



Article An Adjustment Approach for Aerosol Optical Depth Inferred from CALIPSO

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Abstract: The verification and correction of CALIPSO aerosol products is key to understanding the atmospheric environment and climate change. However, CALIPSO often cannot detect the full profile of aerosol for the low instrument sensitivity near the surface. Thus, a correction scheme for the aerosol extinction coefficient (AECs) in the planetary boundary layer (PBL) is proposed to improve the quality of the CALIPSO-based aerosol optical depth (AOD) at 532 nm. This scheme assumed that the aerosol is vertically and uniformly distributed below the PBL, and that the AECs in the whole PBL are equal to those at the top of the PBL; then, the CALIPSO AOD was obtained by vertically integrating AECs throughout the whole atmosphere. Additionally, the CALIPSO AOD and corrected CALIPSO AOD were validated against seven ground-based sites across eastern China during 2007–2015. Our results show that the initial CALIPSO AOD obtained by cloud filtering was generally lower than that of the ground-based observations. After accounting for the AECs in the PBL, the adjustment method tended to improve the CALIPSO AOD data quality. The average R (slope) value from all sites was improved by 7% (46%). Further, the relative distance between the ground track of CALIPSO and the ground station exhibited an influence on the validation result of CALIPSO AOD. The retrieval precision of CALIPSO AOD worsened with the increase in water vapor in the atmosphere. Our findings indicate that our scheme significantly improves the accuracy of CALIPSO AOD, which will help to provide alternative AOD products in the presence of severe atmospheric pollution.

Keywords: CALIPSO; aerosol optical depth; correction; planetary boundary layer

1. Introduction

Atmospheric aerosols, especially those in the planetary boundary layer (PBL), not only directly pose a threat to human health [1–3], they also play significant roles in weather and climate systems [4–8]. Meanwhile, numerous previous efforts have been devoted to precisely elucidating the spatial and temporal distribution of atmospheric aerosols from space-borne and ground-based measurements [9–11], as well as model simulations [12–14].

Compared to passive satellites, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) is the most advanced satellite, which has an equatorial crossing time of 1330 local time (LT) and a 16-day revisit time [15]. As a space-based aerosol observation sensor, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on-board of the CALIPSO satellite, provides three-dimension distribution and properties of clouds (e.g., height, optical depth, phase, particle size) and aerosols (e.g., height, optical depth, and particulate extinction profile) [15,16]. CALIOP, with respect to passive ground-based instruments, e.g., the sun-photometer, can provide the atmospheric extinction profile, which allows the contribution to the total AOD of the PBL and the free troposphere to be separated. It is also can significantly minimize the uncertainties in estimating the climate forcing induced by the lack of vertical cloud and aerosol measurements [17]. Nevertheless, CALIPSO satellite had some uncertainties in instrument calibration biases, low signal-to-noise ratio (SNR), potentially erroneous assumptions of the



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). aerosol extinction-to-backscatter ratio, misclassification of aerosol and cloud, etc. [10,18–21]; therefore, validation with other independent datasets is needed. Several studies have systematically assessed and improved the CALIPSO-based aerosols products over regional or even global scales [19,22–25]. For instance, Schuster et al. [26] pointed out that CALIPSO AOD data were better agreement with the AOD data obtained from the Aerosol Robotic Network (AERONET) after they excluded for dust samples. On the global scale, Omar et al. [27] assessed CALIPSO AOD accuracies using ground-based measurements from 2006 to 2010, and found that CALIPSO AODs were lower than AERONET AODs, especially for AERONET AOD < 0.1. Kim et al. [28] used AOD from the Moderate Resolution Imaging Spectroradiometer (MODIS) to evaluate CALIPSO, indicating that CALIPSO AOD is 63% lower than MODIS AOD over the ocean from June 2006 to December 2010. To reduce the retrieval bias and uncertainties of CALIPSO AOD, Vaughan et al. [29] developed a new approach to determine the base altitudes of aerosol layers in the PBL, which serves as one part of CALIPSO's version 3 products. Oo and Holz [23] found that the integrated attenuated total color ratio could be used to constrain the selection of lidar ratio used in the CALIPSO AOD retrieval and improve the CALIPSO AOD.

