MAIA) mission (Davis etal., 2017) and the Tropospheric Emissions: Monitoring Pollution mission (TEMPO) (Zoogman et al., 2017) are expected to provide aerosol height retrievals as well. These instruments are examples of missions demonstrably more capable of retrieving Aerosol layer height.

The text above was added in the introduction part of the revised manuscript

References:

Chimot, J., Veefkind, J. P., Vlemmix, T., de Haan, J. F., Amiridis, V., Proestakis, E., Marinou, E., and Levelt, P. F.: An exploratory study on the aerosol height retrieval from OMI measurements of the 477 nm O_2-O_2 spectral band using a neural network approach, Atmos. Meas. Tech., 10, 783–809, https://doi.org/10.5194/amt-10-783-2017, 2017.

Chimot, J., Veefkind, J. P., Vlemmix, T., and Levelt, P. F.: Spatial distribution analysis of the OMI aerosol layer height: a pixel-by-pixel comparison to CALIOP observations, Atmos. Meas. Tech., 11, 2257–2277, https://doi.org/10.5194/amt-11-2257-2018, 2018.

de Graaf, M.: Absorbing Aerosol Index: Sensitivity analysis, application to GOME and comparison with TOMS, J. Geophys. Res., 110, 110, https://doi.org/10.1029/2004JD005178, 2005.

Sun, J., Veefkind, P., Nanda, S., van Velthoven, P., and Levelt, P.: The role of aerosol layer height in quantifying aerosol absorption from ultraviolet satellite observations, Atmos. Meas. Tech., 12, 6319–6340, https://doi.org/10.5194/amt-12-6319-2019, 2019.

Xu, X., J. Wang, Y. Wang, J. Zeng,O. Torres, Y. Yang, A. Marshak, J. Reid, and S Miller, Passive remote sensing of altitude and optical depth of dust plumes using the oxygen A and B bands: First results from EPIC/DSCOVRat Lagrange-1 point, Geophys. Res. Lett., 44, 7544–7554, doi:10.1002/2017GL073939, 2017

Xu, X., Wang, J., Wang, Y., Zeng, J., Torres, O., Reid, J. S., Miller, S. D., Martins, J. V., and Remer, L. A.: Detecting layer height of smoke aerosols over vegetated land and water surfaces via oxygen absorption bands: hourly results from EPIC/DSCOVR in deep space, Atmos. Meas. Tech., 12, 3269–3288, https://doi.org/10.5194/amt-12-3269-2019, 2019.

Davis, A. B., Kalashnikova, O. V., and Diner, D. J.: Aerosol Layer Height over Water from O_2 A-Band: Mono-Angle Hyperspectral and/or Bi-Spectral Multi-Angle Observations, https://doi.org/10.20944/preprints201710.0055.v1, 2017

Zoogman, P., Liu, X., Suleiman, R. M., Pennington, W. F., Flittner, D. E., Al-Saadi, J. A., Hilton, B. B., Nicks, D. K., Newchurch, M. J., Carr, J. L., Janz, S. J., Andraschko, M. R., Arola, A., Baker, B. D., Canova, B. P., Chan Miller, C., Cohen, R. C., Davis, J. E., Dussault, M. E., Edwards, D. P., Fishman, J., Ghulam, A., González Abad, G., Grutter, M., Herman, J. R., Houck, J., Jacob, D. J., Joiner, J., Kerridge, B. J., Kim, J., Krotkov, N. A., Lamsal, L., Li, C., Lindfors, A., Martin, R. V., McElroy, C. T., McLinden, C., Natraj, V., Neil, D. O., Nowlan, C. R., O'Sullivan, E. J., Palmer, P. I., Pierce, R. B., Pippin, M. R., Saiz-Lopez, A., Spurr, R. J. D., Szykman, J. J., Torres, O., Veefkind, J. P., Veihelmann, B., Wang, H., Wang, J., and Chance, K.: Tropospheric emissions: Monitoring of pollution (TEMPO), J. Quant. Spectrosc. Ra., 186, 17–39, https://doi.org/10.1016/j.jqsrt.2016.05.008, 2017

P4/L18: Referring to the description of the Absorbing Aerosol Height (AAH) paragraph (Sect 3.1.2): What is the uncertainty of the Level 2 absorbing aerosol height product? Is this study the first to evaluate the aforementioned product against ground-based lidar observations? This would raise the significance of the research and should be, more clearly, mentioned. Are there other studies evaluating the AAH product? The accuracy requirement for GOME-2 AAH product is only mentioned later on in the summary and conclusions section.

