NOTES AND CORRESPONDENCE

Ground-Based Mie-Scattering Lidar Measurements of Aerosol Extinction Profiles during ABC-EAREX 2005: Comparisons of Instruments and Inversion Algorithms

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Abstract

An intercomparison study of ground-based Mie-scattering lidar systems was held at Gosan, Korea during ABC-EAREX 2005 in order to ensure the correctness and accuracy of the lidar retrieval algorithms as well as the aerosol extinction profiles. We compared the vertical profiles of the range-corrected raw lidar signals as well as the aerosol extinction coefficients determined from different types of Mie-scattering lidar systems. Three different aerosol loading cases were selected; in these cases, the mean deviations of the range-corrected raw lidar signals were estimated to be 4.5%, 8.0%, and 7.3%. An intercomparison of the instruments by an identical data-handling procedure (Fernald approach) demonstrated that the aerosol extinction profiles for the three selected cases were in agreement within a bias difference of 0.0051 km^{-1} . The mean deviation of the signals for the aerosol layer between 0.6 and 3.0 km was 3.0%. The systems were intercompared for two lidar inversion algorithms by using simultaneous lidar measurement data sets as input; these input data sets showed agreement with their aerosol extinction profiles within a bias difference of 0.0086 km^{-1} and a mean deviation of 11.6%.

1. Introduction

Tropospheric aerosols are crucial atmospheric constituents that significantly contribute toward

the global climate through a variety of pathways such as direct effects on scattering and absorption of solar radiation, indirect effects on cloud microphysics, and semi-direct effects (Ramanathan et al. 2001; Schwartz and Andrea 1996; Yoon et al. 2005). However, the lack of detailed knowledge about their physio-chemical and optical properties is one of the major sources of uncertainty when assessing the factors that cause climate forcing (Charlson

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et al. 1992; IPCC 2007). In order to reduce the uncertainties in the current estimates of aerosol climate forcing, more integrated studies on aerosols such as ACE-Asia (Huebert et al. 2003), INDOEX (Ramanathan et al. 2001) and TARFOX (Russell et al. 1999) were recently performed, and ground-based aerosol monitoring networks such as AERONET (Holben et al. 1998), MPL-NET (Welton et al. 2000), AD-NET (Murayama et al. 2001), and EARLINET (Matthais et al. 2004) were developed.

Extensive ground-based measurements of the vertical profile of tropospheric aerosol extinction are very important for monitoring the evolution of atmospheric aerosols on a local/regional scale and for understanding their impacts on local/regional climate, i.e., with regard to the radiation budget and atmospheric radiative heating/cooling (Carlson and Benjamin 1979; Quijano et al. 2000; Kim et al. 2004; Won et al. 2004; Schmid et al. 2006; Ramanathan et al. 2007); moreover, they are important for monitoring the regional-scale horizontal transport of wind-blown mineral dust as well as pollution aerosols (Murayama et al. 2001; Böckmann et al. 2004; Chazette 2003; Kim et al. 2005a; Yoon et al. 2006). With regard to the measurement of the vertical distribution of aerosols, a ground-based lidar technique is apparently one of the appropriate methods to measure the vertical profile of ambient aerosol extinction. In the past decades, several lidar systems dedicated to the observation of the vertical profiles of aerosols have been successfully operated (Welton et al. 2000; Murayama et al. 2001; Ansmann et al. 2003; Campbell et al. 2003; Kim et al. 2004; Matthais et al. 2004) and have been used for comparing airborne *in situ* measurements (Murayama et al. 2003; Schmid et al. 2006). Numerous inversion methods have also been proposed for the determination of aerosol extinction (Fernald et al. 1974; Klett 1981; Fernald 1984; Welton et al. 2000; Campbell et al. 2002; Sicard et al. 2002) because for the evaluation of the aerosol extinction from the lidar return signal, researchers must be able to solve the ambiguity between light scattering and absorption (or extinction) of the laser beam by atmospheric aerosols. Within the framework of the European Aerosol Research Lidar Network (EARLINET), which was established to study aerosol climatology, Böckmann et al. (2004) and Matthais et al. (2004) compared 19 independently operated aerosol lidar systems distributed over 11 European countries, but not at similar locations. More recently, Schmid

et al. (2006) concluded that the typical systematic error associated with measuring the tropospheric vertical profile of aerosol extinction with current state-of-the-art instrumentations (e.g., airborne nephelometer/absorption photometer, airborne Sun photometer, ground-based elastic and Raman lidars) is 15–20% at visible wavelengths and potentially larger in the UV and near-infrared regions. However, despite all the previous measurement and intercomparison studies, it is still necessary to intercompare the vertical profiles of ambient aerosols, particularly for ground-based lidar measurements, in order to ensure the correctness of the lidar retrieval algorithm and to verify the uncertainty in the lidar-derived aerosol extinction profile for its application to climate considerations.

Within the framework of the Atmospheric Brown Cloud-East Asian Regional Experiment 2005 (ABC-EAREX 2005; <http://abc-gosan.snu.ac.kr>; Nakajima and Yoon 2005), intercomparison studies of the measurements performed by ground-based Mie-scattering aerosol lidars were conducted at Gosan, South Korea, from March to June 2005 in order to study the performance and reliability of the individual lidar systems.

This study is dedicated to the intercomparison of the lidar-derived vertical aerosol extinction profiles and the quantitative estimation of the uncertainties with regard to two aspects: the inherent discrepancy due to different types of instrumentations and the uncertainty that occurs due to lidar inversion algorithms, which are used for the retrieval of the vertical profiles of aerosol extinction. For this purpose, we used simultaneous measurement data sets from two lidar systems situated at the same field container laboratory during ABC-EAREX 2005. Section 2 provides brief descriptions of the lidar systems and the retrieval algorithms used in this study. In Section 3, we explain the various cases considered for the comparisons. The results of the intercomparison of the aerosol vertical profiles are presented in Sections 4 and 5. We also discuss the source of the discrepancies and suggest the factors that might contribute toward the reduction of these discrepancies.

2. Measurements and Intercomparison Approach

2.1 Two Lidar Systems

The ABC-EAREX 2005 field study at Gosan (33.29°N, 126.16°E), Korea, 2005, yielded the most suitable ground-based lidar measurement data sets

Table 1. Specifications of the two lidars used in this study.

