Retrieval Algorithm for Aerosol Effective Height from the Geostationary Environment Monitoring Spectrometer (GEMS)

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Abstract

An algorithm for aerosol effective height (AEH) was developed for operational use with observations from the Geostationary Environment Monitoring Spectrometer (GEMS). The retrieval technique uses the slant column density of the oxygen dimer (O_2-O_2) at 477 nm, which is converted into AEH after retrieval of aerosol and surface optical properties from GEMS operational algorithms. The retrieved AEHs provide continuous vertical information of severe dust plumes over East Asia with reasonably good validation results and the collection of plume height information for anthropogenic aerosol pollutants over India. Compared to the AEH retrieved from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), the retrieval results show bias of -0.03 km with a standard deviation of 1.4 km for the AEH difference over the GEMS observation domain from January to June, 2021. The AEH difference depends on aerosol optical properties and surface reflectance. Compared to the aerosol layer height obtained from the tropospheric monitoring instrument (TROPOMI), differences of 1.50 ± 1.08 km, 1.59 ± 1.22 km, and 1.71 ± 1.24 km were obtained for pixels with single scattering albedo (SSA) < 0.90, 0.90 < SSA < 0.95, and SSA > 0.95, respectively.

Keywords: aerosol effective height, aerosol optical depth, environmental satellite, GEMS

1. Introduction

Since the launch of the Total Ozone Mapping Spectrometer (TOMS) on Nimbus-7, ultraviolet (UV)-visible satellite measurements have been used for environmental monitoring of the distribution and reaction processes of pollutants (e.g., anthropogenic aerosols, tropospheric ozone, NO_2, and SO_2). Measurements from environmental satellites have been used to estimate gaseous species in the atmosphere, resulting in vertical column integrated amounts. However, these column-integrated amounts and associated surface concentrations have uncertainty due to simultaneous changes in optical path length associated with the vertical distribution of target species and amounts of scattering materials (clouds and aerosols) present. In addition, aerosol vertical information is also important for the application of tropospheric concentration of aerosols. For example, aerosol height information in the free troposphere is particularly important for aviation safety by affecting the visibility. Also, scientific applications including radiative forcing studies, long-range transport modelling and studies of cloud formation processes have been used aerosol vertical information as an input parameter.

Environmental satellite sensors, that measure UV-visible wavelength, have been used the UV aerosol index (UVAI) for aerosol detection (e.g., Buchard *et al.*, 2015; Herman *et al.*, 1997; Torres *et al.*, 1998, 2002; Prospero *et al.*, 2000; de Graaf *et al.*, 2005). Furthermore, scattering radiative index values were investigated for the possibility of the cloud signal detection (Penning de Vries *et al.*, 2009, 2015; Kooreman *et al.*, 2020; Kim *et al.*, 2018). However, these indices only have qualitative characteristics and limitations to identify aerosol amounts.

For the quantitative estimation, measurements of aerosol optical depth (AOD) and

radiative cloud fraction have also been retrieved from pixel-based radiance data in UV-visible wavelength range. Recently, various aerosol retrieval algorithms have been developed to be applied in passive satellite sensors. These algorithms focus on improved trace gas retrieval as well as direct monitoring of aerosol properties, such as AOD and single scattering albedo (SSA) (e.g., Ahn *et al.*, 2014; Kim *et al.*, 2020; Torres et al., 2020).

Although the algorithms developed for environmental satellite sensors indicate the presence and amounts of scattering materials, the accuracy of these retrieval algorithms for trace gases is affected by the relative vertical distributions between trace gases and scattering materials (e.g., Lorente *et al.*, 2017; Hong *et al.*, 2017). For this reason, estimating cloud vertical parameters is important. For cloud vertical information, cloud height information has been estimated simultaneously with cloud optical depth and radiative cloud fraction data using the rotational Raman scattering (Joiner and Vasilkov, 2006; Vasilkov *et al.*, 2008; Joiner and Bhartia, 1995) and absorption intensity of the oxygen dimer (O_2-O_2) (Accarreta *et al.*, 2004; Vasilkov *et al.*, 2018; Choi *et al.*, 2021) combined with normalized radiance.

Similarly, the aerosol vertical distribution can be estimated using the oxygen absorption bands, such as the O_2-O_2 (Park *et al.*, 2016; Chimot *et al.*, 2017; Choi *et al.*, 2019, 2020), O_2-A (Dubisson *et al.*, 2009; Geddes and Boesch, 2015; Sanders *et al.*, 2015; Xu *et al.*, 2017; Zeng *et al.*, 2020), and O_2-B (Chen *et al.*, 2021; Ding *et al.*, 2016) bands, as well as combinations of these bands (Sanghavi *et al.*, 2012; Chen *et al.*, 2021). In addition, an algorithm for aerosol vertical information has been developed based on hyperspectral UV-visible radiance from satellite observation. Nanda *et al.* (2018) demonstrated the possibility of aerosol height retrieval from the O_2-A band

developed an algorithm using Tropospheric Monitoring Instrument (TROPOMI) (Sanders and de Haan, 2016; Nanda *et al.*, 2020) and implemented the algorithm operationally.

However, the vertical distribution of aerosol is difficult to assess because of its large spatio-temporal variability. Although the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) provided the aerosol vertical distribution with high vertical resolution (Omar et al., 2009), other passive satellite sensors are only able to estimate the representative parameter of aerosol height. Veihelmann et al. (2007) showed that the number of degrees of freedom of signal for aerosol is 2-4 for most satellite observation conditions by the ozone monitoring instrument (OMI). In addition, the number of degrees of freedom is not exceeded to 3 from the shortwave satellite measurements (e.g., Rao et al., 2019; Choi et al., 2021). It means that the amount of information for aerosol vertical distribution has a limitation for satellite sensors. Because of limitation for describing the aerosol vertical information, aerosol layer height (ALH) (e.g., Nanda et al., 2018) or aerosol effective height (AEH) (Park et al., 2016) were defined to retrieve the aerosol vertical information from the passive satellite sensors.

The Geostationary Environment Monitoring Spectrometer (GEMS), which was launched by South Korea in February 2020, provides column density of ozone, aerosol, and their precursors (Kim *et al.*, 2020). The main purpose of GEMS is to monitor air quality, and aerosol properties are targets of such monitoring over East Asia. For this reason, the GEMS aerosol algorithm was developed as multiple operational products. The Aerosol algorithm adopted optimal estimation method (Rogers, 2000) to retrieve AOD, SSA, and ALH. Aerosol properties are obtained for the purposes of monitoring air quality and aerosol effects for the air mass factor (AMF) calculation. In addition to

these aerosol products, AEH is provided to represent the upper layer of the peak. Both ALH and AEH help understand the vertical structure of aerosol layer. For the possibility for development of an AEH retrieval algorithm, Park *et al.* (2016) conducted theoretical sensitivity testing of AEH retrieval using solely the O_2-O_2 absorption band along with aerosol and surface properties. Overall, the sensitivity of AEH retrieval was strongly affected by SSA, AOD, and aerosol types including optical and size properties. In addition, case studies of AEH during dust transport over East Asia were conducted using radiance data from the Ozone Monitoring Instrument (OMI) and aerosol optical properties from the Moderate Resolution Imaging Spectroradiometer (MODIS).

Based on theoretical considerations and case study results, we introduce an operational retrieval algorithm for AEH. Section 2 introduces the details of satellite sensors for the comparison and colocation method in this study. Section 3 describes the details of the AEH retrieval algorithm for GEMS and provides a list of the detailed input parameters. Section 4 reports retrieval results based on case studies of aerosol transport, and section 5 contains long-term validation results based on CALIOP and TROPOMI data. Finally, in section 6, the summary and main conclusions are presented.

2. Data

2.1 GEMS

The GEMS instrument on board the Geostationary Korea multipurpose satellite 2B (GK2B) is located at 128.2°E, and scans from 145°E to 75°E with north-south coverage of 5°S-45°N. The GK2B observation schedule shares the GEMS and the Geostationary Ocean Color Imager 2 (GOCI2), and the GEMS scan the 30 minutes duration from every hour from 45 minutes to 15 minutes during daytime. The spatial resolution of

GEMS is 3.5 km (North-South) × 8 km (East-West) for aerosol and gaseous products at 38ºN. The spectral range of 300-500 nm is covered with a spectral resolution (as defined by the full-width and half-maximum of the spectral response function) of 0.6 nm and a spectral sampling of 0.2 nm.

The GEMS Level 2 aerosol operational algorithm (L2AERAOD) retrieves the aerosol index (AI) values for UV and visible wavelengths, as well as AOD and SSA after determining the aerosol types (National Institute of Environmental Research, 2020). The aerosol types are defined as absorbing, non-absorbing, and dust types by using the AI based classification methods exploiting measurements in the UV and visible (e.g., Go et al., 2020). Park *et al.* (2016) noted that the error budget of AEH is significantly affected by uncertainty in AOD and SSA and by the misclassification of aerosol types, which is directly related to the optical property and size information. Overall, uncertainties of 0.2 in AOD, of 20% in particle size, of 10% in SSA, and 0.02 in surface albedo cause AEH errors in the range 739-1276 m (Park et al., 2016). In this study, the L2AERAOD results for AOD at 550 nm and SSA at 443 nm were adopted as input data for aerosol properties, and the AOD and SSA values were spectrally converted to those values at assumed wavelength for the inversion calculation process after considering the spectral dependence of the aerosol optical properties by the aerosol models. In addition, we also used the minimum reflectance under the Lambertian assumption to retrieve AOD and AEH to coincide with the use of surface information on L2AERAOD and AEH retrieval.

2.2. TROPOMI

TROPOMI is a nadir-viewing spectrometer, the only payload of the Sentinel-5 Precursor (S5P), measuring radiance in the UV, visible, near-infrared, and the shortwave

IR (Veefkind et al., 2012). The S5P is a polar orbit satellite that crosses the equator at 13:30 local time at an ascending node. The aerosol layer height product from TROPOMI (AER_LH) provides vertically localized aerosol layers in the free troposphere with cloud free condition by using the level 1b earth radiance measurements from 758 to 770 nm (de Graaf *et al.*, 2022). The definition of ALH from TROPOMI is the optical centroid layer height of the plume above sea level. The spectral fit employs a fast forward model based on a neural network for simulated condition of reflectance around the O_2-A band. After cloud masking, an optimal estimation method is used to retrieve the ALH and AOD by the inversion method from observation. Other aerosol parameters, such as SSA, layer thickness, and scattering phase function, are assumed to be fixed values (Nanda et al., 2020). Furthermore, the ALH retrieval has limitation to the aerosol plume with higher than 12 km, because the ALH neural network product currently provides the plume pressure range of 75-1000 hPa (Michailidis et al., 2023).

The main purpose of the AER_LH product is the retrieval of aerosol layers in the free troposphere (desert dust, biomass burning, and volcanic ash) (Michailidis et al., 2023). The target requirement on the accuracy and precision is 0.5 km or 50 hPa, and the threshold requirement is 1 km or 100 hPa under the elevated aerosol plumes with cloud-free conditions for the layer height and for the associated pressure, respectively (de Graaf et al., 2022, Veefkind et al., 2012). However, the TROPOMI ALH product has strong dependence of the surface albedo, especial to the bright surfaces (Sanders et al., 2015). From Michailidis et al. (2023), a mean bias of -0.51±0.77 and -2.27±1.17 km is estimated over ocean and land, respectively. In this study, we use version 02.04.00 of the TROPOMI offline level 2 AER_LH product (European Space Agency, 2021) with

187 the spatial resolution is 3.5 km × 5.5 km at nadir viewing geometry.