REPLY:

This work is the first validation study for the GOME-2/MetOp Absorbing Aerosol Height product against ground-based lidar systems. We use a dataset from thirteen EARLINET stations for the time period 2007-2019 and satellite data from the three MetopA,B,C platforms

In the GOME-2 AAH ATDB (Tilstra et al., 2019), the AAH is evaluated by CALIOP profiles and MISR plume height with individual cases, including fire events, dust storms and volcano eruptions. Due to the co-located CALIOP and MISR data is not widely available, the comparison is not straightforward but only analytic. The qualitative validation shows that the GOME-2 and CALIOP is generally in good agreement in indicating the vertical distribution of absorbing aerosol layers. The comparison with MISR is less encouraging. Furthermore, RMI compared the GOME-2 AAH with the aerosol layer height determined by Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) for specific volcano eruptions. case studies The GOME-2 AAH product is using aerosol layer height information provided by the CALIOP Vertical Feature Mask product (V4.20) data.

To our knowledge, there exist no other long term operational aerosol layer height products.

The product errors are calculated errors, based on error propagation of (in-) accuracies in the various input parameters. Regarding the GOME-2 AAH ATBD, the retrieved Aerosol layer height is associated with errors in the following fields:

- AAH_AbsorbingAerosolHeight → AAH_AbsorbingAerosolHeightError (km)
- AAH_AbsorbingAerosolPressure → AAH_AbsorbingAerosolPressureError (hPa)

The mean error value for the GOME-2 AAH product, for our validation study, is ~ 0.7 km according to the ATDB and PUM.You can see the example, presented in figure 15 of the paper manuscript. The AAH values of the pixels are presented with their associated standard deviation values. The AAH is currently officially operational (Satellite Application Facility on Atmospheric Composition, ACSAF, https://acsaf.org/). Further details may be found in the relevant parts of the ACSAF GOME2/Metop AAH validation Report, Algorithm Theoretical Basis and PUM documents.

References:

Tilstra, L. G., Tuinder, O., Wang, P. and Stammes, P.: ALGORITHM THEORETICAL BASIS DOCUMENT GOME-2 Absorbing Aerosol Height, SAF/AC//KNMI/ATBD/005, 1.4, Royal Netherlands Meteorological Institute, de Bilt, 32 pp., 2019, https://acsaf.org/docs/atbd/Algorithm_Theoretical_Basis_Document_AAH_Apr_2019.pdf, last access: 15 October 2020.

Tilstra, L. G., Tuinder, O., Wang, P. and Stammes, P.: PRODUCT USER MANUAL GOME-2 Absorbing Aerosol Height, SAF/AC/KNMI/PUM/006, 1.1, Royal Netherlands Meteorological Institute, de Bilt, 28 pp., 2020, https://acsaf.org/docs/pum/Product_User_Manual_AAH_Aug_2020.pdf, last access: 15 October 2020.

De Bock, V., A. Decloo, K. Michailidis, M. Koukouli and D. Balis:SAF/AC VALIDATION REPORT, Absorbing Aerosol Height, SAF/AC/AUTH-RMI/VR/001, issue 1/2020, 03-07-20-2020,https://acsaf.org/docs/vr/Validation_Report_AAH_Jul_2020.pdf, last access: 15 October 2020.

P4/L30: The authors mention "below 2.0 correspond to scenes with too low amount levels of aerosol to result in a reliable AAH retrieval. Also for AAI values larger than2.0 but smaller than 4.0 the aerosol layer is not in all cases thick enough for a reliable retrieval. However, most of our aerosol cases correspond to AAI values below the 4.0 level". The authors have used values above 2 in their study. What is this basically translates to (e.g in terms of AOD)? This would give a broader understanding for future users of AAH product and also for this study regarding the aerosol layers included in the comparison.

REPLY:
Indeed, most of the satellite measurements available from GOME-2 / MetOp refer to cases with AAI between 2.0 and 4.0. We use only AAI values above 2.0, because this value constitutes a threshold for extracting AAH product as suggested in the GOME2/Metop AAH ATBD (Tilstra et al., 2019).

The thresholds on the AAI product are used in the following way:
- AAI<2: No AAH available (there is little absorbing aerosol)
- 2<AAH<4: There is absorbing aerosol, but the reliability is low
- AAH>4: The AAH is supposed to have high reliability.