Note that CALIOP may lose detection capability if the attenuated backscatter signal of aerosol is below $2 \sim 4 \times 10^{-4}$ km⁻¹ sr⁻¹ [30]. In particular, the aerosol profile near the surface (below 1.5 km) always has higher uncertainties [7] and may contribute more errors to CALIPSO AOD. In recent decades, China has undergone rapid economic growth with high aerosol concentrations significantly increased over China [31–35], especially in PBL, implying that all the aforementioned large uncertainties in PBL should be examined [16]. In addition, Schwartz et al. [36] pointed out that high-accuracy AOD observations would be very useful to improve aerosol data assimilation systems, implying that the correction of CALIPSO AOD in the PBL will help us to enhance the ability of aerosol data assimilation and its application in China [37].

Taking eastern China as a study area where the three largest economic areas are located as well as high emission zones, i.e., the Beijing–Tianjin–Hebei (BTH) region, the Yangtze River Delta (YRD) region, the Pearl River Delta (PRD) region, the aims of this work were to evaluate CALIPSO AOD products using ground-based AODs and to propose an adjustment approach to improve the CALIPSO AOD accuracy, which corrects for the attenuated extinction from CALIPSO in the PBL. This new product is termed CALIPSO AOD (corrected). Such a study will serve as the basis for polluted area, modeling aerosol, and aerosol-cloud interaction research in the eastern China. Additionally, this will help us understand the aerosol vertical distribution, the contribution of low-level aerosol in eastern China, and its coupling with the meteorological conditions. Here, we use two aerosol observation datasets from AERONET and the China Aerosol Remote Sensing Network (CARSNET) to verify the CALIPSO AOD and its corrected product. The datasets from the CALIPSO, AERONET, CARSNET, and the meteorological data are described in Section 2. Section 3 introduces the CALIPSO AOD retrieval, correction, matching and comparison methodology. Section 4 gives intercomparisons of the CALIPSO AOD, CALIPSO AOD (corrected), and ground-based AOD, and the effects of the relative humidity on the accuracies of CALIPSO AOD and CALIPSO AOD (corrected). Section 5 discusses the results, while Section 6 concludes this study with a summary.

2. Datasets and Methods

2.1. CALIOP Data

CALIOP is a three channel lidar, with detectors that collect 532 nm parallel, 532 nm perpendicular, and 1064 nm light that is backscattered from molecules and particulates in the atmosphere [38]. CALIOP Level 2 (L2) products include Profile product, Layer product, and Vertical Feature Mask (VFM) product. Profile products mainly provide 532 and 1064 nm column AOD, the vertical distribution of the extinction coefficient, the backscatter coefficient, and the depolarization ratio. CALIOP provides a high horizontally resolution of 333 m (vertically resolution of 30 m) for altitudes of 0–8.2 km, 1.0 km (60 m)

//www-calipso.larc.nasa.gov/products/, last access: 31 June 2021) [38]. A more detailed description of the CALIPSO satellite and its parameters are also available on the NASA website (https://www-calipso.larc.nasa.gov/documents/, last access: 31 June 2021). Here, Level 2 (L2) products of CALIOP's version 3 during the daytime were used from 2007 to 2015 in the present study.

2.2. Ground-Based AOD Data

AERONET is a ground-based aerosol remote sensing network built by NASA and CNRS (Centre National de la Recherche Scientifique). The whole network is uniformly equipped with the multi-band sun-photometer of CIMEL (Cimel Electronique Company, Paris, France), which can automatically measure solar irradiance (direct solar radiation channel) and sky radiance (sky scattering channel) and realize automatic data transmission [39]. The aerosol optical parameters provided by this network can be used to study the global aerosol transport and radiation effect and verify the radiative transfer model and the accuracy of aerosol parameter inversions from the satellite [39]. AERONET contains AOD data of three quality levels: Level 1.0 (without strict cloud filtering and final verification); Level 1.5 (strict cloud filtering but no final verification, which was used in this study); Level 2.0 (quality guaranteed after strict cloud filtering and final verification) [39,40].