Parameter	CML	MPL ¹⁾
Wavelength	532 and 1064 nm	523.5 nm
Laser Power	30 mJ (532 nm), 20 mJ (1064 nm)	6 μ J per pulse, 15 mW
Repetition Rate	10 Hz	2500 Hz
Diameter of Telescope	20 cm	20 cm
Direction of Measurement	Vertical (Fixed)	Vertical
Measurement Range	0~24 km	0~60 km
Range Resolution	6 m	75 m
Temporal Resolution	10 minutes ₂₎	1 min
Measurement Parameters	Backscattering Intensity (532 nm, 1064 nm), Depolarization Ratio (532 nm)	Backscattering Intensity (523.5 nm)
Field Of View (full)	1 mrad	100 μ rad
Laser Beam Divergence	1 mrad	50 μ rad
Detector	Pm Tubes (532 nm) Avalanche Photodiode (1064 nm)	EG&G SPCM-PQ GAPD
Acquisition System	Analog (8 bits, 20-MHz band width)	Photon counting (max. counting rate: 100 MHz)

¹⁾ All the MPL measurements (e.g., maximum altitude and its vertical resolution, temporal average) are performed in accordance with the observational guidelines of the MPL-NET.

²⁾ The CML produced a single aerosol profile for 5 min. This is because the measurement sequence of the CML is that it runs for 5 minutes and then stops working during the next 5 min.

required to assess our ability to measure the aerosol extinction profile. One of the main objectives of the ABC-EAREX 2005 study was to establish the traceability of the instrumentation and analytical methods used in other stations distributed over the East-Asian region and for stable and accurate long-term measurements of natural as well as anthropogenic aerosols in Asia.

A summary of the two lidar systems used in this study, the Seoul National University micro-pulse lidar (MPL) and the Japanese National Institute for Environmental Studies compact Mie-scattering lidar (CML), is provided in Table 1. During the past decade, both of these lidar systems have been widely used to monitor the vertical distribution of aerosols and their regional-scale horizontal transport and evolution (e.g., dust aerosols in Asia) in the East-Asian region. The MPL is a single-channel (523.5 nm) lidar and is permanently deployed at the ABC Gosan site as part of the NASA micro-pulse lidar network (MPL-NET; <http://mplnet.gsfc.nasa.gov>). The CML is a two-wavelength (532 and 1064 nm) Mie-scattering lidar with the depolarization ratio measurement channel at 532 nm; it is operated as part of the Asian dust network (AD-NET) as well as the NIES lidar network (<http://www.lidar.nies.go.jp>). In this study, an intercomparison study is performed for the visible wavelengths

(523.5 and 532 nm), and errors due to slight differences in the wavelength of each lidar system are not considered. The MPL utilizes a high-repetition micro-pulse Nd:YLF laser and a photon counting receiver system. In contrast to the MPL, the CML employs a giant pulse Nd:YAG laser and an analog detection system. Other distinguishing features between the two lidar systems are that the pulse repetition rate of MPL is higher than that of CML, whereas the laser power of MPL is considerably smaller than that of CML. Contrary to the MPL, the CML receives signals and separates them into two polarization components. The sensitivity calibration of the two polarization channels was performed on March 15, 2005. Let us assume that photo multiplier tube (PMT)1 and PMT2 represent p-polarization and s-polarization dedicated PMT signal intensities, respectively. And after the 90-degree rotation of detector system, the respective signals can be defined as PMT1' and PMT2'. Then the following formula can be drawn if adjacent measurements give almost same value of the depolarization ratio:

$$\frac{PMT2 \cdot f}{PMT1} = \frac{PMT1'}{PMT2' \cdot f}$$

Then we can finally obtain the calibration constant f as below:

$$f = \sqrt{\frac{PMT2 \cdot PMT2'}{PMT1 \cdot PMT1'}}$$

We assumed that the depolarization ratio in the dust layer at altitudes of approximately 2–3 km did not change during 08 h 00 m–08 h 20 m on March 15, 2005; then, we finally obtained the calibration constant $f = 0.5$.

2.2 Lidar Retrieval Algorithms

The lidar equation is the fundamental equation in the field of laser remote sensing, which relates the received photon counts (or light power) with other parameters such as the transmitted laser photon counts (or laser power), physical interaction between the laser beam and aerosols, light propagation in the background tropospheric atmosphere, and efficiency and geometry of the lidar systems. According to the studies of Fernald et al. (1974), Klett (1981), Fernald (1984), and Welton et al. (2000), the expected photon counts detected at wavelength λ and distance z , $N_s(\lambda, z)$, is given as follows:

$$N_s(\lambda, z) = \underbrace{\left[\frac{P_L(\lambda) \Delta t}{hc/\lambda} \right]}_{\textcircled{1}} \times \underbrace{[\beta_{mol}(\lambda, z) + \beta_{aer}(\lambda, z)] \times \Delta z}_{\textcircled{2}} \times \underbrace{\left(\frac{A}{z^2} \right)}_{\textcircled{3}} \times \underbrace{\exp \left[-2 \int_0^z [\alpha_{mol}(\lambda, z') + \alpha_{aer}(\lambda, z')] dz' \right]}_{\textcircled{4}} \times \underbrace{[\eta(\lambda) G(\lambda)]}_{\textcircled{7}} + \underbrace{N_B}_{\textcircled{6}} \quad (1)$$

where,

- 1st term: Transmitted laser photon number within the bin time = (Laser Power $\times$ Bin Time) / (Planck's Constant $\times$ Laser Frequency)
- 2nd term: Probability that a transmitted photon is backscattered by aerosols and air molecules into a unit solid angle (β : 180°-backscatter coefficient, subscript *mol*: air molecules, subscript *aer*: aerosols)
- 3rd term: Solid angle that a scattered photon is collected by the receiving telescope (range dependence)
- 4th term: Light transmission during light propagation from the laser source to distance z and from distance z to the receiver (α : extinction coefficient) = $T^2(\lambda, z)$
- 5th term: $\eta(\lambda)$ denotes the optical efficiency of the lidar hardware (e.g., detectors, interference fil-

ter, mirrors), and $G(z)$ denotes the geometrical form factor, which is mainly concerned with the area of laser irradiation that overlaps with the field of view of the receiver optics

6th term: Background noise (e.g., solar background radiation)

