Optimized Broadband Extinction Method for Retrieving 500 nm AOD with Long-Term Direct Solar Radiation: Model Test and Application

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ABSTRACT

A traditional broadband extinction method is improved by introducing the cloud-screening module and aerosol modal adjustment module, and the new approach is known as optimized broadband extinction method (OBEM). Based on OBEM, it could retrieve 500 nm aerosol optical depth (AOD) database with the use of direct solar radiation. Comparison of the monthly average AOD from OBEM and Chinese Sun Hazemeter Network (CSHNET) for 2006–2010 over Beijing site shows that the retrievals and observations display a high degree of consistency. The correlation equation is \( Y = 1.00X - 0.01 \) with a correlation coefficient \( R^2 \) of 0.83 and root-mean-square error (RMSE) of 0.08. The largest relative error for the yearly average value is only 3.85%. So it is clear that the OBEM could serve as an effective tool to retrieve highly accurate historical 500 nm AOD data and implement homogenization with the current observational 500 nm AOD monitored by satellites and sun-photometers. The yearly average AOD of Beijing in 1993–2010 is 0.58 ± 0.03, and the seasonal AODs in MAM (March–April–May) and JJA (June–July–August) are obviously higher than SON (September–October–November) and DJF (December–January–February), with values of 0.70 ± 0.14 and 0.64 ± 0.16, respectively. The long-term 500 nm AOD reveal significant periodic inter-annual characteristics with a slight downward trend, and the irradiance also decreased due to the extinction of increasing total-cloud amount.

Keywords: Aerosol optical depth at 500 nm; Optimized broadband extinction method; Cloud screening module; Aerosol modal adjustment module.

INTRODUCTION

Atmospheric aerosols play an important role in the terrestrial climate system and air quality monitoring. The aerosols can scatter and absorb the sunlight and directly affect the balance of earth's solar radiation and energy budget, in addition, it can also act as cloud condensation nuclei (CCN) and ice nuclei (IN), affecting the formation process and lifetime of clouds and precipitation events indirectly (Charlson et al., 1992; Penner et al., 1994; Che et al., 2013; Tao et al., 2014). On the other hand, aerosol particles are severe environment pollutants that reduce the air quality. Those aerosol particles with diameter less than 10 µm and 2.5 µm are defined as PM10 and PM2.5, respectively. They can invade to human bronchial area and lungs, causing serious human health problems. Furthermore, their extinction effects show significant impact on the atmospheric visibility, threatening the transportation safety and human daily life (Zhang, 2009). Thus the noteworthy climate effects and air-pollution effects of aerosols have gradually become a high-interest field of study in atmospheric science worldwide.

AOD is a key physical parameter in aerosol climate effect research and environmental pollution evaluation, besides, this parameter also shows greater significance in correction of satellite remote sensing. Currently, ground-based and remote-sensing are two main methods used to monitor AOD values. Satellite remote-sensing is a highly effective
tool for obtaining high-spatial resolution AOD data, but due to the influence of surface albedo and uncertainty in aerosol distribution, the accuracy of the satellites should be further improved (Li et al., 2007; Wang et al., 2007a, 2010). Relatively speaking, ground-based observation is a more exact approach to capturing aerosol optical properties. At the beginning of this century, many organizations established their own aerosol-monitoring networks on the Chinese mainland. In 2002, the Aerosol Robotic Network (AERONET) established more than 30 sites in succession across China (Beijing, Yulin, et c.), equipping them with CE-318 sun-photometers. To obtain in-depth knowledge of dust aerosol optical properties in northern China and to test the accuracy of satellites, the China Meteorological Administration (CMA) first built more than 20 sites to organize the China Aerosol Remote Sensing Network (CARSNET) and also used CE-318 sun-photometers to measure solar radiation. In 2004, this network began professional and normal operation. CSHNET was established by the Institute of Atmospheric Physics (IAP) in August 2004 using portable LED hazemeters in the initial 23 sites (Xin, 2007). The relative error of this type of AOD product is less than 5.00% compared with the CIMEL instrument, thus demonstrating its reliability and veracity (Xin, 2006).