CARSNET, which is similar to AERONET and has 50 sites across China, is a groundbased aerosol observation network set up by the China Meteorological Administration. The network also uses a CE-318 sun-photometer to observe aerosol parameters. CE-318 measures direct solar radiation to retrieve AOD and column precipitable water vapor [39]; its sky scanning data can be analyzed to retrieve aerosol particle size spectrum and aerosol phase function. The refractive index and single scattering albedo of aerosols can also be calculated [41]. In general, CARSNET AOD measurements across China are approximately 0.03, 0.01, 0.01, and 0.01 larger than the measurements by AERONET in the 1020, 870, 670, and 440 nm channels, respectively [40]. The differences between the AOD data measured by non-calibrated instruments and those measured by reference instruments range from 4.5% to 15.3%. However, after calibrating with a standard sensor, the difference of daily average AOD is less than 1.5% compared with the observed result of a standard instrument [40]. Therefore, five AERONET sites and two CARSNET quality-controlled sites (both named ground-based sites) were selected in eastern China (see Figure 1), which were used to validate the accuracy of CALIPSO-AOD and corrected CALIPSO-AOD.

2.3. Meteorological Observation

As satellite inversions of aerosol parameters, such as the extinction coefficient, are often affected by relative humidity (RH) and other meteorological conditions [42–44], we selected the corresponding relative humidity data to illustrate their influences on the aerosol extinction coefficient, and CALIPSO AOD inversion and correction. Other meteorological variables (e.g., annual average SP, Tem, RH, WS, and AOD) were used to describe the climate characteristics of the study sites. To match the passing time of the CALIPSO satellite around 1330 BJT, ground-based RH data at 1400 BJT from 2007 to 2015 were chosen, which were provided by the National Meteorological Information Center of China Meteorological Administration. A detailed statistical analysis of the climate characteristics of all sites is shown in Table A1. The land types for all sites are shown in Table 1.



Figure 1. The geophysical distribution of AERONET sites (Hong_Kong_PolyU (HK), Beijing (BJ), Xianghe (XH), Xuzhou-CUMT (CUMT) and Taihu (TH) and CARSNET sites (Lin'an (LA) and Tianjin (TJ)) in China. The respective fill colors of the circles at the site locations represent the corresponding annual mean AOD values during the selected years. The Beijing–Tianjin–Hebei (BTH) region (red solid box), the Yangtze River Delta (YRD) region (green solid box), and the Pearl River Delta (PRD) region (blue solid box) are also shown.

Table 1. Statistics on the selected AERONET and CARSNET sites, including latitude, longitude, site type, and tin	ne
period. The position relationship of AERONET sites and CARSNET sites relative to CALIPSO ground tracks, and three	ге
scenario types.	

Station/Region	Lat. (°)	Lon. (°)	Alt. (m)	Site Type	Time Period	Min Distance (km)	Crossing Time (UTC)	CALIPSO Orbits	Matched Samples	Scenario Types
Lin'an (LA) */YRD	30.30	119.73	138.6	Forest	2007, 2010	4	5:26	43	6	2
Tianjin (TJ) */BTH	39.10	117.17	3.3	Urban	2010	5	5:30	21	10	2
Hong_Kong_PolyU (HK)/PRD	22.30	114.18	30.0	Urban	2007.01-2014.01	23	~5:55	153	27	2
Xianghe (XH) / BTH	39.75	116.96	36.0	Urban	2007.01-2015.06	3	~5:30	173	63	2
Xuzhou-CUMT (CUMT) /YRD	34.22	117.14	59.0	Urban	2013.06-2015.12	6	~5:33	49	11	2
Beijing (BJ)/BTH	39.98	116.38	92.0	Urban	2007.01-2015.12	43	~5:29	181	60	3
Taihu (TH) /YRD	31.42	120.22	20.0	Lake	2007.01-2015.12	60 or 70	~5:20 or ~5:27	232	31	1

* Indicates the CARSNET sites. BTH: The Beijing–Tianjin–Hebei region; YRD: The Yangtze River Delta region; PRD: The Pearl River Delta region. Two CALIPSO satellite trajectories were within this circle were defined as scenario 1; one CALIPSO satellite trajectory was within this circle, but the shortest distance to ground-based sites less than 37.5 km were defined as scenario 2; and one CALIPSO satellite trajectory was within this circle, but the shortest distance to ground-based sites more than 37.5 km were defined as scenario 3.