188

189 **2.3. CALIOP**

190 The CALIOP is a spaceborne lidar onboard the Cloud-Aerosol Lidar and Infrared
191 Pathfinder Satellite Observations (CALIPSO) to measure the vertical information of
192 aerosol and cloud with estimating the optical properties. The CALIOP has two different
193 wavelength channels (532 and 1064 nm) by using the Nd:YAG laser to generate the
194 signals (Winker et al., 2009). The CALIPSO is Sun synchronous orbit constellated to
195 the A-train with period of 98.3 minutes. It crosses the equator at 13:30 local time on an
196 ascending node. To cover the GEMS observation area, we used CALIOP data of 3-4
197 orbits per day. For the vertical information, the resolution for vertical sampling is 30 m
198 below 8 km altitude, and 60 m from 8 to 20 km altitude, respectively. Although the
199 CALIOP retrieves the data with extremely high horizontal and vertical resolutions, the
200 spatial coverage is narrow because the footprint of the CALIOP is about 90 m at the
201 Earth surface. In this study, the data of Level 2 aerosol profile product (APro, version
202 3.41) was used (Tackett et al., 2018). The aerosol profile product simultaneously
203 includes both aerosol and cloud optical depth. In addition, extinction quality flag
204 (Extinction_QC_Flag) data shows the quality of extinction profile. In this study, we
205 checked and used the quality flag value at 532 nm for the aerosol extinction coefficient
206 profile data. The AOD from CALIOP is vertically integrated aerosol extinction
207 coefficient from surface to top of atmosphere, and representative layer height
208 parameters (ALH and AEH) are directly estimated by using the vertical profile of
209 aerosol extinction coefficient at 532 nm to minimize the spectral discrepancy of aerosol
210 extinction. For the ALH retrieval, we adopted mean extinction height from the CALIOP

211 extinction coefficient profile (e.g., Koffi et al., 2012; Xu et al., 2019). Similarly, the
212 AEH estimation from CALIOP is also used to the extinction coefficient profile.
213
214 **2.4 Data Selection and Colocation**
215 In this study, we used data within 75ºE-145ºE for east-west and 5ºS-45ºN for north-
216 south direction, which is the observation area of GEMS. From Park et al. (2020), the
217 spatial range of highly coincident AOD is 30-40 km. To ensure that the number of
218 retrieved observation pixels that can be analyzed in this study is sufficiently high, we
219 relax the spatial limits for colocation matching. For spatial colocation, we selected
220 pixels for which distance between GEMS and CALIOP (or TROPOMI) observations
221 was less than 50 km. In addition, only the closest 10% of pixels were used. Given the
222 different orbital characteristics of CALIOP (or TROPOMI) and GEMS, temporal
223 colocation was also considered. During the period of image scanning from east to west
224 over Asia by GEMS, CALIOP and TROPOMI pass through the GEMS observation area
225 from south to north every 98.3 minutes. On average, two low earth orbit (LEO)
226 satellites pass three to four orbits through the GEMS scan area during a single day of
227 daytime observation. To consider these different orbital characteristics, only
228 observations taken within ±1 hour of the GEMS observation time was selected for
229 temporal colocation. As GEMS observes hourly, colocated pixels between the two
230 satellites shift from east to west over time.
231 To ensure the accuracy of ALH from TROPOMI, only pixels with quality assurance
232 (QA) values of 1.0 were used. To minimize the cloud contamination, the TROPOMI
233 ALH product uses the VIIRS cloud mask information and cloud parameters from the
234 Fast Retrieval Scheme for Clouds from the Oxygen A-band (FRESCO). To consider the

cloud contamination for the aerosol products, in addition, the VIIRS cirrus cloud reflectance (viirs_cirrus_reflectance < 0.4), VIIRS cloud mask (viirs_cloud_mask < 0.1), and cloud fraction from the FRESCO (cloud_fraction < 0.1) are considered in this study (Michailidis et al., 2023). However, de Graaf *et al.* (2022) showed that respective cloud masking methods have difficulty detecting various clouds. For this reason, cloud contamination remains a critical source of uncertainty in the ALH retrieval. From previous studies, the UVAI is used to detect the presence of absorbing aerosol (e.g., Chen et al., 2021; Griffin et al., 2020; Michailidis et al., 2023; Sanders et al., 2015), and the aerosol height information was only retrieved on the absorbing aerosol pixels. However, the GEMS aerosol product is retrieved not only the absorbing aerosols, but also the non-absorbing aerosols. For this reason, the pixels for which with an AOD at 443 nm (AOD_{443} hereafter) taken from the GEMS aerosol product exceed 0.3 are selected for AEH retrieval.

3. AEH retrieval algorithm

AEH is a layer height parameter that considers the penetration of photons into the aerosol layer. It is defined such that the integral of the vertical aerosol extinction profile from the surface to the AEH is equal to $(1\text{-}e^{-1}) \times$ AOD, as defined by Park *et al.* (2016). Numerous previous studies have used the aerosol top layer height (Kohkanovsky and Rozanov, 2010) or middle layer height (i.e. ALH or centroid height) (e.g., Sanders *et al.*, 2015; Nanda *et al.*, 2020) as the aerosol vertical layer parameter. AEH is similar to the aerosol top layer height but with a slight bias.

For AEH retrieval, the vertical distribution assumption is also important. The Gaussian Density Fitting (GDF) distribution, which is a modified Gaussian distribution

structure by considering the range of upper and lower boundary height, is assumed for AEH retrieval. The full-width at half-maximum (FWHM) of the aerosol layer is assumed to be 1 km. A schematic description of AEH and other aerosol vertical parameters are shown in Figure 1. Based on the assumptions about the aerosol vertical distribution, the AEH value is higher than the peak height of the Gaussian distribution and lower than the aerosol top layer height. Otherwise, the ALH is defined as the integral of the vertical aerosol extinction profile from the surface to the ALH is equal to 0.5 × AOD. This assumption is used by Nanda et al. (2016). Therefore, the ALH equals the peak height of the profile in the conditions shown in Figure 1.

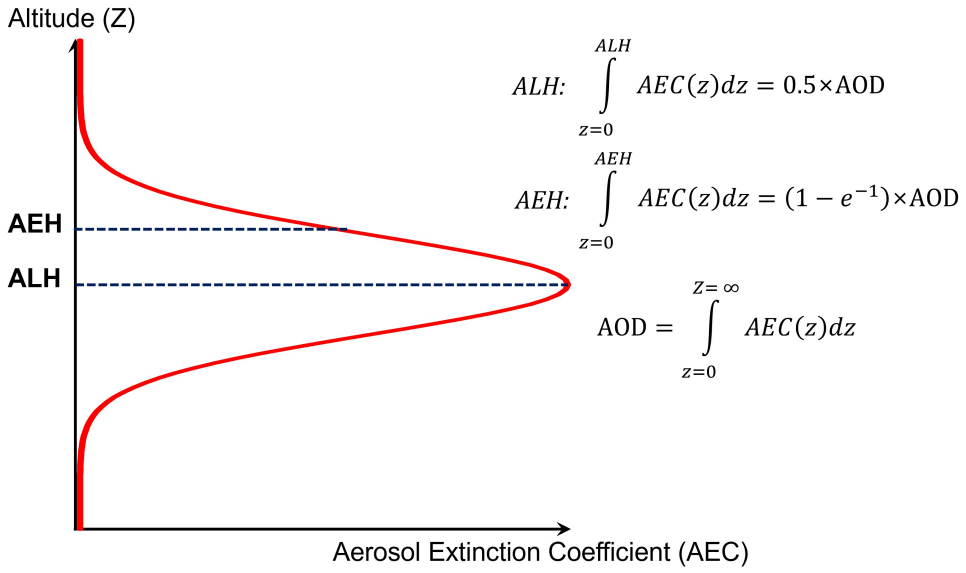


Figure 1. A schematic illustration of AEH and ALH definitions in an idealized Gaussian shape of aerosol vertical distribution.

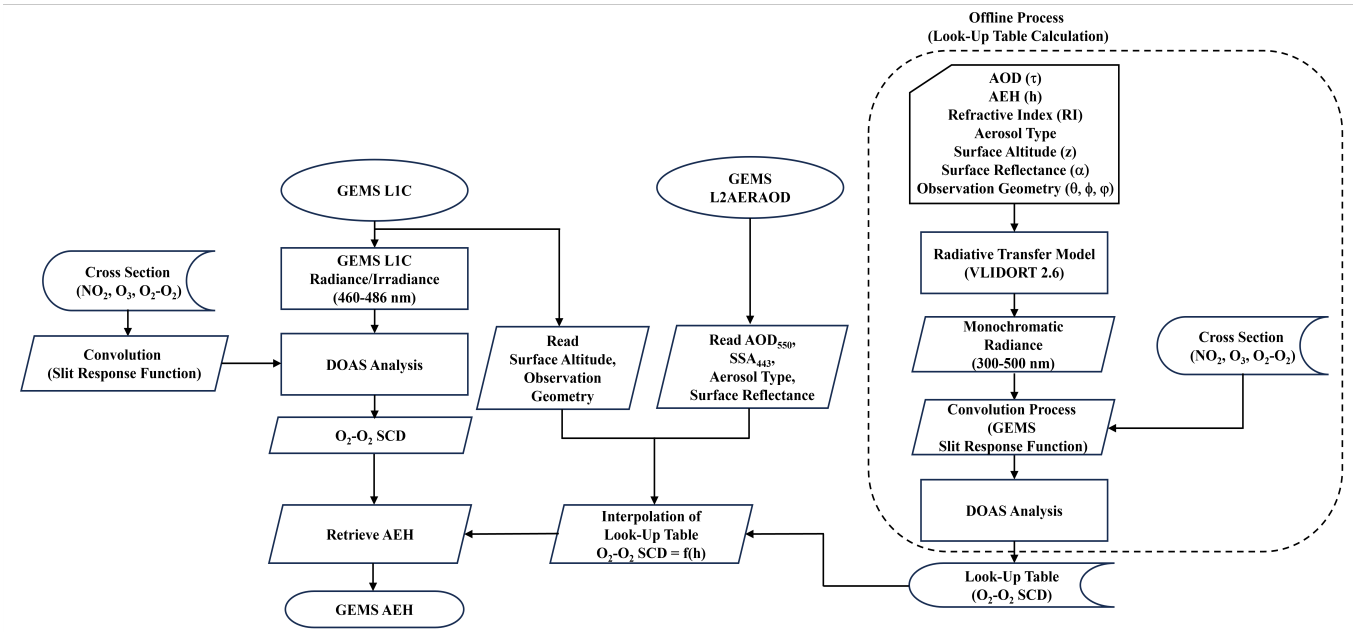


Figure 2. Flowchart of the AEH retrieval algorithm for GEMS satellite observation.

For AEH retrieval, the basic idea is the identification of changes in optical path length caused by effective aerosol layer height variation. To measure the optical path length change, O_2-O_2 SCD retrieved by the DOAS method was used because the spectral coverage is limited to 300-500 nm (Park et al., 2016, Kim et al., 2020). In the GEMS product, the O_2-O_2 SCD at 477 nm absorption band is the most useful absorption band because this absorption band is strongest absorption band within the GEMS spectral observation range. Figure 2 shows the overall flowchart of the AEH algorithm for GEMS satellite. The AEH algorithm for GEMS employs a look-up table (LUT) that contains O_2-O_2 slant column density (SCD) values for many scenarios with a variety of observation geometries [solar zenith angle (SZA; θ), viewing zenith angle (VZA; Φ), relative azimuth angle (RAA; φ)], surface altitude (z), surface reflectance (α), AOD (τ), AEH (h), Refractive Index (RI) for SSA, and aerosol type. During the radiance simulation, the radiance is monochromatically simulated and then convolved with the

GEMS instrument spectral response function. Finally, the radiance information is converted to the O_2-O_2 SCD from differential optical absorption spectroscopy (DOAS) method (Platt, 1994).

DOAS method has been frequently used to estimate the amount of trace gases (i.e., SCD of trace gas) from ground (e.g., Cheng et al., 2023; Irie et al., 2008; Platt and Stutz, 2008; Wagner et al., 2011; Wang et al., 2017) and satellite (e.g., Kwon et al., 2019; Li et al., 2023; Wagner et al., 2007, 2010) measurements. Detailed DOAS fitting parameter and setting information is provided in Table 1 for the estimation of O_2-O_2 SCD from both the simulation and observation data. For the O_2-O_2 SCD estimation at 477 nm, the fitting window ranges from 460 to 486 nm to cover the full absorption structure of O_2-O_2. Within the fitting window, the absorptions of NO_2 and O_3 are significant. To describe these two absorbing species, temperature dependent cross section information is adopted. The temperature dependent cross section setting considers stratosphere and troposphere, simultaneously.

Table 1. Details of fitting parameter for O_2-O_2 SCD estimation via the DOAS method.

Parameter	
Fitting window	460 – 486 nm
Absorption cross section	NO_2 at 220 and 294 K (Vandaele *et al.*, 1998) O_3 at 223, 243 and 293K (Bogumil *et al.*, 2001) O_2-O_2 at 293 K (Thalman and Volkamer, 2013) Ring

305 **Table 2.** Ratio between SCD error and the SCD of O_2-O_2 according to the polynomial
306 order and offset settings used for DOAS fitting.

