Calibration and Retrieval of Aerosol Optical Properties Measured with Coherent Doppler Lidar

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(Manuscript received 19 November 2020, in final form 8 February 2021)

ABSTRACT: A practical method for instrumental calibration and aerosol optical properties retrieval based on coherent Doppler lidar (CDL) and sun photometer is presented in this paper. To verify its feasibility and accuracy, this method is applied into three field experiments in 2019 and 2020. In this method, multiwavelength (440, 670, 870, and 1020 nm) aerosol optical depth (AOD) from sun-photometer measurements are used to estimate AOD at 1550 nm and calibrate integrated CDL backscatter signal. Then it is validated by comparing the retrieved calibrated AOD at 1550 nm from CDL signal and that from sun-photometer measurements. Good agreement between them with the correlation of 0.96, the RMSE of 0.0085, and the mean relative error of 22% is found. From the comparison results of these three experiments, sun photometer is verified to be an effective reference instrument for the calibration of CDL return signal and the aerosol optical properties measurement with CDL is feasible. It is expected to promote the study on the aerosol flux and transport mechanism in the planetary boundary layer with the widely deployed CDLs.

SIGNIFICANCE STATEMENT: A practical method to calibrate and retrieve the vertical profiles of aerosol optical properties with coherent Doppler lidar (CDL) is proposed. Besides the wind field measurement ability, the extended capability of CDL in observing the aerosol optical properties is developed. In this method, a collocated sun photometer is operated as the reference instrument to calibrate and validate the aerosol optical properties from CDL. Since sun photometers and CDLs are world-widely deployed, this method has significant practical value. Additionally, once a CDL is well calibrated, it is promising to mount it on various platforms for simultaneous observations of aerosol optical properties and wind fields. Consequently, the CDL has the potential to measure the aerosol fluxes and vertical transport within the planetary boundary layers.

KEYWORDS: Boundary layer; Lidars/Lidar observations; Remote sensing; Aerosol optical properties

1. Introduction

As one of the most complicated and important atmospheric constituents, aerosol particles interact with solar radiation through absorption and scattering. Atmospheric physical and chemical processes are significantly affected by direct and indirect radiation forcing of aerosol (Boucher et al. 2013). To better understand the mechanism of radiation forcing and energy transmission, vertically resolved measurements of aerosol optical properties and aerosol vertical transport processes are of great interest (Weitkamp 2006).

Due to the spatiotemporal variation of the aerosol properties, it is difficult to evaluate the aerosol influences on the radiation transport and climate model. Fortunately, with the development of the laser remote sensing technology, lidar has become a reliable technique in measuring the aerosol optical properties. Aiming at the routine observation of high-quality aerosol optical properties, the Raman lidar (Ansmann et al.

1990, 1992) and the high-spectral-resolution lidar (HSRL) techniques (Eloranta 2005; Shipley et al. 1983; Sroga et al. 1983) are state-of-the-art active remote sensing methods. Considering the long-range transport and physicochemical changes of aerosol, the establishment of large coverage lidar observation networks is necessary. Presently, several lidar observation networks including the European Aerosol Research Lidar Network (EARLINET) (Böckmann et al. 2004; Matthais et al. 2004; Pappalardo et al. 2004), the Asian dust network (AD-NET) (Murayama et al. 2001), the Latin America Lidar Network (LALINET) (Antuña-Marrero et al. 2017; Barbosa et al. 2014; Guerrero-Rascado et al. 2016), the NOAA Center for Remote Sensing Science and Technologies (CREST) Lidar Network (CLN) (Hoff et al. 2009), the Eurasian Commonwealth of Independent States Lidar Network (CIS-LiNet) (Chaikovsky et al. 2005), and Global Atmosphere Watch (GAW) Aerosol Lidar Observation Network (GALION) (Hoff et al. 2008) are established to perform comprehensive aerosol measurement worldwide (Chaikovsky et al. 2016). Additionally, the space-borne lidars including the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) carried by CALIPSO (Winker et al. 2009), and the Atmospheric Laser Doppler Instrument (ALADIN) carried by Atmospheric Dynamics Mission (ADM)-Aeolus (Ansmann et al. 2007; Baars et al. 2020; Flamant et al. 2008;