3. Retrieval of CALIPSO AOD

Figure 2 shows the flow chart of CALIPSO AOD inversion and correction. First, the aerosol extinction coefficients were obtained from CALIPSO L2 data (which underwent data preprocessing and cloud filtering), and then these were used to retrieve the CALIPSO AOD by using vertical integration. Moreover, the CALIPSO AOD (corrected) can be derived by using the vertical correction scheme and integration of the aerosol extinction

coefficient profile within the atmospheric boundary layer. Finally, both the CALIPSO AOD and CALIPSO AOD (corrected) accuracies were verified by ground-based AOD. The detailed process steps are as follows.



Figure 2. The flow chart of CALIPSO AOD retrieval, CALIPSO AOD retrieval corrected for the aerosol extinction coefficient in atmospheric boundary layer (CALIPSO AOD), and intercomparison analyses between both CALIPSO AOD retrievals and AERONET/CARSNET AOD measurements.

3.1. CALIPSO AOD Retrieval and Quality Control

The uncertainties in the inversion process of the atmospheric extinction coefficients mainly come from the distinction between cloud and aerosol, and the identification of aerosol type, etc. [45,46]; these should be addressed with the following steps: Extinction_Coefficient_532_Uncertainty < 99.9 was set to indicate less uncertainty in the obtained data. The atmospheric volume description (AVD) parameter included the category information of the characteristic layer in the product data (cloud, aerosol and no signal) and the confidence level of the discriminant condition. The 1–3 bit value of AVD was set to 3 for identifying the samples that contained aerosol information. Selecting CAD_SCORE below -70 was to ensure that aerosol confidence was high enough. In addition, when the 1–3 bit of AVD in a single profile is 2, the profile should be removed to ensure that the retrieved AOD is not contaminated by clouds [18,20,47,48]. More details on quality control can be found in the works of [15,49]. After the above data processing, the high-quality aerosol extinction coefficient data can be obtained to retrieve the CALIPSO AOD at any thick column by integrating the aerosol extinction coefficient profile in the vertical direction. When integrating, the ground height difference of the Digital Elevation Model (DEM) and the ground-based site should be within 100m, to ensure that the length of their integral path is the same.

3.2. CALIPSO AOD Correction

Figure 3 shows a sketch of the revised aerosol extinction coefficients in the PBL. Note that aerosols in the PBL include anthropogenic activities and biomass burning, etc. Here, the black dots represent aerosol particles, and the red solid lines are aerosol extinction coefficient profiles detected and obtained by CALIOP; based on the red solid line, the red dashed lines are the revised aerosol extinction coefficient profiles. The aerosol extinction coefficient near the surface layer is likely to have a lot of uncertainty and even some inversion errors. Moreover, if the backscattering signal emitted CALIOP is lower than its detection sensitivity of the instrument, the CALIOP sensor will not be able to detect the aerosol below PBL, which is important for the retrieval of AOD, PM_{2.5}, and data assimilation and simulation [36,49,50]. To address the aforementioned issues, in this study, we assume that the meteorological conditions were relatively stable and that a uniform vertically distribution of the aerosol extinction coefficient below PBL height (the detailed PBLH retrieval method from CALIPSO can be found in Zhang's work [51]). Therefore, we considered that the aerosol extinction coefficient below the top of the PBL was uniformly equal to the aerosol extinction coefficient value at the top of the PBL (see the dash red line).



Figure 3. Schematic diagram of CALIPSO AOD that corrected by the aerosol extinction coefficient in the atmospheric boundary layer. The red solid line denotes the aerosol extinction coefficient profile, and the red dashed line denotes the corrected aerosol extinction coefficient profile.

3.3. Matching Method

To estimate the AOD values at the 532 nm from CALIPSO, the ground-based AOD observation data of the two 440 nm and 870 nm bands from CE-318 sun-photometer were interpolated to match the value of the 532 nm band, then the parameter value of α , β was calculated by the Equation (1). Finally, the ground-based AOD values of the 532 nm band are obtained by Equation (2).

$$\alpha = -\frac{\ln\left[\frac{\tau_a(\lambda_1)}{\tau_a(\lambda_2)}\right]}{\ln\left(\frac{\lambda_1}{\lambda_2}\right)}, \quad \beta = \frac{\tau_a(\lambda_1)}{\lambda_1^{-\alpha}} \tag{1}$$

$$\tau_a(\lambda) = \beta \lambda^{-\alpha} \tag{2}$$

where $\tau_a(\lambda)$ is the aerosol optical depths at wavelength λ and α and β are the dimensionless scattering Ångström exponent and conversion constant, respectively.