In 2011, the Campaign on Atmospheric Aerosol Research network of China (CARE-China) was built based on CSHNET with 36 sites equipped with Microtots-II sun-photometers to collect unified observations (Xin et al., 2015). These 36 sites represent the typical ecosystems of China, and the observation results can describe the spatial and temporal distribution characteristics of aerosol optical properties for regional backgrounds in China. In addition, this network also offers the observations necessary to validate and assess the applicability of international satellites over China (Li et al., 2007; Wang et al., 2007a, b; Liu et al., 2010; Wang et al., 2010) and is evaluated to apply the aerosol direct radiation effect in China (Kwon et al., 2007; Li et al., 2010) and to test the accuracy of regional climate and environment models, such as Reg-CM3 (Xin et al., 2010), RAMS-CMAQ (Han et al., 2009, 2010, 2011), MATCH (Yin et al., 2009; Zhang et al., 2012). However, including all of the networks mentioned above, only ten years of AOD observation data have been available until now, and thus reconstructing the historical AOD database is necessary for climate research and air pollution evaluation in China.

Since the International Geophysical Year (IGY) during 1957–1958, measurements of solar radiation have been collected routinely worldwide. During that campaign period, a large amount of radiation observation instruments and an entire set of radiation observation methods offered by the former Soviet Union were introduced to China, and 122 radiation observation sites were set up in the initial stage to monitor the daily solar radiation. In 1989, CMA began to upgrade the old solar radiation network using the new comprehensive radiometers developed by China to replace the outdated instruments and perform the latest meteorological radiation observations. As of 1993, the improvement project was fundamentally completed, and the monitoring temporal resolution was increased to a new level of hourly values. After years of efforts, a great number of observational radiation data were accumulated. These databases document the decadal variation of solar radiation and also contain potential information for aerosols and clouds. Consequently, how to make effective use of these databases to reveal aerosol variations has become an important issue for many experts and scholars (Xu, 2008). Dating back to 1972, Unsworth and Monteith (1972) first proposed a parameterized model by applying broadband solar radiation to retrieve the broadband aerosol optical depth (BAOD). Subsequently, many professors worked to establish the broadband extinction method (BEM) using broadband direct solar radiation to calculate the AOD (Blanchet, 1982; Qiu, 1995, 1997; Guymard, 1998; Qiu, 1998; Kudo et al., 2010a, b, 2011). Until now, scientists in China have obtained many long-term historical AOD databases at 700 nm or 750 nm (the equivalent wavelength was 700 nm or 750 nm) with BEM (Luo et al., 2000; Qiu et al., 2000; Luo et al., 2001, 2002; Zong et al., 2005). But in general, 500 nm is the most widely monitored (Both by satellites and ground-based instruments) and analyzed wavelength, and thus the retrieval result cannot be compared with the observations. In another aspect, the retrieval model is based on the ideal Junge spectral distribution, assuming $\nu = 3$, but the main-control models under various backgrounds show significant differences according to the CSHNET monitoring results. In addition, effective removal of cloud-contamination radiation data is another key point for use of the retrieval model. All of these factors might result in a relatively higher error in the retrieval process.

We propose the OBEM model for retrieval of the AOD at 500 nm with the introduction of a cloud-screening module and an aerosol modal adjustment module. This research innovatively reconstructs the historical 500 nm AOD and achieves the normalized AOD variation characteristics for the most recent 18 years of Beijing.

**OPTIMIZED BROADBAND EXTINCTION METHOD**

**Introduction to the Cloud-Screening Module**

When retrieving AOD using the direct solar radiation data, it cannot be ignored that cloudy skies and random cloudlets can exhibit certain extinction effects on direct solar radiation, ultimately causing an increase in the retrieved AOD values. Hence, screening for clearness data is a prerequisite for retrieving AOD with direct solar radiation. In the optimized model, a cloud-screening module with high accuracy is added to filter the observational radiation data. Because the cloudy weather often accompanies with higher moisture and shorter sunshine, we set a threshold to total bright sunshine duration and relative humidity (RH), respectively, to screening the clearness. If the meteorological conditions satisfy $\text{①}$ or $\text{②}$ simultaneously, it can be estimated as a clear day.

$\text{①}$ Daily total bright sunshine duration observed by sunshine recorder is larger than 4 hours.

$\text{②}$ Daily mean relative humidity (RH) is less than 70%.