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DOI: 10.1175/JTECH-D-20-0190.1

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Martinet et al. 2018; Straume et al. 2019) are capable of providing the global aerosol optical properties profiling. Furthermore, the Earth Cloud Aerosol and Radiation Explorer (EarthCARE), which is planned to launch in 2021 will contribute to study how clouds and aerosols affect the weather and climate (http://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/EarthCARE_mission_to_improve_weather_forecasts). Besides, the Aerosol Robotic Network (AERONET) (Dubovik and King 2000), which is a ground-based remote sensing aerosol network established by NASA and CNRS and is expanded by international collaboration (https://aeronet.gsfc.nasa.gov/new_web/system_descriptions.html), has been realized to provide the reliable and continuous data of aerosol column-integral properties like aerosol optical depth (AOD) for different data quality levels and generally used for collaborative observation or validation with other instruments.

The coherent Doppler lidar (CDL) basically performs wind measurements by detecting Doppler shift of the backscattered light excited by atmospheric aerosols, retrieving the line-of-sight (LOS) velocity and eventually obtaining atmospheric wind field by three-dimensional components (Reitebuch 2012; Schwiesow et al. 1985, 1983; Weitkamp 2006; Wu et al. 2016). It is widely used for wind field measurements and atmospheric dynamics investigations (Reitebuch 2012; Reitebuch et al. 2001; Smalikho 2003; Smalikho and Banakh 2017; Zhai et al. 2017, 2018). To retrieve the vertical aerosol flux and investigate the aerosol transport process, it is frequently used to combine the CDL and other types of aerosol lidars (Engelmann et al. 2008; Wandinger et al. 2004) to accomplish the simultaneous measurements. However, the cost of comprehensive observations with several lidars is expensive. Considering that the intensity of the CDL echo signals can characterize the concentration of atmospheric particles as well, it is worthwhile to perform the retrieval of the aerosol optical properties based on CDL signals. It should be emphasized that the CDL-retrieved aerosol optical properties have to be calibrated by the collocated reference instruments, such as Raman lidars, HSRL, and sun photometer. Many related studies have been conducted since the 1980s. Bufton et al. (1983) calibrated the mean backscatter of the airborne oceanographic lidar, which emitted laser beams at the wavelengths of 355 nm, 532 nm, and 9.5 μm , and compared beach, sand, and ocean backscatter signals (Bufton et al. 1983). Bou Karam et al. (2008) studied the dust transport in the intertropical discontinuity (ITD) region over western Niger by combination of an airborne wind lidar at 10.6 μm and an airborne differential absorption Lidar pour l'Etude des interactions Aerosols Nuages Dynamique Rayonnement et du cycle de l'Eau (LEANDRE) 2 at 732 nm (Bou Karam et al. 2008). Schumann et al. (2011) investigated volcanic ash plumes over Europe between southern Germany and Iceland by airborne 2 μm Doppler wind lidar and in situ aerosols and trace gases measurements as well as comparing results of two techniques (Schumann et al. 2011). Weinzierl et al. (2012) determined the lower and upper boundaries of the aerosol layers with a vertical resolution of 100 m and the uncertainty is ± 150 m relied on an airborne 2 μm Doppler wind lidar (Weinzierl et al. 2012). Recently, Chouza et al. (2015) presented a new

calibration and aerosol optical properties retrieval method from airborne 2 μm Doppler wind lidars and applied this method to the SALTRACE experiment in June–July 2013. The retrieved backscatter and extinction coefficient profiles are within 20% of Portable Lidar System (POLIS) aerosol lidar and CALIPSO satellite measurements (Chouza et al. 2015). Then Chouza et al. (2016) retrieved wind and aerosol optical parameters simultaneously and investigated the Saharan dust long-range transport based on airborne Doppler wind lidars for the first time. In this research, they compared the results with the Monitoring Atmospheric Composition and Climate (MACC) model and analyzed the different characteristics related to the long-range transport of three regions (Chouza et al. 2016). This method needed to provide other input parameters to retrieve aerosol backscatter coefficient profiles including vertical distribution, aerosol type, and particle depolarization coefficient.