Polynomial	Offset = none	Offset = 0^{th}
2^{nd} order	6.06 ± 2.07	6.79 ± 2.31
3^{rd} order	6.32 ± 2.20	6.79 ± 2.32
4^{th} order	7.86 ± 2.78	7.34 ± 2.85

307

308 To minimize the noise effect and improve DOAS fitting quality, the optimal settings
309 for fitting were also analyzed. Table 2 shows ratios of O_2-O_2 SCD error to the O_2-O_2
310 SCD for various polynomial and bias orders from observed radiance. The polynomial
311 and offset are basic fitting parameters for the DOAS fitting. Two parameters describe
312 the broadband spectral feature of radiance before identifying the gas absorption
313 structure. The ratio between SCD error and the SCD of O_2-O_2 is important to determine
314 the AEH retrieval quality. When the fitting error increases, the uncertainty of AEH is
315 also enhanced during the retrieval. Smallest AEH fitting errors are obtained by a DOAS
316 fit with a 2^{nd} order of polynomial, and 'none' offset. These settings are used in the
317 GEMS AEH algorithm.
318 In estimating AEH, other aerosol characteristics, including AOD and aerosol optical
319 properties, affect retrieval accuracy. Park et al. (2016) have shown that the largest
320 contributor to the AEH uncertainty is associated with the uncertainty in SSA. In
321 addition, the AEH retrieval uncertainty due to error in the aerosol optical properties (e.g.,
322 AOD and phase function) and surface reflectance has dependence on observation
323 geometries. After the estimation of O_2-O_2 SCD, for this reason, conversion from O_2-O_2

SCD to AEH is an essential process. Table 3 shows dimensions of the LUT for the AEH retrieval algorithm. To calculate the LUT, a linearized pseudo-spherical vector discrete ordinate radiative transfer model (VLIDORT) version 2.6 was used (Spurr, 2013). During the radiative transfer model simulation, reference wavelength for the SSA and AOD is assumed to be 440 nm. The aerosol type is defined by the radiative absorptivity and particle size information. The aerosol type is classified as absorbing, dust, and non-absorbing aerosol. Absorbing and non-absorbing aerosol types are assumed to be the fine-mode dominant particles. For the spectral conversion of AOD, the angstrom exponents of 1.186, 0.222, and 1.179 are used for absorbing, dust, and non-absorbing aerosol, respectively. The SSA is assumed to be spectrally constant within the spectral range for O_2-O_2 estimation. Although the spectral O_2-O_2 absorption band is around 477 nm, the spectral discrepancy between reference wavelength for aerosol optical properties and center wavelength of O_2-O_2 absorption is assumed to be ignored in this study. After calculating spectral radiance with 0.1 nm sampling, the convolution with the GEMS slit response function was applied, and the spectra were sampled on the spectral grid of the GEMS radiance data (Level 1C) prior to the DOAS fitting. Radiative transfer calculations were performed accounting for the temperature dependence of absorption cross section for O_2-O_2 (e.g., Park *et al.*, 2017).

348 **Table 3.** The dimension of the LUT for the GEMS AEH retrieval algorithm used to
349 estimate AEH from O_2-O_2 SCD. (SZA: solar zenith angle, VZA: viewing zenith angle,
350 RAA: relative azimuth angle, SUR: surface reflectance).

Variable [unit]	**No. of entries**	**Entries**	
Spectral range [nm]	-	455-491 nm (0.1 nm interval)	
SZA [º]	7	0.01, 10, 20, 30, 40, 50, 60	
VZA [o]	7	0.01, 10, 20, 30, 40, 50, 60	
RAA [o]	10	0.01,20, 40, 60, 80, 100, 120, 140, 160, 180	
SUR	3	0.0, 0.05, 0.2	
AOD at 440 nm	11	0.04, 0.2, 0.4, 0.7, 1.0, 1.3, 1.6, 2.0, 2.5, 3.0, 5.0	
Refractive Index (Imaginary) at 440 nm	3×3	**Absorbing** (Real: 1.45)	0.000, 0.0074, 0.0314
		Dust (Real: 1.53)	0.0, 0.0030, 0.0080
		Non-Absorbing (Real: 1.41)	0.0, 0.0040, 0.0156
AEH [km]	13	0.0 (Extrapolate), 0.2, 0.5, 1.0, 1.3,1.6, 2.0, 2.3, 2.7, 3.0, 3.5, 5.0, 10.0 (Extrapolate)	
Terrain Height [km]	2	0.0, 2.0	

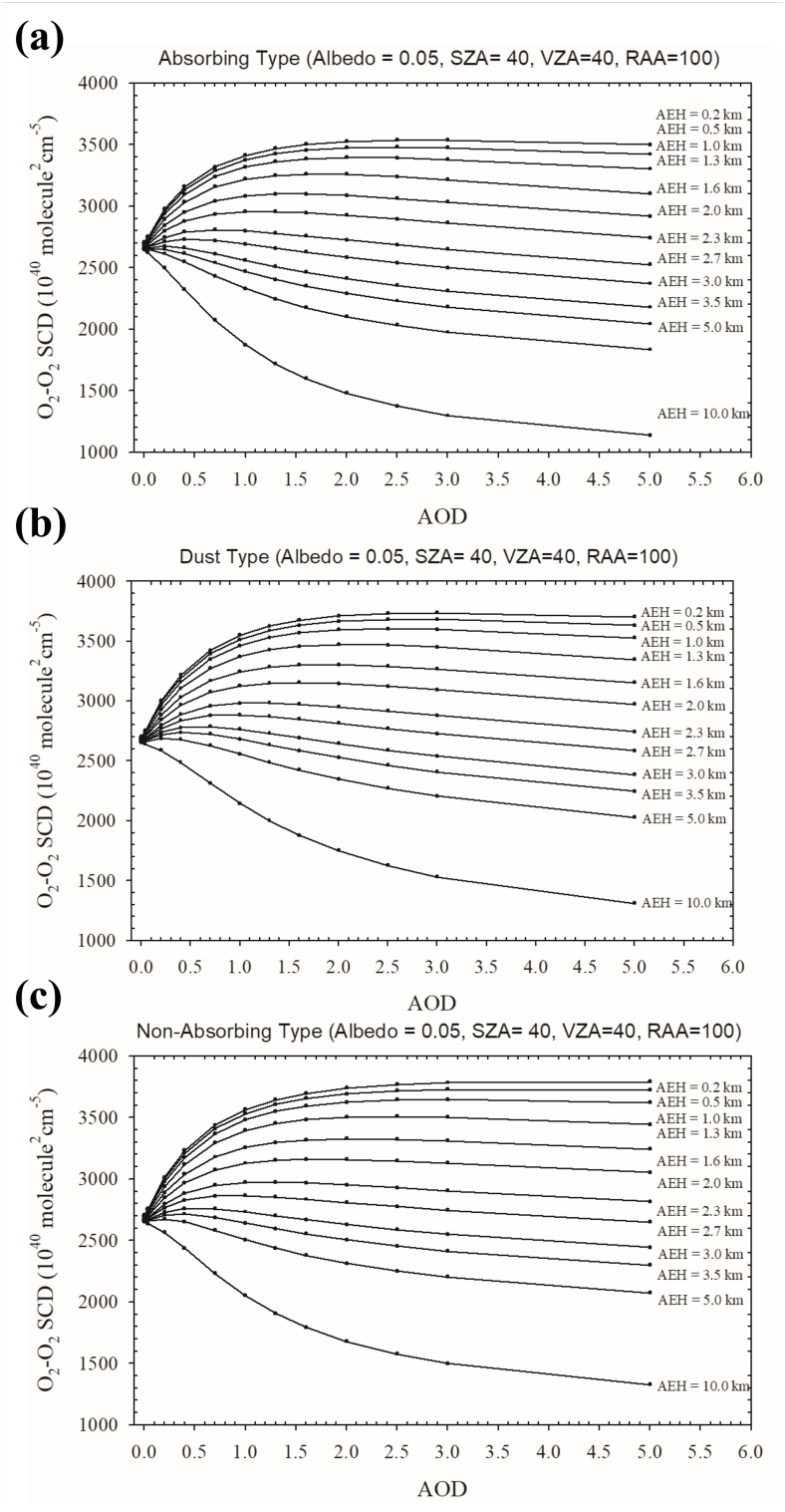


Figure 3. O_2-O_2 SCD dependence as a function of AOD and AEH for (a) Absorbing, (b) Dust, and (c) Non-Absorbing aerosol types.

Figure 3 shows the example of O_2-O_2 SCD dependence as a function of AOD and AEH from the LUT according to the respective aerosol types and AOD. O_2-O_2 SCD decreases with increasing AEH for all aerosol types and AOD (Park *et al.*, 2016). Similar to the previous study, the O_2-O_2 SCD sensitivity is enhanced at high AOD and absorbing aerosol cases from GEMS LUT. In addition, the contrast of O_2-O_2 SCD is greater for absorbing aerosols than non-absorbing aerosols. During the radiance passing through the aerosol layer, the absorbing aerosol is more efficiently absorbed the radiance. For this reason, the effective optical path length is significantly shorter for absorbing aerosols.

The AEH algorithm used the GEMS operational AOD and surface reflectance. However, those retrieval results include the uncertainties. Figure 4 shows the AEH retrieval uncertainty based on the O_2-O_2 SCD LUT with an AOD error of 0.2. The retrieval uncertainty of AEH was evaluated as the relative ratio of SCD changes with respect to input variables. This ratio is defined by the relationship between changes in SCD per unit AEH and changes in SCD due to uncertainties in input variables. The AOD error of 0.2 is twice the target accuracy of the GEMS standard algorithm product. Because the O_2-O_2 SCD change is small in high AOD, the AEH retrieval uncertainty is relatively small in high AOD condition. In addition, the SCD sensitivity in high AEH is weak due to the vertical distribution characteristics of O_2-O_2. Thus, the AEH uncertainty is up to 0.9 km at high AEH case in moderate AOD cases (around 0.5-1.0).

Figure 5 shows the AEH retrieval uncertainty with the surface reflectance error of 0.02. Because surface reflection and aerosol scattering simultaneously affect the increase in optical path length, surface reflectance uncertainty has a significant impact especially to low AOD. The AEH retrieval error due to uncertainty in surface

reflectance is larger than 1 km in cases with AOD < 0.4. In addition, the AEH error by the surface reflectance uncertainty linearly decreases with increasing AOD, indicating relatively small impact with aerosol height change.

