Response to Reviewer #1

Thank you for the reviewer's effort to review our manuscript. During the revision processes of our manuscript, we re-wrote most parts of the manuscript. In addition, we added results of sensitivity tests and error analysis for additional aerosol parameters. During the revision, we changed the radiative transfer model to improve the interface of previous model for surface albedo as well. For this reason, we also revised the methodology to explain the new radiative transfer model and its condition.

*The manuscript describes an ambitious attempt to determine an aerosol effective height from a combination of OMI spectra and MODIS aerosol retrieval. The method, if it were to be improved to operational maturity, is of high interest to remote sensing and modeling communities in search of observational data on aerosol profiles. However, I see important obstacles on the road to practical application of this method, several of which are not or only barely addressed in the manuscript. In particular, these regard the choice of aerosol parameters (size, shape), possible mismatches between OMI and MODIS data, and cloud contamination of OMI data.*

→ In addition to the revision, we added the sensitivity study of additional aerosol parameters as shown in Section 3.2. Section 3.2.1, 3.2.2, 3.2.4, and 3.2.5 respectively describes the sensitivity test of previously mentioned parameters, including AOD, SSA, surface albedo, and aerosol vertical distribution. In addition, Section 3.2.3 describes the result of sensitivity test for particle size. Please refer to this section for the details.
In addition, in the revised manuscript, the cloud contamination was carefully screened out by using cloud fraction less than 0.02, which is a strict threshold value for clear pixel selection. Because aerosol height retrieval is very challenging, we retrieved the aerosol height information over cloud free pixel only. For this reason, this study did not consider the cloud contamination of OMI data, although cloud is one of potential error source for aerosol height estimation.

*In addition, the method is currently not described in sufficient detail; e.g., it remains unclear why MODIS AOD and type are used instead of OMI data, or why the DOAS fit of O4 is explicitly included in the AEH retrieval algorithm (when a look-up-table of air mass factors would appear to be sufficient: O4 has a broad absorption spectrum and fitting the SCD is relatively straightforward). As I noted in my review of the initial draft, there are too little references and comparisons to previous work (similar sensitivity studies have been performed by Veihelmann et al., 2007 and Wagner et al., 2010 ). The literature is cited in the introduction, but a summary of the previous findings and the relation to the current findings is missing from the manuscript.*

→ In the revised manuscript, we added the details of method. For example, in Section 4, we described the reason to use MODIS AOD and type instead of those from OMI as below:

"Although OMI aerosol product provides AOD at 500 nm, AOD from OMI was partially affected by aerosol height and suffered from cloud contamination due to its large footprint (Torres et al., 2002). For this reason, AOD from MODIS allocated to the OMI pixels as a reference AOD for the AEH retrieval. For type selection, the AE from MODIS and AI from OMI is respectively used for the information of size and absorptivity, to classify aerosol type into four following the method from Kim et al. (2007) and Lee et al. (2007)."

Main reason of MODIS AOD selection is aerosol height dependence for OMI AOD. Furthermore, this study basically used the MODIS and OMI data for type selection. Therefore, we determined that selection of MODIS data for AOD is reasonable.

For directly comparison between our method and OMI standard product, we use SCD value for O4, although O4 has a broad absorption band and SCD fitting is relatively straight-forward. Details of algorithm flow are described in Figure 1 and 12 for model simulation and case study, respectively. In addition, details are explained in Section 2.1 and Section 4 for simulation and case study, respectively. Furthermore, we compensated the previous work from reviewer's suggestion in the introduction.

*Lastly, and as mentioned in my review of the initial version, the presented case study does not provide convincing evidence that the algorithm works. First of all, only a single case is presented; second, CALIOP backscatter profiles are shown of which only a small part is detected by OMI (at 35-40 N, 122.5-123 E) — and these values do not agree very well (CALIOP doesn't exceed 1.7 km, whereas the retrieved AEH appears to vary from 1-5 km in this region). The comparison would have been more meaningful if AOD and aerosol type from CALIOP had been included, and a longer orbital segment had been selected. Third, as mentioned in the previous review, the comparison with ground-based lidar is not at all appropriate for reasons of collocation mismatch (the station is over land; the OMI measurement >100 km away and over ocean).*

→ In Section 4, we described the AEH retrieval for two transported aerosol cases over East Asia. Furthermore, we also presented the scatterplot of AEH between CALIOP and OMI for 8 severe aerosol transport cases as listed in Table 8. Details are shown in Section 4 and Figs. 12 ~ 15.

*In summary, I recommend that this paper be thoroughly revised before being resubmitted.*

*The most important revisions (addressed above) include:*

*- More references and comparisons to literature*

*- Detailed, step-by-step description of the AEH algorithm in a separate section*

*- Assessment of additional error sources (wrong aerosol model assumptions; cloud*

*contamination)*
*- Addition of more, and more appropriate case studies*
*Some suggestions for improvement of the paper are given below, but because in my opinion the manuscript requires extensive re-writing, more suggestions would follow in the next round of review.*

→ We appreciate the reviewer's suggestion and comments to revise our paper. Basically we reflected all the comments and added all answers for the issues raised the revised manuscript. Reference and literatures are also added in Section 1 and 2. In Section 1, we revised as below with appropriate reference for example:

"The Differential Optical Absorption Spectroscopy (DOAS) technique has been used widely to retrieve trace gas concentration both from ground-based (e.g., Platt, 1994; Platt and Stutz, 2008) and space-borne (e.g., Wagner et al., 2007; Wagner *et al*., 2010) measurements. After the work of Platt (1994) to retrieve trace gas concentration by using DOAS, Wagner et al. (2004) suggested to derive atmospheric aerosol information from $O_4$ measurement by using Multi Axis Differential Optical Absorption Spectroscopy (MAX-DOAS). Friess et al. (2006) analyzed the model studies to calculate the achievable precision of the aerosol optical depth and vertical profile. In addition, several studies (e.g., Irie *et al*., 2009 and 2011; Lee *et al*., 2009 and 2011; Clemer *et al*., 2010; Li *et al*., 2010) provided aerosol profiles from ground-based hyperspectral measurements in UV and visible wavelength ranges on several ground sites."