CALIPSO passes over the ground stations at about 1330 local time, so the qualitycontrolled ground-based AOD during 1300-1400 local time were averaged to match the CALIPSO AODs. The sample statistics in this study indicate that the AOD values of most samples were below 1. In addition, CALIOP can easily identify clouds as aerosols under thin-cloud conditions, which leads to larger AOD values [27,52,53]. Therefore, the samples with AOD >1, which were derived from CALIPSO, were also excluded in this study. Note that the transit track of the CALIPSO satellite is not fixed, and Zhang et al. [51] summarized that the location relationships between CALIPSO and the ground station can be classified into three scenarios in China. According to the above method, Figure 4 shows three scenarios of locations for AERONET sites and CARSNET sites relative to CALIPSO passing tracks. The hollow red dots represent ground observation stations based on CARSNET and AERONET, and the black lines represent CALIPSO satellite trajectories selected for comparative analysis. Two CALIPSO satellite trajectories were within this circle were defined as scenario 1; one CALIPSO satellite trajectory was within this circle, but the shortest distance to ground-based sites less than 37.5 km were defined as scenario 2; and one CALIPSO satellite trajectory was within this circle, but the shortest distance to ground-based sites more than 37.5 km were defined as scenario 3. The solid circles show that BJ station belongs to type 3, TH station belongs to type 2, and other stations belong to type 1. Spatially, we averaged the CALIPSO AODs (which fall into the circle) and match them with the ground station. Finally, the samples of the CALIPSO satellite matched with each ground station are also given in Table 1.



Figure 4. The spatial distribution of the locations of AOD sites relative to CALIPSO ground tracks over China. The black dots denote the ground-based CARSNET/AERONET AOD sites, and the black lines show CALIPSO ground tracks chosen for comparison analysis. The solid circles in blue, cyan and green correspond to scenario 2, 3, and 1.

4. Results

4.1. Intercomparisons of the CALIPSO AOD, CALIPSO AOD (Corrected) and Ground-Based AOD

The intercomparison results between CALIPSO AOD and ground-based AOD at each site are show in Figure 5 and Table 2. It can be seen that the correlation coefficient (R) values are 0.97, 0.74, 0.62, 0.82, 0.88, 0.71, and 0.35 over LA, TJ, HK, XH, CUMT, BJ, and TH, respectively, with corresponding slopes of 0.67, 0.7, 0.34, 0.68, 0.46, 0.64, and 0.29, and intercepts of -0.03, 0.01, 0.16, 0.02, 0.14, 0.03, and 0.27, respectively. The CALIPSO AOD at the TH site did not agree with the ground-based AOD values, and the R value at this site was lower (failed the 95% confidence test). Note that TH station is located next to the wetland waters, with high relative humidity. Therefore, this weak correlation may be related to the impact of relative humidity on the lidar ratio of CALIPSO and sun-photometer observations. Moreover, we found that the multi-year average of AOD at the TH station from 2007 to 2015 was 0.74, which is higher than that in any other site, suggesting that relative humidity probably effects on the ground-based AOD observation. In most sites of eastern China, the CALIPSO AOD retrieval exhibited good consistency with the ground-based and the ground-based AOD observation.

based AOD values, but the CALIPSO AOD values were obviously underestimated. This indicated that the CALIPSO AOD exhibited different error characteristics at the ground stations of eastern China [53,54].



Figure 5. Comparison of 532 nm CALIPSO AOD and 532 nm ground-based AOD (CARSNET/AERONET) at the following sites: LA (a), TJ (b), HK (c), XH (d), CUMT (e), BJ (f), and TH (g). The red line is the linear fit as described by the correlation coefficients for the corresponding regression equation. The black dashed line represents 1:1 line, and RMSE denote root-mean-square error; MB denotes mean bias.