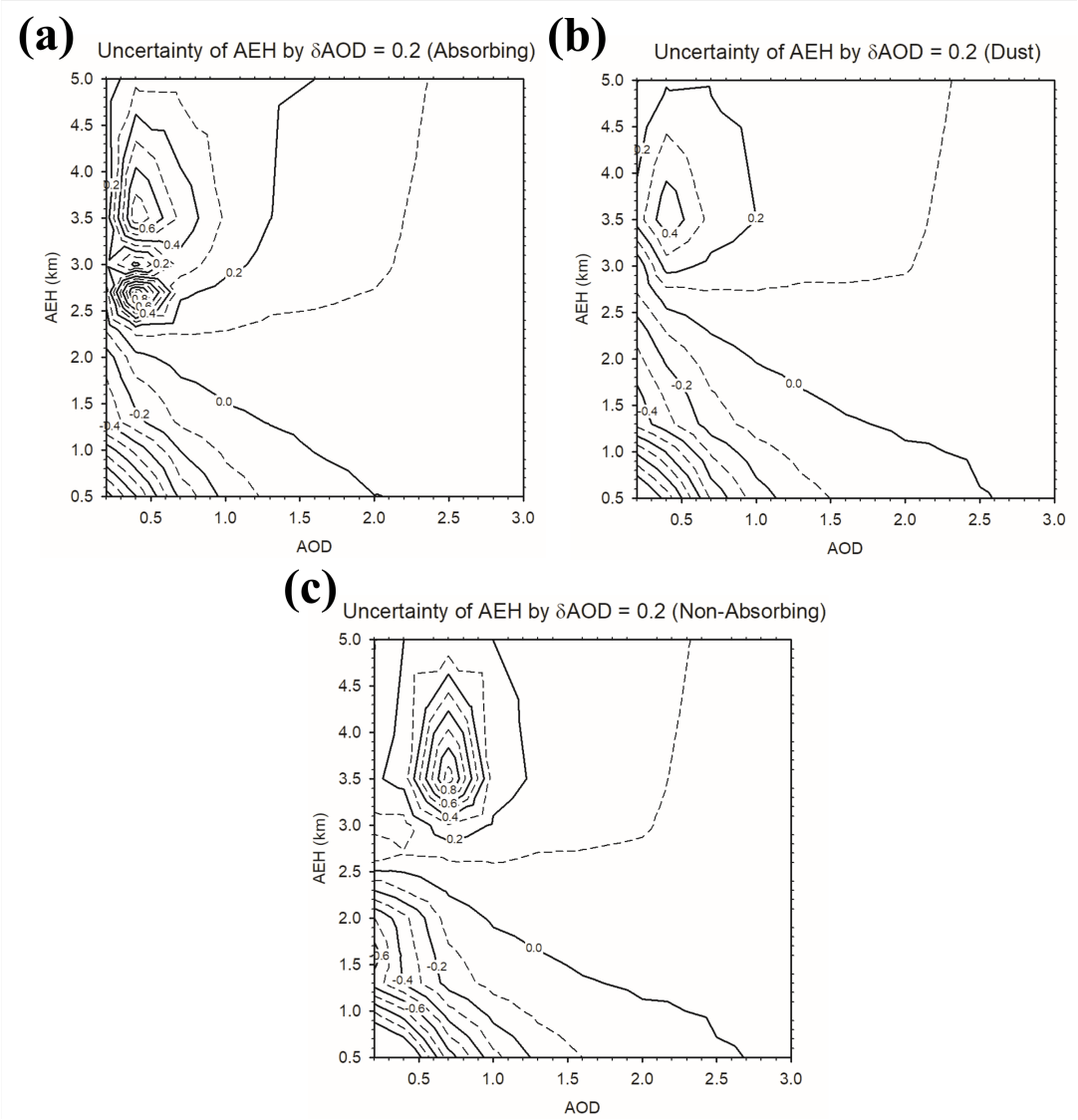
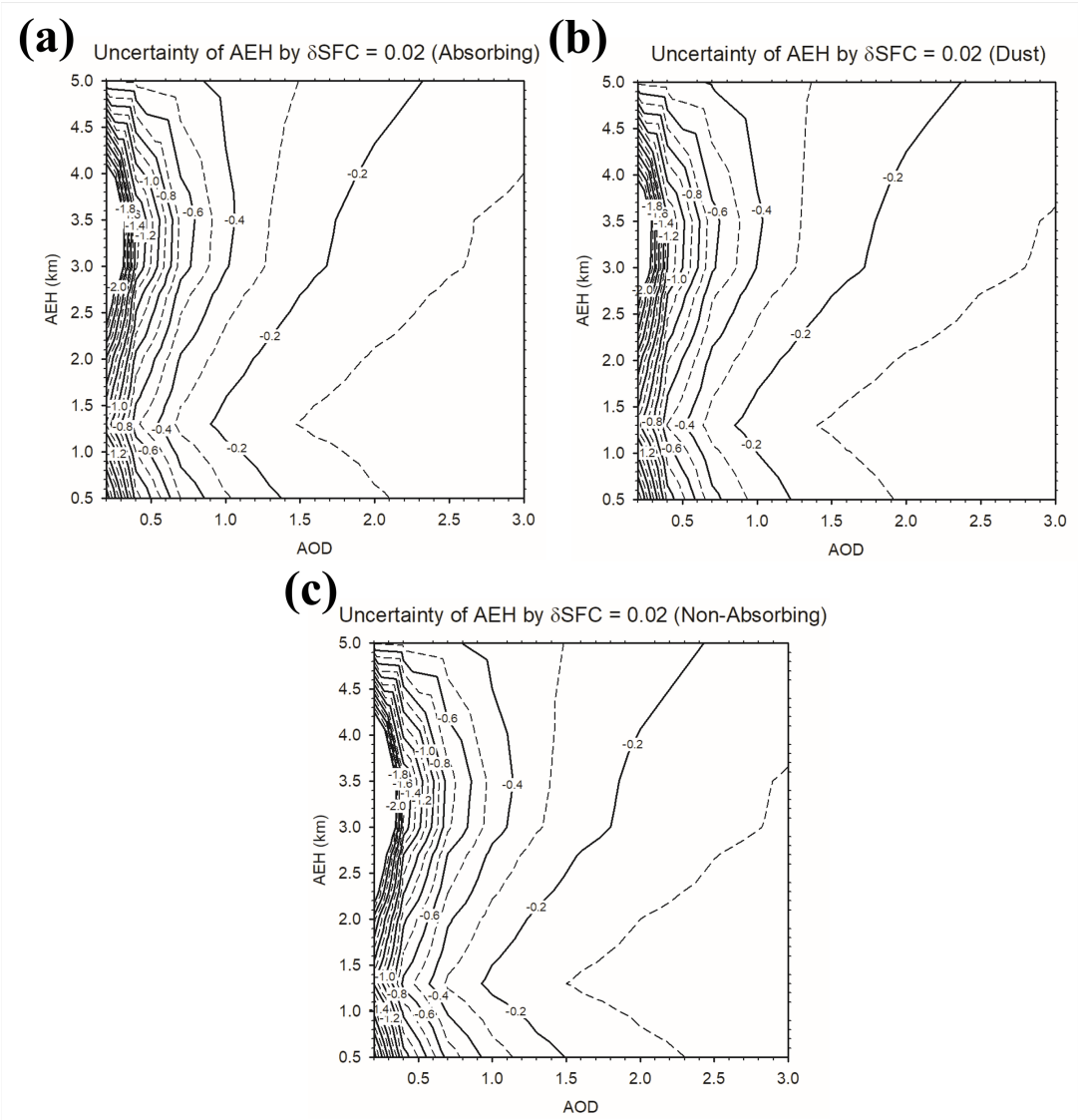


Figure 4. AEH retrieval uncertainty due to the AOD error of 0.2 for cases with (a) Absorbing, (b) Dust, and (c) Non-Absorbing aerosol types.



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386 **Figure 5.** AEH retrieval uncertainty due to the surface reflectance error of 0.02 for

387 cases with (a) Absorbing, (b) Dust, and (c) Non-Absorbing aerosol types.

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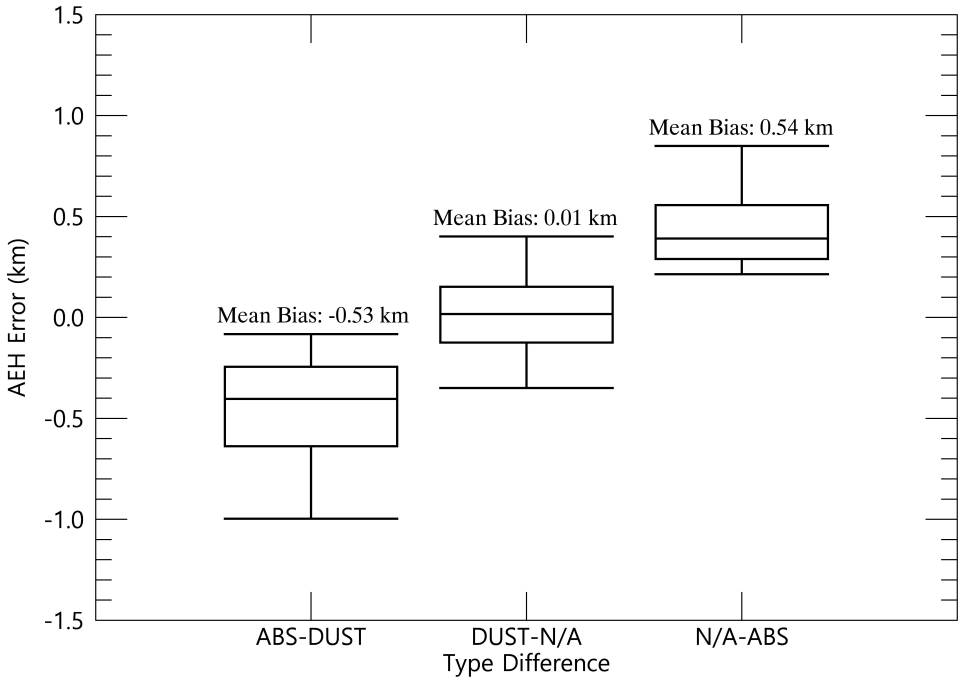


Figure 6. AEH retrieval uncertainty caused by the aerosol type misclassification.

Figure 6 shows the retrieval uncertainty caused by misclassification of the aerosol types. On average, the AEH retrieval uncertainty takes values up to 0.5 km, but this uncertainty shows larger than 2 km under low AOD and short optical path length conditions. From the sensitivity analysis, aerosol type (in terms of SSA) and AOD, and surface reflectance are carefully considered as input parameters for AEH retrieval.

In the AEH retrieval, the AOD, aerosol type, and SSA are obtained from the L2AERAOD, which is standard aerosol product of GEMS. The aerosol vertical distribution is always fixed as GDF function profiles as shown in Spurr and Christi (2014).

4. Case studies

Figure 7 shows retrieval results for AEH from GEMS on March 29 over East Asia. Because the operational schedule is hourly during the daytime, the GEMS retrieval results are shown at 1-hour intervals from 01:00 to 07:00 Universal Time Coordinated (UTC). AOD_{443} and SSA at 443 nm (SSA_{443} hereafter) are also shown in Figures S1 and S2, respectively. Pixels with low AOD_{443} values have large AEH uncertainty due to weak aerosol scattering information (see also Park *et al.*, 2016). For this reason, only AEH retrieval results with AOD greater than 0.3 are shown in this study. In addition, the AEH retrieval results are only shown to the "Reliable" quality flag of L2AERAOD, which is estimated to the aerosol optical properties with significant averaging kernel for optimal estimation in L2AERAOD. A case was analyzed in which a dust plume was located along the coast of China and South Korea with AOD_{443} of 0.8-1.2. Simultaneously, another plume was also present over the northeastern Korean Peninsula with AOD_{443} of 1.0-2.0. SSA_{443} was 0.90-0.93 for the plume over South Korea and 0.87-0.90 for the plume over the northeastern Korean Peninsula. Retrieved AEH results from these different plumes show similar ranges. For both detected plumes, the AEH shows similar patterns and takes values ranging between 1.0 and 2.0 km in this case.

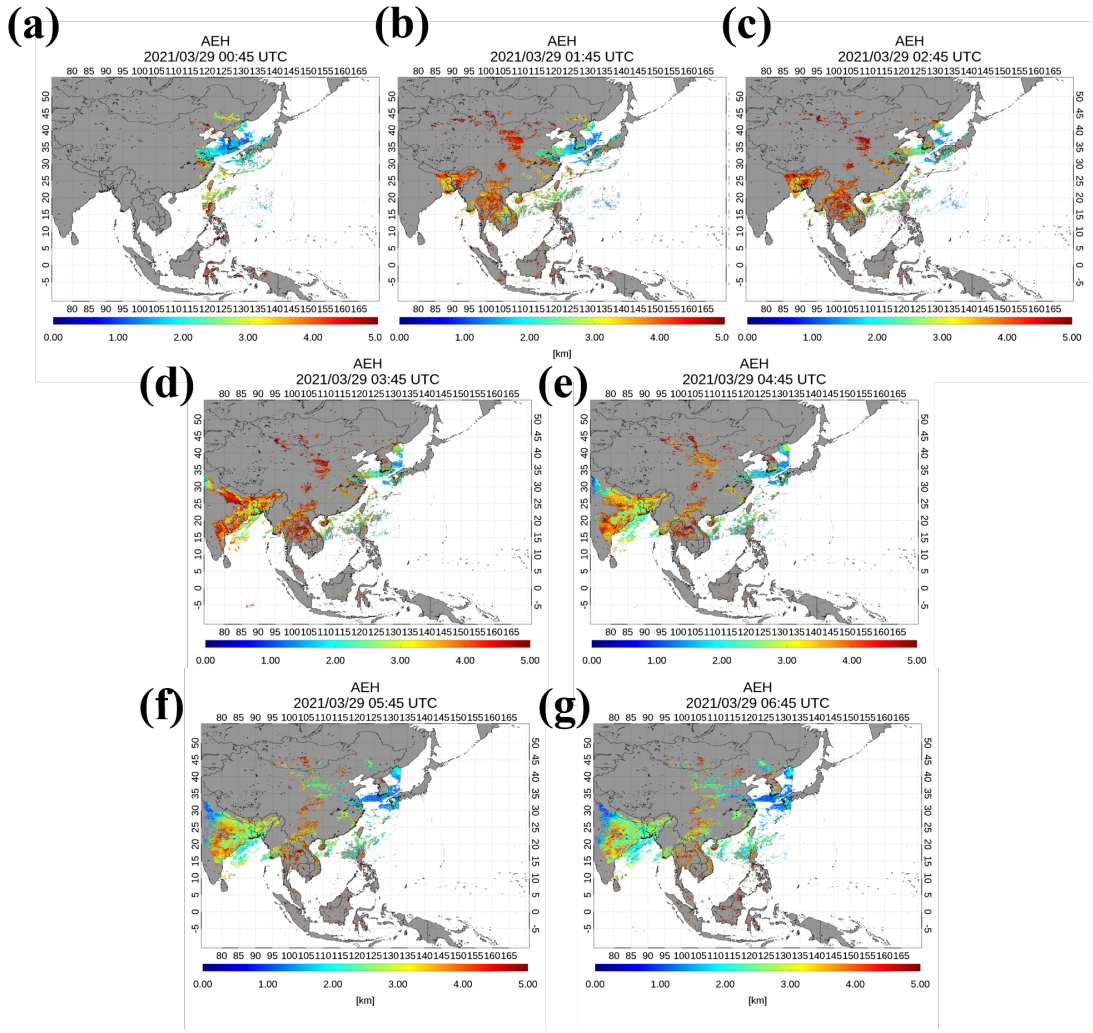


Figure 7. Case study results for AEH based on GEMS observations on March 29, 2021 [(a) 00:45 UTC, (b) 01:45 UTC, (c) 02:45 UTC, (d) 03:45 UTC, (e) 04:45 UTC, (f) 05:45 UTC, and (g) 06:45 UTC].