Figure 1 shows the flow of the lidar signal retrieval process and the intercomparison approach adopted in this study. The data intercomparison procedure comprises three main steps: (1) data preprocessing of two lidar systems, (2) calculations of the aerosol extinction profile by the Fernald approach (Fernald 1984), and (3) intercomparison of the vertical profiles of aerosol extinction as well as aerosol back-scattered intensity by combining each result. In this study, a total of four extinction profiles derived from two lidars as well as two retrieval algorithms of SNU and NIES are carefully intercompared. As well depicted in Fig. 1, the background noise (6th term) and the range dependence (3rd term) of the overlap-corrected lidar signals are removed as an initial step in the retrieval of the lidar signal. The background noise in both the MPL and CML measurements was estimated by averaging the uppermost 100 data points for each single-shot measurement. The molecular parts (in the 2nd and 4th terms) of Eq. (1) are calculated from the standard atmospheric profiles; however, when a single profile is obtained, two parameters, aerosol extinction coefficient [AEC; $\alpha_{aer}(\lambda, z)$] and 180°-backscattered intensity [$\beta_{aer}(\lambda, z)$], continue to remain unknown as well as dependent on the altitude. The air-molecular density in both the algorithms was determined in the same manner by using the U.S. standard atmosphere 1976. Here, it should be noted that the discrepancy of air-molecular density between the U.S. standard atmosphere 1976 and radiosonde data (every 12 hours; 00 and 12 UTC) for the comparison periods of this study was about 2–3%. This discrepancy caused about 3% difference in aerosol extinction coefficient, especially for the boundary layer aerosols. However, this discrepancy does not alter the principle discussions in this paper, because same tendency are apparent on both MPL and CML.

In this study, we need to determine an altitude-independent extinction-to-backscatter ratio (S_1) through an aerosol layer in order to solve the ill-posed problem of the lidar equation and extract the two unknown parameters. However, the parameter S_1 varies with height and location, and the selection of S_1 widely controls the absolute value

Fig. 1. Flowchart of the retrieval process of lidar signals and the intercomparison approach adopted in this study.

¹⁾ Note that the NIES algorithm performs the process of the new α_{aer} determination at the calibration altitude only once (dashed line).

of AEC. For example, the AECs calculated by the SNU algorithm using the MPL data are proportional to S_1 : for example, changes in the values of S_1 by ± 10 sr and ± 20 sr result in a change of $\pm 15\sim 17\%$ and $\pm 31\sim 35\%$ in the AECs, respectively. However, if we use the same values of S_1 in both the SNU and NIES algorithms, the differences in AECs are not distinct (not shown). We used an S_1 value of 50 sr for both the SNU and NIES algorithms. This value is based on the value of S_1 measured on the NCAR/NSF C-130 aircraft during ACE-Asia (45.8 sr for the entire flight; Anderson et al. 2003; Doherty et al. 2005) and the value 50 sr from Hayasaka et al. (1998). This is because, in contrast to the Raman lidar, the elastic Mie-scattering lidar used in this study cannot derive a value of S_1 .

The vertical profiles of aerosol back-scattered intensity and extinction were retrieved independently from the MPL and NIES lidar systems by using two retrieval algorithms, which were used by the SNU (Kim et al. 2004, 2007; Won et al. 2004; Kahn et al. 2004) and NIES (Shimizu et al. 2004) groups and are based on the Fernald approach (Fernald et al. 1974; Fernald 1984). First, we assume that the total extinction coefficient (TEC,

α_{total}) at the calibration altitude (or reference level; hereafter " z_{cal} "; assumed to be 6 km in this study) is equal to the extinction of air molecules (α_{mol}). That is, the AEC (α_{aer}) is set to zero at 6 km. Then, we start to calculate AEC iteratively from z_{cal} toward the ground (downward) by removing the part that includes α_{mol} . A complete description of the lidar data analysis in successive steps that move downward from the assigned z_{cal} is provided in Fernald et al. (1974) and Fernald (1984). If the calculated AEC is negative, we reset the AEC at 6 km and then repeat the calculation until the results agree, that is, until $AEC \geq 0$ between the altitudes of 0.6 and 6 km. Hereafter, we call this method the "non-zero extinction" method. In fact, this non-zero extinction method can also be called a "non-negative" or "positive" method. Non-zero methods result in an approximate parallel shift of the AECs, although an AEC below the reference altitude does not linearly increase during the lidar signal inversion procedure. Here, it is worth mentioning that a unique difference between the SNU and NIES lidar algorithms is the determination of non-zero extinction at 6 km. If a negative AEC is retrieved at a certain altitude, the SNU algorithm sets a new AEC (α'_{aer}) at z_{cal} by an AEC increment

of 0.0005 km^{-1} (hereafter, called “SNU addition adjustment method”), whereas the NIES algorithm sets a new AEC (α'_{aer}) for z_{cal} by multiplying the empirical coefficient (-1.2) by the minimum value of AEC (hereafter, called “NIES multiplication adjustment method”). It is worth mentioning that the NIES algorithm performs the process of the determination of the new AEC (α'_{aer}) only once. A detailed flow of the analysis is presented in Fig. 1 (see step 2 for details). The retrieved AECs from the MPL and CML measurements and by the two algorithms are carefully intercompared to assess the correctness of the retrieval algorithm and the accuracy of the vertical profile of the aerosol extinction measurement.

2.3 Intercomparison Approach and Considerations of the Potential Sources of Uncertainties in the Measurement of the Aerosol Extinction Profiles

Though their theoretical background and measurement techniques are identical, intercomparison of vertically resolved aerosol backscatter signals obtained by different lidar systems is difficult to reconcile. For example, the vertical resolution and sampling rate of MPL and CML are different. In order to estimate the impact of the coincidence criteria during the intercomparison, we introduced three sets of criteria. First, we formed the coincident data sets by averaging both the lidar data for 30 min at an altitude of 150 m in order to avoid any intercomparison errors due to different sampling frequencies and vertical resolutions. Empty sampling bins between the instruments were excluded from the comparisons. The MPL provides a vertical extinction profile every 1 min with a vertical resolution of 75 m (i.e., bin time = 500 ns); these profiles are in accordance with the observational guidelines of the MPL-NET. However, the CML provides a vertical extinction profile every 10 min with a vertical resolution of 6 m (i.e., bin time = 40 ns). That is, the MPL data are averaged for 5 min only when the CML is in operation because the measurement sequence of the CML is such that it runs for 5 min and then stops working during the next 5 min (see Table 1 for details). The second criterion is that these averaged profiles are not only used to compare the range-corrected backscatter lidar signals but also used as input for two lidar algorithms. Finally, we discuss the observational accuracy or uncertainty of the vertical profiles of the AEC with regard to two aspects: discrepancies that occur from the retrieval algo-

rithms and the inherent differences in the optical and physical devices of both the lidar systems (see Table 1).

