Evaluation and Correction of the Ambient Particle Spectral Light Absorption Measured Using a Filter-based Aethalometer

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ABSTRACT

Spectral light-absorption properties measured with an Aethalometer (AE; Model AE33; Magee Scientific) are widely used in radiative forcing studies and source appointment in China. However, considerable uncertainty regarding the measured absorption coefficient (σ_{abs}) exists because of the multiple-scattering effects, loading effects, and differences in filter tape. This study evaluated σ_{abs} by comparing the values measured with an AE33 using Tape 8050, an AE33 using Tape 8060 (which differs from Tape 8050 in material), and a three-wavelength photoacoustic soot spectrometer (PASS-3) during two field campaigns in eastern China. The results indicated that the AE33-measured σ_{abs} using either tape exceeded the PASS-3-measured value by approximately three times, mainly owing to the multiple-scattering effect. A wavelength-independent multiple-scattering compensation factor (2.90), which varies slightly (± 0.04) for eastern China, is recommended for these regions. When σ_{abs} was measured with the AE33 using Tape 8050, the value highly depended on the loading on the tape, which led to significant uncertainty and discontinuity in the absorption Å ngström exponent compared to using Tape 8060. A method was proposed to effectively correct the historical datasets of σ_{abs} and the absorption Å ngström exponent by using the AE33 with Tape 8050. This work provides insight into the quality of measured absorption data when filter-based measurement technology is applied.

Keywords: Black carbon; Absorption; Multiple-scattering compensation; Loading effects.

INTRODUCTION

Light-absorbing particles exert considerable effects on aerosol radiative force by absorbing radiation, changing the aerosol single-scattering albedo and interacting with clouds (Koch and Del Genio, 2010; Bond *et al.*, 2013). Black carbon (BC) dominates the light absorption of atmospheric particles (Saturno *et al.*, 2017). Ice and snow albedos can be markedly changed when BC particles are deposited on them (Bond *et al.*, 2013), which leads to great uncertainty when estimating aerosol climate effects. Absorbing aerosols can also influence the environment by suppressing turbulence in the atmospheric boundary layer (Wilcox *et al.*, 2016).

Considerable uncertainty may also arise regarding radiative effects when the light-absorbing ability is measured at one wavelength or over a limited range because ambient aerosol light absorption is dependent on wavelength. The absorption Å ngström exponent (α_{abs}) (Å ngström, 1929) is used to describe the aerosol light-absorption property as follows:

$$\frac{\sigma_{abs}(\lambda_1)}{\sigma_{abs}(\lambda_2)} = \left(\frac{\lambda_1}{\lambda_2} \right)^{-\alpha_{abs}} \quad (1)$$

where $\sigma_{abs}(\lambda_1)$ and $\sigma_{abs}(\lambda_2)$ are the absorption coefficient at wavelength λ_1 and λ_2 respectively. Different characteristics of wavelength dependence are observed for different aerosol types (Schmid *et al.*, 2006). The theoretical α_{abs} values of BC from the fuel is 1.0 (Martinsson *et al.*, 2017) whereas some organic absorption classes have α_{abs} values spanning a wide range between 3.5 and 7.0 (Schmid *et al.*, 2006). Thus, spectral light-absorption information can provide knowledge regarding the source and aging process of ambient aerosols (Zotter *et al.*, 2017).

Many methods have been developed to measure spectral light-absorbing properties, and these methods have been well summarized and described by Bond *et al.* (2013) and Petzold *et al.* (2013). Filter-based instruments, such as Aethalometers (AEs) (Hansen *et al.*, 1984), Particle Soot Absorption Photometers (Bond *et al.*, 1999) and Multi-Angle Absorption Photometers (Petzold and Schönlinner, 2004), are widely used for both ground measurements and airborne studies because they are easy to operate (Coen *et al.*, 2010). The σ_{abs} at different wavelengths is obtained by measuring

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the attenuation of light when it passes through an aerosol-laden filter. AEs are the most frequently used commercial instruments to measure ambient aerosol σ_{abs} . However, it is necessary to post-process AE-measured data to compensate for the well-known multiple-scattering effects and loading effects (Bond *et al.*, 1999; Coen *et al.*, 2010). Ample effort has been devoted to the methods of correcting measured σ_{abs} (Coen *et al.*, 2010; Virkkula *et al.*, 2015; Saturno *et al.*, 2017). Recently, a new dual-spot Aethalometer (AE33), which measures σ_{abs} at seven different wavelengths from 370 nm to 950 nm with real-time loading effects compensation, was developed (Drinovec *et al.*, 2015).