To assess the veracity of the cloud screening method, we filter the clearness cases from 2009 and 2010 for the Beijing site using this method, and the screening results
are compared with those days that contain real hazemeter observations (Shown in Fig. 1). The cloud-screening (red circles) results from 2009 and 2010 are 253 and 248, with corresponding observational clearness values of 257 and 248, among which the misjudgment percentages (B*/total*) of the two years are 9.49% and 9.68%, and the erroneous rejection percentages (C*/total*) are 10.89% and 9.68%, respectively. Another critical point that should be considered in this cloud screening process is that the sunshine duration and RH datasets are obtained at the Beijing Observatory, whereas the hazemeter observations are collected in the yard of the Iron Tower, IAP. A 20-kilometer distance exists between the two locations, and this factor might be highly important in increasing the misjudgment. Based on these factors, it can be assuredly concluded that the method is reliable for cloud screening.

**Introduction to the Aerosol Modal Adjustment Module**

Common sense observes that the different aerosol modals display various extinction effects for separated wavelengths. Under the assumption of a Junge spectral distribution, \( \tau(\lambda) \) can be calculated using the equation:

\[
\tau(\lambda) = \tau_{BAOD} \left( \frac{\lambda_{E}}{\lambda} \right)^{n} = \tau_{BAOD} \left( \frac{\lambda_{E}}{\lambda} \right)^{v-2}
\]

(1)

where

- \( \lambda_{E} \) is the equivalent wavelength.
- \( \tau_{BAOD} \) is the broadband aerosol optical depth.
- \( \alpha \) is the Angstrom exponent.
- \( v^{*} \) is the Junge spectral distribution parameter within a range of 2–4 (Sheng et al., 2003). However, in the previous calculation process, it is common to assume \( v^{*} \approx 3 \) to represent the particles with diameters larger than 0.1 µm suspended on land, and the corresponding Ångström exponent \( \alpha \approx 1 \) (Qiu et al., 2004).

The perennial observational results of CSHNET based on the Chinese ecosystem research network (CERN) showed that due to the seasonal differences of the aerosol modes under various ecosystems, the AOD and Angstrom exponent exhibit a certain regular cycle for seasonal variation. The range of the Angstrom exponents are 0.0–3.0, which illuminates that the preceding \( v^{*} \approx 3 \) (\( \alpha \approx 1 \)) assumption might not be accurate. According to the observational Angstrom exponents datasets offered by CSHNET, Xin (2007) gave the statistical Angstrom exponents according to different geographical area, ecosystem type and seasonal classification (Shown as Table 1). Thus, it is more precise to modify the aerosol spectral distribution parameter and achieve the optimization scheme for different ecosystem types.

**Model Construction**

The parameterized program for OBEM is shown in the following:

1. **Parameterized model for broadband aerosol optical depth** \( \tau_{BAOD} \) (Qiu, 2001). The parameterized model that uses broadband direct solar radiation \( S \) to retrieve AOD is determined as follow:

\[
\tau_{BAOD} = \frac{1}{m_{a}} \ln \left( \frac{\int_{\lambda_{1}}^{\lambda_{2}} S_{\lambda}(\lambda) T_{\lambda}(\lambda, \theta_{h}) A_{\lambda} T_{\lambda}(\lambda, \theta_{h}) d\lambda}{\int_{\lambda_{1}}^{\lambda_{2}} A_{\lambda} T_{\lambda}(\lambda, \theta_{h}) d\lambda} \right)
\]

(2)

\[
= \frac{1}{m_{a}} \ln \left( \frac{I_{a\text{max}}^{\lambda \text{max}}}{I_{a}} \right)
\]

**Fig. 1.** Tests of the cloud-screening module. Red circles shown for 2009 and 2010 represent the cloud screening results and blue circles represent the observational clearness (the observational clearness is defined as those days that have hazemeter observations). A- denotes the available results; B- denotes misjudgment components (misjudgment means that observed cloudy sky is classified as clearness by the cloud screening module); C- denotes the erroneous rejection components (errorneous rejection means observed clearness is classified as cloudy sky by the cloud screening module).
Table 1. Statistical analysis for seasonal average Angstrom exponents of different regional ecosystem stations of CSHNET (Xin, 2007).

