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Interactive comment on "Validating TROPOMI aerosol layer height retrievals with CALIOP data" *by* Swadhin Nanda et al.

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Reviewer comment (general): The paper presents the first attempt to validate the TROPOMI ALH data product and therefore, bears lots of research interest from the community. The work overall is sound. However, given the unprecedented observation from TROPOMI and its potential for the wide use of ALH, the paper should be revised to provide an uncertainty estimate to the community. In fact, from what is presented in the paper, the ALH at the pixel level appears to have large uncertainties. Perhaps changing 'validating' to 'first evaluating" is more appropriate for this paper – this is a suggestion though. Major recommendations are provided below.

Author's response: That ALH at pixel level appears to have large uncertainties is

a generalised statement, especially since the comparisons are against co-located CALIOP aerosol extinction heights and backscatter profiles and not the true aerosol layer height. The authors acknowledge the suggestion of renaming the paper, but see no difference between 'validating' and 'first evaluating' - albeit for a different instrument, the ALH product developed at the KNMI has been evaluated with different datasets previously. The data product is also being evaluated by a separate paper that compares it to MISR (see https://www.atmos-meas-tech-discuss.net/amt-2019-411/ for more information), which is now in the response phase. These conditions make renaming it to a first evaluation inapplicable. Alternatively, considering that the paper is a comparison of TROPOMI ALH to CALIOP aerosol heights derived from extinction profiles, the paper is renamed to — A first comparison of TROPOMI aerosol layer height to CALIOP data.

Reviewer comment (specific 1): While the introduction part mentioned several papers regarding ALH retrieval, it didn't go in depth to the method themselves. A few notes are highlighted below; more details can be found in Xu et al. (2017).

1. MISR offers stereo height information; this is simply done by geometric optics, and providing top height of the aerosol layer
2. Xu et al., 2017: used primarily O2 A band (I think) for ocean, while Xu et al. 2019 used O2 B band primarily over land. In both cases, these two papers demonstrate for the first time in the literature that diurnal variation of ALH can be retrieved. They are also the first to define the method to evaluate ALH from such retrievals. Somewhere, it is worthy mentioning these, for example, in the method part for equation 2, and in the analysis and discussion part regarding surface reflectance.
3. MAIA by Davis et al. This is really a theoretical work as MAIA is not launched yet. This work should be separated from the work that uses the real data, and should be lumped with other theoretical work (such as Ding et al., 2017).

Reference: Xu et al., (2018), Passive remote sensing of aerosol height, in Remote Sensing of Aerosols, Clouds, and Precipitation, edited by T. Islam, Y. Hu, A. Kokhanovsky, and J. Wang, pp.1-22, Elsevier, Cambridge, MA.

Ding et al. (2016), Polarimetric remote sensing in O2 A and B bands: Sensitivity study and information content analysis for vertical profile of aerosols, AMT

Author's response: Accepted. The authors have decided to mention the details that the referee suggests in the introduction section.

Changes to the manuscript: Changes to introduction section.

Some notablementions of missions that retrieve aerosol layer height are Multiangle 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 mission (Chimot et al., 2017, 2018; Choi et al., 2019), and finally the TROPOMI instrument on board the Sentinel-5 Precursor mission (Veefkind et al., 2012). In the near future, missions like the upcoming Multi-Angle Imager for Aerosols (MAIA) mission (Davis et al., 2017), the Geostationary Environment Monitoring Spectrometer (GEMS) and the Tropospheric Emissions: Monitoring Pollution mission (TEMPO) are expected to provide aerosol height retrievals as well (Kim et al., 2018; Park et al., 2016; Zoogman et al., 2017). These instruments are examples of missions demonstrably (some theoretically, others practically) capable of retrieving aerosol layer height.

Reviewer comment (specific 2): The analysis part is really short in this paper. A few questions are suggested here with a hope to improve the analysis and add more 'meat' to the paper.

1. It is worth mentioning that aerosols, unlike cloud droplets, are ubiquitous in the atmosphere. So, a single layer representation is rather a crude approximation. The algorithm by Xu et al. assumes a continuous profile (and so are some others in the theoretic work). within 1M collocated pairs, will ALH comparison be different or be the same regardless one single layer or multiple layer aerosols? Can CALIPSO be helpful to identify or illustrate some cases of multiple layer of aerosols?
2. The ALH retrieval co-vary with AOD and UVAI. Xu et al. (2020) show some analysis on that. It might be interesting to plot ALH vs. UVAI for different AOD value ranges (as Xu et al.) and see if the finding is consistent with Xu's finding.
3. It remains puzzling while 1M collocation pairs only give less 800 data points in the Figure 7. Why? Can we show all the collocated data points and find out how many percentage of TROPOMI ALH lies in +/- one sigma of the CALIOP ALH? This information is needed, and will the similar as MODIS AOD validation (which says, 76% or more data points are in +/- STD and have uncertainty of 0.05+/-0.10 AOD over land). Can such uncertainty envelope be derived?
4. The illustration case is almost exclusively for Saharan dust layer over ocean. A suggestion is to change the title of this paper to say validation or evaluation over the ocean? For this reviewer, it is bit difficulty to comprehend how well TROPOMI ALH over land, unless one case can be demonstrated.