The official filter tape of AE33 has been changed from Model 8050 to 8060 because the nonlinear filter-loading effect from Tape 8050 causes dysfunction in the compensation process. Although AE33 with Tape 8050 has long been used for measurement worldwide, the performance of measured σ_{abs} is not well characterized. It is widely accepted that the uncorrected σ_{abs} data from AE33 is too high and that correction of the multiple-scattering effect is necessary (Moosmüller *et al.*, 1998; Saturno *et al.*, 2017; Sharma *et al.*, 2017). Moreover, the σ_{abs} measured with Tape 8050 is unstable, and the loading effects of the measured σ_{abs} are not satisfactorily corrected, which was confirmed in this study. Furthermore, there have been more than 30 AE33 instruments employed to measure ambient σ_{abs} in China since 2015 (personal communication), and these data are used to infer information regarding BC emissions in China. However, these data require reconstruction to accurately reveal the light-absorption properties of ambient aerosol.

In this study, we evaluated measured σ_{abs} by using AE33 with Tape 8050 and Tape 8060 from two field measurements in eastern China. Based on the inter-comparison of the measured σ_{abs} from AE33 and a three-wavelength photoacoustic soot spectrometer (PASS-3), a wavelength-independent multiple-scattering correction factor (C_f) value was recommended for eastern China. Using the same correction

factor of 2.9 for eastern China makes it easier to reconstruct the historical observation data measured by AE33.

MEASUREMENTS AND INSTRUMENTS

Measurement Sites

The field measurements were conducted at two sites: Peking University (PKU) and Taizhou. The suburban measurement at site Taizhou (119°57'E, 32°35'N), as shown in Fig. 1(a), lies at the south end of the Jianghuai Plain in eastern China. It is located approximately 118 km southeast of the megacity Nanjing and approximately 200 km northeast of another megacity, Shanghai. The industrial area between Nanjing and Shanghai has experienced severe pollution over the past 30 years. The average aerosol optical depth at the wavelength of 550 nm during 2017, as measured by the Moderate Resolution Imaging Spectroradiometer, indicates that the measurement site is more polluted than the surrounding area (Fig. 1(b)). Taizhou is a representative location polluted mainly by secondary organic aerosol and biomass burning in eastern China (Zhao *et al.*, 2019a). The PKU site is located northwest of Beijing, between the Fourth and Fifth Ring Road. It is 11 km away from the center of the Beijing, which is surrounded by Hebei Province and the megacity Tianjin. The Beijing-Tianjin-Hebei region suffers from heavy air pollution due to various industrial activities. As revealed in Fig. 1(b), the PKU site is on the edge of the heavily polluted area of the North China Plain. Datasets for this location are representative of the urban aerosol pollution in the North China Plain (Guo *et al.*, 2012; Guo *et al.*, 2013; Tang *et al.*, 2018; Zhao *et al.*, 2018; Zhao *et al.*, 2019b).

Measurements at the PKU site were recorded in the spring (March 20–April 30) and in the autumn (October 10–19) of 2018, whereas observations at the Taizhou site took place in the summer (May 22–June 17) in 2018. For both sites, all of the instruments were placed in a container, in which the temperature was well controlled within $24 \pm 2^\circ\text{C}$. The

Fig. 1. Measurement sites of Taizhou and PKU (marked with a hexagonal star). Filled colors represent (a) the topography of eastern China and (b) the average aerosol optical depth at 550 nm during 2017 from the Moderate Resolution Imaging Spectroradiometer on board the Aqua satellite.

sample air was collected using a PM₁₀ impactor (Model SSI2.5; Mesa Labs) mounted on top of the container. Next, the sample air was passed through a Nafion dryer tube. The relative humidity of the sample particles measured with each instrument was controlled below 30%.