"For OMI measurement, the $O_4$ band at 477 nm has been widely applied to estimate cloud information (e.g., Accarreta et al., 2004; Sneep et al., 2008). Especially, the cloud information retrieved by O4 band at 477 nm was used for air mass factor (AMF) analysis with the consideration of aerosol optical effects for the NO2 column retrieval (e.g., Castellanos et al., 2015, Chimot et al., 2015; Lin et al., 2014; Lin et al., 2015). Although O4 absorption band around 477 nm varies also due to cloud existence, it can be also used for the aerosol optical parameter estimation. Veihelmann et al. (2007) introduced that the 477 nm channel, which locates major O4 band, significantly adds degree of freedom for aerosol retrieval by using principal component analysis, and Dirksen et al. (2009) adopts the pressure information obtained from OMI O4 band to identify a plume height for aerosol transport cases."

→ Detailed description of algorithm is added in Section 2 and 4 for model study and case study, respectively. In section 2.1, we revised the details of radiative transfer model regarding its change from LIDORT to VLIDORT.

"….the Linearlized pseudo-spherical vector discrete ordinate radiative transfer

(VLIDORT) model (Spurr, 2006). The VLIDORT model is based on the linearized discrete ordinate radiative transfer model (LIDORT) (Spurr et al., 2001; Spurr, 2002). This RTM is suitable for the off-nadir satellite viewing geometry of passive sensors since this model adopts the spherically curved atmosphere to reflect the pseudo-spherical direct-beam attenuation effect (Spurr *et al.*, 2001)."

→ Furthermore, we revised the assumption of aerosol vertical distribution for model input in the Section 2.1.2 as below:

"On the other hands, the aerosol vertical distribution does not always follow exponential profile. For the long-range transported aerosol such as dust cases, the aerosol layer profile is quite different than exponential profile and occasionally transported to well above the boundary layer (e.g., Reid et al., 2002; Johnson et al., 2008). The peak height of aerosol extinction profile in long-range transport cases was reported to be located between 1 and 3 km during the Dust and Biomass-burning Aerosol Experiment (DABEX) campaign (Johnson et al., 2008). From these previous studies, standard aerosol vertical profile is difficult to determine. For algorithm development, previous studies assumed that the vertical distribution is assumed to be Gaussian function defined by peak height and half width as representative parameters (Torres et al., 1998; Torres et al., 2005). To supplement the simplicity of assumption for aerosol vertical distribution, aerosol vertical distributions are assumed to be quasi-Gaussian generalized distribution function (GDF), which is Gaussian distribution with dependence on aerosol peak height, width, and layer top and bottom height. Details of GDF can be found in Spurr and Christi (2014) and Yang et al. (2010). In this study, AEH ranges from 1 to 5 km with 1 km width as 1-sigma for the RTM simulation."

→ We also revised the Section 2.2 for the step-by-step description of model simulation and clear-sky comparison test between modeled and observed O4 value. Because of large value of O4 SCD, we newly investigated the O4 Index as dividing O4 SCD by $10^{40}$ $\text{molecule}^2\text{cm}^{-5}$ which were also used in error studies in Section 3.2

"To estimate the error amount, the AEH error is converted from the half of O4I difference between adding and deducting perturbation of variables as shown in equation (1).

$$\varepsilon(Z) = \left| \frac{O4I(x+\delta x,Z) - O4I(x-\delta x,Z)}{2.0 \times dO4I/dZ(x,Z)} \right| \quad (1)$$

where $\varepsilon(Z)$ is the AEH error amount due to variable of error source, x, in AEH of Z, and $\delta x$ is perturbation of AEH retrieval error source. The $\varepsilon(Z)$ value also depends on viewing geometries. Therefore $\varepsilon(Z)$ is represented for specific geometries together with averaging over all geometries."

→ For the details of case study, we revised the algorithm flowchart in Figure 12 in the revised manuscript, and added the details as below:

"Figure 12 describes an AEH retrieval algorithm for the case study. In retrieving AEH, AOD is obtained from MODIS standard product (e.g., Levy et al., 2007). Although OMI aerosol product provides AOD at 500 nm, AOD from OMI was partially affected by aerosol height and suffered from cloud contamination due to its large footprint (Torres et al., 2002). For this reason, AOD from MODIS allocated to the OMI pixels as a reference AOD for the AEH retrieval. For type selection, the AE from MODIS and AI from OMI is respectively used for the information of size and absorptivity, to classify aerosol type into four following the method from Kim et al. (2007) and Lee et al. (2007). After determining AOD and aerosol type, LUT, which is generated as functions of geometries (SZA, VZA, and RAA), aerosol types and AODs, is used to determine the AEH information by using comparison between simulated and measured O4I value. The variables and their dimensions for the LUT calculations are shown in Table 7. Due to the limitation of the accuracy of aerosol type classification and those of AOD over land, this study estimates the AEH only over ocean surface. Although temporal and spatial variation of surface albedo influences the AEH result from error study, surface albedo is assumed to be a fixed value of 0.10, which is used in sensitivity study. For case study, the LUT of O4I is developed by the aerosol model based on AERONET data over East Asia. Extensive AERONET dataset over East Asia are used to provide represent aerosol optical properties for the LUT calculation."