An additional severe aerosol plume was present over northeastern India, with AOD_{443} of 1.0-2.0 and SSA_{443} of 0.85-0.90. According to Rana *et al.* (2019), metropolitan cities and industrial clusters in India are heavy emitters of black carbon, and high concentrations of black carbon are distributed over the Indo-Gangetic Plain (IGP). Therefore, the aerosol plume with high AOD and low SSA (high absorbing) is

considered a physical rather than an artifact due to edge of GEMS observation field. Except for the inland parts of India, AEH in high AOD pixels ranged from 1.5 to 3.5 km.

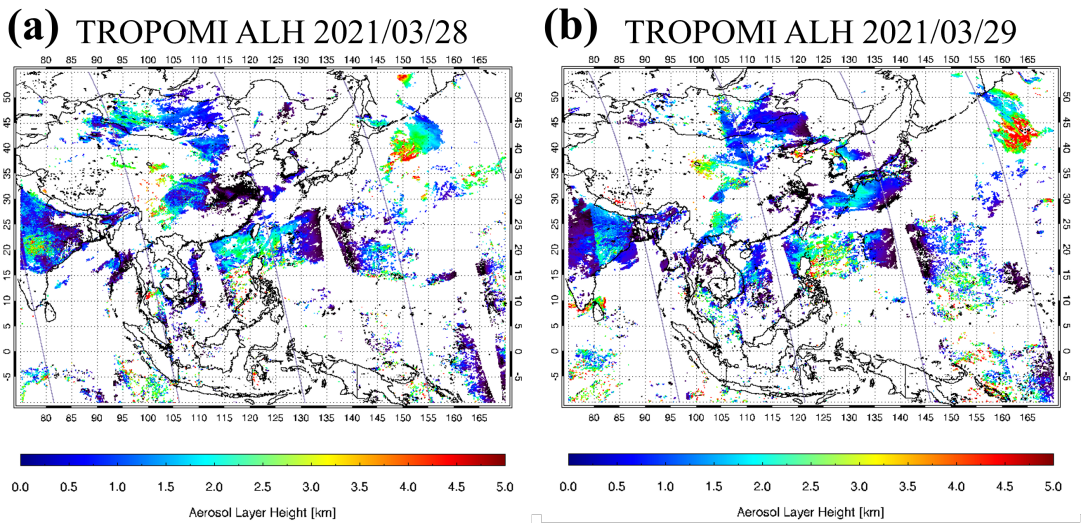


Figure 8. ALH retrieved from TROPOMI and orbit path of CALIOP on (a) March 28 and (b) March 29, 2021 (Unit: km).

For comparison of the retrieval, Figure 8 shows the ALH retrieved from TROPOMI on March 28 and 29, 2021 over East Asia. A dust plume was transported from China to South Korea during this period, then split into two distinct plumes over northeastern China and the coastal area of South Korea. The ALH retrieved from TROPOMI for both plumes range between 0.5 and 1.5 km. Given the difference in definition for the aerosol height parameters between ALH and AEH as shown in Fig. 1, AEH values retrieved from GEMS were higher than the ALH values retrieved from TROPOMI. In an ideal case under symmetric gaussian distribution with a width of 1 km, the AEH from GEMS was around 0.5 km higher than the peak height of aerosol layer. The ALH expresses the center (or peak) height, thus, the AEH from GEMS was overestimated by around 0.5 km relative to the ALH from TROPOMI. Although AEH had higher values than ALH from

TROPOMI, the GEMS AEH retrieval provided meaningful physical results for the dust transport case study.

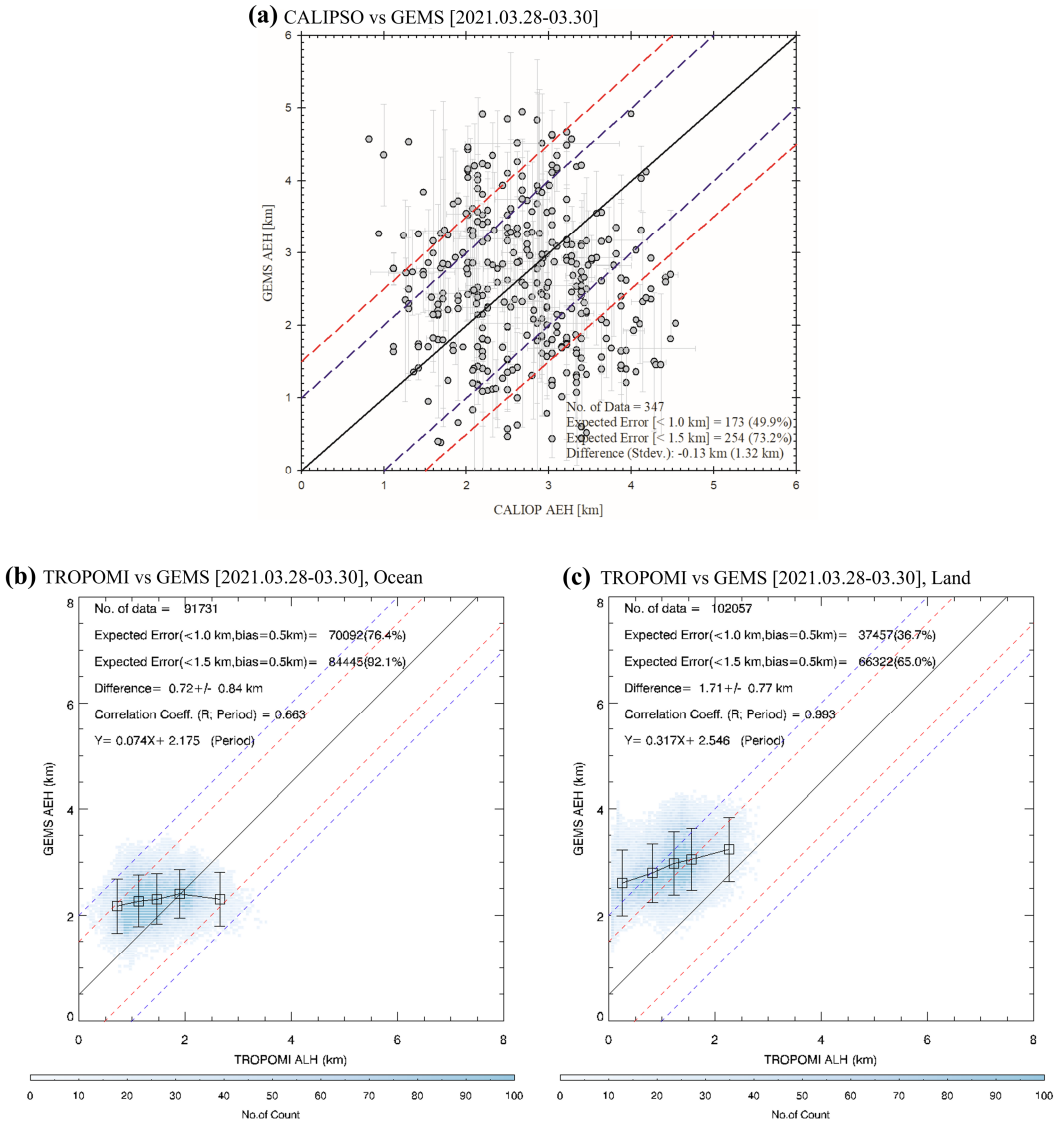


Figure 9. Intercomparison of (a) AEH between CALIOP and GEMS and (b) ALH from TROPOMI and AEH from GEMS over ocean and (c) over land (Black box and error bar is mean and standard deviation in 20% interval of each TROPOMI ALH) over the period from March 28 to 30, 2021.

Figure 9 shows intercomparison results for aerosol plume height among GEMS,

CALIOP, and TROPOMI during the case study of dust transport in East Asia from March 28 to 30, 2021. For the direct comparison shown in Figure 9a, the difference in AEH between GEMS and CALIOP was -0.13±1.32 km. Nanda *et al.* (2020) reported that the difference in ALH between TROPOMI and CALIOP was 0.53 km for 4 cases of thick Saharan dust plumes. Large AEH uncertainty occurred mostly over the inland area of China. Because AEH from GEMS uses only the O_2-O_2 absorption band, the accuracy of AEH is sensitive to uncertainty in surface reflectance and AOD. From Park et al. (2016), total error budget of AEH is 0.74-1.28 km, and the total error budget considered the uncertainty of AOD, SSA, aerosol particle size, and surface reflectance in the aerosol retrieval process. The total error budget amount from the previous study is similar value of standard deviation of AEH difference between GEMS and CALIOP.

Figures 9b and 9c illustrate the comparison results between GEMS AEH and TROPOMI ALH, for the period of March 28-30, 2021, over land and ocean surface, respectively. The difference between GEMS AEH and TROPOMI ALH was 0.72 ± 0.84 km and 1.71 ± 0.77 km over ocean and land in this case, respectively. In addition, 82.4% and 37.3% of all pixels had differences of less than 1.5 km over ocean and land, respectively. However, the ALH from TROPOMI is generally lower than the AEH from GEMS because of the discrepancy in definitions. Based on the assumption of aerosol vertical distribution for AEH retrieval, the difference between AEH and center height of aerosol extinction profile is around 0.5 km. To consider the inconsistency of definition between ALH and AEH, the difference between two retrieval results decreased to 0.5 km bias. After consideration of definition inconsistency, the proportion of pixels within the expected error ranges of 1.5 km are enhanced to 92.1% and 65.0% over ocean and land, respectively.

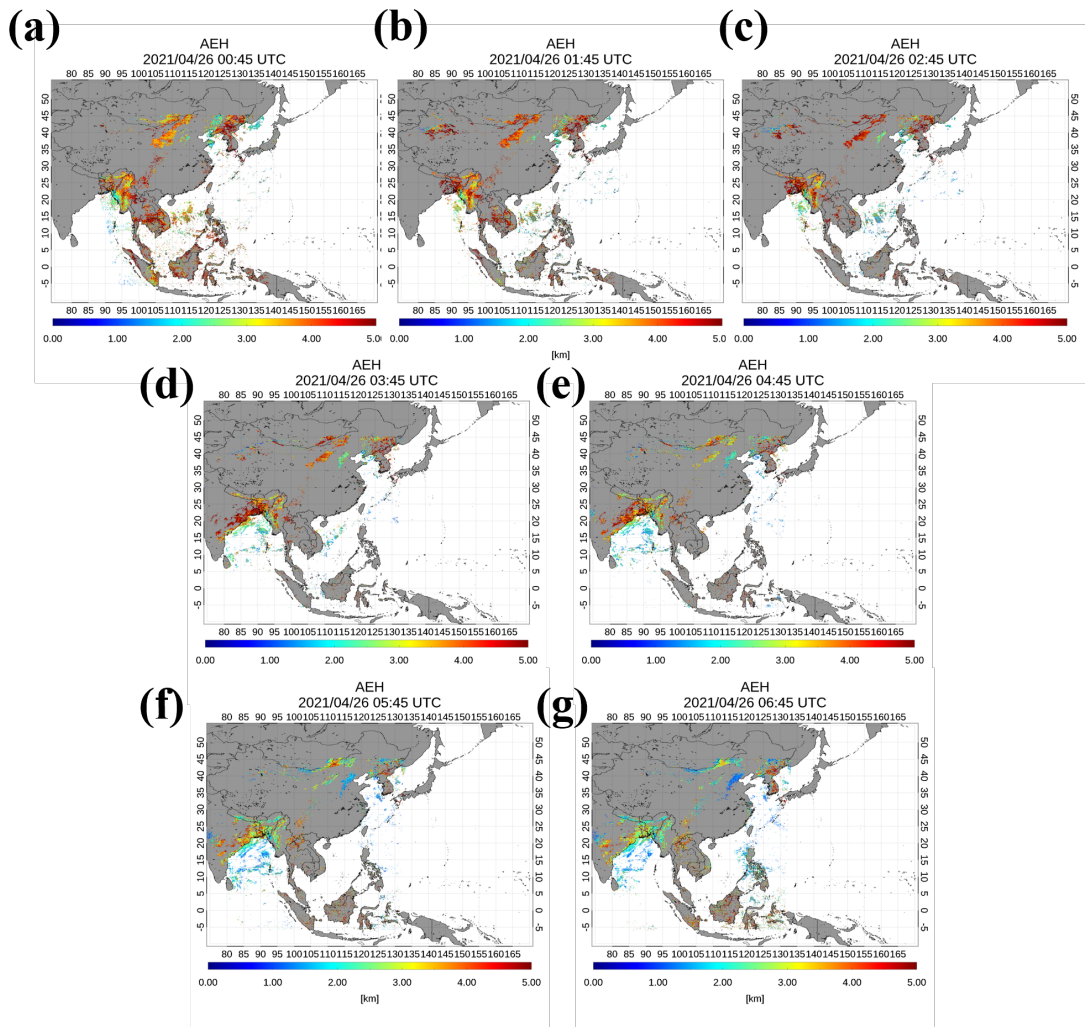


Figure 10. Case study results for AEH based on GEMS observations on April 26, 2021 [(a) 00:45 UTC, (b) 01:45 UTC, (c) 02:45 UTC, (d) 03:45 UTC, (e) 04:45 UTC, (f) 05:45 UTC, and (g) 06:45 UTC].