Instruments

The instruments used for the two field measurements are listed in Table S1. The corresponding time periods when data were available are marked in blue. The σ_{abs} was measured by the PASS-3 at three wavelengths (405, 532, and 781 nm) and by two AE33s with different types of filter tape at seven wavelengths (370, 470, 520, 590, 660, 880, and 950 nm). The two AE33s had the serial numbers 0345 and 0582 and were labeled as AE33-345 and AE33-582, respectively. The aerosol scattering coefficient (σ_{sca}) was measured using an Aurora 3000 nephelometer (Müller *et al.*, 2011) at wavelengths of 450, 525, and 635 nm. Data correction was performed following Müller *et al.* (2011). The aerosol particle number size distribution (PNSD), ranging from 20 nm to 10 µm, was measured by using the Scanning Mobility Particle Size spectrometer (SMPS; Model 3936; TSI Inc.) and Aerodynamic Particle Sizer (APS; Model 3321; TSI Inc.).

Because the SMPS and APS provided the aerosol PNSD data every 5 minutes, all σ_{abs} and σ_{sca} data were averaged with the same time resolution of 5 minutes for further study.

PASS-3

The principle of PASS-3 has been described elsewhere (Terhune and Anderson, 1977; Utry *et al.*, 2014; Nakayama *et al.*, 2015; Cremer *et al.*, 2017; Davies *et al.*, 2018), and thus only a brief introduction is presented here. First, the PASS-3 continuously pumps the sample aerosol into an acoustic resonator, and these absorbing aerosols are irradiated by laser lights at 405, 532 and 781 nm. The laser is an amplitude-modulated square wave with a frequency of 1500 Hz. The absorbing aerosols absorb light energy and then generate periodic pressure waves in the resonator. Finally, σ_{abs} is retrieved from the amplitude of the pressure wave by using a microphone. The PASS-3 installs a scattering integrating sphere to measure the aerosol σ_{sca} concurrently with the σ_{abs} .

The PASS-3 is capable of measuring the σ_{sca} , σ_{abs} , and the extinction coefficient (σ_{ext}) independently for high aerosol concentrations, which makes it easy to calibrate (Terhune and Anderson, 1977; Davies *et al.*, 2018). In our study, σ_{sca} of the integrating sphere was calibrated using pure scattering aerosol ammonium sulfate, and σ_{abs} was calibrated using Aquadag soot particles by subtracting σ_{ext} from σ_{sca} . The PASS-3 can provide σ_{abs} data with high accuracy if it is properly calibrated (Davies *et al.*, 2018). The uncertainty of the absorption measurements was estimated to be 4%, 8%, and 11% from 405, 532, and 781 nm, respectively (Nakayama *et al.*, 2015). Several studies have used σ_{abs} data measured by a PASS as reference to evaluate the σ_{abs} measured by a filter-based instrument (Arnott *et al.*, 2005; Schmid *et al.*, 2006; Lack *et al.*, 2014; Utry *et al.*, 2014).

Here, calibration of the PASS-3 was conducted at the beginning of field observations at the PKU site, and at the

beginning and near the end of the observations at the Taizhou site. The status of the instrument did not exhibit considerable change, and the variations of the calibrated parameters were within 3%. Thus, the calibration results at the beginning of the measurement were used to derive the observations for each site.

AE

The AE is a well-designed instrument that is used to measure the light intensity transmitted through a fiber filter on which the aerosols are deposited (Masey *et al.*, 2020). The filter attenuation (ATN) is calculated as:

$$ATN = 100 \cdot \ln\left(\frac{I_0}{I}\right) \quad (2)$$

where I and I_0 are the concurrently measured light intensities that pass through the fiber with and without aerosol loading, respectively. The aerosol attenuation coefficient $\sigma_{ATN,0}$ can be calculated as follows:

$$\sigma_{ATN,0} = \frac{A \cdot \Delta ATN}{100 \cdot F \cdot \Delta t} \quad (3)$$

where ΔATN is the change in ATN over time period Δt ; A is the sample spot area, and F is the aerosol flow rate. The $\sigma_{ATN,0}$ values are corrected as σ_{ATN} after filter-loading correction. The AE33 model succeeds in correcting the loading effects by performing real-time measurements of two parallel spots at different flow rates. More details on correcting the loading effects by using AE33 are provided by Drinovec *et al.* (2015). In this study, the corrected attenuation coefficient σ_{ATN} from the AE33 was compared with the σ_{abs} measured using the PASS-3.