→ In section 3, we showed the result of sensitivity test for additional error sources of aerosol parameters, especially aerosol particle size in Section 3.2.3. Furthermore, AEH sensitivity showed the result with changing viewing geometries in Figure 8. Finally, case study results are also added in Section 4. In detail, we described one additional specific scene result in Figure 14 in the revised manuscript. Details are shown as below:

"Figure 14 is another case study of the retrieved AEH on February, 21, 2008. MODIS products of AOD and FMF on this date show thick anthropogenic aerosol transported with the AOD ranging from 0.6 to 1.0 [Figure 14(b)] and the FMF ranging from 0.8 to 1.0 [Figure 14(c)] all over Yellow sea. The mean retrieved AEH is 1.4±1.2 km over 1480 pixels in East Asia as shown in Figure 14(d). On this date, CALIOP passed over coastal line between China and Yellow Sea. The aerosol layer height ranged from 0.5 to 2.5 km during the overpass over East Asia as shown in Figure 14(e). The AEH from OMI is 0.6±0.4 km over 601 pixels in 30~40 ˚N and 120~125 ˚E. Contrary to large spatial variation of the AEH from CALIOP, the AEH from OMI shows spatially stable values on this date."

→ Furthermore, we showed direct comparison test between CALIOP and OMI for 2-

year transported aerosol cases over East Asia. The results are shown in Figure 15 in the revised manuscript with the list of cases in Table 8 in the revised manuscript. Details are explained as below:

"Figure 15 shows the scatter plot of AEH between CALIOP and OMI on the date listed in Table 8, which lists aerosol transport cases over East Asia with simultaneous observations by OMI and CALIOP in 2007 and 2008. Because the O4I sensitivity for AEH is not large at AEH higher than 4 km, the comparison test was limited to cases with AEH less than 4.5 km from OMI. For data collocation, the latitude and longitude difference between two sensors are within 0.25 degree. Figure 15(a) shows the comparison of AEH from OMI and CALIOP with MODIS AOD larger than 0.5. It is assumed that the reference expected error (EE) is 1 km (Fishman et al., 2012). Almost 60% of retrieved pixel shows the AEH result within the EE. Because of large AEH error for low AOD, the accuracy of AEH result from OMI is poor. Furthermore, this case study assumes constant surface albedo value over ocean. However, ocean surface albedo is also changed by turbidity due to sediments and wind. For this reason, the AEH error is enlarged for low AOD cases. If threshold of AOD for the comparison is set to be 1.0, the proportion of pixel within EE improves up to 80% as shown in Figure 15(b). Furthermore, the correlation of the AEH between the two sensors is 0.62 as a slope with 0.65 of correlation coefficient (R) on thick aerosol layer cases. Therefore, the AEH algorithm from OMI provides the reasonable information about the parameter of aerosol vertical distribution, if accurate aerosol model is provided for forward calculation."

During the revision, the manuscript reflected all other comments as shown below.

*Other comments*

*P.7934, ll. 11-14: "Overall, the error (...) vertical distribution type." Mention that the cited error values apply to the base case (SZA=30, VZA=30; I was unable to find the reference AOD and AEH). More importantly, the overall error here does not include the uncertainty due to vertical distribution. Although this is mentioned in the quoted sentence, it does not appear to be fair to leave out this major error contribution — particularly because its magnitude was explicitly determined.*

In the revised manuscript, the error analysis for aerosol vertical distribution was changed as shown in Section 3.2.5. We estimated errors using all viewing geometries, AOD and AEH as shown in Table 3 in the revised manuscript. Because aerosol vertical distribution cannot estimate high-resolution information, the error budget for aerosol vertical distribution is summarized in Table 5 in the revised manuscript.

*P. 7935, ll.15ff: "The information on the aerosol height is important (...)" Also for the improvement of trace gas retrievals (better air mass factor calculation) the aerosol profile is of importance.*

We reflect the comment in the revised manuscript as below:

"The information on the aerosol layer height is important, because the variation of the aerosol vertical distribution affects radiative process in the atmosphere near the surface and trace gas retrieval for air mass factor calculation."

*P. 7936, l.8: "(Wagner et al., 2010)" This reference is not appropriate, better would be, e.g: Wagner, et al., 2008, doi: 10.1088/1464-4258/10/10/1040192008), but there are many others, too.*

*P. 7936, ll.8-28: "Recently, several studies (...) aerosol transport cases." The results from the cited studies need to be summarized and discussed in more detail, probably in a separate section. The findings from those previous studies should be used as starting points for your own studies, and you should explain what your own studies add to the existing body of knowledge.*

We reflect the comment in the revised manuscript as below:

"The Differential Optical Absorption Spectroscopy (DOAS) technique has been used widely to retrieve trace gas concentration both from ground-based (e.g., Platt, 1994; Platt and Stutz, 2008) and space-borne (e.g., Wagner et al., 2007; Wagner *et al*., 2010) measurements. After the work of Platt (1994) to retrieve trace gas concentration by using DOAS, Wagner et al. (2004) suggested to derive atmospheric aerosol information from $O_4$ measurement by using Multi Axis Differential Optical Absorption

Spectroscopy (MAX-DOAS). Friess et al. (2006) analyzed the model studies to calculate the achievable precision of the aerosol optical depth and vertical profile. In addition, several studies (e.g., Irie *et al.*, 2009 and 2011; Lee *et al.*, 2009 and 2011; Clemer *et al.*, 2010; Li *et al.*, 2010) provided aerosol profiles from ground-based hyperspectral measurements in UV and visible wavelength ranges on several ground sites. Wagner *et al.* (2010) investigated the sensitivity of various factors to the aerosol layer height using the data obtained from the SCanning Imaging Absorption SpectroMeter for Atmospheric ChartographY (SCIAMACHY) on ENVISAT. The sensitivity of the Ring effect and the absorption by oxygen molecule ($O_2$) and its dimer ($O_4$) calculated by DOAS method were examined to estimate aerosol properties including the layer height. Kokhanovsky and Rozanov (2010) estimated dust altitudes using the $O_2$-A band between 760 and 765 nm after the determination of the dust optical depth. In addition, several previous studies are also investigated estimation methods for aerosol height information by using hyperspectral measurement in visible (e.g., Dubuisson *et al.*, 2009; Koppers and Murtagh, 1997; Sanders and de Haan, 2013; Sanghavi *et al.*, 2012; Wang *et al.*, 2012). Because in the near UV the surface signal is significantly smaller than the aerosol signal, the UV and near UV regions are useful to derive aerosol height information from space borne measurements."