Based on the above studies and the existing experimental condition, in this paper, we present a practical method to retrieve and calibrated the aerosol optical properties with CDL and sun photometer. Besides the wind field measurement ability, the extended capability of CDL in observing the aerosol optical properties is developed. For the calibration process, we use the AOD at multiwavelength (440, 670, 870, and 1020 nm) from sun-photometer measurements to estimate the AOD at 1550 nm, which is used to calibrate the integrated return signal of CDL. Afterward the calibration constant and the wavelength conversion factors are determined. The AOD at the wavelength of 1550 nm from CDL measurements is obtained by integrating the calibrated extinction coefficient. Then it is compared with the AOD at 1550 nm estimated from sun-photometer measurements.

The paper is organized as follows. The description of the involved instruments is provided in section 2. Section 3 introduces the aerosol optical properties retrieval method based on CDL including estimation of AOD at 1550 nm with sun photometer, calibration, and validation. Then three field experiments are described and the results of aerosol optical properties retrieval are analyzed and discussed in section 4. Section 5 summarizes the conclusions and describes the outlook of future studies.

2. Instruments

a. Sun-photometer description

In this work, a sun photometer of the type CIMEL-318 is deployed to provide the AOD and Ångström exponent at the wavelengths of 440, 670, 870, and 1020 nm, which have minimal molecular absorption (Holben et al. 1998). The temporal resolution of AOD from sun-photometer measurements is about 10 min. For each wavelength, the sun photometer measures the sun and sky radiance on the sun-photometer surface and based on Beer–Lambert–Bouguer law, the total optical depth $\tau(\lambda)$ can be derived from Eq. (1) (Bayat et al. 2011):

$$L(\lambda) = \frac{L_0(\lambda)}{R^2} \exp[-m\tau(\lambda)], \quad (1)$$

where $L(\lambda)$ is the solar radiance detected, $L_0(\lambda)$ is the solar radiance before passing through the atmosphere, R is mean

TABLE 1. The key specifications of the CDL system.

Qualification	Specification
Wavelength (nm)	1550
Pulse repetition rate (kHz)	10
Pulse energy (μJ)	160
Pulse width (ns)	250 (100–400, adjustable)
Linewidth of laser (kHz)	15
Measurement range (m)	45 to 6000
Range resolution (m)	15 (15/30)
Temporal resolution (s)	1
Scanner pointing accuracy ($^\circ$)	0.1
Beam radius (mm)	28

distance between the sun and Earth in astronomical units (au; 1 au = 149 597 870 700 m) when observing, and m is the relative optical air mass. The total optical depth $\tau(\lambda)$ can be regarded as the sum of aerosol optical depth $\tau_a(\lambda)$, Rayleigh optical depth $\tau_r(\lambda)$, and optical depth of other mixed gases in the atmosphere $\tau_g(\lambda)$. So $\tau_a(\lambda)$ is calculated by Eq. (2) (Bayat et al. 2011):

$$\tau_a(\lambda) = \tau(\lambda) - \tau_r(\lambda) - \tau_g(\lambda). \quad (2)$$

The Rayleigh optical depth $\tau_r(\lambda)$ depends on the wavelength and the site pressure and can be determined relied on empirical relationship (Bodhaine et al. 1999). For optical depth of other mixed gases in the atmosphere $\tau_g(\lambda)$, it is frequently neglected except at 670 nm because the ozone absorption needs to be considered (Holben et al. 1998). The ozone optical depth at 670 nm is estimated based on daily averaged ozone column abundance from Total Ozone Mapping Spectrometer (TOMS) (Bayat et al. 2011; Burrows et al. 1999; McPeters et al. 1998).