In addition to the measurement sequences of lidar systems, several uncertainties in the measurements of the vertical profiles of AEC can occur as a result of the different optical and physical efficiencies of the hardware (e.g., detector, laser beam power, lens etc.) of the instrumentations in this study. As indicated by the field of view (FOV) in Table 1, the overlap correction is one of the dominant potential sources of uncertainty, particularly for the MPL measurements taken near the surface due to its small FOV. The overlap correction factor of MPL is obtained from the horizontal measurements under horizontal homogenous and very low aerosol loading conditions on a clear day, whereas that of CML is taken from the vertical measurements under the lowest aerosol loading conditions during the field study, because the orientation of the CML is fixed at the zenith. In this study, the overlap corrections were performed for altitudes of $\sim 4.5 \text{ km}$ and $\sim 0.6 \text{ km}$ for the MPL and CML measurements, respectively. The comparisons of the aerosol extinction profiles are presented for altitudes above 0.6 km in order to avoid the potentially large uncertainty that can arise from the overlap correction. At altitudes above the overlap region, the discrepancies in aerosol extinction between both the instruments can arise from the laser energy. For example, the laser beam from the MPL will be more attenuated if a dominant aerosol layer is present below z_{cal} (i.e., 6 km) because the accuracy of lidar return signals at 6 km is important in the retrieval process of aerosol extinction, as discussed in Section 2.1. Further discussion on the determination of AEC at z_{cal} and the uncertainty associated with it is provided in Section 5.

After considering the above mentioned factors, the remaining uncertainties can be probably attributed to a small difference in the wavelengths of the two lidars (523.5 and 532 nm), the constant value of S_1 (50 sr), the frequency of the laser shoot, and different types of photon detectors. The uncertainties that arise from these factors can affect the evaluation of the aerosol extinction profiles. However, in this study, we discussed the overall combined effects of these potential factors with regard to the uncertainty of the vertical profile of aerosol extinction because it is not easy to estimate the effect of each factor on the uncertainty in the comparison of aerosol extinction profiles.

3. Designation of Intercomparison Periods: three Cases

We selected a lidar profile for the intercomparison based on the condition that it satisfied the following two coincidence criteria. First, we selected the lidar profiles that were not contaminated by the cloud below the altitude of at least 7 km for stable calculation of the aerosol extinction profiles. A strong cloud signal at z_{cal} (6 km) makes it difficult to solve the lidar equation by the Fernald method and can possibly induce negative values of AEC below the cloud layer. Further discussion is provided in Section 5. Second, we selected the lidar profiles under different aerosol loading conditions in order to verify the performance and reliability of the individual lidar systems and algorithms. In this study, we have selected three periods of measurements. Figure 2 shows the time-to-height indicator (THI) plots of the range-corrected lidar signals obtained from the co-located MPL and CML as well as the selected periods of the three cases, as stated below:

Case 1. May 24, 2005, 03:00 UTC
~ May 25, 2005, 03:00 UTC (24 h)

Case 2. May 26, 2005, 06:00 UTC
~ May 27, 2005, 03:00 UTC (21 h)

Case 3. May 28, 2005, 21:00 UTC
~ May 29, 2005, 12:00 UTC (15 h)

In all the cases, most of the aerosols were present below the altitude of 3 km and no clouds were observed below the altitude of 7 km. In case 1, the aerosol loading conditions were relatively low, although a fairly thin aerosol layer continuously existed between the altitudes of 1.5 and 2.7 km. Case 2 is similar to case 1, but the lidar return signals from elevated aerosol layers were stronger than those in case 1. Contrary to cases 1 and 2, relatively thick aerosol layers were observed both above and within the planetary boundary layer (PBL) in case 3. The elevated aerosol layer around altitudes of 1.0~2.2 km was merged with the PBL aerosols during the daytime on May 29, 2005 (local time: UTC + 09 h.) due to the PBL development induced by the incoming solar radiation. However, we could not use the MPL data on May 25, 2005, when the weakest lidar return signals were observed due to the condensation of dewdrops on the glass window on the roof of the container with the lidar.

Fig. 2. THI plots of the range-corrected lidar signals obtained from co-located MPL (upper panel) and CML (bottom panel). The three cases selected for the intercomparison are represented by a dashed, bold line.

4. Comparison of the Vertical Profiles of Back-scattered Intensity

The range-corrected raw lidar signals obtained from co-located MPL and CML measurements for the three cases are shown in Fig. 2 in Section 3. We note that the range-corrected raw lidar signals have been processed only for step 1 (data preprocessing), as shown in Fig. 1, and used in the lidar retrieval algorithms as input in Section 5 (step 2 in Fig. 1). It is impossible to directly compare the absolute value of range-corrected signals due to the difference in the lidar systems (e.g., laser energy and detector). Figure 2 shows a visual evaluation of the range-corrected raw lidar signals on a profile-by-profile basis of each time step. Apparently, the temporal and vertical variations of MPL signals are in good agreement with the NIES lidar measurements. However, in order to evaluate the discrepancy quantitatively, we have calculated the relative difference between the range-corrected lidar signals of the two lidar systems.

Figure 3 shows the relative differences between the range-corrected backscattered intensities in the MPL and CML measurements for the three selected cases. Here, the relative difference was calculated from the backscattered signals of MPL that were divided into those of CML for each profile [i.e., back-scattered intensity (MPL)/back-scattered intensity (CML)]. Because we start to calculate the AEC iteratively from 6 km, as explained in Section 2.2, we first normalized the lidar signal ratio between the two instruments as 1 (unity) at 6 km, and then calculated the relative difference for each altitude. A negative (positive) relative difference indicates that the range-corrected signal of MPL is weaker (stronger) than that of CML. The mean relative difference (MRD, solid line) is inclined toward negative side with similar patterns, except for the layers below 1.2 km and 0.8 km in cases 1 and 2, respectively. The variations in the relative difference with altitude are similar, but not distinct within or above the aerosol layer. The CML signal is always greater than that of the MPL. For cases

Fig. 3. Comparisons of the relative differences of the range-corrected backscattered intensities between the MPL and CML measurements for the three selected cases. The crosshair, solid, and dashed lines represent the instantaneous difference, mean, and ± 1 standard deviation, respectively.