Table 2. The linear fitting results between CALIPSO AOD, CALIOPSO AOD (corrected), and ground-based AOD (CARSNET/AERONET) over China. The differences of linear fitting results between CALIPSO AOD and CALIOPSO AOD (corrected) are also listed.

C:1-	CALIPSO AOD			CALIPSO A	Difference			
Site	Fitting Equation	R	Р	Fitting Equation	R	Р	Slope	R
LA	y = 0.67x - 0.03	0.97	0.00	y = 0.90x - 0.01	0.99	0.00	0.23	0.02
TJ	y = 0.70x + 0.01	0.74	0.04	y = 1.04x - 0.03	0.82	0.01	0.34	0.08
HK	y = 0.34x + 0.16	0.62	0.00	y = 0.75x + 0.16	0.66	0.00	0.41	0.04
XH	y = 0.68x + 0.02	0.82	0.00	y = 0.87x + 0.06	0.84	0.00	0.19	0.02
CUMT	y = 0.46x + 0.14	0.88	0.00	y = 0.71x + 0.12	0.95	0.00	0.25	0.07
BJ	y = 0.64x + 0.03	0.71	0.00	y = 0.82x + 0.07	0.73	0.00	0.18	0.02
TH	y = 0.29x + 0.27	0.35	0.06	y = 0.44x + 0.31	0.43	0.02	0.15	0.08

The R values of CALIPSO AOD (corrected) and ground-based AOD are also shown in Figure 6 and Table 2, which are 0.99, 0.82, 0.66, 0.84, 0.95, 0.73, and 0.43 over LA, TJ, HK, XH, CUMT, BJ, and TH, respectively, and the corresponding slopes are 0.9, 1.04, 0.75, 0.87, 0.71, 0.82 and 0.44, respectively. The value of *R* of the ground-based AOD and CALIPSO AOD (corrected) tended to increase after the aerosol extinction coefficient correction in PBL at the seven sites, relative to CALIPSO AOD, revealing that the CALIPSO AOD correction in PBL improves the CALIPSO AOD data quality. After correction, specifically, the *R* (slope) values were increased from 0.97 to 0.99 (from 0.67 to 0.90), from 0.74 to 0.82 (from 0.70 to 1.04), from 0.62 to 0.66 (from 0.34 to 0.75), from 0.82 to 0.84 (from 0.68 to 0.87), from 0.88 to 0.95 (from 0.46 to 0.71), from 0.71 to 0.73 (from 0.64 to 0.82), and from 0.35 to 0.43 (from 0.29 to 0.44) at LA, TJ, HK, XH, CUMT, BJ, and TH, respectively. Note that the number of matched samples at LA (seven samples) was particularly small, but the correction effect was still



good, and the corresponding *R* and slope were enhanced by 0.02 and 0.23, respectively (both at the 95% confidence level).

Figure 6. Same as Figure 5, but for CALIPSO AOD corrected by the aerosol extinction coefficient in the PBL.

4.2. Error Analysis

Figure 7 shows the scatter distribution of ground-based AOD, CALIPSO AOD and CALIPSO AOD (corrected) for three scenarios, indicating that the correlation between CALISPO AOD and CALIPSO AOD (corrected) was best for all three types (Table 3). The correlation between ground-based AOD and CALIPSO AOD (corrected)/CALIPSO AOD was the highest in scenario 2, followed by scenario 3 and scenario 1. These results show that the closer the relative distance between the satellite orbit and the ground station is, the better the CALIPSO AOD validation is.



Figure 7. The scatterplots of CALIPSO AOD, CALIPSO AOD (corrected), and ground-based AOD at all sites for (**a**) scenario 1, (**b**) scenario 2, (**c**) scenario 3. The red dots, green dots and brown dots correspond to ground-based versus CALIPSO AOD, CALIPSO AOD versus CALIPSO AOD (corrected), and ground-based versus CALIPSO AOD (corrected).