The relationship between $\tau_a(\lambda)$ and λ can be obtained by using a quadratic polynomial fitting in logarithmic coordinates as shown in Eq. (3) (King and Byrne 1976):

$$\ln \tau_a(\lambda) = \alpha_0 + \alpha_1 \ln \lambda + \alpha_2 (\ln \lambda)^2. \quad (3)$$

By the output Ångström exponent from sun photometer, the most appropriate lidar ratio was chosen in our calculation based on the location and weather according to the empirical value that Müller et al. (2007) reported.

b. Coherent Doppler lidar description

The CDL of type Wind3D 6000 applied in this study has been jointly developed by Ocean University of China (OUC) and Qingdao Leice Transient Technology Co., Ltd. It is designed with consideration for the needs of the meteorological application, wind energy industry and aviation safety. The CDL works at the wavelength of 1550 nm. The pulse energy is 160 μJ and the pulse repetition rate is 10 kHz. The specifications of CDL are summarized and listed in Table 1 and the schematic diagram is presented in a separate literature (Wu et al. 2016). After the analog-to-digital converter (A/D) and a fast Fourier transform (FFT) transform, the range-resolved power spectrum can be calculated. For a single shot, with a given range gate at distance r , the backscatter power spectrum

FIG. 1. The normalized backscatter power data points (blue stars) and the polynomial fitting heterodyne efficiency function (red line) corresponding to line-of-sight distance (1015 LST 15 Mar 2019 at the meteorological observatory of Suizhong, China).

is expressed as $\hat{P}_s(r, n)$. To reduce the influence caused by large amplitude variations of single shots (Chouza et al. 2015) and improve the signal-to-noise ratio (SNR), the power spectrum of many shots are averaged as shown in Eq. (4):

$$\hat{P}_s(r, n)_{\text{shot-averaged}} = \frac{1}{N} \sum_{k=1}^N \hat{P}_s(r, n), \quad (4)$$

where $\hat{P}_s(r, n)$ is the backscatter power spectrum at distance r of the shot k and N is the number of averaged shots, which is set as 10 000 because the pulse repetition frequency of the CDL is 10 kHz and it corresponds to the highest temporal resolution (1 s) of the CDL (Wu et al. 2019, 2016). During the data preprocessing, the background noise that is determined as the mean value of the power spectrum of last five range gates is removed from the $\hat{P}_s(r, n)$. Hence the backscatter power $P(r)$ is rewritten as Eq. (5) presented by Chouza et al. (2015):

$$P(r) = \sum_{n=n_1}^{n_2} \hat{P}_s(r, n)_{\text{shot-averaged}}, \quad (5)$$

where $n_1 = n_{\max} - n_w/2$, $n_2 = n_{\max} + n_w/2$, $n_{\max}$ is the position where the power spectrum of a given range gate is maximum, and n_w is the width of spectral peak.

According to the lidar equation (Weitkamp 2006), for a given LOS, the backscatter power could be expressed as Eq. (6):

$$P(r) = KE_0 \eta_h(r) \frac{1}{r^2} \beta(r) \exp \left[-2 \int_0^r \alpha(R) dR \right], \quad (6)$$

where E_0 is pulse energy, η_h is heterodyne efficiency, $\beta(r)$ is the backscatter coefficient, and $\alpha(R)$ is the extinction coefficient. System constant K can be written as Eq. (7):

$$K = \frac{c}{2} A \frac{\eta}{\eta_h(r)} O(r), \quad (7)$$

FIG. 2. Estimation of AOD at 1550 nm from sun-photometer measurements based on polynomial fitting (15 Mar 2019 at the meteorological observatory of Suizhong, China).

where c is the light speed, A is the aperture of the telescope, η is the overall system efficiency, and $O(r)$ is the overlap function. After the range, pulse energy and heterodyne efficiency correction, the return signal is expressed as Eq. (8). The output pulse energy of the CDL is modulated with temperature and current and it is monitored with the pump current. The heterodyne efficiency function is estimated by polynomial fitting to the normalized backscatter power (Chouza et al. 2015) as shown in Fig. 1:

$$\frac{P(r)r^2}{E_0\eta_h(r)} = K\beta(r) \exp \left[-2 \int_0^r \alpha(R) dR \right]. \quad (8)$$

To make it sample, the left part of Eq. (8) is expressed as $\langle P_{CDL,1550nm}(r) \rangle$. Because it is difficult to confirm the specific instrumental parameters of CDL system accurately, the system constant K cannot be calculated directly according to Eq. (7). In this paper, one practical method is introduced in section 3 to determine the CDL system constant based on the simultaneous observations with the sun photometer.