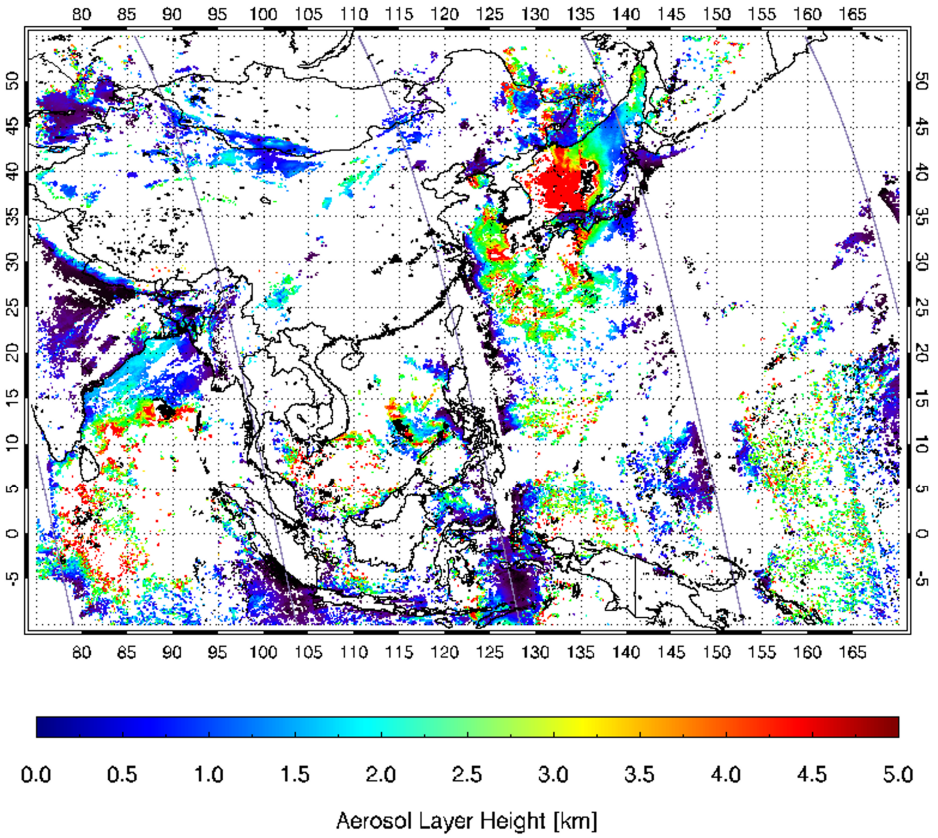
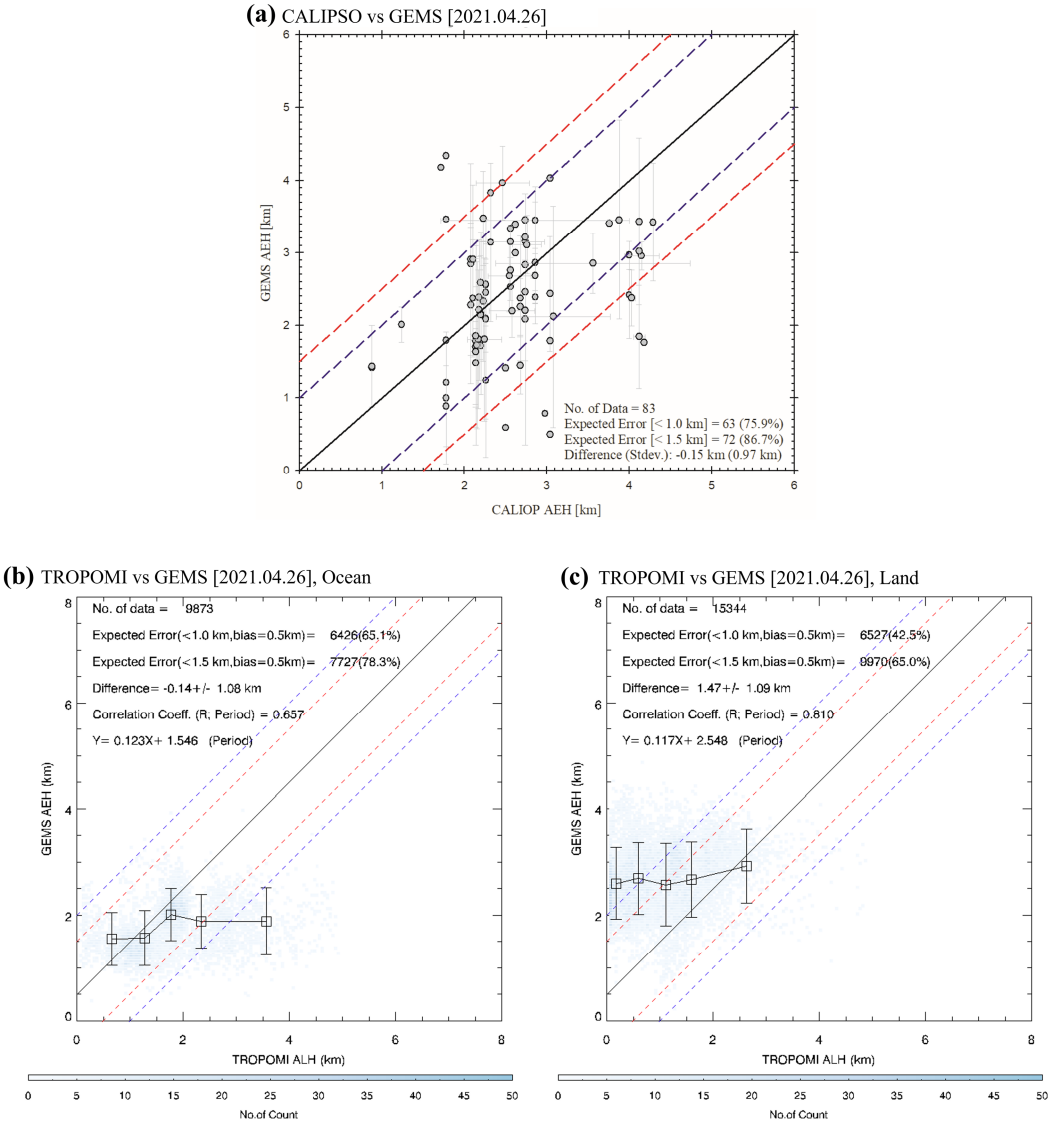


Figure 11. ALH retrieved from TROPOMI and orbit path of CALIOP on April 26, 2021 (Unit: km).



487

488 **Figure 12.** Intercomparison of (a) AEH between CALIOP and GEMS, and (b) ALH
489 from TROPOMI and AEH from GEMS over ocean and (c) over land (black dot and
490 error bar is mean and standard deviation in 20% interval of each TROPOMI ALH) on
491 April 26, 2021.

492

493 An additional intercomparison case of April 26, 2021, is shown in Figures 10
494 (GEMS) and 11 (TROPOMI). During the transport of the dust plume from inland China
495 to the coastal area, AEH changed from 4.0 km at 02:00 UTC to 2.0 km at 06:00 UTC.

By contrast, ALH from TROPOMI only observed the 1.5-2.5 km layer height over East Asia around 04:00 UTC. Although the AEH from GEMS had spatio-temporal uncertainty, this case demonstrates the advantage of AEH retrieval from GEMS for continuous monitoring of changes in plume height during dust transport, in particular. As shown in Figure 12, AEH from GEMS showed differences in height of -0.15 ± 0.97 km (compared to CALIOP). In addition, the differences in height of -0.14 ± 1.06 and 1.47 ± 1.09 km over ocean and land as compared to TROPOMI ALH.

From two different case results, proportion values within 1.0 km (or 1.5 km) height difference between TROPOMI and GEMS have strong dependence of surface types. The proportion over land (over ocean) was lower (higher) than the corresponding result from the comparison of GEMS and CALIOP. The TROPOMI ALH from version 2 exhibits a strong surface type dependence as compared to the ground lidar data (Michailidis et al., 2023). However, the relationship between TROPOMI ALH and GEMS AEH in 20% interval of each TROPOMI ALH have high correlation coefficients. In the case of March 28-30, the correlation coefficients between TROPOMI and GEMS are 0.663 and 0.993 over ocean and land, respectively. In the case of April 26, the correlation coefficients are 0.657 and 0.810 over ocean and land, respectively.

5. Long-term validation

For long-term validation, we used the AEH retrieval results from January to June, 2021. The CALIOP and TROPOMI satellites passed over the study area around 13:30 local time, which is around 04:30 UTC for East Asia and around 06:30 UTC for India. Most temporal colocation pixels aligned with observation times of 04:00-06:00 UTC, respectively. To check the dependence of several retrieval variables, the UVAI, AOD,

SSA, and dominant aerosol type in each pixel (TYPE) were obtained from the L2AERAOD. Although the GEMS algorithm retrieved AEH in the range of 0-10 km, the sensitivity of O_2-O_2 SCD to the optical path length was weak in cases of high AEH because the vertical distribution of O_2-O_2 SCD is related to the square of the air molecule densities. To ensure sufficient quality of retrieved data, therefore, the AEHs from GEMS and CALIOP, and the ALH from TROPOMI were used only in pixels where the AEH from GEMS were lower than 5 km.