*P.7937, l.10: The term SCD is not explained. I think some DOAS theory, or at least a discussion of radiative transport, is needed in this section. I strongly encourage the use of AMFs instead of SCDs, because the numbers are more intuitive. Apart from that, since the O4 VCD is well known, it might as well be removed (i.e., divided out) for simplicity.*

To supplement the DOAS theory and to explain the disadvantage of directly used O4 SCD value, we revised the manuscript as below:

"Figure 1 shows the flowchart of the method to estimate the $O_4$ SCD from the simulated radiance. Because the magnitude of the $O_4$ SCD values is too large to express the sensitivity results, this paper defines the $O_4$ index (O4I) which divides $O_4$ SCD by $10^{40}$ molecules$^2$cm$^{-5}$."

*P. 7940, l.19: "the noise level" Where does the (relatively large) noise in the simulations come from?*

Although cross section database are identified, the noise from fitting residual is estimated during DOAS fitting from simulated radiance because DOAS fitting is independently tested.

*P. 7940, l.22- P.7941, l.19: "Figure 2 shows the comparison (...) to retrieve aerosol height." This section raises some issues, e.g.: how do the data look for AOD=0? An AOD of 0.15 appears rather high, although this might account for occasional cloud contamination of OMI data. The correlation is good, but not perfect, and it would be* *interesting to know if there are systematic deviations (e.g., for certain solar/viewing geometries). I would expect some deviations, particularly at larger viewing angles, simply due to the coarse resolution of the LUT (at the swath edges SCD probably depends strongly on viewing angle). The fact that the O4 cross section needs scaling for a better agreement of results is attributable to the difference in cross-sections used by the authors on the one hand, and the OMICLDO2 retrieval team on the other hand.*

We revised the clear-sky comparison test in Section 2.2, and Figure 2 and 3 in the revised manuscript.

*P. 7942, l.21: I would rename this section to, e.g., "Sensitivity of O4 SCDs at various wavelengths to AEH", and then add another section, e.g. "Sensitivity of 477nm O4 SCDs to various aerosol parameters" at page 7944, line 4 to improve readability. This is the section where a comparison with previous sensitivity studies should be presented.*

→ After revision this sentence is deleted.

*P. 7942, ll.4-6: "However, the absorbing aerosols in low AEH cases (...) and 380 nm." What do you mean by "fluctuated" ? And what is the cause of the large fitting error?*

→ After revision this sentence is deleted.

*P. 7942, ll.6-8: "For this reason (...) in the AEH range of 2.0 to 4.0 km." This is a quite clear definition of -dO4/dZ, but in the next lines, you often use a different definition, e.g. in lines 9-10 on the same page. This appears to be the maximum -dO4/dZ for a certain altitude, which is not in agreement with the definition cited above and confuses the reader.*

→ After revision this sentence is deleted and more detailed analysis is added in Figs. 4-5.

*P. 7942-7943: The results in this section should be presented in a more clear and concise way. In fact, they can be summarized (somewhat crudely) by simply saying that O4 absorption features at wavelengths other than 477 are not suitable for AEH retrieval because the sensitivity of the O4 SCD to AEH is smaller than or comparable to the fitting error.*

→ We revised in the revised manuscript as below:

"The O4Is are estimated at 360 and 380 nm band as shown in Figure 4(a) ~ (f). The O4I is significantly decreased with increasing AEH at 360 and 380 nm for all aerosol types. However negative O4Is are occasionally estimated at 360 nm. Furthermore the fitting errors are too large to estimate the AEH, which range from 160 to 410 at 360 nm and from 350 to 1060 at 380 nm. From large fitting error with small O4I, the fitting results are insignificant at these two absorption bands."

*P. 7944, ll.13-14: "Torres et al., (...) due to the cloud contamination." This is not very* *relevant to the current study, as no OMI aerosol data are used.*

*P. 7944, ll.14-15: "SSA varies widely as the categorizing aerosol types." Do you mean: SSA varies widely for different aerosol types?*

→ To clarify the SSA error test we revised on Section 3.3 in the manuscript as below:

"The mean errors from 10% variation in the SSA for all of the variable conditions in Table 3 correspond to 726, 576, and 1047 m for the MITR, COPO, and WASO, respectively. For the total error budget calculations, however, 5% change in the SSA was used according to Torres *et al.* (2007), which reported the variation of the SSA less than 0.03 for the given aerosol type. The error from the vertical distribution is estimated to be 720, 1480, and 690 m for the COPO, MITR and WASO, respectively.

The errors from the SSA and the aerosol profile shape are the two important error sources in estimating the AEH, followed by the errors related to the AOD and the surface albedo. From these results, the errors of the AEH due to the error from OMI AOD of 0.1 and the surface albedo of 0.02 are less than 300 m for WASO and COPO, and about 400 m for MITR. However, the AEH error from surface albedo is important for cases with low AOD at high AEH, which is surface reflectance dominant case."

*P. 7945, Sect. 3.2: Discuss uncertainties arising from errors in assumed particle size and shape (phase functions). Also missing is the uncertainty due to mis-classification of aerosols (e.g., COPO as WASO). Cases with more than one layer of aerosols also deserve attention here.*

→ We added the Section 3.2.3 in the revised manuscript. In this study, aerosol vertical distribution also concerned to be error source. However mis-classification of aerosol types and cases with more than one layer of aerosols are difficult to identify the parameter for aerosol vertical information.

We mentioned in the revised manuscript as below:

"Although this study is not able to show all kinds of aerosol vertical distributions due to its large variability in profile, aerosol vertical distribution by changing the half-width of GDF distribution can reflect large-scale changes in its vertical profile."