The relation between AAI and AOD is not linear, since scattering particles that induce negative AAI values which are not considered in the AAH retrieval may have large AOD values and vice-versa. Sun et al. (2018) explicitly mention in their study the requirement of accurate aerosol layer height (ALH) estimates in order to derive aerosol absorption from the UVAI. Additionally, The paper by de Graaf et al. (2005) provides several sensitivity analyses that detail the importance of the aerosol height in interpreting the UVAI.

P6/L1: It is not clear from this section that the authors have used the WCT for the retrieval of the geometrical boundaries of the aerosol layers. They do mention PBL and cloud geometrical boundaries with WCT method but they quickly refer to being used in a previous study to retrieve the aerosol layers too. Please, consider adding this information in a clearer manner. One more comment for this section is whether the authors have merged aerosol layers close to each other and in general, how the aerosol layer information was handled? A more detailed description is needed in order to understand better the discrepancies shown in the amount of aerosol layers between the ground-based lidars and the satellite (e.g Fig. 3 and Fig.8). How the selection of a dilation value of 500 m affects the amount of the detected aerosol layers in the lidar signal?

REPLY:
In this study, we aim to apply the wavelet covariance transform (WCT), a methodology of Baars et al. (2008), to the EARLINET database products in order to extract geometrical features of aerosol layers. The WCT is used to detect discontinuities in the lidar signal as the base, the top, and the peak backscatter of individual particle layers and PBL height (e.g., Flamant et al., 1997; Menut et al., 1999; Brooks, 2003; Bravo-Aranda et al., 2016). Some EARLINET optical products as more reliable to use than others. The longer wavelengths magnify the differences in the vertical distribution of the aerosol load, resulting in layers that are more easy to be identified. Generally, the 1064nm channel is more structured than the 355nm and more sensible to the calibration procedure (Engelmann et al., 2016). Given that,

EARLINET lidars operate at 355nm, 532nm and 1064nm, the 1064 channel is the more preferable for the layering detection. In this validation study, backscatter profiles at 1064nm have been chosen primarily, and in some cases backscatter profiles at 532nm.

At first, the WCT is computed for each lidar backscatter profile according to equations in Section 3.2.1. Next, applying the WCT The local minima and maxima of the vertical signal are calculated. The main problem is to find robust and objective criteria to distinguish between aerosols and clouds, as both of them appear as layer in lidar signals (Baars et al., 2008). Usually cloud layers are more sharp than the aerosol ones and also the time variability is stronger. For this reason, the most common approach to distinguish between aerosols and clouds is to fix thresholds and to identify everything above the fixed threshold as clouds and the rest as aerosols. The cloud base is characterized by a very strong increase in the backscattered signal. In this way using this information, we check and exclude the cloudy profiles.

A critical step to the accurate WCT application on the signal is the selection of an appropriate value of the window (dilation) so as to distinguish cloud layers from aerosol layers. From previous studies, - (Brooks et al., (2003) and Baars et al. (2008)) the dilation parameter a, can affect to the number of WCT coefficient local minima. Larger values of dilation factor, reveal a few large local minima, at the height of the biggest aerosol loading in the aerosol backscatter profiles. In addition, lower dilation values create local minima at heights of smaller aerosol loads in the backscatter profiles. In our case, we decided to identify only the first three major lofted layers. For this reason, a dilation of 0.5 km has been used. Finally, the top of detected layers is calculated. Selecting a large value of dilation we expect to have less multiple detecting layers. We have not merged the detected aerosol layers. For all the lidar profiles we apply the WCT, and we select the uppermost detected layer. This “feature” is compared against to the GOME-2 AAH satellite product.

Figure 2a demonstrates a case of an aerosol backscatter profile for 29 June 2019, in Barcelona station. In Fig. 2b the corresponding WCT is presented. The horizontal red dashed lines correspond to the altitude chosen as the top aerosol layer, detected using the wavelet algorithm. The vertical dashed lines represent some thresholds for the detection of the boundaries of aerosol layers. If the coefficient values falls below that threshold, one can assume that that no significant aerosol layer exists. Applying the WCT we can check if there are strong variations in the backscatter coefficient profile within an aerosol layer, which may lead to a classification of a separate layer.

References:

Baars, H., Ansmann, A., Engelmann, R., and Althausen, D.: Continuous monitoring of the boundary-layer top with lidar, Atmos. Chem. Phys., 8, 7281–7296, https://doi.org/10.5194/acp-8-7281-2008, 2008.