1, 2, and 3, the MRD is estimated by the following Eq. (2) as $-5.20 \pm 1.13\%$, $-13.43 \pm 2.22\%$, and $-18.48 \pm 2.27\%$, respectively.

$$\text{MRD}_j = \left\{ \frac{1}{N} \sum_{i=1}^N \left[\frac{\text{Backscattered Intensity}_{ij}(\text{MPL})}{\text{Backscattered Intensity}_{ij}(\text{CML})} \div \text{Ref}_i \right] \right\} \times 100(\%) \quad (2)$$

where, MRD_j denotes the mean relative difference at the j^{th} altitude. Backscattered intensity $_{ij}$ (MPL) and backscattered intensity $_{ij}$ (CML) represent the returned signal intensity of MPL and CML, respectively, at the j^{th} altitude of the i^{th} profile; N , the total number of calculation points; and Ref_i , the normalized signals between the MPL and the CML at a given reference altitude of the i^{th} profile.

5. Comparison of the Vertical Profiles of Aerosol Extinction

The S_1 value and calibration values of the AEC at z_{cal} are the key parameters required to retrieve the AEC from the lidar return signals. Regarding S_1 , we use an altitude-independent constant value of 50 sr for both the SNU and NIES retrieval algo-

rithms based on the previous experimental results performed over East Asia, as discussed in Section 2. The second important factor is the method to determine the calibration values of AEC at z_{cal} for each measurement because the calibration values of AEC at z_{cal} are closely related to the accuracy of the measured lidar signal. The density of aerosols decreases with increase in the altitude, whereas the noise in the lidar return signals increases. As mentioned in Section 2, the altitude of 6 km was used as z_{cal} , and then a non-zero extinction method was applied for both the SNU and NIES Fernald algorithms.

The reason for using the non-zero extinction method in this study is well illustrated in Fig. 4, which represents the THI plots of AEC retrieved by the SNU algorithm using the “zero” (upper) and “non-zero” (bottom) extinction methods. The MPL measurement data were used for the analysis. Here, in the zero extinction method, we set the value of AEC to be zero at z_{cal} under the assumption of the nonexistence of aerosols and calculate the AEC without an iterative process. However, if we use the zero extinction method, the negative values of AEC are dominant in the free atmo-

Fig. 4. Comparison of the AECs retrieved by the SNU Fernald algorithm with the “zero” (upper) and “non-zero” (bottom) extinction methods and by using the MPL measurement. The black shaded area in both the figures indicate that the retrieved AEC is negative for different reasons. See the text for details.

sphere, where the aerosol loadings are low, during the entire comparison period. The black shaded area in Fig. 4 represents the retrieved AEC having negative values, which is not realistic. The actual ambient aerosol extinction at z_{cal} as well as the observational uncertainty of the lidar signals would account for the negative AEC values retrieved by the zero extinction method. The negative AECs were also calculated by both the zero and non-zero methods when the reflected lidar signals were contaminated by clouds at z_{cal} . For example, strong cloud signals at z_{cal} between 06 and 18 UTC on May 28, 2005 (see Fig. 2 for details) induced the negative values of AEC below the cloud layer. However, we obtained stable results for the AEC values by an iterative process performed for the determination of the AEC at z_{cal} (non-zero extinction method) for both the PBL and free atmosphere under cloud-free atmospheric conditions in the three selected cases.

Figure 5 shows the THI plots of the AEC derived from the MPL (upper) and the CML (bottom) measurements and retrieved by the SNU algorithm. The THI plots of AEC retrieved by the NIES algorithm for the same three cases are depicted in Fig. 6. As discussed in Section 2.3, the profiles from the two lidar systems were averaged in 150-m altitude bins between 0.6 and 6 km as well as in 30-min intervals in order to facilitate the comparisons. This plotting of the temporal evolution of the vertical aerosol extinction allows a limited visual assessment that the AEC shows apparently good agreement and that the differences are virtually indistinguishable. The SNU algorithm retrieves the AEC very well for the elevated aerosol layer as well as for the traceable thin aerosol layer at altitudes above 3 km. For example, a fairly thin aerosol layer around 4 km, which is clearly separated from the aerosol layer that appears below, can be observed in case 2. Similarly, Fig. 6 also shows a good comparison of the AEC for the distinct aerosol layer; however, the NIES algorithm shows negative values of AEC, particularly for altitudes having very weak return signals from aerosols. We believe that these negative values of the AEC in Fig. 6 are primarily due to the determination of the AEC at z_{cal} . If a negative AEC is obtained, as discussed in Section 2.2 and Fig. 1, the NIES retrieval algorithm iterates the process of the determination of the AEC at z_{cal} only once by its own empirical equation [i.e., new AEC at $z_{cal} = \text{AEC (minimum)} \times -1.2$], and then produces

the final results of the AEC. Although the AEC at z_{cal} increases, the possibility for the retrieval of a negative AEC exists because the AEC below z_{cal} does not linearly increase during the lidar signal inversion procedure (Fernald 1984). It is worth mentioning that the SNU algorithm appears to be a more rational method because it continuously iterates and resets the AEC at z_{cal} if a negative value of the AEC is calculated in the aerosol extinction profile. However, it is clear that the SNU algorithm can overestimate the value of AEC, and it is necessary to consider the noise properly and treat the Rayleigh return appropriately.

Simultaneously, a sudden change in the vertical distribution of aerosol extinction is observed at 04~05 UTC on May 29, 2005 (case 3) in both Figs. 5 and 6. The discrepancy in the AEC during this period is not clear in the retrievals of the SNU algorithm (Fig. 5); however, a noticeable disagreement is apparent when the AECs are retrieved from the MPL measurements and by the NIES algorithm. The reason(s) for the occurrence of this phenomenon is not clear because there was no cloud contamination and the two lidar systems were handled properly and operated well without any problem. From Figs. 5 and 6, we can arrive at a preliminary conclusion that the uncertainty that arises from the lidar retrieval algorithms used in this study is greater than that caused by any systematic differences in the lidar optical and physical hardware/devices. These different AECs, which result from the SNU and the NIES algorithms, are well illustrated in Section 5.2.