RESULTS AND DISCUSSION

Measurement and Model of the Aerosol Scattering Coefficient

The PASS-3 is capable of measuring aerosol σ_{sca} and σ_{abs} concurrently. We first proved the reliability of the measured σ_{sca} by using the PASS-3, after which the reliability of the measured σ_{abs} by the PASS-3 was guaranteed. The σ_{sca} values measured by the PASS-3, measured by a nephelometer and calculated using the scattering model with measured aerosol PNSD were compared first. The data used were obtained from the measurements at the PKU site. Comparison within the Taizhou site yielded results that were almost the same.

The Mie scattering model (Bohren and Huffman, 2007) was employed to calculate the σ_{sca} at different wavelengths. When running the Mie scattering model, the aerosol PNSD and BC mass concentration were required. The BC mass concentrations were calculated using the corrected σ_{abs} from the AE33 at a wavelength of 880 nm, with the assumption that the mass absorption coefficient was 7.77 m² g⁻¹. All of the BC particles were also assumed to have mixed internally with other aerosol components. The refractive indices of BC and non-light-absorbing aerosols are 1.8 + 0.54i (Wex *et al.*, 2002;

Kuang et al., 2015) and $1.53 + 10^{-7}i$ (Wex et al., 2002) respectively. With this information, σ_{sca} at different wavelengths can be calculated. More details regarding this calculation process can be found in Zhao et al. (2018).

The results of inter-comparisons between the σ_{sca} values measured by the nephelometer and those calculated using the Mie scattering model are shown in Fig. S1. We observed strong consistency between the measured and calculated σ_{sca} values ($R^2 = 0.99$ for different wavelengths), which indicated that the aerosol PNSD and σ_{sca} measurements by the nephelometer were reliable. Because the σ_{sca} values measured using the nephelometer in the present study were raw measured data, and truncation error corrections were not conducted, the calculated σ_{sca} values were always slightly larger than the measured values, with regressed larger regression slope than unity for each wavelength.

The measured σ_{sca} values using the PASS-3 and the nephelometer at similar wavelengths were compared. The measured σ_{sca} were adjusted to the same wavelength using the scattering Ångström exponent. Our findings are presented in Fig. S2 and show that great consistency was achieved between σ_{sca} values at 525 nm from the nephelometer and σ_{sca} from the PASS-3. The slope (1.06) was slightly higher than 1.0, which was mainly caused by the different truncation errors between nephelometer and PASS-3. The σ_{sca} values measured at other wavelengths had almost the same trends ($R^2 > 0.99$). Our inter-comparison of the σ_{sca} values measured by the PASS-3 and nephelometer demonstrated that the measurements of both instruments were reliable.

Finally, σ_{sca} values were measured by PASS-3 and calculated using the Mie scattering model at wavelengths of 405, 532, and 781 nm; the results were compared and presented in Fig. 2. Notably, the measured and calculated σ_{sca} values exhibited strong consistency. The relative difference between them was primarily less than 20%.

Overall, the closures achieved between the measured σ_{sca} values by the PASS-3, the measured σ_{sca} values by the nephelometer and the calculated σ_{sca} values by the Mie scattering model demonstrated that the PASS-3 provided σ_{sca} values with high accuracy. Therefore, the measured σ_{abs} by the PASS-3 was reliable. We thus used the measured σ_{abs} by the PASS-3 as a reference for the other instruments.