3. Methodology

a. Estimation of AOD at 1550 nm with sun photometer

As a reference instrument in observing the aerosol optical properties, the sun photometer is able to provide the $AOD_{SPM}^{\lambda_s}$ at the multiwavelength of 1020, 870, 670, and 440 nm with a temporal resolution of 10 min. To calibrate the signal of CDL, the $AOD_{SPM}^{\lambda_s}$ at the wavelength of 1020, 870, 670, and 440 nm have to be converted to the AOD_{SPM}^{1550} . As described in section 2a, by performing a quadratic polynomial fit in logarithmic coordinates, the relationship between $\tau_a(\lambda)$ and λ is confirmed. Hence the AOD_{SPM}^{1550} could be estimated. A measurement case of AOD_{SPM}^{1550} is presented in Fig. 2. It should be emphasized that the AOD_{SPM}^{1020} is not included to make polynomial fitting because it may be affected by the water vapor absorption and induce the inaccuracies (Bayat et al. 2011).

b. Calibration method and validation

As introduced in section 2b, Eq. (8) would be expressed as Eq. (9):

$$\langle P_{CDL,1550nm}(r) \rangle = K\beta^{1550}(r) \exp \left[-2 \int_0^r \alpha^{1550}(R) dR \right]. \quad (9)$$

FIG. 3. Overview of the calibration procedure.

FIG. 4. Flowchart of the instrumental calibration and the retrieval procedure.

To use the AOD_{SPM}^{1550} to calibrate the $\langle P_{CDL,150nm}(r) \rangle$, we need to obtain the extinction coefficient $\alpha^{1550}(r)$ for integral and calculation of the AOD_{CDL}^{1550} . The 1-min averaged backscatter signals of CDL were used to integrate in calibration and validation processes. Then the calibration constant is determined from Eq. (10):

$$C = \frac{AOD_{SPM}^{1550}}{AOD_{CDL}^{1550}}. \quad (10)$$

The extinction coefficient $\alpha^{1550}(r)$ can be retrieved through an iterative process, which is shown in Fig. 3.

For the first step, the initial value of $\alpha^{1550}(r)$ is assumed as Eq. (11):

$$\alpha_{initial}^{1550}(r) = 0.01\beta_m^{1550}(r), \quad (11)$$

where $\beta_m^{1550}(r)$ is the molecular backscatter coefficient at 1550 nm and it can be calculated based on the Rayleigh scattering theory and the standard atmosphere model of the United States of 1976. The value of 0.01 has no special meaning here. We just set a small initial value and to determine the calibration constant by iterating until it converges as described below. Then atmospheric attenuation $T_{1550}^2(r)$ can be obtained by Eq. (12):

FIG. 5. Layout of CDL and sun-photometer joint observation, at (a) the meteorological observatory of Suizhong ($40^{\circ}19'44''\text{N}$, $120^{\circ}18'80''\text{E}$), (b) Qingdao Leice Transient Technology Co., Ltd. ($36^{\circ}8'50''\text{N}$, $120^{\circ}28'43''\text{E}$), and (c) OUC ($36^{\circ}9'34''\text{N}$, $120^{\circ}29'30''\text{E}$).

$$T_{1550}^2(r) = \exp \left[-2 \int_0^r \alpha^{1550}(R) dR \right]. \quad (12)$$

So that by transposition, $\beta^{1550}(r)$ is calculated by means of Eq. (13):

$$\frac{\langle P_{\text{CDL}, 1550\text{nm}}(r) \rangle}{T_{1550}^2(r)} \frac{1}{K} = \beta^{1550}(r). \quad (13)$$

According to the lidar ratio set based on sun-photometer measurements, and through first iteration, $\alpha^{1550}(r)$ is retrieved following Eq. (14):

$$\alpha^{1550}(r) = \beta^{1550}(r)S, \quad (14)$$

where S is the lidar ratio, which equals to the aerosol extinction coefficient divided by aerosol backscatter coefficient.