*P. 7947, ll.6ff: Large parts of this section, particularly the description of the OMI instrument and the description of the AEH derivation algorithm, should be put into a separate Methods section. The section should also contain an explanation of how MODIS data are selected and integrated into the AEH algorithm.*

→ We revised the method of AEH algorithm and data selection for case study in the beginning of Section 4 in the revised manuscript as below:

"To demonstrate the feasibility from real measurements, the AEHs are derived using hyperspectral data from OMI. OMI channels are composed of UV-1 (270-314 nm), UV-2 (306-380 nm), and a visible wavelength range (365-500 nm) with a spectral resolution (FWHM) of 0.63, 0.42, and 0.63 nm, respectively (Levelt *et al.*, 2006). The spatial resolution is 13 km × 24 km at nadir in "Global Mode". In the present study, the spectral data over the visible wavelength range are used to derive the O4I at 477 nm and the AEH information.

Figure 12 describes an AEH retrieval algorithm for the case study. In retrieving AEH, AOD is obtained from MODIS standard product (e.g., Levy et al., 2007). Although OMI aerosol product provides AOD at 500 nm, AOD from OMI was partially affected by aerosol height and suffered from cloud contamination due to its large footprint (Torres et al., 2002). For this reason, AOD from MODIS allocated to the OMI pixels as a reference AOD for the AEH retrieval. For type selection, the AE from MODIS and AI from OMI is respectively used for the information of size and absorptivity, to classify aerosol type into four following the method from Kim et al. (2007) and Lee et al. (2007). After determining AOD and aerosol type, LUT, which is generated as functions of geometries (SZA, VZA, and RAA), aerosol types and AODs, is used to determine the AEH information by using comparison between simulated and measured O4I value. The variables and their dimensions for the LUT calculations are shown in Table 7. Due to the limitation of the accuracy of aerosol type classification and those of AOD over land, this study estimates the AEH only over ocean surface. Although temporal and spatial variation of surface albedo influences the AEH result from error study, surface albedo is assumed to be a fixed value of 0.10, which is used in sensitivity study. For case study, the LUT of O4I is developed by the aerosol model based on AERONET data over East Asia. Extensive AERONET dataset over East Asia are used to provide represent aerosol optical properties for the LUT calculation."

*P. 7948, ll.12-13: "From CALIOP observation, . . . for most observed regions." What about the small region that is collocated with the OMI/MODIS measurement?*

→ In the revised manuscript, we compared the AEH from OMI and CALIOP AEH within 0.25 degree for latitude and longitude of GSD, and we showed the result in Figure 15.

*P. 7948, ll.25-26: "the investigated algorithm quantitatively estimates the AEH over East Asia." This statement is rather too bold (as mentioned previously). You have not proven this with the one case study presented in the manuscript.*

→ We added two cases for scene analysis and direct comparison result between CALIOP and OMI in several cases from 2007 to 2008 over East Asia as shown in Figs. 13-15 in the revised manuscript.

*P. 7949, Sect. 5: Add the error from profile shape assumptions to the total error; this would appear to be more fair.*

*PP. 7963-7964: Why not merge Tables 6 and 7?*

→ Because the error from aerosol profile shape assumption is relatively large, we separately showed the result in Table 5.

*Fig. 3 : the lower panel is wrong; it shows results for 360 nm instead of 340 nm*

→ We revised in the revised manuscript.

*Figs. 3-6: Add the Rayleigh AMF (more informative than the geometrical AMF); it is given in Fig. 7 for 477 nm (at AOD=0).*

→ We revised in the revised manuscript as converting O4 index value.

*Fig. 9a: What is the cause of the red color?*

*Fig. 9e: Add the CALIOP ground track.*

→ We revised the Figs. 13 and 14 in the revised manuscript as removing ground LIDAR results, because ground LIDAR site is too far to compare directly. Because CALIOP ground track addition would be confusing to show the scene result, we mentioned the sentences to explain the track information for respective case study as below:

"The retrieved result is compared with the backscattering intensity from the CALIOP observation over Yellow sea as shown in Figure 13(e). From CALIOP observation, the aerosol layer height over Yellow sea is located around 1 km altitude for most observed regions."

"On this date, CALIOP passed over coastal line between China and Yellow Sea. The aerosol layer height ranged from 0.5 to 2.5 km during the overpass over East Asia as shown in Figure 14(e)."

Response to reviewer #2

Thank you for the reviewer's effort to review our manuscript. During the revision processes of our manuscript, we re-wrote most parts of the manuscript. In addition, we added results of sensitivity tests and error analysis for additional aerosol parameters. During the revision, we changed the radiative transfer model to improve the interface of previous model for surface albedo. For this reason, we also revised the methodology to explain the new radiative transfer model and its condition

*This paper explores the possibility to retrieve the aerosol altitude from the O2-O2 spectral band. This is a very important topic, in particular for trace gases retrievals from the UV and Visible spectral bands where there is a need to correct for aerosol effects. I agree with the comments written by Referee #1. The study presented here appears incomplete and gives rise to various questions about all the error sources which impact the quality of the retrievals. As highlighted by Referee #1, the presented study case does not allow to validate the proposed algorithm. Some sections include some confusing elements which need to be clarified (see below for details). Moreover, it is very hard to have a critical judgement and understanding of some results as some technical details are missing on the employed approaches for the analysis and the AEH algorithm.*

→ In the revised manuscript, we added further details of our AEH retrieval algorithm and methodology for sensitivity test in Section 2 and 4. For error budget analysis, we added the aerosol particle size as an error source parameter in the Section 3.2.3. Furthermore, we also retrieved other aerosol loading cases over East Asia for validation in Section 4 with the details of cases listed in Table 8. The algorithm was validated by using CALIOP data as a reference as shown in Figs. 13-15. Details of methodology for case study is described in Figure 12 and explained in the beginning of Section 4 as below:

"Figure 12 describes an AEH retrieval algorithm for the case study. In retrieving AEH, AOD is obtained from MODIS standard product (e.g., Levy et al., 2007). Although OMI aerosol product provides AOD at 500 nm, AOD from OMI was partially affected by aerosol height and suffered from cloud contamination due to its large footprint (Torres et al., 2002). For this reason, AOD from MODIS allocated to the OMI pixels as a reference AOD for the AEH retrieval. For type selection, the AE from MODIS and AI from OMI is respectively used for the information of size and absorptivity, to classify aerosol type into four following the method from Kim et al. (2007) and Lee et al. (2007). After determining AOD and aerosol type, LUT, which is generated as functions of geometries (SZA, VZA, and RAA), aerosol types and AODs, is used to determine the AEH information by using comparison between simulated and measured O4I value. The variables and their dimensions for the LUT calculations are shown in Table 7. Due to the limitation of the accuracy of aerosol type classification and those of AOD over land, this study estimates the AEH only over ocean surface. Although temporal and spatial variation of surface albedo influences the AEH result from error study, surface albedo is assumed to be a fixed value of 0.10, which is used in sensitivity study. For case study, the LUT of O4I is developed by the aerosol model based on AERONET data over East Asia. Extensive AERONET dataset over East Asia are used to provide represent aerosol optical properties for the LUT calculation."

*Finally, as this manuscript focuses on the feasibility to implement an algorithm, I wonder if a submission to Atmos. Meas. Tech. would not be more appropriate than ACP. Therefore, I suggest major revisions and clarifications for this paper before being submitted again. The most important revisions (addressed in detail in the following section) include: A complete and detailed description of the proposed algorithm and the employed approaches of analysis, in particular for the error analysis (Section 3.2) and for the DOAS analysis (Section 2.2); Clarification of the results and issues risen below: in particular about the error analysis, clarify please all the reference scenarios considered, how this can change depending on the variability of the geophysical conditions, and explain in detail the reason of the somewhat surprising small impact of surface albedo; Inclusion of more than 1 study case, or at least a more convincing case.*

→ We improved the input interface of radiative transfer model. For this reason, RTM was changed from LIDORT to a newly developed radiative transfer model, VLIDORT. Details of VLIDORT and new methodology are described in Section 2.1. Details of methodology for DOAS are also additionally described on Section 2.2 in the revised manuscript with clear-sky comparison test.

After updating the model, we found that previous result for the impact of surface albedo was underestimated, thus revised all error budget and sensitivity studies for aerosol parameters and surface albedo. Furthermore, we additionally included the result about geometrical dependence as shown in Figure 8. Details are explained in Section 3.1.

*Specific comments*

*Table 6 shows a summary of error sources and the total error budget for the AEH retrieval. The methodology of deriving this table should be described in more detail in section 3.2, using equations for example and giving a clear methodology. Moreover, the reference surface albedo should be given. We can expect that these numbers will change with respect to the geophysical conditions. Are these numbers based on a standard error propagation (i.e. assuming that each parameter will impact the result as random error)? If yes, the presented results may be somewhat underestimated.*

→ We revised details of methodology in Section 3.2 with equation as below:

"Errors are also estimated in terms of key variables in the estimation of the O4I at 477 nm, with the variables and their dimensions as summarized in Table 3. For the error analysis of AEH retrieval, characteristics for all of extinction material are essential to consider. In this study, errors are analyzed in terms of AOD, aerosol vertical distribution, particle size and SSA for aerosol amount and properties. Surface albedo variation is also considered to represent surface condition. To estimate the error amount, the AEH error is converted from the half of O4I difference between adding and deducting perturbation of variables as shown in equation (1).

$$\varepsilon(Z) = \left| \frac{O4I(x+\delta x,Z)-O4I(x-\delta x,Z)}{2.0 \times dO4I/dZ(x,Z)} \right| \quad (1)$$

where $\varepsilon(Z)$ is the AEH error amount due to variable of error source, x, in AEH of Z, and $\delta x$ is perturbation of AEH retrieval error source. The $\varepsilon(Z)$ value also depends on viewing geometries. Therefore $\varepsilon(Z)$ is represented for specific geometries together with averaging over all geometries."

→ The error study is basically estimated from radiative transfer model result. Therefore, the error analysis reflects result by changing target parameter only, while other variables are not changed.

*Indeed, uncertainties on the AOD for example will likely result in a systematic error (i.e. bias) on the aerosol altitude. The evaluated uncertainty on the AEH retrieval induced by an error on the surface albedo of 0.02 appears surprising and should be explained (around 50 m for WASO case, less than 100 m for the other cases). It is much lower than the uncertainty due to the AOD (less than 200m) and SSA (between 229 and 2155 m). As explained in this paper, the AEH is strongly constrained by the O2-O2 SCD. However, this variable is also strongly driven by the O2-O2 continuum reflectance [Acarreta et al., 2004; Chimot et al., 2015] which, by definition, results from a combination of AOD (and associated additional scattering caused by aerosols) and surface albedo. Therefore, the surface albedo should be a key component (at least for a given range of AOT), and it is not understood why here this has so little impact. [Veihelmann et al., 2007] has also shown the importance of the knowledge of surface albedo for aerosol retrievals from the OMI spectral measurements.*

→ After changing radiative transfer model, the AEH error due to surface albedo was redone, and the error budget results were also changed. Revised result is shown in Section 3.2.4 for surface albedo, and all error budget results are listed in Table 6 in the revised manuscript. From this result, the surface albedo is one of key factor for AEH estimation.