Bravo-Aranda, J. A., de-Arruda-Moreira, G., Navas-Guzmán, F., Granados-Muñoz, M. J., Guerrero-Rascado, J. L., PozoVázquez, D., Arbizu-Barrena, C., Olmo, F. J., Mallet, M., and Alados-Arboledas, L.: PBL height estimation based on lidar depolarisation measurements (POLARIS), Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2016-718, in review, 2016

Caicedo, V., Rappenglück, B., Lefer, B., Morris, G., Toledo, D., and Delgado, R.: Comparison of aerosol lidar retrieval methods for boundary layer height detection using ceilometer aerosol backscatter data, Atmos. Meas. Tech., 10, 1609–1622, https://doi.org/10.5194/amt-10-1609-2017, 2017.

Flamant C., Pelon J., Flamant P.H., Durand P. (1997). 'Lidar determination of the entrainement zone thickness at the top of the unstable marin atmospheric boundary-layer'. Boundary-Layer Meteorol. 83, 247–284

Davis, K. J., N. Gamage, C. R. Hagelberg, C. Kiemle, D. H. Lenschow, and P. P. Sullivan, 2000: An objective method forhttps://doi.org/10.1175/1520-0426(2003)020<1092:FBLTAO>2.0.CO;2.

Engelmann, R., Kanitz, T., Baars, H., Heese, B., Althausen, D., Skupin, A., Wandinger, U., Komppula, M., Stachlewska, I. S., Amiridis, V., Marinou, E., Mattis, I., Linné, H., and Ansmann, A.: The automated multiwavelength Raman polarization and water-vapor lidar PollyXT: the neXT generation, Atmos. Meas. Tech., 9, 1767–1784, https://doi.org/10.5194/amt-9-1767-2016, 2016.

P8/L30-35: This paragraph is a bit confusing. The authors have excluded aerosol layers close to ground due to the overlap limitation. This translates to aerosol layers above 1 km as indicated in Fig.8. To this direction, when lidar observations are not available at some upper height threshold then I would assume that the specific case is not included in the comparison as it would bias both the height of the observed aerosol layer between the lidar and the satellite. Correct? Also, it was made clear during this paragraph that dissimilar to the satellite product which assumes a single aerosol layer in the whole atmospheric column, the lidar observations can efficiently detect more layers. Could you include a better description of the comparison procedure and may be specify this feature earlier in the manuscript? Were there any cases with single aerosol layer detected by the lidar for the while atmospheric column and how the comparison with the satellite looked then? I am not sure if there will be any cases, though.
REPLY: The reviewer is correct.

As we perform a comparison study between data from different instruments (active/passive and ground-based/satellite) should take into account some assumptions for the best analysis and meaningful results. A common source of uncertainty when working with lidar data, due to the hardware restrinctions, is the system's overlap function (Wandinger and Ansmann, 2002), that determines the altitude above which a profile contains trustworthy values. Most of the vertical profiles begin over 0.8-1.0 km and is indeed quite rare to find profiles starting below of these values. In this study a threshold value for signal altitude – 1000m - is selected, under which we will not take into account in the comparison any available measurement. The backscatter profiles archived in the EARLINET database have a variable height range which typically extends up to 5-6 km where the most of the lidar signals have an optimal signal-to-noise ratio. Collocated cases where the lidar values are greater than 7km have been removed from the analysis.

Lidar systems can detect multiple aerosol layers across vertical profile. There are various methods to derive an ALH value from a given lidar profile. One can calculate the aerosol effective heights, for example, the aerosol mean height weighted by the aerosol properties or the aerosol scale height at which the aerosol profile or the cumulative profile passes a predetermined threshold. One can also detect the geometric boundary or center the so-called aerosol layer real height (Sun et al., 2020). In this work we use the uppermost top layer as detected from lidar profiles for comparison against GOME-2 AAH. The AAH algorithm is developed based on heritage of the remote sensing of cloud altitude (FRESCO, Wang et al., 2008). However, the retrieval of aerosol height is much more challenging because aerosols are in general less optically thick and have more complex optical properties.

There are very few collocated cases in our study, where single layers with significant particle load are cleary detected by lidar. We demonstrate a case during saharan dust transport over Iberian Peninsula (see manuscript, Fig. 14).

<u>Technical corrections:</u>

P1/L16: PBL → (PBL). There are a few places in the manuscript with the same feature, for example, P2/L32 and P11/L2. Please correct.

REPLY: Changed as requested.