σ_{ATN} Properties of Different Filter Tapes in AE33 Instruments

Two AE33 instruments (AE33-345 and AE33-582) were used to measure σ_{ATN} using Filter Tapes 8050 and 8060, respectively. Notably, the σ_{ATN} values obtained from the AE33 used in the present study were different from the σ_{abs} values by a factor of C_f . As shown in Table S1, four inter-comparisons were conducted to evaluate the performance of Filter Tapes 8050 and 8060. The σ_{ATN} values measured from the AE33-345 and AE33-582 were compared using (1) Tape 8060 and Tape 8060 from March 20 to April 24; (2) Tape 8050 and Tape 8060 from March 24 to April 30; (3) Tape 8060 and Tape 8050 from October 10 to October 15; and (4) Tape 8050 and Tape 8050 from October 15 to October 19.

Figs. 3(a), 3(b), 3(c) and 3(d) present a comparison of the measured σ_{ATN} values in Table S1 at 880 nm for Groups (1), (2), (3), and (4), respectively. According to Fig. 3(a), the σ_{ATN} values from the two instruments with Tape 8060 exhibited strong agreement ($R^2 = 0.99$, slope = 1.08). Moreover, almost all of the σ_{ATN} values from the two instruments had a relative difference of less than 20%. However, the consistency between σ_{ATN} values from the two instruments decreased when one of the instruments switched to Tape 8050 ($R^2 = 0.95$ and 0.97 for Test Groups [2] and [3], respectively). The slopes of 1.13 and 1.12 demonstrate that the σ_{ATN} values measured by the AE33-582 is about 1.1 times that of measured value by the AE33-345. However, when both instruments switched to Tape 8050, the consistency between σ_{ATN} values worsened ($R^2 = 0.87$); in many cases, the relative difference between the measured σ_{ATN} values was greater than 20%. Overall, the relative difference in σ_{ATN} values between the two instruments did not indicate a clear relationship with the ATN values. Thus, the stability of the measured σ_{ATN} values were not improved by changing the tape more frequently.

Our inter-comparison results suggested that the σ_{ATN} values measured by Tape 8060 was more stable than that measured by Tape 8050. Nonetheless, a relative difference of 10% still existed among different AE instruments.

The σ_{abs} value was calculated using Eq. (1) with the σ_{ATN} values at 470 nm and 950 nm measured using the AE33, which can be used as the source attribution for traffic and wood burning (Martinsson et al., 2017; Zotter et al., 2017).

Fig. 2. Comparison of the σ_{sca} measured using the PASS-3 and calculated using the Mie scattering model at wavelength of (a) 405 nm, (b) 532 nm and (c) 781 nm. The dashed lines in each panel represent 1:1 and a relative difference of 20%.

Fig. 3. Comparison of the σ_{abs} at 880 nm measured using the AE33. The σ_{abs} values on the x and y axes were measured using the AE33-345 and AE33-582 respectively. Each panel shows comparisons of using (a) Tape 8060 versus Tape 8060, (b) Tape 8050 versus Tape 8060, (c) Tape 8060 versus Tape 8050 and (d) Tape 8050 versus Tape 8050.

The discussion in Section 3.3 reveals that the calculated α_{abs} values from σ_{ATN} and σ_{abs} were the same. The measured α_{abs} values at different accumulated ATNs and on different days using Tape 8050 and Tape 8060 are shown in Figs. 4(a) and 4(b), respectively. The calculated α_{abs} values from Tape 8060 (Fig. 4(b)) did not exhibit a clear relationship with accumulated ATN, and the variations in α_{abs} were mainly a result of the diversity in ambient aerosol absorption properties. However, the α_{abs} from Tape 8050 was highly correlated with the ATN values shown in Fig. 4(a). When the ATN changed from 22–60 to 120, the mean α_{abs} values changed from 1.6–1.8 to 2.0, respectively. However, the variation in α_{abs} was approximately 0.6, which is almost the same degree of α_{abs} variation caused by different ATNs when using Tape 8050. Therefore, the α_{abs} value measured using the AE33 using Tape 8050 was associated with great uncertainty.

The α_{abs} at the Taizhou site had almost the same properties as that at the PKU site, as shown in Fig. S3. The results indicated that α_{abs} changed significantly with the ATN for Tape 8050, but that there were no clear variations with the increased accumulation of ATN for Tape 8060.