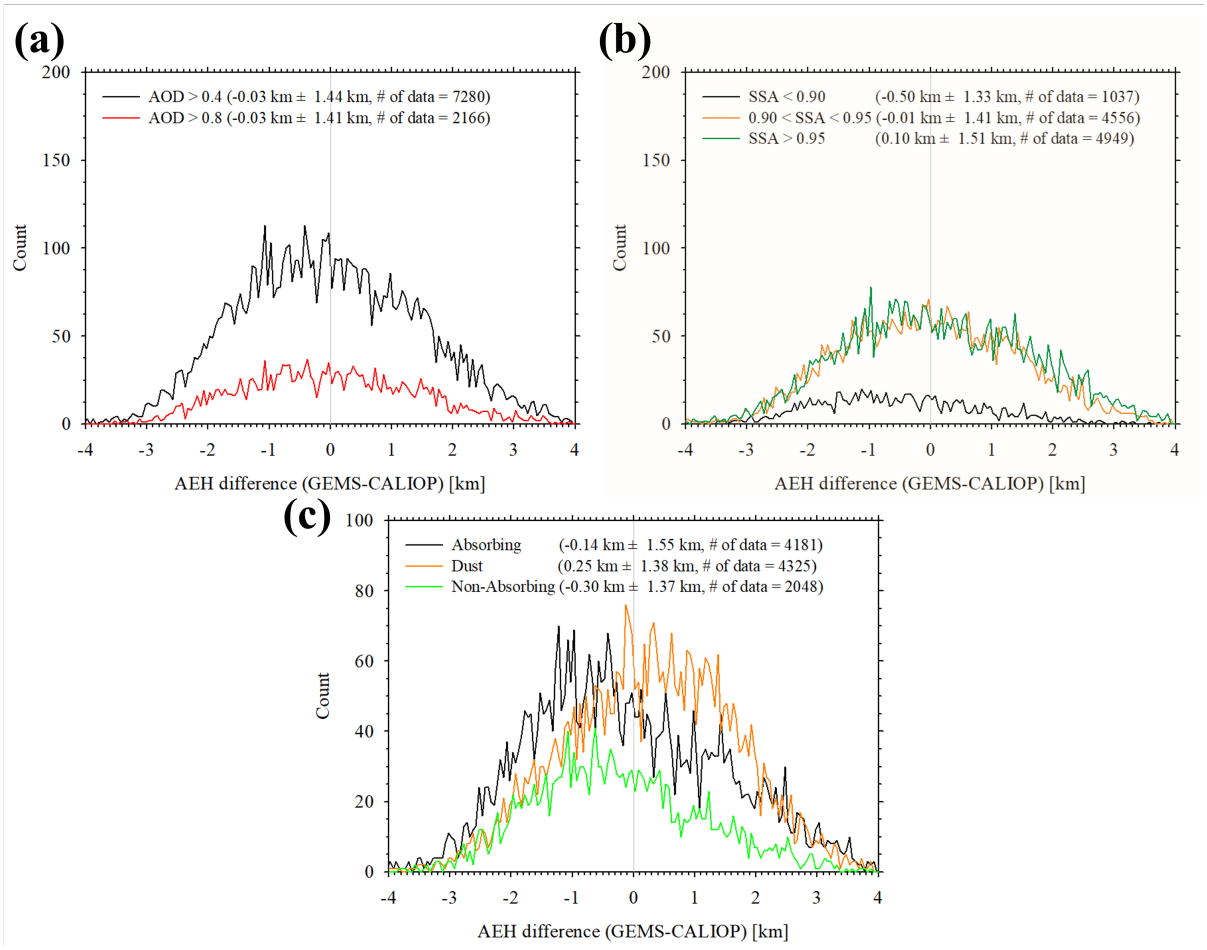


Figure 13. Histogram of AEH difference between CALIOP and GEMS with respect to (a) AOD, (b) SSA, and (c) TYPE from GEMS over the period from January 1 to June 30, 2021.

Figure 13 shows histograms of difference in AEH between GEMS and CALIOP according to AOD_{443}, SSA_{443}, and TYPE from GEMS. From Figure 13a, the dependence on AOD threshold was insignificant; the average estimated AEH difference was -0.03 km, but the variation in AEH difference was around 1.4 km based on the standard deviation for AOD_{443} > 0.4. Because of uncertainty in GEMS aerosol operational products, AEH from GEMS exhibits large variability. Although L2AERAOD from GEMS retrieved the AOD, SSA, and aerosol types, the retrieved results from L2AERAOD include significant uncertainty. Go et al. (2020) reported that the root-mean square error (RMSE) of AOD between MODIS and OMI UV aerosol algorithm is 0.276-0.341.

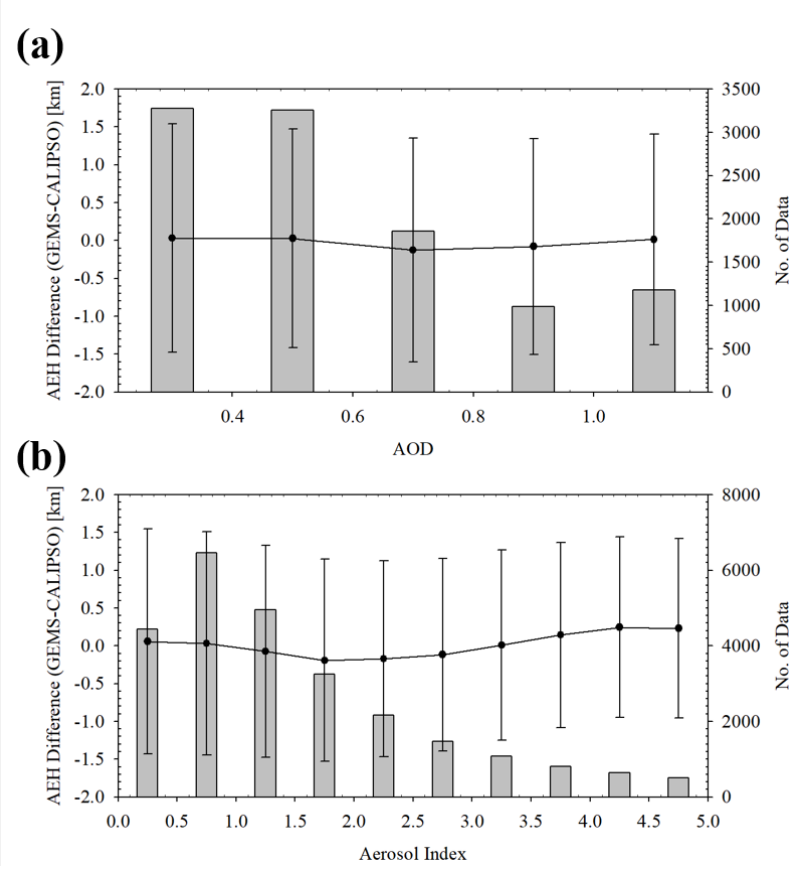
In addition, fitting error perturbs the fitting signals and tends to result in the underestimation of SCD. Although the fitting error of O_2-O_2 SCD from GEMS radiance was minimized, the fitting error has still remained around 6%, as indicated in Table 2. The discrepancy in fitting condition between the simulated and observed radiance biased the SCD estimation, which in turn led to bias and variation in the AEH retrieval. Combined with the high sensitivity of AEH errors to aerosol optical properties, uncertainty arising from L2AERAOD causes AEH variability.

The variation in AEH difference between observation platforms is shown in Figure 13b as a histogram according to SSA threshold. Across the entire SSA threshold range, the standard deviation of the AEH difference was 1.33-1.51 km. In particular, this standard deviation decreased slightly with decreasing SSA. The aerosol height parameter is more sensitive to absorbing-dominant aerosols than scattering-dominant aerosols (e.g., Park *et al.*, 2016; Nanda *et al.*, 2020). For this reason, the variability of AEH is smaller in absorbing-dominant aerosols than scattering-dominant aerosols, if the

555 uncertainty of other aerosol parameters (AOD, SSA, and TYPE) is the same conditions.

556 Figure 13c shows the dependence of AEH difference on TYPE. The TYPE product
557 included dependence on the aerosol size and optical absorptivity. For this reason, the
558 AEH difference graphs for the “Dust” and “Absorbing” types differ, despite both types
559 being absorbing-dominant aerosols. The AEH difference for the “Absorbing” type
560 showed a negative bias with a large standard deviation, whereas a positive bias with a
561 small standard deviation was obtained for the “Dust” type. The AEH difference for the
562 “Non-Absorbing” aerosol type showed the largest negative bias in this comparison.
563 These results suggest that the aerosol size distribution of fine particles affects the
564 negative bias of AEH. Combined with the AEH difference bias illustrated in Figure 8b,
565 these findings indicate that the bias in AEH difference for “Absorbing” aerosols is
566 weakened by their absorbing-dominant property.

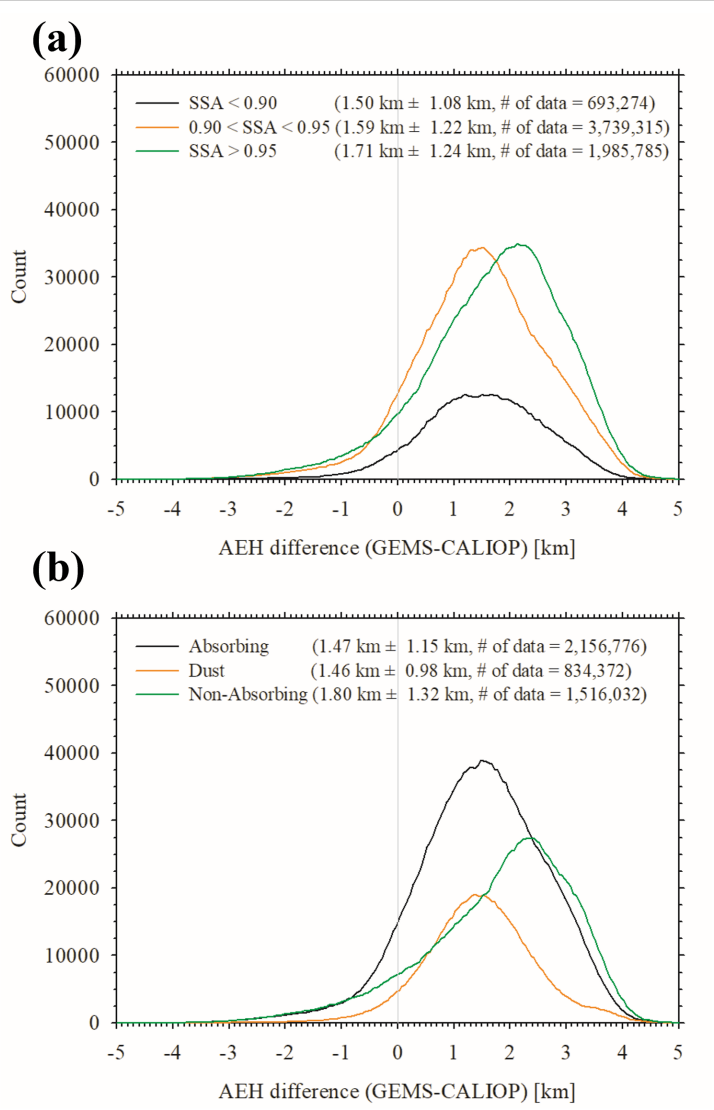
567 Figure 14 shows means and standard deviations for AEH difference between
568 CALIOP and GEMS according to AOD and AI values from GEMS. For AOD, the mean
569 AEH difference ranged from -0.13 to 0.03 km with a standard deviation of
570 approximately 1.45 km. Similar to Figure 13a, the variation in AEH difference with
571 AOD change was insignificant. For the AI, the lowest AEH difference was -0.19 km,
572 obtained for the AI range of 1.5-2.0. The largest AEH difference was 0.24 km for the AI
573 range of 4.0-4.5. Although the AEH difference varied slightly, no consistent tendency in
574 AEH variation with AI was observed. Overall, the standard deviation of AEH difference
575 ranged from 1.49 km ($0.0 < AI < 0.5$) to 1.18 km ($4.5 < AI < 5.0$), and a consistent
576 tendency of decreasing variance in AEH difference was found with increasing AI.



577

578 **Figure 14.** AEH difference between CALIOP and GEMS with respect to ranges of (a)
579 AOD and (b) AI obtained from GEMS from January 1 to June 30, 2021 (Black dots and
580 error bars denote the mean and standard deviation of AEH difference, while the gray-
581 box indicates the number of data).

582



583

584 **Figure 15.** Histograms of differences between TROPOMI ALH and GEMS AEH
585 with respect to (a) SSA, and (b) TYPE from GEMS in the period from January 1 to June
586 30, 2021.

587

588 Figure 15 shows histograms of differences between GEMS AEH and TROPOMI
589 ALH according to the SSA_{443} and TYPE obtained from GEMS. The difference between
590 GEMS AEH and TROPOMI ALH depends on both SSA and TYPE. The mean
591 difference value between GEMS AEH and TROPOMI ALH decreased as the aerosol

592 absorptivity increased. This difference was 1.50 ± 1.08, 1.59 ± 1.22, and 1.71 ± 1.24 km
593 for pixels of $SSA_{443} < 0.90$, $0.90 < SSA_{443} < 0.95$, and $SSA_{443} > 0.95$, respectively.
594 Comparing these results to Figure 13b, we find that the standard deviation of the
595 comparison with TROPOMI was approximately 75% of the corresponding value for
596 CALIOP. It is because both TROPOMI and GEMS are passive sensors that use similar
597 retrieval methods for oxygen absorption bands. Nanda *et al.* (2020) showed that the
598 operational algorithm of TROPOMI operational algorithm can provide ALH pixel
599 retrievals only for scenes dominated by absorbing aerosol particles. In addition, Griffin
600 *et al.* (2020) reported that the pixels with low positive UVAI values (weak absorbing
601 cases) are identified with low QA values ($QA \leq 0.5$) in the offline product of ALH.
602 Although the TROPOMI ALH algorithm updated for the expansion of retrieval range,
603 the contrast of O_2-O_2 SCD to the aerosol layer height change is fundamentally weak
604 sensitivity in scattering dominant aerosols (e.g., Park et al., 2016). For this reason, the
605 bias and standard deviation of height difference between GEMS and ALH is generally
606 larger in high SSA.