Then we can repeat the process mentioned above and operate the next iteration to retrieve backscatter coefficient $\beta^{1550}(r)$ and extinction coefficient $\alpha^{1550}(r)$. And at the end, $\text{AOD}_{\text{CDL}, i}^{1550}$ and C_i could be calculated by Eqs. (15) and (16):

$$\text{AOD}_{\text{CDL}, i}^{1550} = \int_0^r \alpha_i^{1550}(R) dR \quad \text{and} \quad (15)$$

$$C_i = \frac{\text{AOD}_{\text{SPM}}^{1550}}{\text{AOD}_{\text{CDL}, i}^{1550}}, \quad (16)$$

where i is the iteration number. It needs to be emphasized that linear extrapolation was made to $\alpha^{1550}(r)$ in the range of 15–120 m before integration. Then the integral from ground to 15 m was negligible and the atmospheric attenuation equaled to 1 in this range (Stachlewska et al. 2010). We can find that C_i will be converged after three iterations in all the observations so the results of the third iteration are used in this paper.

To check the performance of the described method, by applying the procedure introduced above to the processing

of validation measurements datasets, the extinction coefficient $\alpha^{1550}(r)$ and the calibrated $\text{AOD}_{\text{CDL-corrected}}^{1550}$, which is the integral of $C\alpha^{1550}(r)$ are determined. Hence the $\text{AOD}_{\text{SPM}}^{1550}$, which is obtained from sun-photometer measurements and the $\text{AOD}_{\text{CDL-corrected}}^{1550}$, which is estimated from CDL measurements are compared. The flowchart of the instrumental calibration and the retrieval procedure are provided in Fig. 4.

4. Experiments and measurements

a. Experiments

To confirm the calibration constant and verify the retrieval method, three field joint experiments with CDL and sun photometer were specially designed and conducted. The first experiment is performed at the meteorological observatory of Suizhong ($40^{\circ}19'44''\text{N}$, $120^{\circ}18'80''\text{E}$), Liaoning Province, from 9 to 19 March 2019. The second experiment is operated at the observation platform of Qingdao Leice Transient Technology Co., Ltd. ($36^{\circ}8'50''\text{N}$, $120^{\circ}28'43''\text{E}$), Shandong Province, on 9, 11, and 24 September in 2019. The third experiment is carried out at OUC ($36^{\circ}9'34''\text{N}$, $120^{\circ}29'30''\text{E}$) on 11 August and 5, 7, and 9 September in 2020. The layout of CDL and sun photometer is shown in Fig. 5. And the other details of these three experiments and CDL scanning mode setting are listed below

TABLE 2. Details of experiments and CDL scanning mode setting.

Expt	Date	Scanning mode	Purpose
First	15 Mar 2019	DBS	Calibration
	9–19 Mar 2019		Validation
Second	9 and 11 Sep 2019	Vertical pointing	Validation
	24 Sep 2019		Calibration
Third	11 Aug 2020	Vertical pointing	Calibration
	5, 7, and 9 Sep 2020		Validation

FIG. 6. (a) Sun-photometer results of 15 Mar at the meteorological observatory of Suizhong, China, and data for calibration are framed in a blue box. (b) Calibration constants (after quality control) based on original iteration data (blue dots) and data after near-surface linear interpolation (red dots).

in Table 2. The results and discussion of three experiments will be discussed in section 4b.

b. Results and discussion

Resulting from the depolarization effect on the backscatter signal from aerosol particles, the backscatter signal consists of vertically polarized and horizontally polarized signal. In the CDL system, the backscatter signal and the reference signal from laser are combined by an optical coupler and then detected by a balanced detector. During the coupling and heterodyne processes, for a polarization-sensitive CDL, only the backscatter signal component with the same polarization direction as the reference signal could be measured. Hence, this method should be used with caution for the polarization-sensitive CDL when the depolarization ratio of aerosol load is too high, e.g., dust and volcanic ash aerosols with depolarization ratios larger than 0.1 (at 532 nm). In the first experiment, measurement tests are operated in several dusty days and it is proved that the polarization-sensitive CDL will

underestimate the AOD. Fortunately, the CDLs those are capable of detecting dual-polarization backscatter signals are developed as well (Abari et al. 2015). In this case, this method is applicable to all the aerosol loads. In this paper, the calibration methodology is introduced. With the development of the dual-polarization CDL, this method will have a wider application scope.