Multiple-scattering Correction Factor

The PASS-3 estimated the instrument noise and recorded the value in its reported data. The statistical results for noise during the measurement are shown in Fig. S4. The mean and standard deviation of σ_{abs} for instrument noise were 0.34 and 0.066, respectively, with a 95.5% possibility (sum of the mean and double the standard deviation) that the noise was less

Fig. 4. Measured α_{abs} values at different ATNs for (a) Tape 8050 and (b) Tape 8060 at the PKU site. The dots with almost the same color and small difference in ATN share the same tape spot. The number in the color bar represents the Julian days in 2018.

than 0.473. To confirm that the measured σ_{abs} noise comprised a small partition of the measured σ_{abs} , we compared these data when the surrounding σ_{abs} was larger than 10.50 Mm^{-1} [$0.473/(1 - 95.5\%)$], under which condition the noise would account for less than 4.5% of the measured σ_{abs} value.

Figs. 5(a), 5(b), and 5(c) present a comparison of the σ_{abs} values measured using the PASS-3 and the σ_{ATN} values by the AE33 at wavelengths of 405, 532, and 781 nm, respectively, at the PKU site. Section 3.2 reveals that the measured results of the AE33 with Tape 8060 were more reliable and stable than those from the AE33 with Tape 8050. Thus, the σ_{ATN} value from the AE33 with Tape 8060 was used for comparison. The σ_{ATN} value at 405 nm was calculated using the α_{ATN} value that had been previously calculated using the σ_{ATN} values at 370 nm and 470 nm. The corresponding σ_{ATN} values of AE33 at 532 and 781 nm were calculated using the σ_{ATN} values at the wavelength pairs of 520 and 590 nm, and 660 and 880 nm, respectively. σ_{abs} can be derived by dividing σ_{ATN} by C_f . Here, C_f was determined by calculating the ratio of the σ_{ATN} values measured using the AE33 and the σ_{abs} values measured using the PASS-3. As revealed in Fig. 5, C_f was determined to be 2.91, 2.94 and 2.94 at 405, 532, and 781 nm, respectively, by using the linear regression forcing the intercept to zero. C_f did not exhibit obvious variations with changes in wavelength. The comparison was conducted for the Taizhou site and the corresponding C_f values were 2.88, 2.88 and 2.86 at 405, 532, and 781 nm, respectively, as shown in Fig. S5. The C_f value is smaller than that of 4.35 in central Oregon, USA (Laing et al., 2020).

Therefore, the C_f was recommended to be 2.90 (± 0.04) for both sites, which is an average of all the ratios. Notably, this value was the same for different wavelengths.

Correction Method of σ_{ATN}

According to the findings presented in Section 3.3, it is clear that the AE33 with Tape 8060 provided a reliable σ_{abs} measurement with a C_f value of 2.90. By contrast, the σ_{ATN} and α_{abs} values measured with Tape 8050 were related to the accumulation of ATN (see Section 3.2). Moreover, the σ_{ATN} values measured with Tape 8060 was relatively stable and unrelated to the accumulation of ATN. However, because the AE33 with Tape 8050 has long been used worldwide for measuring ambient BC mass loadings, historical observation data from the AE33 with Tape 8050 should be corrected. We propose a straightforward method to correct σ_{ATN} values measured with Tape 8050 on the basis of σ_{ATN} values measured with Tape 8060.

First, the σ_{ATN} values measured with Tape 8050 were grouped according to their ATN values from 20 to 140 with a step of 5. We also recorded the concurrently measured σ_{ATN} values from Tape 8060. For each group, the σ_{ATN} values measured with 8050 and 8060 were compared and the regression slope value was used as the correction factor for the σ_{ATN} values measured with Tape 8050.

Fig. 6 shows the correction factors at different wavelengths and ATN values, revealing that the correction factors varied significantly with the amount of ATN. When the ATN was less than 80, the correction factors did not exhibit clear differences among different wavelengths. They did, however, become increasingly diverse across different wavelengths as ATN increased. The σ_{ATN} values measured with Tape 8050 were slightly lower than those measured with Tape 8060 when the ATN was less than 90 across the seven wavelengths.