<table>
<thead>
<tr>
<th>Station</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>DJF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanjiang</td>
<td>0.91</td>
<td>0.68</td>
<td>1.40</td>
<td>1.66</td>
</tr>
<tr>
<td>Hailun</td>
<td>2.23</td>
<td>1.31</td>
<td>2.50</td>
<td>2.21</td>
</tr>
<tr>
<td>Changbai Mt.</td>
<td>1.12</td>
<td>1.12</td>
<td>2.02</td>
<td>1.89</td>
</tr>
<tr>
<td>Shenyang</td>
<td>0.84</td>
<td>0.89</td>
<td>1.22</td>
<td>1.11</td>
</tr>
<tr>
<td>Fukang</td>
<td>0.77</td>
<td>0.82</td>
<td>1.28</td>
<td>1.05</td>
</tr>
<tr>
<td>Ordos</td>
<td>0.26</td>
<td>0.15</td>
<td>0.68</td>
<td>0.90</td>
</tr>
<tr>
<td>Shapotou</td>
<td>0.49</td>
<td>0.61</td>
<td>0.85</td>
<td>0.95</td>
</tr>
<tr>
<td>An sai</td>
<td>0.25</td>
<td>0.20</td>
<td>1.15</td>
<td>1.56</td>
</tr>
<tr>
<td>Haibei</td>
<td>0.47</td>
<td>0.88</td>
<td>1.09</td>
<td>1.10</td>
</tr>
<tr>
<td>Beijing</td>
<td>0.94</td>
<td>1.14</td>
<td>1.11</td>
<td>1.11</td>
</tr>
<tr>
<td>Beijing Forest</td>
<td>0.66</td>
<td>0.71</td>
<td>1.09</td>
<td>1.19</td>
</tr>
<tr>
<td>Dinghu Mt.</td>
<td>0.72</td>
<td>0.49</td>
<td>0.96</td>
<td>1.07</td>
</tr>
<tr>
<td>Xishuangbanna</td>
<td>1.67</td>
<td>1.11</td>
<td>1.40</td>
<td>1.65</td>
</tr>
<tr>
<td>Feng qiu</td>
<td>0.91</td>
<td>1.02</td>
<td>1.15</td>
<td>1.22</td>
</tr>
<tr>
<td>Taoyuan</td>
<td>0.92</td>
<td>0.92</td>
<td>1.13</td>
<td>1.10</td>
</tr>
<tr>
<td>Yanting</td>
<td>0.91</td>
<td>1.12</td>
<td>1.01</td>
<td>1.04</td>
</tr>
<tr>
<td>Lake Tai</td>
<td>0.72</td>
<td>0.57</td>
<td>1.00</td>
<td>0.95</td>
</tr>
<tr>
<td>Jiaozhou Bay</td>
<td>0.92</td>
<td>0.88</td>
<td>1.24</td>
<td>1.19</td>
</tr>
<tr>
<td>Sanya Bay</td>
<td>0.66</td>
<td>0.00</td>
<td>0.19</td>
<td>0.13</td>
</tr>
</tbody>
</table>

\[
n = \int_{\lambda_1}^{\lambda_2} S_0(\lambda) d\lambda = \frac{\int_{\lambda_1}^{\lambda_2} S_0(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S_0(\lambda) d\lambda}
\]

\[
m = \int_{\lambda_1}^{\lambda_2} S_0(\lambda) d\lambda
\]

where

- \( S_0(\lambda) \) is the broadband transmission rates of the atmosphere in the aerosol-concentrated area.
- \( t_a \) is the broadband transmission rates of molecules in the aerosol-concentrated area.
- \( S \) is the broadband direct solar radiation.
- \( S_0(\lambda) \) is the solar irradiance of \( \lambda \) nm at the top of the atmosphere.
- \( \theta_0 \) is the zenith angle.
- \( m_a(\theta_0) \) is the aerosol optical air mass.
- \( \lambda_1 \) and \( \lambda_2 \) are the lower and upper limits of the sun radiometer for 0.3 \( \mu \)m and 4 \( \mu \)m, respectively.
- \( T_m \) is the molecular transmittance function, which can be calculated by the MODTRAN radiative transfer model.