In this study, the uncertainties in the vertical profiles of ambient aerosol extinction are quantitatively estimated and discussed with focus on the inherent difference in the lidar system efficiency and geometry of both the instruments in Section 5.1 and the lidar retrieval algorithms in Section 5.2.

5.1 Instrumentation Intercomparison: Estimation of the Effects of the Uncertainty in the Measurement on the Retrievals of the AEC

Figures 7 and 8 show the vertical profiles of the absolute differences between the AECs in the MPL and CML measurements. We applied the SNU algorithm in Fig. 7 and the NIES algorithm in Fig. 8 to the same data sets. We then calculated the differences in AEC to observe the effects of the observational uncertainty in the retrievals of AEC. The complete statistics of the AEC comparisons, which are shown in Figs. 7 and 8, are pro-

Fig. 5. Comparison of the AECs derived from the MPL (upper) and the CML (bottom) measurements and retrieved by the SNU Fernald algorithm.

Fig. 6. Comparison of the AECs derived from the MPL (upper) and the CML (bottom) measurements and retrieved by the NIES Fernald algorithm. The black shaded area in the upper panel represents the negative values of the AEC.

Fig. 7. Effects of the observational uncertainty on the retrievals of AEC: the absolute differences between the AECs in the MPL and CML measurements retrieved by the SNU Fernald algorithm. The crosshair, bold, and bold solid lines represent an instantaneous difference, mean, and ± 1 standard deviation, respectively.

Fig. 8. Effects of the observational uncertainty on the retrievals of AEC: the absolute differences between AECs in the MPL and CML measurements retrieved by the NIES Fernald algorithm.

Table 2. Comparison between the bias difference (BD, km⁻¹), root mean square difference (RMSD, km⁻¹), standard deviation of the difference (SDD, km⁻¹), slope and intercept of the best regression line, and number of lidar profiles in the aerosol extinction profiles for both the algorithms: the effects of the observational uncertainty on the retrievals of aerosol extinction based on the Fernald approach. The MPL was set as the reference instrument.

	SNU Fernald Algorithm ¹⁾			NIES Fernald Algorithm ²⁾		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
BD ³⁾	0.0063	-0.0016	0.0057	0.0028	0.0017	0.0121
RMSD ⁴⁾	0.0157	0.0240	0.0187	0.0113	0.0235	0.0363
SDD ⁵⁾	0.0017	0.0025	0.0030	0.0010	0.0014	0.0030
Slope ⁶⁾	0.8762	0.9886	0.9582	0.9472	0.9581	0.7652
Intercept	-0.0018	0.0008	0.0014	-0.0012	0.0014	0.0029
N (TN) ⁷⁾	48 (1,728)	42 (1,512)	36 (1,296)	48 (1,728)	42 (1,512)	36 (1,296)

¹⁾ Statistical results between the MPL and CML measurements were calculated by the SNU algorithm.

²⁾ Statistical results between the MPL and CML measurements were calculated by the NIES algorithm.

$$3) \text{ BD} = \frac{\sum_{i=1}^N \{ \text{AEC}_i(\text{MPL}) - \text{AEC}_i(\text{CML}) \}}{N}$$

$$4) \text{ RMSD} = \sqrt{\frac{\sum_{i=1}^N \{ \text{AEC}_i(\text{MPL}) - \text{AEC}_i(\text{CML}) \}^2}{N}}$$

$$5) \text{ SDD} = \sqrt{\frac{\sum_{i=1}^N \{ [\text{AEC}_i(\text{MPL}) - \text{AEC}_i(\text{CML})] - \text{BD} \}^2}{N-1}}$$

⁶⁾ The slope and intercept are calculated as $\text{CML} = (\text{Slope} \times \text{MPL}) + \text{Intercept}$.

⁷⁾ N is the number of lidar profiles used for comparison. TN denotes total number of lidar data points used for intercomparison: $\text{TN} = N \times \text{vertical data points (36)}$.

vided in Table 2. The statistical values shown in Table 2 are averaged from altitudes of 0.6 to 6 km and for the periods in each selected case. We used the MPL measurement as a reference.

The three data sets show fairly good agreement with regard to the vertical distribution of aerosol layers, including a fairly thin aerosol layer, although an instantaneous absolute difference of up to $\pm 0.095 \text{ km}^{-1}$ was observed for the aerosol layer. The bias difference (BD, km⁻¹) [root mean square difference (RMSD, km⁻¹)] ranged from 0.0016 [0.0113] to 0.0063 [0.0240], except in Fig. 8c. The BD of 0.0121 between the MPL and CML measurements retrieved by the NIES algorithm in Fig. 8c was one order greater than those in other cases. The arithmetical mean of the difference is close to zero within the aerosol layer, but the instantaneous points are distributed over a wide range, as indicated by one standard deviation. Contrary to cases 1 and 2, the relatively large differences in the AEC in Fig. 8c were apparent both within and above the

aerosol layer. A large portion of this discrepancy was contributed by the noticeable disagreement at 04~05 UTC on May 29, 2005, as shown in Fig. 6. The AEC derived from the MPL measurements is greater than that derived from the CML measurements, both within and above the aerosol layer, as indicated by the slope (< 1) in Table 2, except for the case in Fig. 7b. Although there is no relation between the range-corrected lidar return signal and the calculated AEC, the reversal of the signal-size relationship between the MPL and CML data in the lowermost heights can be explained by a higher steep of the MPL backscatter signal profiles, which might provide higher values of AECs. One possible uncertainty for steep MPL signals at low troposphere is the overlap correction factor, which affects the retrieval of AEC at the lowermost heights.

Table 3 lists the percentage difference (PD) for the three cases. Contrary to the statistical values in Table 2, the PD in this study is calculated only

Table 3. Summary of the mean percent difference (MPD) of AECs due to different lidar profile measurements.