For CALIPSO satellites, the AOD inversion results are not only affected by the CALIOP sensor signals (e.g., lidar ratio, measurement noise), but also by factors such as aerosolcloud classification, cloud, and water vapor. Relative humidity was chosen as one source of error on CALIPSO AOD inversion and correction under clear sky conditions [38,43,55]. The effect of relative humidity on the inferred aerosol extinction coefficient and AOD was studied [42,56,57]. We matched the RH data with the corresponding CALIPSO AOD at the same spatiotemporal scale. Moreover, the RH values were sorted in ascending order, and then the samples for the smallest (largest) one-third of total RH samples were classified as low (high) RH conditions, and the others as middle RH conditions. Figure 8 shows the relationship between CALIPSO AOD/CALIPSO AOD (corrected) and ground-based AOD under different RH conditions, all of which were higher under low RH (0.78/0.82) than under higher RH (0.56/0.62). This implies that an increase in water vapor in the atmosphere may change the optical thickness of the aerosol (the aerosol extinction coefficient increases with an increase in water vapor, which will affect the CALIPSO AOD value. Meanwhile, relative humidity will also naturally affect the AOD measured by ground-based sunphotometers.) and affect the correlation of AOD obtained by ground-based and satellite observation [58]. Similarly, compared with the CALIPSO AOD, the fitting regression of CALIPSO AOD (corrected) and ground-based AOD with higher correlation coefficients both under low and high RH conditions were clearly improved.

Table 3. Summary of the linear fitting between CALIPSO AOD, CALIPSO AOD (corrected) AOD and ground-based AOD (AERONET/CARSNET) at all the ground-based sites according to the three typical scenarios.

Scenario	Ground-Bas CALIPS	ed AOD vs. O AOD	Ground-Based AOD vs. CALIPSO AOD (Corrected)		
	Slope	R	Slope	R	
1	0.29	0.35	0.44	0.43	
2	0.75	0.76	0.97	0.77	
3	0.64	0.71	0.65	0.73	



Figure 8. The values for the correlation between ground-based AOD and (**a**) CALIPSO AOD and (**b**) CALIPSO AOD (corrected) for different relative humidity at all stations, including the correlation coefficient and slope. Blue and red represent low relative humidity and high relative humidity conditions, respectively.

Although the accuracy of the cloud aerosol classification algorithm is obviously higher than that of the previous version [19], there are still some misjudgment cases for dust and smoke, such as the presence of thick dust which appears at high altitudes and is sometimes classified as cirrus cloud [59,60]. The existence of local cloud can also induce a difference in AOD between the CALIPSO and ground-based instruments (especially,

when one detects cloud, while the another does not). For the ground-based AOD data, AERONET often cannot identify thin-layer cirrus cloud, which can cause AOD retrieval errors [61]. In addition, for band matching the ground data with the CALIPSO data, the quadratic polynomial fitting algorithm used to interpolate the AOD to wavelengths of 532 nm and 1064 nm, and this interpolation step also may also introduce some errors during validation of the CALIPSO AOD. Moreover, in this study, due to the data available on the ground, the overpass period of the satellite, and the existence of cloud and other factors, the matched samples from ground data with CALIPSO data were few, which may also incur errors in validating the CALIPSO AOD. Note that many more CALIPSO AODs (corrected) are needed to further validate the accuracies, which can be used to monitor air quality in eastern China, especially in the regions of BTH, YRD, and PRD characterized by high emissions.

5. Discussion

To observe how the CALIPSO AOD performs under severely polluted conditions (especially when ground-based AOD values are more than 1), we also compared CALIPSO AOD with ground-based AOD at all sites (see Figure A1). The consistency of CALIPSO AOD and ground-based AOD was very poor, and the CALIPSO AOD values were generally less than 1. This phenomenon is also consistent with the results of many previous studies [62–65]. On the one hand, compared with these studies based on the ground-based AOD, the mean R of CALPSO AOD and CALPSO AOD (corrected) in our study reached as high as 0.72 and 0.77, respectively, and the slope was closer to the line of 1:1. On the other hand, our CALIPSO AOD (corrected) perform better than CALIPSO AOD under severely polluted conditions. Overall, our results demonstrate the improved retrieved accuracy of our corrected method. Note that the AOD components near the surface layer are complex, and the concentration is high in the high-pollution areas [33,66,67]. Aerosol distribution at these heights can be obtained from ground-based lidar observations, which can be used to improve the accuracy of our correct method. However, ground-based lidar sites are few and unevenly distributed [68]. Therefore, we did not adjust the CALIPSO extinction coefficient with the ground-based lidar. However, in future work on CALIPSO AOD adjustments, we shall further improve the accuracy of the AOD data by collecting more profiles of the vertical distribution of aerosol extinction coefficients in different regions from ground lidar observations, and then compare and adjust the CALIPSO extinction coefficients.