During the field experiments we conducted, it should be emphasized that because the CDL we used only samples copolarization component of backscattering signal to beat with the local oscillation, all the observation data measured on dusty days has to be excluded with the help of “dust score index” data provided by AIRS/Aqua. Once the dusty data are dropped, the rest aerosol depolarization ratios are smaller than 0.08 (Burton et al. 2012), which are acceptable for the calibration and validation procedures. Hence, the datasets of 15 March 2019, 24 September 2019, and 11 August 2020 when the synoptic conditions are free of high-depolarization aerosol load (e.g., dust, volcanic ash) are chosen to perform

FIG. 7. (a) Sun-photometer results of 24 Sep at Qingdao Leice Transient Technology Co., Ltd., China, and data for calibration are framed in blue boxes. (b) Calibration constants (after quality control) based on original iteration data (blue dots) and data after near-surface linear interpolation (red dots).

FIG. 8. (a) Sun-photometer results of 11 Aug at OUC, China, and data for calibration are framed in a blue box. (b) Calibration constants (after quality control) based on original iteration data (blue dots) and data after near-surface linear interpolation (red dots).

the calibration procedure and the data from the other days are applied to verify the retrieval method. From the sun-photometer measurements, it is found that weather is stable within the time period marked in the blue boxes in Figs. 6a, 7a, and 8a, thus the data in these three periods are selected for the calibration procedure. The calibration results are shown in Figs. 6b, 7b, and 8b. In these figures, the calibration constants based on original iteration data (blue dots) and data after near-surface linear interpolation (red dots) are presented individually. The linear extrapolation was used when interpolating. We can see that they have the same tendency but slight differences in values, which means the differences are slight whether or not to make near-surface interpolation. Additionally, the calibration constants are time-variant within the chosen period, hence the atmospheric conditions have to be monitored and the quality control for the SNR of CDL and AOD of sun photometer is necessary. Besides, we use the Grubbs test (Grubbs 1969; Stefansky 1972) to make quality control and reject outliers. In this paper, the confidence interval is set to 90%. Finally, we average all calibration constants after quality control and regard the mean value as the calibration constant C , which is used in validation. Because another CDL was used to make observations in the third experiment, it is reasonable that calibration constant calculated in this experiment was slightly different from the other two experiments due to system differences.

Then the corresponding validation results of all the low-depolarization aerosol load days are presented in Fig. 9, which contains the results of original data (blue dots) and the results after near-surface interpolation (red dots). Most of the dots are distributed along the line of $y = x$, which means the AOD_{CDL}^{1550} retrieved from CDL measurements and AOD_{SPM}^{1550} from sun-photometer measurements show a good agreement. However, there are still some pairs far away from $y = x$. The divergences may result from the different observation zone and the different temporal resolution of these two instruments. Additionally, AOD from sun-photometer

measurements would also introduce errors including 1% of the standard deviation for AOD and 5% of the standard deviation in sky radiance measurements (Dubovik et al. 2000). Specific validation results including comparison numbers N , the coefficient of determination R^2 , the root-mean-square error (RMSE), and the mean relative error σ are summarized and listed in Table 3. The equation to estimate relative error σ_1 is expressed as Eq. (17). We can find that the correlation between AOD_{CDL}^{1550} and AOD_{SPM}^{1550} is greater than or equal to 0.96, and RMSE is less than or equal to 0.0085. The mean relative error σ is less than or equal to 22%. Consequently, for R^2 and RMSE, the results of data after near-surface interpolation are slightly better while the mean relative error of original data is smaller:

$$\sigma_1 = \frac{|AOD_{SPM}^{1550} - AOD_{CDL}^{1550}|}{AOD_{SPM}^{1550}}. \quad (17)$$

FIG. 9. Validation results of all the low-depolarization aerosol load days, which include results of original data (blue dots) and data after near-surface interpolation (red dots).