*Finally, what is also missing is a theoretical discussion about the impact of clouds (e.g. in case of low cloud fractions). In the case of O2-O2 cloud retrievals, [Acarreta et al., 2004; Chimot et al., 2015] have shown that the effective cloud pressure value is very sensitive to the range of effective cloud fraction. For low cloud fraction, and thus low* *continuum reflectance and so low AOD, the relative variability of O2-O2 SCD is quite small and so it is more challenging to retrieve the aerosol altitude with a low uncertainty. The sensitivity of the AEH accuracy to AOD, and in general everything which impacts directly the O2-O2 continuum reflectance magnitude, should be discussed. It is expected that the AEH retrieval algorithm will be more accurate for large AOTs, while for low AOTs the AEH uncertainties should be higher.*

→ This study focused on the aerosol retrieval over cloud-free pixels. For this reason, corresponding pixel is selected with extremely low cloud fraction value (0.02 for the case study in Section 4). In the revised manuscript, we added the result of AEH uncertainties as a function of reference AOD and AEH for respective error sources. Details are described in Section 3.2 with Figs. 7 to 11 in the revised manuscript.

*Table 8 presents the input parameters of the LUT used for the AEH retrieval. Following my comment above, it is not clear why the surface albedo is not one of the parameters. Does it mean this LUT is generated for one single surface albedo case (in line with the value given from OMLER over your study case)? Section 3 says that "the climatological value from OMI Level 3 (OMLER) is used in this study". How is it used exactly since no input parameter is present in Table 8? Same for surface pressure or surface altitude. What was assumed for these parameters? How does it impact the result of your study case? Section 2.2 (DOAS analysis) mentions that a factor of 1.25 is used as a correction factor on the O4 absorption cross section as suggested by [Irie et al., 2011; Lee et al., 2011]. However, such a factor is commonly employed for ground-based in- struments like MAX-DOAS (as done by these 2 papers). There is no explicit evidence this is needed in the general case of satellite measurements. Please explain why you considered it here. On the other hand, it is mentioned that such a factor should cover the temperature dependence of the O4 SCD. I do not think that such a scale factor can cover this effect in satellite measurements. The work by [Maasakkers et al., 2013] demonstrates that this dependence varies in time and space. This can have major impact on the effective cloud retrieval, in case of the O2-O2 cloud algorithm, mostly for cases with low effective cloud fraction (change in cloud pressure between 100 and 200 hPa). Impacts on the aerosol altitude retrieval should be investigated as well, and for different AOD. More literature review, where the impacts of aerosols on the effective cloud retrievals should be added e.g. [Castellanos et al., 2015; Chimot et al., 2015; Lin et al., 2013; Lin et al., 2015], as they analysed the impacts on the O2-O2 spectral measurements.*

→ To reflect your comment, we did not use the correction factor value after revising manuscript. In section 2.2, we described the details of surface albedo assumption. Instead, the surface albedo is assumed to be 0.10, because frequent Lambertian equivalent reflectance (LER) is larger than minimum LER as described in Kleipool et al.

(2008). In the revised manuscript, we revised in Section 2.2 as below:

"Figure 3 shows the comparison of the $O_4$ SCD at 477 nm from a look-up table (LUT) with the dimension as in Table 2 against OMCLDO2 for aerosol and cloud free pixels in year 2005. The clear sky region is selected for the Pacific Ocean with cloud fraction less than 0.02 from OMI observation. The surface albedo is assumed to be 0.05, which is similar to the minimum Lambertian equivalent reflectance (LER) over clear ocean surface (e.g., Kleipool et al., 2008). Because the standard product of the $O_4$ SCD is only estimated at the 477 nm band, the results can be compared only at this band. To minimize the DOAS fitting error, the observed data from OMI is selected by the fitting precision less than 2% and the quality flags for spectral fitting and pixel condition are also considered. As shown in Figure 3(a), the correlation coefficient of determination ($R^2$) is 0.864 with a slope of 1.050, and the LUT exhibits a ratio of 0.86±0.05 to the values obtained from OMI standard values. Despite the statistically significant $R^2$ and slope values between the two values, there exists negative bias by about 14%.
The bias between the retrieved from LUT and estimated from standard product values can be attributed to the differences in the $O_4$ cross section data and the lack of their temperature and pressure dependence as noted from the previous works by Wagner *et al.* (2009), Clemer *et al.* (2010), and Irie et al. (2015). For this reason, ground-based measurements adopted the correction factors to cross section database. However the bias effect for the cross section difference is limited as shown in Figure 2, and the correction factor for the cross section database in the previous studies cannot be adopted to the space-borne measurements. From Kleipool et al. (2008), the minimum LER is defined to be the 1% cumulative probability threshold, and frequent LER value is typically higher than minimum LER over clear ocean, although cloud screening was perfectly executed before LER calculation. To account for the difference between simulated and observed SCD, the LUT was re-calculated by changing condition to the surface albedo of 0.10. The corrected result is shown in Figure 3(b), where the $R^2$ is 0.865 similar to that before the correction, but the negative bias is removed to 0.98±0.05 and the regression line slope is 1.123. Although the comparison result is not perfect, the calculation by the VLIDORT simulates the satellite observation and can be used for sensitivity tests to retrieve aerosol height."

→ Although correction factor of O4 is still challenging issue for satellite and ground observation, we used the method to modify surface albedo.

We also added the literature review in Section 1 in the revised manuscript as below:
"For OMI measurement, the $O_4$ band at 477 nm has been widely applied to estimate cloud information (e.g., Accarreta *et al.*, 2004; Sneep *et al.*, 2008). Especially, the cloud information retrieved by $O_4$ band at 477 nm was used for air mass factor (AMF) analysis with the consideration of aerosol optical effects for the $NO_2$ column retrieval

(e.g., Castellanos et al., 2015, Chimot et al., 2015; Lin et al., 2014; Lin et al., 2015). Although $O_4$ absorption band around 477 nm varies also due to cloud existence, it can be also used for the aerosol optical parameter estimation. Veihelmann *et al.* (2007) introduced that the 477 nm channel, which locates major $O_4$ band, significantly adds degree of freedom for aerosol retrieval by using principal component analysis, and Dirksen *et al.* (2009) adopts the pressure information obtained from OMI $O_4$ band to identify a plume height for aerosol transport cases.