P1/L17: Fourteen -> thirteen. The amount of EARLINET stations is 13 in total, correct? The same comment for **P7/L12.**

REPLY: Changed as requested.

P1/L18-21. I assume that the authors are referring to the height of the aerosol layers but this information is missing from these sentences.

REPLY: The reviewer is right. The text has been modified to:

"For the 172 carefully screened collocations, the mean aerosol height bias was found to be -0.18±1.68km, with a near Gaussian distribution. On a station-basis, and with a couple of exceptions where very few collocations were found, their mean aerosol height biases fall in the ±1 km range with an associated 20 standard deviation between 0.5 and 1.5 km"

P1/L31: Consider adding the Ice nuclei (IN) to include ice crystal formation.

REPLY: The reviewer is right. The text has been modified accordingly in the revised manuscript, which now reads:

"The interaction of aerosol particles with clouds and the related climatic effects have been in the focus of atmospheric research for several decades. Aerosols can act as cloud condensation nuclei (CCN) in liquid water clouds and as ice-nucleating particles (INPs) in mixed-phase and ice clouds. Changes in their concentration affect cloud extent, lifetime, particle size and radiative properties (Altaratz et al., 2014; Tao et al., 2012). As important these interactions are, they are the source of the highest uncertainty in assessing the anthropogenic climate change (IPCC, 2014)."

<u>References:</u>

Tao, W. K., Chen, J. P., Li, Z.. Wang, C. and Zhang C. Impact of aerosols on convective clouds and precipitation, Rev. Geophys., 50, RG2001, doi:10.1029/2011RG000369, 2012.

Altaratz, O., Koren, I., Remer, L. A., and Hirsch E.: Review: Cloud invigoration by aerosols - Coupling between microphysics and dynamics, Atmos. Res., 140–141, 38–60, doi:10.1016/j.atmosres.2014.01.009, 2014.

P2/L1 **"**Moreover, the vertical ... their dynamic processes". Please rephrase the sentence. Where do the authors refer to with the dynamic process", the weather conditions or the aerosol particles?

REPLY: The sentence has been rephrased. The following sentence has been added in the text:

"The spatial and temporal variation aerosol layer height is associated with the major aerosol sources and the atmospheric dynamics. Aerosol vertical distributions are affected by aerosol emissions and deposition processes, aerosol micro-physical properties, meteorological conditions, chemical processes, etc. Which one is the dominant factor determining the aerosol vertical distributions depend on aerosol species (Kipling et al., 2016)."

<u>References:</u>

Kipling, Z., Stier, P., Johnson, C. E., Mann, G. W., Bellouin, N.,Bauer, S. E., Bergman, T., Chin, M., Diehl, T., Ghan, S. J.,Iversen, T., Kirkevåg, A., Kokkola, H., Liu, X., Luo, G., vanNoije, T., Pringle, K. J., von Salzen, K., Schulz, M., Seland, Ø.,Skeie, R. B., Takemura, T., Tsigaridis, K., and Zhang, K.: Whatcontrols the vertical distribution of aerosol? Relationships be-tween process sensitivity in HadGEM3–UKCA and inter-modelvariation from AeroCom Phase II, Atmos. Chem. Phys., 16,2221–2241, https://doi.org/10.5194/acp-16-2221-2016, 2016.

P2/L8:"Active lidar sensors...individual locations". Lidars are active remote sensors but as written it gives the impression that passive lidar sensors might be an option. Please rephrase. I would recommend also changing the word "belonging" to "part of" or some-thing similar.

REPLY: The sentence has been rephrased, following the reviewer's comment:

"Active remote-sensing instruments, like lidars that are part of the European Aerosol Research Lidar Network (EARLINET; Pappalardo et al, 2014), have been used to distinguish between different aerosol types by providing vertical profiles of aerosol optical properties, as well to understand the three-dimensional structure and variability in time of the aerosol field. Although they provide great details in the vertical direction, lidar measured profiles are subjected to limited spatial and temporal coverage"

In addition, we have replaced the word "belonging" with "are part of", in the revised manuscript.

P2/L14: "Therefore, combined studies....on a global scale". I assume that the authors are talking about improvements in temporal and spatial distribution regarding the aerosol particles but the word "aerosol" is missing from this sentence. please add it.

REPLY: Changed as requested.

P2/L20: The acronym AAH is not introduced before.
REPLY: Changed as requested.

P2/L33: Replace Global Ozone Monitoring Experiment-2 to GOME-2 (The acronym is already defined in the beginning of this paragraph)
REPLY: Changed as requested.