607 In addition, the difference between GEMS AEH and TROPOMI ALH depends on
608 TYPE, as shown in Figure 15b. The difference was 1.47 ± 1.15, 1.46 ± 0.98, and 1.80 ±
609 1.32 km for “Absorbing”, “Dust”, and “Non-Absorbing” type aerosols, respectively.
610 Similar to Figure 13c, the TYPE dependence of aerosol height information was
611 influenced by both absorptivity and size information. “Dust” type of aerosol is mainly
612 transported in the free troposphere with gaussian-like vertical distribution, and the
613 associated plume thickness is highly variable. However, “Absorbing” aerosols mainly
614 originate from anthropogenic emissions in East Asia and mostly distributed near the
615 surface with homogeneous concentration (e.g., Gao *et al.*, 2014; Wang *et al.*, 2012;

Peng *et al.*, 2016). Transport patterns and vertical distribution shape depending on aerosol types, can affect the accuracy of aerosol height retrieval results.

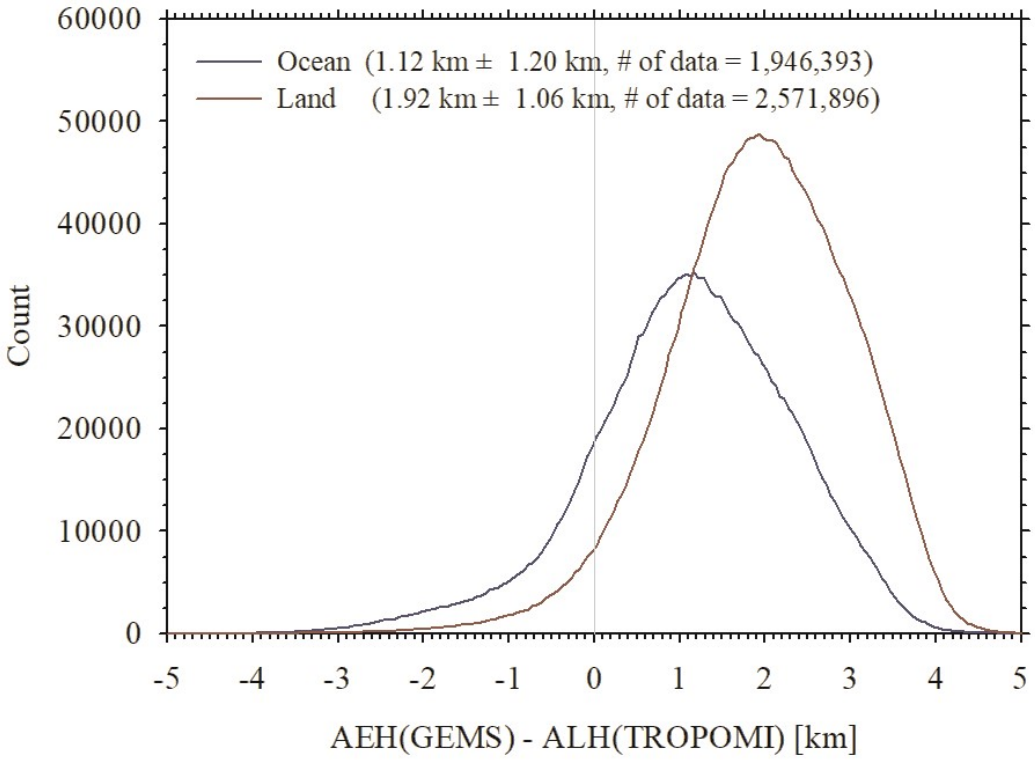


Figure 16. Histogram of the difference between TROPOMI ALH and GEMS AEH over land and ocean pixels, respectively, from January 1 to June 30, 2021.

The non-Lambertian effect on the land surface impacted surface reflectance uncertainty during AEH retrieval, and this effect led to bias and variance in AEH. In this study, the minimum Lambertian equivalent reflectance was used as the reference reflectance value. However, surface reflectivity has geometric dependence due to non-Lambertian effects, which leads to a bias of 0.01-0.02 for surface reflectance over the land surface (e.g., Qin *et al.*, 2019). To identify the sensitivity of surface property, a histogram was constructed of difference between GEMS AEH and TROPOMI ALH

after classification into land and ocean surface types, as shown in Figure 16. From the statistical results, the mean differences were estimated to be 1.12 ± 1.20 and 1.92 ± 1.06 km for ocean and land pixels, respectively. The bias has significant difference between two different surface types. Michailidis et al. (2023) explained that the experimental retrieval range of ALH from TROPOMI is 0.27-6.5 km and 0.06-2.15 km over ocean and land, respectively. Constrained retrieval range over land by the TROPOMI influences the negative bias of aerosol height retrieval and increases the mean difference of aerosol height between GEMS and TROPOMI. In addition, the non-Lambertian effect for surface reflectance is also affecting the increasing discrepancy of aerosol height information.

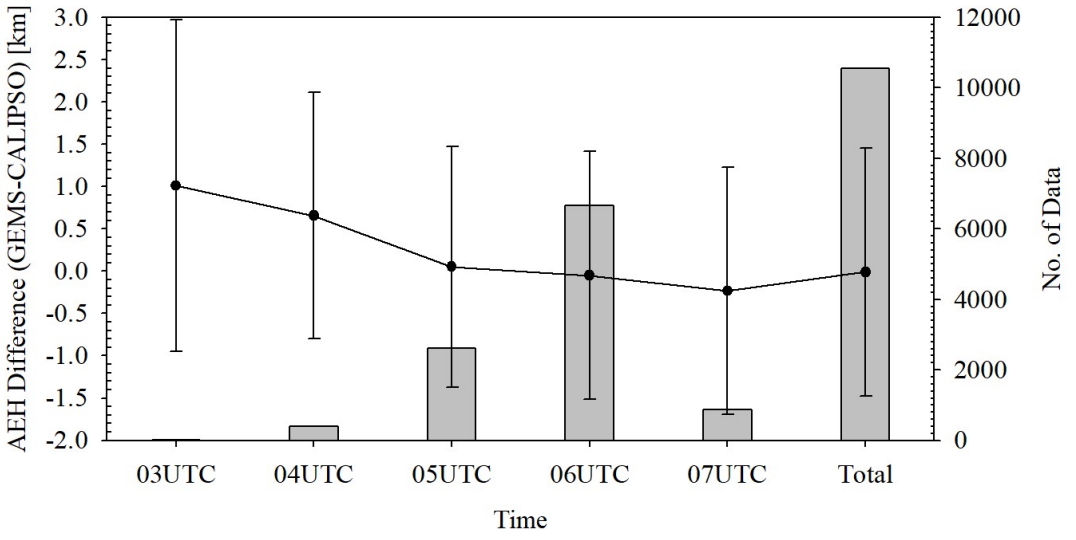


Figure 17. Diurnal dependence of AEH difference between CALIOP and GEMS from January 1 to June 30, 2021 (Black dots and error bars denote the mean and standard deviation of AEH difference, while the gray-box indicates the number of data).

The results of hourly statistical analyses are presented in Figure 17. Because they use

a consistent definition of AEH, we show only a comparison of GEMS and CALIOP. The diurnal variation in AEH difference ranged from -0.23 ± 1.45 km (07:00 UTC, Number of Data = 867) to 1.01 ± 1.96 km (03:00 UTC, Number of Data = 23). However, the number of pixels observed at 03:00 UTC was insufficient for the identification of diurnal variation of retrieval uncertainty. The AEH difference of 0.66 ± 1.45 km was the next highest value obtained at 04:00 UTC (Number of Data = 395). The inhomogeneous number of data is mainly due to the lack of spatial homogeneity among retrieval pixels. Over India, very high AOD values were consistently observed during the comparison period. Otherwise, the AEH was only retrieved under conditions of severe anthropogenic emissions over East Asia. In addition, the diurnal variation in AEH difference was caused by spatial characteristics of AEH difference. From 03:00 to 05:00 UTC, CALIOP mainly passed over East Asia, which has numerous sources of aerosol emissions, including biomass burning, dust, and industrial activity. In addition, GEMS observed only the eastern part of India, which is dominated by anthropogenic aerosols. The spatial distribution of the dominant aerosol types may impact the diurnal variation in AEH difference.

6. Summary & Conclusions

Based on the possibility of retrieving AEH from environmental satellite sensors, an AEH retrieval algorithm for GEMS was developed that solely uses the O_2-O_2 absorption band with considering of aerosol and surface properties. Because the sensitivity of AEH retrieval is strongly affected by optical depth and properties of aerosols, as well as surface reflectivity, the AEH retrieval algorithm for GEMS uses the GEMS operational product, L2AERAOD. With the newly developed retrieval algorithm, GEMS can be

used to monitor aerosol vertical information with high temporal and spatial resolution.

For dust plumes over East Asia, AEH retrieval results from GEMS indicated appropriated aerosol vertical information. After spatial and temporal colocation, the AEH from GEMS aligned well with the AEH information obtained from CALIOP. The differences in AEH between GEMS and CALIOP for dust plume cases were -0.13 ± 1.32 and -0.15 ± 0.97 km, with 49.9-75.9% and 73.2-86.7% of all pixels showing differences less than 1.0 and 1.5 km, respectively. Large AEH uncertainty was found mostly over inland China due to uncertainty in surface reflectance and AOD over the land surface. In addition, AEH from GEMS was overestimated compared to the TROPOMI ALH results. The overestimation is partially caused by different definitions of ALH from TROPOMI and AEH from GEMS.

In long-term intercomparison with CALIOP, the average AEH difference was estimated to be -0.03 km, with a standard deviation of 1.4 km under the scenario of AOD > 0.4. The large variation in AEH difference between GEMS and CALIOP was caused by uncertainty in the input parameters estimated from L2AERAOD. In the long-term intercomparison against TROPOMI, this difference was dependent on both SSA and TYPE. The difference was 1.50 ± 1.08 km, 1.59 ± 1.22 km, and 1.71 ± 1.24 km for pixels with SSA < 0.90, 0.90 < SSA < 0.95, and SSA > 0.95, respectively. In addition, differences of 1.47 ± 1.15 km, 1.46 ± 0.98 km, and 1.80 ± 1.32 km were obtained for the “Absorbing”, “Dust”, and the “Non-Absorbing” types of aerosols, respectively. The AEH difference also has diurnal dependence, which ranged from -0.23 ± 1.45 km to 1.01 ± 1.96 km, due to the spatial characteristics of dominant aerosol types.

The case studies and results of the long-term validation show that AEH retrieved from GEMS can provide information on aerosol vertical distribution, with applications

693 in diverse research fields. The AEH results with long-term statistical accuracy make it
694 possible to use the application study for AMF calculation of GEMS trace gas retrieval.
695 In addition, AEH considerably affects the surface particulate matter (PM) concentration
696 obtained from satellite-based AOD because PM estimation is significantly affected by
697 the mixing layer height of aerosols. For this reason, the AEH can provide effective
698 mixing layer height of aerosols for anthropogenic aerosols and also provide the vertical
699 patterns for long-range transport of aerosols.

700 Although several fields of study may apply the AEH retrieval results, retrieval
701 uncertainty in AEH remains due to the uncertainty of retrieved AOD and SSA. In
702 addition, the uncertainty in surface reflectance and the discrepancy in O_2-O_2 SCD
703 values between the simulation results and observations can be affected to the potential
704 error sources of AEH from GEMS. To minimize the AEH retrieval uncertainty, further
705 analysis related to the optimized input parameters of AOD, SSA, and aerosol type
706 information is essential. For this reason, the quantitative analysis of AEH uncertainty
707 due to aerosol and surface property is important for the improvement of AEH retrieval
708 algorithm. In addition, aerosol optical property retrieval by the visible channel will be
709 needed for further study to improve the aerosol type determination. Although the
710 aerosol indices of UV and visible provide the aerosol type information, developing the
711 aerosol type classification algorithm is necessary to make synergy with AEH retrieval.
712 AEH provides representative layer height information as only one variable because of
713 its sole reliance on O_2-O_2 SCD for direct estimation of aerosol height information. This
714 method is limited to the consideration of aerosol vertical structures (i.e., Gaussian or
715 exponential vertical distribution structures). To increase the information contents, it
716 would be valuable to combine other oxygen absorption bands from other satellite

717 instruments together with extinction information of aerosols.

718

719 **Data Availability**

720 The TROPOMI ALH product is available from http://doi.org/10.5270/S5P-7g4iapn,
721 and the CALIOP aerosol extinction profile product is available from
722 https://doi.org/10.5067/CALIOP/CALIPSO/CAL_LID_L2_05kmAPro-Prov-V3-41.
723 The GEMS AEH and AERAOD products are available from the Environmental Satellite
724 Center in National Institute of Environmental Research (NIER) of the Republic of
725 Korea.

726

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730

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