Author's response: The reviewer's questions are valid and definitely add to the paper. However, some of the questions posed by the reviewer are either answered in a separate paper or are beyond the scope of this current analysis. The authors respond as follows.

1. The continuous aerosol profile framework is a feature yet to be added to our radiative transfer code. While we do observe some sensitivity to the thickness

of the aerosol layer, so far we have not been able to successfully retrieve it. CALIPSO on the other hand does observe multiple layers and, while not explicitly mentioned in this paper, the comparison does show several cases with multiple aerosol layers present (especially in the selected cases).

2. This analysis is presented in a separate paper (currently under review as well) that focuses on the TROPOMI UVAI data, which is why it is not mentioned in this paper. The results from this paper are mentioned in the amended manuscript.

3. Figure 7 is an aggregate of co-locations presented in Figure 6, where the focus is on four selected cases which are visually screened for clouds. This is why there are significantly less number of data points in Figure 7. With regards to uncertainty values presented by the reviewer, Figure 7 provides numbers that represent the differences between TROPOMI and CALIOP. This is further clarified in the text.

4. Considering that the paper does present analyses of retrievals over land, it would be incorrect to further rename the paper. Citation for the comparison of TROPOMI ALH retrievals over land with other retrieval techniques is provided in the amended manuscript.

Changes to the manuscript: The following statements are added to the manuscript (for each of the reviewer's comments).

1. The algorithm assumes a single aerosol layer for the entire atmosphere, within which aerosols are uniformly distributed and the aerosol volume extinction coefficient is constant. This is an important simplification to note when comparing with CALIOP profiles, since these lidar profiles have the capability to detect multiple aerosol layers. The simplicity in the aerosol profile parameterisation arises from the fact that it is impossible to know, without prior information, whether the scene

consists of a single or multiple aerosol layers. While fitting of the aerosol layer pressure thickness along with the aerosol layer mid pressure does not result in large errors in the retrieved aerosol layer height, the precision of the retrieved aerosol layer mid pressure significantly deteriorates with increasing errors in the surface albedo (Sanders et al., 2015). More research has to be done before more information on the aerosol profile is retrieved from the oxygen A-band alone.

2. This altitude dependence increases with aerosol absorptions (i.e. SSA) and aerosol loading (i.e. AOD), whereas it becomes weaker over brighter surfaces where the importance of molecular scattering reduces significantly (Figure 9b). On the other hand, little altitude dependence is found for non-absorbing aerosols (i.e. SSA = 0.99). The conclusions from this synthetic experiment are replicate with real TROPOMI data in a separate manuscript, where for retrieved ALH for pixels with a UVAI greater than 1 for measurements from TROPOMI showed an increase in the correlation between ALH and UVAI for an increase in MODIS aerosol optical depth values for the same scenes. This manuscript is currently submitted to Atmospheric Chemistry and Physics and awaits review.

3. A direct comparison of the CALIOP $\mathrm{ALH_{ext}}$ and TROPOMI ALH for these four selected cases are presented in Figure 7. For this comparison, every cloud-filtered and sun-glint-filtered TROPOMI pixel with ALH information colocated to a specific CALIOP level-2 aerosol extinction profile in Figure 6 is averaged and a standard deviation is also computed. These averaged TROPOMI ALH are then compared to the CALIOP $\mathrm{ALH_{ext}}$, and show that TROPOMI ALH differ from CALIOP $\mathrm{ALH_{ext}}$ by 0.53 km, with a pearson correlation coefficient of 0.64 and a slope of 1.0; CALIOP $\mathrm{ALH_{ext}}$ are systematically higher than TROPOMI ALH (indicated by a y-intercept of the fit at 0.53 km). The CALIOP $\mathrm{ALH_{ext}}$ is also higher than TROPOMI ALH almost consistently in most cases. This could possibly be due to CALIOP possibly underestimating the aerosol layer thickness due to strong attenuation of the lidar signal at the top of the aerosol layer (Rajapakshe et al., 2017), whereas

TROPOMI ALH product does not suffer from such attenuation.

4. A significant majority of successful the retrievals in these selected scenes are over a dark surface, owing to the bright surface albedo of the Saharan desert. The reader is point to Griffin et al. (2019) for comparison of the TROPOMI ALH retrievals over land for biomass burning aerosol plumes with the same from several other instruments including CALIOP.

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