P3/L20: Siomos et al., -> Siomos et al.,
REPLY: Changed as requested.

P3/L27: multiwavelength -> multi-wavelength.
REPLY: Changed as requested.

P7/L21: A similar comment, ground based -> ground-based
REPLY: Changed as requested.

P3/L34: with multi-wavelength Raman -> with multi-wavelength Raman channels.
REPLY: Changed as requested.

P4/L7: elevated amounts absorbing -> elevated amounts of absorbing.
REPLY: Changed as requested.

P5/L23: vertical distribution backscatter and aerosol extinction -> vertical distribution of aerosol backscatter and extinction.
REPLY: Changed as requested.

P5/L32: Remove the word "more"
REPLY: We assume that the reviewer means the word "core", which is removed.

P5/L25: In this study we use -> In this study, we use
REPLY: Changed as requested.

P5/L27: Here we use -> Here, we use
REPLY: Changed as requested.

P5/L32: I assume the authors mean Table 2 not Table 1. I would also suggest to combine Tables 2 and 4.
REPLY: Indeed, Table2 instead Table 1. As suggested, **t**ables 2 4 have been merge, in one table. The text has been modified accordingly in the revised manuscript.

P6/L17: and -> to
REPLY: Changed as requested.

P7/L14: Do you mean Table 4 and not Table1? Table 1 doesn't contribute to the argument in the same sentence.
REPLY: Yes, the reviewer is right. We refer to Table 4.

P7/L20: Consider changing the word "is enforced" to the word "necessary" or similar.
REPLY: Changed as requested. The word "is enforced" replaced by "necessary".

P7/L22: in the comparison study -> for the comparison.
REPLY: Changed as requested.

P7/L24: "In addition, unconverging pixels with AAH set to be 15 km are also excluded". Could you elaborate a bit on this?
REPLY:
As we have mentioned in the previous comments, the GOME-2 AAH is derived based on the GOME-2 UVAI product (Tilstra et al., 2010) and the FRESCO cloud algorithm (Wang et al., 2008, 2012). Due to the use of FRESCO algorithm, GOME-2 is limited to a maximum height of 15km for the AAH retrieval and hence cannot detect layers higher than 15km. An upper limit imposed by the FRESCO algorithm allowing range of cloud heights in FRESCO to 0-15km. If the cloud (or aerosol) heights in retrievals are either 0 or 15 km this is not realistic because 0 and 15km are the lower and upper limits in the FRESCO cloud height retrieval Wang et al. (2008, 2012) (See manuscript, Section 3.1.2)

The following sentence is added to the revised version of the manuscript: " Due to the use of FRESCO algorithm, GOME-2 is limited to a maximum height of 15km for the AAH retrieval and hence cannot detect layers higher than 15km"

References:

Tilstra, L. G., O. N. E. Tuinder, and P. Stammes, GOME-2 Absorbing Aerosol Index: statistical analysis, comparison to GOME-1 and impact of instrument degradation, in Proceedings of the 2010 EUMETSAT Meteorological Satellite Conference, EUMETSAT P.57, ISBN 978-92- 9110-089-7, Cordoba, Spain, 2010

Tilstra, L. G., Tuinder, O., Wang, P. and Stammes, P.: ALGORITHM THEORETICAL BASIS DOCUMENT GOME-2 Absorbing Aerosol Height, SAF/AC//KNMI/ATBD/005, 1.4, Royal Netherlands Meteorological Institute, de Bilt, 32 pp., 2019, https://acsaf.org/docs/atbd/Algorithm_Theoretical_Basis_Document_AAH_Apr_2019.pdf, last access: 15 October 2020.

Tilstra, L. G., M. de Graaf, I. Aben, and P. Stammes (2012), In-flight degradation correction of SCIAMACHY UV reflectances and Absorbing Aerosol Index, *J. Geophys. Res.*, 117, D06209, doi:10.1029/2011JD016957.

P7/L24: Do you mean Table 3 here?
REPLY: Indeed table 3.

P7/L31: due system overlap-> due to the system overlap
REPLY: Changed as requested. We add the words "to the" in the sentence.

P7/L33: 0-1km -> 0-1 km. The same feature can be found in a few places in the manuscript. Please correct.
REPLY: Changed as requested.

P8/L4: Correct Table 3 to Table 4.
REPLY: Changed as requested.

P8/L8: Bucharest is missing from the list.
REPLY: Changed as requested.