6. Conclusions

A correction scheme for the aerosol extinction coefficient in the PBL was proposed to improve the accuracy of the CALIPSO AOD. The CALIPSO AOD (corrected) was validated with the ground-based measured data, and the possible error sources were analyzed. Overall, the initial CALIPSO AOD obtained by cloud filtering was generally lower than the ground-based observations. In contrast, after correcting for the aerosol extinction coefficient in PBL, the *R* and slope values of the CALIPSO AOD (corrected) and ground-based AOD increased over all stations. Specifically, the R (slope) values were increased from 0.97 to 0.99 (from 0.67 to 0.90), from 0.74 to 0.82 (from 0.70 to 1.04), from 0.62 to 0.66 (from 0.34 to 0.75), from 0.82 to 0.84 (from 0.68 to 0.87), from 0.88 to 0.95 (from 0.46 to 0.71), from 0.71 to 0.73 (from 0.64 to 0.82), and from 0.35 to 0.43 (from 0.29 to 0.44) at LA, TJ, HK, XH, CUMT, BJ, and TH, respectively. It is revealing that the CALIPSO AOD adjustment method improved the CALIPSO AOD data quality. The correlation between ground-based AOD and CALIPSO AOD (corrected)/CALIPSO AOD was highest in type 2, followed by type 3 and type 1, indicating that the closer the distance between the satellite footprint and the ground station, the better validation of CALIPSO AOD. In addition, the inversion precision of AOD worsened with the increase in water vapor in the atmosphere as this may have caused a change in the extinction coefficient and optical thickness of aerosol and affected the retrieval of the AOD. In general, our approach improved the accuracy of the CALIPSO AOD, and will help to enhance the environmental-monitoring ability of CALIPSO [62]. The

improved CALIPSO AOD can also be used to improve the assessment of aerosol radiative forcing and as an indicator to assess the effects of air quality on human health [69,70].

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Data Availability Statement: CALIPSO aerosol products are available at https://subset.larc.nasa. gov/calipso/ (last access: 31 June 2021). The CARSNET AOD and meteorological data used in the study can be obtained from the China Meteorological Data Service Center (CMDC, http://data.cma. cn/en/, last access: 31 June 2021). AERONET AOD data are available at https://aeronet.gsfc.nasa. gov/ (last access: 31 June 2021).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Descriptive statistics of meteorological variables at all sites.

Station/Variable	LST	SP	RH	Tem	WS	Pre	AOD
LA	18.94	1002.44	73.80	16.48	2.18	4.49	0.60
TJ	14.98	1016.61	52.30	13.74	1.56	1.49	0.55
HK	25.70	1005.38	71.81	23.13	2.23	5.38	0.45
XH	14.32	1015.57	55.87	12.86	1.56	1.52	0.62
CUMT	15.81	1011.93	65.32	15.05	1.87	2.21	0.68
BJ	13.79	1011.05	56.03	12.84	1.74	1.76	0.62
TH	18.79	1016.24	70.91	16.84	2.44	3.56	0.74

Terminology	Definitions					
CALIESO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite					
CALII 50	Observations					
AEC	Aerosol extinction coefficient					
PBL	Planetary boundary layer					
AOD	Aerosol optical depth					
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization					
AERONET	Aerosol Robotic Network					
CARSNET	China Aerosol Remote Sensing Network					
BTH	Beijing–Tianjin–Hebei					
YRD	Yangtze River Delta					
PRD	Pearl River Delta					
VFM	Vertical Feature Mask					
CIMEL	Cimel Electronique Company, France					
RH	Relative humidity					
AVD	Atmospheric volume description					
SNR	Signal-to-noise ratio					
LST	Land surface temperature					
SP	Surface press					
Tem	Temperature					
WS	Wind speed					
Pre	Precipitation					



Figure A1. Comparison of (**a**) CALIPSO AOD, (**b**) CALIPSO AOD (corrected) and ground-based AOD at all sites, including correlation coefficient and slope.

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