Because the correction factors were different for different wavelengths, we calculated the difference in α_{abs} values at the wavelengths of 470 nm and 950 nm. The results, presented in Fig. 6, indicated that corrections of σ_{ATN} can lead to variations in α_{abs} from 0.02–0.15 to 0.23 when ATN increased from 30–60 to 130. The variations in α_{abs} were consistent with the results presented in Section 3.2, namely that the measured α_{abs} values first decreased and then increased with the increase in ATN. This suggests that the correction factors can provide a more reliable σ_{ATN} and α_{abs} values for Tape 8050.

Fig. 7 provides one example of the effects of correction on the measured σ_{ATN} and α_{abs} values. Specifically, Figs. 7(a) and 7(b) show the raw and corrected σ_{ATN} values at wavelengths 470, 590, and 950 nm. Figs. 7(c) and 7(d) display the corresponding α_{abs} values calculated from Figs. 7(a) and 7(b) using the respective wavelengths of 470 and 950 nm. The location at which the tape was switched can be recognized directly when the ATN decreased from higher than 135 to less than 40, as shown in Figs. 7(c) and 7(d). Figs. 7(a) and 7(c) reveal that both σ_{ATN} and α_{abs} exhibited large discrepancies when the tape was switched for the raw measured σ_{ATN} . However, the situation improved when σ_{ATN} was corrected using the factors shown in Fig. 6, resulting in more continuous σ_{ATN} and α_{abs} values than before.

In conclusion, two steps of correction should be applied

Fig. 5. Comparison between the σ_{abs} values measured using the PASS-3 and σ_{ATN} values measured using the AE33 at (a) 405 nm, (b) 532 nm and (c) 781 nm at the PKU site.

Fig. 6. Correction factors for the σ_{ATN} measured using Tape 8050 for different wavelengths and the corresponding variations in α_{abs} of 470 nm and 950 nm at different ATNs.

Fig. 7. (a–b) The σ_{ATN} and (c–d) α_{abs} time series: (a) and (c) show the raw data, (b) and (d) show the corrected data, (a) and (c) share the same color bar, and (b) and (d) share the same wavelengths.

for σ_{ATN} values measured with Tape 8050. The first step is to correct the measured σ_{ATN} values by the factor shown in Fig. 6 for different ATNs and wavelengths. The second step is the same as that used for correction for Tape 8060: correcting the multiple-scattering effects by using a recommended factor of 2.9 for each wavelength.

CONCLUSIONS

In this study, we evaluated the reliability of σ_{abs} values measured with an AE33 during two field campaigns in Taizhou and at PKU. Comparing the values measured with two different AE33s, one using Tape 8050 and the other using Tape 8060, we found that using Tape 8060 produced more stable σ_{ATN} values.

As no clear relationship between the α_{abs} and the ATN was observed, the loading effects were apparently sufficiently corrected for Tape 8060; thus, only the multiple-scattering correction should be applied when measuring σ_{ATN} values with this tape. However, since the loading effects were not

adequately corrected for Tape 8050, both the loading effect and multiple-scattering corrections for σ_{ATN} should be considered when using this tape.

Based on the comparison between the σ_{abs} values measured with the PASS-3 and the σ_{ATN} values measured with the AE33 using Tape 8060, we recommend a mean C_f value of 2.9 ± 0.4 to correct the measured σ_{ATN} independent of wavelength. We also obtained a correction factor for the σ_{ATN} measured using Tape 8050 by regressing values measured using Tape 8060 against those measured using Tape 8050 for different ATNs and wavelengths. This factor corrected the discrepancy in the measured σ_{ATN} between the tape sampling values and the raw data, thereby resolving α_{abs} 's variation with the ATN.

This study can serve as a reference for σ_{abs} measurements and for source appointments. Using one correction factor for the North and East China Plain offered the advantage of increasing the inter-comparability of the measurements from different sites and facilitating the reconstruction of the AE33-measured historical observation data.

DATA AVAILABILITY

The measurement data involved in this study are available upon request.

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COMPETING INTERESTS

The authors declare that they have no conflict of interest.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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