P8/L10: Have you excluded Regime C cases? If not, why? This should be mentioned.
REPLY:
We do not exclude the cases that are flagged as Regime C. We use all the available satellite points for all Regimes (see manuscript, Section 3.1.2). In the GOME-2 AAH product, reliability flags are used to define the confidence level of the AAH. The Regime flag is related to the effective cloud fraction of the GOME-2 pixels. The effective cloud fraction is used to check in which of the Regimes inside the parameter space the solution is likely to be found. According to Wang et al., (2012) Regime C is the situation of a thick cloud layer present in the scene. In this case, an aerosol layer is only retrieved successfully when the aerosol layer is sufficient thick. It could be expected that the high confidence levels AAH pixels have a better agreement with the aerosol layer height extracted from EARLINET data, however this is not the case.

The following sentence is added to the revised version of the manuscript: "We take into account all the Regime flags of pixels regardless of the reliability. According to Wang et al. (2012) Regime C is the situation of a thick cloud layer present in the scene. In this case, an aerosol layer is only retrieved successfully when the aerosol layer is sufficient thick."

P8/L17-19: Consider rephrasing the sentence. As it written it is difficult to read.
REPLY: The text has been modified: "In Figure 7 shows the distribution of GOME-2 AAH and EARLINET aerosol height differences. The histogram plot refers to the total of 172 collocated cases."

P8/L21: Do you mean Table 5 here?
REPLY: Yes, we refer to the Table 5.

P9/L8: aerosol type -> aerosol types
REPLY: Changed as requested.

P9/L12: The equipment includes -> the instrument features
REPLY: Changed as requested.

P9/L13: and a further (polarization) -> and a polarization
REPLY: Changed as requested.

P8/L17-19: Consider rephrasing the sentence.

REPLY: The text has been modified in the revised version.

P9/L23: under intense Saharan dust air masses conditions -> under the intense Saharan dust outbreak.
REPLY: Changed as requested.

P10/L3: The unit is missing.
REPLY: Changed as requested. The unit in meters (m) is added to the text.

P10/L6: Provide a reference for MODIS.
REPLY: Done. We have added two references related to MODIS satellite instrument and products. . The text has been modified accordingly and the full reference has added to new manuscript.

Added to the revised text: "In Fig.12, satellite maps from Moderate resolution Imaging Spectroradiometer (MODIS, Kaufman et al. 1997; Levy et al., 2013) …."

Reference:
Kaufman, Y. J., Tanre, D., Remer, L. A., Vermote, E. F., Chu, A., and Holben, B. N.: Operational remote sensing of tropospheric aerosol over the land from EOS-Moderate Resolution Imaging Spectroradiometer, J. Geophys. Res., 102, 17051–17067, 1997.

Levy, R. C., Mattoo, S., Munchak, L. A., Remer, L. A., Sayer, A. M., Patadia, F., and Hsu, N. C.: The Collection 6 MODIS aerosol products over land and ocean, Atmos. Meas. Tech., 6, 2989– 3034, https://doi.org/10.5194/amt-6-2989-2013, 2013.

P10/L9: The Absorbing Aerosol Height is expressed through the AAH acronym. Please, use the acronym since it has been introduced in earlier section. Same comment for **P10/L12** for the AAI and AAH.
REPLY: The text has modified accordingly in the revised manuscript.

P10/L17: As mentioned above both ground and satellite followed...-> Maybe, "As mentioned above, both ground-and satellite-based observations have followed..."
REPLY:. The text it is modified in the new manuscript

P10/L19: Do you refer to Figure 14 instead of Figure 15?
REPLY: Yes, We refer to Figure 15.

P10/L32: Very long sentence.
REPLY: The text is modified accordingly in the new manuscript:

"In Fig.15, we show the comparisons for all GOME-2 pixels against the simultaneous lidar observation for the 23rd of February, over Évora station. The collocated points are color-coded by their associated AAI value. In this way, we can assess whether the general agreement shown by the collocations of Fig. 13, can be turned into a generalized comment as to behavior of the GOME-2 AAH algorithm for cases of high AAI and good temporal collocations."

P11/L12: geometrical features-> geometrical feature. Also, "make uses" -> makes use.
REPLY: Changed as requested.

P12/L7: Acronym and reference for TROPOMI?
REPLY: Done. We add the acronym and a reference for TROPOMI instrument. The text has been modified accordingly and the full reference has added to new manuscript.