TABLE 3. Validation results of all the low-depolarization aerosol load days in the three experiments.

Data type	N	R^2	RMSE	σ
Original iteration data	58	0.96	0.0085	21%
Data after near-surface linear interpolation	58	0.97	0.0080	22%

Last, a weather process case on 18 March 2019 is presented and discussed. According to the experiment log, aerosol layers appeared near the ground after 1105 LST. The resulting corrected extinction and wind field products are shown in Fig. 10. From Fig. 10, we can find after 1105 LST, some vertical convection appeared below 800 m and corresponding horizontal wind speed was increased at the same time. This phenomenon may have caused well-mixed aerosol at this special scale and its transport to the higher altitude. Thus, extinction coefficient at 1550 nm within this height range was significantly larger.

5. Conclusions

In this paper, a method to calibrate the CDL return signals based on simultaneous sun-photometer measurements and to retrieve aerosol optical properties is introduced. Three field experiments are conducted to verify the feasibility of the method. We discussed the results of the aerosol optical properties retrieval and major conclusions are summarized as below.

Through the results of these three experiments, the sun photometer is verified to be an effective reference instrument for the calibration of CDL return signal.

After the calibration of the return signal, the backscatter power of CDL could be iterated and corrected to retrieve the aerosol optical properties at 1550 nm, which contains backscatter coefficient, extinction coefficient and AOD. In the validation of these three experiments, the AOD_{CDL}^{1550} retrieved from CDL measurements and AOD_{SPM}^{1550} from sun-photometer measurements show good agreement with the correlation between AOD_{CDL}^{1550} and AOD_{SPM}^{1550} is greater than or equal to 0.96, the RMSE is less than or equal to 0.0085 and the mean relative error σ is less than or equal to 22%. That means aerosol optical properties retrieved relied on CDL measurement accurately becomes possible.

It should be emphasized that, for the polarization-sensitive CDL, this method should be used with caution when the depolarization ratio of atmospheric aerosol load is too high, e.g., dust and volcanic ash aerosols with depolarization ratios larger than 0.1 (at 532 nm). For the CDLs those are capable of detecting dual-polarization backscatter signals, this method would be applicable to all the aerosol loads.

In further studies, it is planned to continue conducting joint observation of CDL and sun photometer aiming at reducing calibration constants fluctuation and making calibration more accurate. Furthermore, with simultaneous observation of aerosol and wind, the CDL has the potential to measure the aerosol fluxes within the planetary boundary layers and to contribute to the study of the aerosol transport process and physical mechanism.

FIG. 10. (a) Coherent Doppler lidar extinction coefficient at 1550 nm in 1 min and 15 m resolution, along with wind field results with 5 min and 15 m resolution that contain (b) horizontal wind speed, (c) horizontal wind direction and, (d) vertical velocity measured of 18 Mar 2019 at the meteorological observatory of Suizhong, China. The aerosol layer near surface is framed in the red box, and the range of enhanced vertical convection and horizontal wind speed near surface is framed in the blue box.

Acknowledgments. This work is jointly supported by National Key Research and Development Program of China under Grant 2016YFC1400904, Key Research and Development Program of Shandong Province (International Science and Technology Cooperation) under Grant 2019GHZ023, and the National Natural Science Foundation of China (NSFC) under Grants 41905022 and 61975191. We thank our colleagues including Tong Cui, Jie He, Ziwang Li, and Junbo Wang from Ocean University of China (OUC) for preparing and operating the CIMEL sun photometer and Dahai Wang from Qingdao Leice Transient Technology Co., Ltd., for preparing and operating the CDL.

Data availability statement. Due to confidentiality agreements, supporting data can only be made available to bona fide researchers subject to a nondisclosure agreement. To get the data, please contact wush@ouc.edu.cn at Ocean University of China.

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