	SNU Fernald Algorithm			NIES Fernald Algorithm		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
MPD	8.16	0.00	6.81	1.24	1.55	0.25
N ¹⁾	509	669	381	488	668	378

¹⁾ N denotes the number of extinction data used for comparison. In this study, the MPD were calculated for aerosol layers at altitudes between 0.6–3 km for $AEC \geq 0.03 \text{ km}^{-1}$. See the text for details.

for the cases in which the AEC is greater than 0.03 km^{-1} within the dominant aerosol layer between 0.6 and 3 km because it is difficult to satisfy the quality criteria of aerosol extinction under clean conditions, according to Kim et al. (2005b) and McArthur et al. (2003), who compared ground-based Sun photometer-derived aerosol optical depths under both high and low aerosol loading conditions. The small AEC bias for a fairly thin aerosol layer between altitudes of 3 and 6 km can cause a large PD due to the low absolute value of AEC. The PD values can exceed up to 8.15% for case 1 when the AEC is retrieved by the SNU algorithm, as shown in Fig. 7a. In this case, compared to Fig. 8a, the AEC derived from the MPL is greater than that derived from the CML throughout the compared layer. The AEC calculated by the NIES algorithm shows a low PD for the aerosol layer because instantaneous differences are uniformly distributed on both the positive and negative sides. The effect of observational uncertainty derived from different instrument measurements on the retrievals of AEC is 3.0% for the aerosol layer. As discussed above, a part of this difference near the surface is most probably caused by the overlap correction factor of the MPL.

Overall, the AECs for all the cases generally agreed within the following limits: 0.02 km^{-1} (mean), 0.0051 km^{-1} (BD), 0.0216 km^{-1} (RMSD), and 3.00% (PD), despite the different data sets from the co-located MPL and CML.

5.2 Algorithm Intercomparison: Estimation of the Effects of the Algorithm on the Uncertainty in the Retrieval of AEC

Figures 9 and 10 show the vertical profiles of the absolute difference between the AECs in the MPL and CML measurements. To observe the uncertainty in AEC due to the different algorithms, we applied both the SNU and NIES algorithms to the data sets obtained from the MPL (Fig. 9) and

from the CML (Fig. 10), respectively. Further, we calculated the differences in AEC for comparison. The complete statistics of the AEC comparisons shown in Figs. 9 and 10 are provided in Tables 4 and 5.

Contrary to Figs. 7 and 8, the vertical distribution of the difference in AEC shown in Figs. 9 and 10 is inclined toward the positive side, i.e., the AEC retrieved by the SNU algorithm is generally greater than that retrieved by the NIES algorithm, particularly for the aerosol layer between 0.6–3 km. This result is supported by the positive BD and the slope (< 1) (Table 4). The BD (RMSD) ranges from 0.0024 (0.0052) km^{-1} to 0.0186 (0.3629) km^{-1} . These values are greater than those caused by the uncertainties due to the instruments (see Table 2). The mean deviation reaches up to 0.04 km^{-1} within the aerosol layer with a large standard deviation. The difference in AEC in a fairly thin aerosol layer regime is almost identical ($< 0.01 \text{ km}^{-1}$). A possible reason for the retrievals of larger AECs by the SNU algorithm as compared to the NIES algorithm is because of the adoption of the non-zero extinction method, which is a different approach used for the determination of AEC at z_{cal} , as discussed in Section 2 and Fig. 4. In the case of the SNU algorithm, if the retrieved AEC is negative, the algorithm resets the AEC at z_{cal} and then repeats the calculation until the result satisfies the condition $AEC \geq 0$. Therefore, all the AECs produced by the SNU algorithm are greater than zero. The NIES retrieval algorithm iterates the process of the determination of AEC at z_{cal} only once and then produces the final results of AEC. Although the AECs at z_{cal} are increased, a negative AEC can be retrieved from the NIES algorithm. That is, the difference in the rules of the adjustment methods is an important factor that controls the results. For example, when we calculated the AEC profiles by using an identical MPL data and SNU algorithm, the differences between the AEC values in the

Fig. 9. Effects of the algorithm uncertainty on the retrievals of AEC: the absolute differences between the AECs in the SNU and NIES Fernald algorithms. The MPL data sets are used as the input.

Fig. 10. Effects of the algorithm uncertainty on the retrievals of AEC: the absolute differences between the AECs in the SNU and NIES Fernald algorithms. The CML data sets are used as the input.

Table 4. Comparison between the bias difference (BD, km^{-1}), root mean square difference (RMSD, km^{-1}), standard deviation of the difference (SDD, km^{-1}), slope and intercept of the best regression line, and number of lidar profiles in the aerosol extinction profiles: the effects of the retrieval algorithm uncertainty on the retrievals of aerosol extinction (Fernald approach).

	MPL data ¹⁾			CML data ²⁾		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
BD ³⁾	0.0058	0.0097	0.0186	0.0024	0.0096	0.0054
RMSD ⁴⁾	0.0109	0.0239	0.3629	0.0052	0.0171	0.0094
SDD ⁵⁾	0.0016	0.0042	0.0044	0.0008	0.0020	0.0015
Slope ⁶⁾	0.8159	0.9061	0.7682	0.9146	0.9228	0.9384
Intercept	0.0004	-0.0016	-0.0021	0.0002	-0.0024	-0.0010
N ⁷⁾	48 (1,728)	42 (1,512)	36 (1,296)	48 (1,728)	42 (1,512)	36 (1,296)

¹⁾ Statistical results between the SNU and NIES algorithms were calculated by using MPL data sets.

²⁾ Statistical results between the SNU and NIES algorithms were calculated by using CML data sets.

^{3)–7)} The Footnotes in Table 2 provide details on the manner in which the statistical results were calculated.

Table 5. Summary of the MPD of AECs due to different retrieval algorithms (Fernald approach).

	MPL data			CML data		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
MPD	15.29	11.74	19.79	7.38	8.62	6.99
N	541	661	403	492	672	431

SNU addition and NIES multiplication adjustment procedures for the three selected cases was in the range $0.002\sim 0.005 \text{ km}^{-1}$. Compared to the BDs in Table 4, these values suggest that the difference in the adjustment process is one of major factor that controls the AEC results in this study.