The text was rephrased to: "as the TROPOspheric Monitoring Instrument (TROPOMI S-5P; Veefkind et al., 2012) on board Sentinel-5 Precursor (S5P) satellite, for the validation of aerosol layer height products."

Reference:
Veefkind, J. P., Aben, I., McMullan, K., Forster, H., de Vries, J., Otter, G., Claas, J., Eskes, H. J., de Haan, J. F., Kleipool, Q., van Weele, M., Hasekamp, O., Hoogeveen, R., Landgraf, J., Snel, R., Tol, P., Ingmann, P., Voors, R., Kruizinga, B., Vink, R., Visser, H., and Levelt, P. F.: TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications, Remote Sens. Environ., 120, 70–83, https://doi.org/10.1016/j.rse.2011.09.027, 2012.

Table 6: You could add in the asterisk part at the bottom: "The station of Sofia has only one collocation, therefore it is not shown".
REPLY: The text, at the bottom of Table 6, is modified accordingly.

Figure 2: Are the colors in the legend in the opposite way? The blue line seems to be the smoothed S-G signal and the yellow one the noisy signal. What are the horizontal and vertical lines in the panels? Please include a better description for the figure. Also, the different panels should be marked as (a), (b). Please correct all the figures featuring more than one panel.

REPLY: Yes, the legend labels were mixed up. Figure 3 has changed correctly in the revised manuscript. In addition, following the reviewer's suggestion, we marked the subpanels of Figure 5 as (a) (left) and (b) (right). Also, we corrected all the figures in the article featuring more than one panel.

This figure is reasonably to show the ability of the lidar to detect multiple layers. The blue lines refer to S-G (Savitzky –Golay smoothed signal) and the yellow one to the noisy backscatter lidar signal. The horizontal red dashed line represents the detected aerosol layer top applying the WCT methodology (see the section 3.2.1) and three aerosol layers are detected, according the methodology that we follow. The vertical dashed lines represent some thresholds for the detection of the boundaries of aerosol layers. If the coefficient values falls below that threshold, one can assume that that no significant aerosol layer exists (Brooks et al., 2003; Baars et al., 2008). Applying the WCT we can check if there are strong variations in the backscatter coefficient profile within an aerosol layer, which may lead to a classification of a separate layer. The colored "star" symbols represent the local maxima (purple) and minima (red) of wavelet transform signal. (See comment P6/L1)

The caption of Figure 6 has modified in the new manuscript: "Figure 2. Barcelona lidar station (Universitat Politechnica de Catalunya, Barcelona – UPC): (a) Lidar backscatter profile at 1064nm and (b) resulting WCT profile from the on June 29, 2019. The horizontal red dashed line represents the detected aerosol layer top applying the WCT methodology The label "S-G" indicates that a Savitzky-Golay filter was used to reduce to noise variance in the backscatter profile. The colored "star" symbols represent the local maxima (purple) and minima (red) of wavelet transform signal."

Figure 5: What are the individual dots? Please include a better description for the figure.
REPLY: This figure is very important part of our study and it is therefore necessary to described properly for the readers what exactly it represents.

The individual dots represent the collocated pairs between GOME-2 pixels and EARLINET measurements. Figure 5 shows the spatial distribution of all collocated pairs around each EARLINET station considered (Athens, Barcelona, Belsk, Bucharest, Granada, Évora, Lecce, Limassol, Minsk, Potenza, Sofia, Thessaloniki and Warsaw) while the concentric red circles denote regions of 150 km from the location of these stations. The color-codes denote the absolute difference between GOME-2 AAH and the aerosol layer height retrieved from EARLINET database using the WCT algorithm (see manuscript, Section 3.2.1) on backscatter lidar profiles (532 and 1064nm).

The caption of Figure 5 has modified to: "Figure 5. Spatial distribution of collocated pairs between GOME-2/MetOp and EARLINET stations for the sites including in the validation study. The color codes denote the absolute difference between GOME-2/MetOp AAH and the retrieved aerosol height from EARLINET data for each collocated pair..The concentric red circles denote regions of 150 km from the location of EARLINET stations refer to Table 4 for the EARLINET code names shown in the legend."

Figure 6: Add the specification for Regime A, B and C in the caption.
REPLY: The caption of Figure has modified to: "Figure 6. Distribution of AAH product reliability (Regime flag) related to degree of cloud cover (effective cloud fraction) for the selected collocated observations as per Sect. 3.1.2. (A: High reliability, B: medium reliability, C: Low reliability)"