Parameterized model for equivalent wavelength \( \lambda_E \) (Qiu, 2001):

\[
\lambda_E = \lambda_0 + a(m_a - 1) + b(m_a - 1)^{1.78} + f_{size}
\]

\[
\lambda_0 = 0.787 - 0.02 u + 0.00232 u^2 - \frac{0.0854\alpha - 0.0103\alpha^2}{1+0.048u} + \frac{0.074(\alpha - 0.161\alpha^2)}{1+0.05u} \lambda
\]

\[a = 0.0433(1-0.036u) \left[ 0.456\tau_{BAOD} + \frac{2(1+\alpha)(1+4.6\alpha)\alpha^2}{1+2\alpha^2+9.2\alpha^2} \right]
\]

\[b = 0.0074\alpha^2 \tau_{BAOD}^2
\]

\[
f_{BAOD} = \frac{0.19(\alpha_2 - \alpha_1)^3}{1+(\alpha_2 - \alpha_1)^2} + \frac{0.402(\alpha_2 - \alpha_1)}{1+(\alpha_2 - \alpha_1)^2 + \tau_{BAOD}}
\]

\[
m = \left[ \frac{\mu_0 + 0.031141\theta_0^{-1}}{(92.471 - \theta_0)^{-1}} \right]^{-1}
\]

where

- \( m_a \) is the aerosol optical air mass (Gueymard, 1998).
- \( u \) is the water vapor content (cm).
- \( \mu_0 = \cos(\theta_0) \).
- \( \alpha_1 \) and \( \alpha_2 \) are the Angstrom exponents located in the range of \( \lambda \leq \lambda_M \) and \( \lambda \geq \lambda_M (M = 0.732 \mu \text{m}) \), respectively.

All wavelength parameters use an unified \( \mu \text{m} \). With the assumption of a non-Junge aerosol distribution, if \( \alpha_1 < \alpha_2 \), and \( f_{size} < 0, \lambda_E \) has longer wavelengths (Qiu et al., 2002).

Retrieval model:

The relationship between \( \tau_{BAOD} \) retrieved by the broadband direct solar radiation and equivalent wavelength \( \lambda_E \) can be expressed as:

\[
\tau(\lambda_E) = \tau_{BAOD}
\]

Assuming that the aerosol spectral distribution \( n(r) \) obeys the Junge distribution, the relationship between AOD (\( \tau(\lambda) \)) and wavelength \( \lambda \) can be expressed as follows:

\[
\tau(\lambda) = \beta \lambda^{-\alpha}
\]

where, \( \beta \) is the turbidity coefficient. Combined with Eqs. (11) and (12) and assigning \( \lambda = 0.50 \mu \text{m} \) (i.e., 500 nm), the AOD at 500 nm can be calculated using the following formula:

\[
\tau_{500nm}(\lambda) = \tau_{BAOD} \left( \frac{\lambda_E}{\lambda} \right)^{\alpha}
\]

DATA INTRODUCTION

The solar radiation datasets used in this paper are the hourly direct radiation collected by the Beijing observatory (54511, 39°48’N, 116°28’E).

The AOD observation datasets are supported by the Beijing site of CSHNET, which is located in the yard of the Iron Tower, IAP. CSHNET was established in August 2004, with 23 stations equipped with unified LED hazemeters across China in the initial construction. Langley calibration and transfer calibration were used to calibrate the hazemeters and three calibration experiments were conducted in July of 2004, December of 2005 and August of 2006 during the 3-year CSHNET project, which ensured the precision of the data quality. The LED hazemeters contain 4 channels...
(440 nm, 500 nm, 650 nm and 880 nm) and have a field angle of 2.5°. This type of instrument was widely used in the GLOBE (Global Learning and Observations to Benefit the Environment) project. In addition, the U.S. Forest Bureau also conducted selected regional aerosol observational experiments using this tool. Based on stability and reliability advantages, this approach is universally accepted in global science research (Brooks and Mims, 2001; Hao, 2005).

According to the Lambert-Beer law, the AOD process equation predefined in LED hazemeter is shown below:

\[
\tau(\lambda) = -\frac{1}{m(\theta)} \ln \left( \frac{v(\lambda) - v_{\text{dark}}(\lambda)}{d \times v_0(\lambda)} \right)
\]

where \( \tau(\lambda) \) is the atmospheric optical properties at \( \lambda \) \( \mu \text{m} \), i.e., \( \tau(\lambda) = \tau_{\text{aero}}(\lambda) + \tau_{\text{R}}(\lambda) + \tau_{\text{abs}}(\lambda) \). \( \tau(\lambda) \) is the optical depth of rayleigh scattering, and \( \tau_{\text{aero}}(\lambda) \) is the optical depth of absorbing gas. \( m(\theta) \) is the relative atmospheric air mass, and \( \theta \) is the zenith angle.