It should be noted that we made the adjustments at z_{cal} for each profile individually and the AECs at z_{cal} did not change considerably with time. For example, the mean and ± 1 standard deviation of AECs at z_{cal} estimated by the SNU algorithm using the MPL data for the three selected cases in this study are as follows:

(i) SNU addition adjustment method [unit: km^{-1}]: 0.013 ± 0.004 (Case 1), 0.007 ± 0.006 (Case 2), and 0.018 ± 0.017 (Case 3).

(ii) NIES multiplication adjustment method [unit: km^{-1}]: 0.012 ± 0.003 (Case 1), 0.006 ± 0.005 (Case 2), and 0.013 ± 0.009 (Case 3).

Table 5 shows the PD calculated for the dominant aerosol layer between 0.6 and 3 km. The PD values exceed up to 19.8% for case 3 when the AEC is derived from the MPL measurements and retrieved by both the algorithms. We conclude that the effect of the uncertainty due to the al-

gorithm with regard to the retrievals of the AEC is approximately 11.6% (the mean PD for all the cases) which is almost four times greater than the uncertainty due to the different instrumental observations, as mentioned earlier (mean PD = 3.0%). In summary, the BD, RMSD, and PD of the retrieved AEC over the course of the comparison involving different retrieval algorithms are 0.0086 km^{-1} , 0.0720 km^{-1} , and 11.6%, respectively.

5.3 Comparing With the Results Obtained From Previous Intercomparison Studies

The comparison results of this study, deviations of approximately 3.0% and 11.6% due to the different lidar systems and lidar retrieval algorithms, respectively, are comparable with those listed by Böckmann et al. (2004), Matthais et al. (2004), and Schmid et al. (2006). Böckmann et al. (2004) and Matthais et al. (2004), who performed an intercomparison of an aerosol backscatter lidar and its algorithms within the framework of the EARLINET in order to study aerosol climatology, showed that the typical deviations between aerosol backscatter profiles among networked instruments were approximately 10% in the planetary bound-

ary layer and $0.1 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$ in the free troposphere; however, these deviations vary with different cases. For some cases, they showed that the mean relative errors between aerosol backscatter profiles originating from the algorithm generally agreed well within the order of 2~4% for the lower troposphere (0.3075~3.0075 km) and $0.1 \times 10^{-5} \text{ m}^{-1} \text{ sr}^{-1}$ for the aerosol layer between altitudes of 3.0225 and 15.0675 km; however, the mean relative errors for the other cases showed values up to 14.5% for the layer between 0.3225~1.9875 km and 11.7% for the aerosol layer between 3.2175~3.8925 km.

The results of this study are consistent with the comparison results of the current state-of-the-art instrumentations, as reported by Schmid et al. (2006). Schmid et al. (2006) concluded that the typical systematic error associated with measuring the tropospheric vertical profile of ambient aerosol extinction from six different instruments was 15~20% at visible wavelengths. In particular, they found that the BDs in airborne Sun photometer-derived AECs and ground-based two MPLs-derived AECs were 13% (MPL-NET) and 24% (MPL-ARM), respectively.

Finally, the RMSD results of this study, 0.0216 km^{-1} and 0.0720 km^{-1} due to different lidar systems and lidar retrieval algorithms, respectively, are also comparable with those of column-integrated aerosol extinction, namely, aerosol optical depth (AOD) and the comparisons derived from ground-based Sun photometers. For example, Kim et al. (2005b) and Schmid et al. (1999) showed the agreement of the AOD with RMSD values of 0.015 and 0.025, respectively.

6. Summary and Conclusions

The best measurement data sets of the vertical profiles of ambient aerosol extinction were obtained from two co-located elastic Mie-scattering lidar systems as part of the ABC-EAREX2005 field study at the Gosan ground station in Korea in May 2005. We compared the vertical profiles of the range-corrected raw lidar signals as well as the aerosol extinction coefficient obtained from the Seoul National University micro-pulse lidar (MPL) and the Japanese National Institute for Environmental Studies-Compact Mie-scattering lidar (CML) for three selected cases. By using a constant value of an altitude-independent extinction-to-backscatter ratio (50 sr) and the non-zero extinction method for the determination of the calibration values of the aerosol extinction coefficient

(AEC) at z_{cal} for each measurement along with two lidar retrieval algorithms developed by the SNU and NIES groups and based on the Fernald approach, we were also able to compare the vertical profiles independently by using simultaneous lidar data sets as input.

For the three different aerosol loading cases, the overall MRD of the range-corrected raw lidar signals in the MPL and the CML measurements are estimated as 4.5%, 8.0%, and 7.3%.

An instrument intercomparison shows that the three case studies agree well for the vertical distribution of aerosol layers between 0.6 and 6 km, including a fairly thin aerosol layer, despite different optical and physical devices (e.g., detector, laser energy etc.) in the two lidar systems. The absolute differences in AEC are relatively small for the aerosols in the free atmosphere (above 3 km), whereas large absolute differences in AEC are observed within the aerosol layer (0.6~3 km). Over the course of the intercomparison periods, the bias difference (BD) and root mean square difference (RMSD) were observed to be 0.0051 km^{-1} and 0.0216 km^{-1} , respectively. The calculated percentage difference (PD) for the aerosol layer between 0.6 and 3 km ($\text{AEC} \geq 0.03 \text{ km}^{-1}$) is 3.0%. A part of this difference near the surface is probably caused by the overlap correction factors of the MPL.

The algorithm intercomparison shows that the retrieved AEC for all the cases generally agrees well within a bias difference of 0.0086 km^{-1} and a RMSD of 0.0720 km^{-1} . The mean AEC difference is smaller than 0.04 km^{-1} and 0.01 km^{-1} for the aerosol layer and fairly thin aerosol layer in the free atmosphere, respectively. The effect of the algorithm uncertainty on the retrievals of AEC is approximately 11.6% (mean PD for the three selected cases), which is almost four times greater than the uncertainty due to the different instruments, as mentioned above. The largest part of this discrepancy originates from the different methods of determining the AEC at z_{cal} (non-zero extinction method).

The comparison results of this study over the course of study are similar to, or show good agreement with previous field studies, although there is no definitive proof that either of the lidars or the retrieval algorithms are fundamentally flawed. We have quantified the systematic errors associated with different retrieval algorithms; however, we need to retrieve an altitude-dependent extinction-to-backscatter ratio and verify the associated un-

certainties on the vertical aerosol extinction profile retrievals.

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