“

*As Referee #1 pointed out, appropriateness of the selected study case is questionable. It is mentioned that the AEH derived from OMI is performed for a scene at 1.5 deg (i.e. around 150 km) away from the LIDAR site. This is a very long distance. The comparison with CALIOP seems to present some large differences (1.-1.5 km for CALIOP vs. 2.6 +- 1.7 km for AEH). More or different study cases should be presented for a more robust comparison.*

*Furthermore, Section 2 mentions that OMI data are selected with cloud fraction fraction less than 0.02. [Chimot et al., 2015] and [Boersma et al., 2011] have shown that the OMI effective cloud fraction is very sensitive to aerosols and AOD, and can reach values between 0.1 and 0.15 for AOT = 1. However values of 0.02 may indicate very little aerosols present in the OMI data (AOT likely less than 0.2).*

→ For the validation study, we added the comparison results in multiple aerosol loading cases. Furthermore, we directly compared to the AEH from CALIOP, and presented the result in Figs. 13-15. Cases for Figure 15 are listed in Table 8 in the revised manuscript. To estimate the AEH from OMI, we used the MODIS AOD after collocating OMI pixel, because of its low sensitivity to aerosol vertical distribution. Detail of method is described in Figure 12. If co-located MODIS AOD is not shown in specific OMI pixel, we did not estimate the AEH, although cloud fraction from OMI is lower than 0.02. By restricting those criteria, most of cloud effect can be neglected because spatial resolution of MODIS is better than those of OMI.

*Technical corrections*

*P. 7934, 2-4: “using simulated radiances by a radiative transfer model, ... (LIDORT), and ... (DOAS) technique”. Please separate LIDORT and DOAS techniques in this statement. Here, DOAS could be understood as a model name, not as a retrieval technique.*

→ We separate the methodology of VLIDORT and DOAS in the revised manuscript.

*P. 7934, 13-14: “knowledge on the aerosol vertical distribution type”: please reformulate. Do you mean aerosol vertical distribution and aerosol type?*

→ We revised the paragraph “assuming knowledge on the aerosol vertical distribution shape”.

*P. 7934, 25: "in regional and global scale": replace "in" by "at"*

→ We revised on the paragraph "at regional and global scale" in the revised manuscript.

*P. 7935: The necessity to know aerosol layer height for trace gases retrievals should be mentioned too.*

→ We revised on the sentence "The information on the aerosol layer height is important, because the variation of the aerosol vertical distribution affects radiative process in the atmosphere near the surface and trace gas retrieval for air mass factor calculation." in the revised manuscript.

*P. 7935, 12: Change "Vertical structures" to "Vertical profiles"*

→ We changed in the revised manuscript.

*P. 7935, 25: "CALIOP haS been successful (not "have")*

→ We changed in the revised manuscript.

*P. 7937, 12-14: Please specify that this refers to the impact of aerosols on the O4 signal. Reformulate "path length of light" as "length of the average light path".*

→ We changed in the revised manuscript.

*P. 7940, Section 2.2.: Please give more details about the approach implemented for the DOAS retrievals, based on the WinDOAS software. In particular, specify what you mean by "using a non-linear least squares method". Some equations with the retrieval state vectors and considered / assumed elements would help the reader.*

→ We referred the reference of WinDOAS software for methodology. In addition, we revised Section 2.2 to explain the details of methodology.

*P7940, 22-23: "comparison of the 477 nm O4 SCD between the inversion from a LUT": which LUT are you refereeing here? No LUT is explained before in the manuscript. And there is no use of a LUT usually to derive the O4 SCD.*

→ We mentioned the sentence for the clear-sky LUT calculation in the revised manuscript as below:

"Figure 3 shows the comparison of the $O_4$ SCD at 477 nm from a look-up table (LUT) with the dimension as in Table 2 against OMCLDO2 for aerosol and cloud free pixels in year 2005."

*Recommended additional literature*

*Acarreta, J. R., De Haan, J. F., and Stammes, P.: Cloud pressure retrieval using the O2-O2 absorption band at 477 nm, J. Geophys. Res., 109, D05204, doi:10.1029/2003JD003915, 2004. 8388, 8399, 8400, 8402*

*Castellanos, P., Boersma, K. F., Torres, O., and de Haan, J. F.: OMI tropospheric NO2 air mass factors over South America: e_ects of biomass burning aerosols, Atmos. Meas. Tech. Dis25 cuss., 8, 2683–2733, doi:10.5194/amtd-8-2683-2015, 2015. 8389, 8408.*

*Chimot, J., Vlemmix, T., Veefkind, J. P., de Haan, J. F., and Levelt, P. F.: Impact of aerosols on the OMI tropospheric NO2 retrievals over industrialized regions: how accurate is the aerosol correction of cloud-free scenes via a simple cloud model?, Atmos. Meas. Tech. Discuss., 8, 8385-8437, doi:10.5194/amtd-8-8385-2015, 2015.*

*Lin, J.-T., Martin, R. V., Boersma, K. F., Sneep, M., Stammes, P., Spurr, R., Wang, P., Van Roozendael, M., Clemer, K., and Irie, H.: Retrieving tropospheric nitrogen dioxide from the Ozone Monitoring Instrument: e_ects of aerosols, surface reflectance anisotropy, and vertical profile of nitrogen dioxide, Atmos. Chem. Phys., 14, 1441–1461, doi:10.5194/acp-25 14-1441-2014, 2014.8388, 8389, 8408.*

*Lin, J.-T., Liu, M.-Y., Xin, J.-Y., Boersma, K. F., Spurr, R., Martin, R., and Zhang, Q.: Influence of aerosols and surface reflectance on satellite NO2 retrieval: seasonal and spatial characteristics and implications for NOx emission constraints, Atmos. Chem. Phys. Discuss., 15, 12653–12714, doi:10.5194/acpd-15-12653-2015, 2015. 8409.*

→ We added the recommended literature in the revised manuscript.