\( v(\lambda) \) is the measurement value of the sun-photometer. \( v_{\text{dark}}(\lambda) \) is the sun-photometer grey value. \( v_0(\lambda) \) is the sun-photometer calibration constant. \( d \) is the sun-earth distance parameter and calculated by the following formulas (Xin, 2007).

\[
d = \left( \frac{d_m}{d_f} \right)^2 = 1.000110 \times 0.034221 \times \cos(\theta) - 0.001280 \times \sin(\theta) + 0.00719 \times \cos(2 \times \theta) + 0.000077 \times \sin(2 \times \theta)
\]

MODEL TEST AND APPLICATION

In this section, the AOD at 500 nm is first retrieved from the hourly direct radiation. To test the accuracy of the retrieval results, the valid AOD is compared with the CSHNET products. Finally, we analyze the long-term variation of AOD over the Beijing region.

Model Test

Fig. 2 presents a comparison of the daily average AOD for the observation data of CSHNET and the retrieval results of OBEM for 2006–2010. The OBEM-retrieved AODs show good agreement with the CSHNET products, with correlation coefficients \( R^2 \) in the range of 0.78–0.85 during the 5 years at a significance level of 0.001, and the RMSEs are in the range 0.17–0.21. The retrieved consequence of 2007 (Fig. 2(b)) is the best of the 5 years, with the largest \( R^2 \) of 0.85 and the corresponding smallest RMSE of 0.17. The slopes for the 5 correlation equations (Figs. 2(a)–2(e))
are 0.97, 0.94, 1.00, 0.94 and 1.00, respectively. All of these models are similar to $Y = X$. The correlation equation $Y = 1.00X + 0.00$ for 2010 (Fig. 2(e)) coincides with the $Y = X$ line, whereas the RMSE reaches 0.21, and thus the data are much more discrete. Analyzing the overall correlation results for 2006–2010 (Fig. 2(f)), the equation is $Y = 0.97X + 0.01$, with $R^2$ reaching 0.82 and RMSE reaching 0.19, illustrating accurate and reliable retrieval results.

Fig. 3 presents a comparison of the monthly average AOD for the observation data of CSHNET and the retrieval results of OBEM for 2006–2010. The values of OBEM and CSHNET generally agree with each other. The correlation equation is $Y = 1.00X - 0.01$, with $R^2$ reaching 0.83 at the significance level of 0.001, and the RMSE is 0.08, far less than those of the daily comparisons in Fig. 2, demonstrating that the monthly retrieval results are much more accurate than the daily values. The percentage falling within the expected error boundaries of $Y = 1.15X \pm 0.05$ (Dot lines) is 86.44%. Xu et al. (2015) performed a similar monthly comparison analysis (BEM vs. AERONET) for the Beijing site during 2002–2012 and found a correlation equation of $Y = 0.822X + 0.112$, $R^2 = 0.72$, and approximately 82% dots falling in the expected error boundaries. Thus, we can conclude that the OBEM increases the retrieval precision. The observations (blue line in Fig. 4) show that the AOD exhibited a slight downward trend during 2006–2010. The fitting equation is $Y = -0.0012X + 0.5807$ with a slope of $-0.0012$. The fitting equation for the OBEM retrieval values is $Y = -0.0008X + 0.5583$ with a slope of $-0.0008$. The slope difference is only 0.0004, and the fitting lines are nearly coincident. The retrieval result also shows an AOD downward trend in the 5 years.

Fig. 5 presents a seasonal comparison of AOD values for the observation data of CSHNET and the retrieval results of OBEM during 2006–2010. The range of the correlation coefficient $R^2$ in the 4 seasons is 0.79–0.84 with all data exceeding the significance level of 0.001, and the RMSE values fall in the range of 0.17–0.24. Among the 4 seasons, the retrieval result of JJA is the worst, and the dispersion degree is comparatively high with the highest RMSE value of 0.24. This result is primarily related to strong solar energy, instability of the atmosphere, and powerful convection accompanied by the high humidity environment that occurred in JJA, leading to a prominent cloud-formation effect that sequentially further increased the difficulty in eliminating blocky clouds and cirrus clouds and eventually caused a larger retrieval error. The correlation equation of JJA is $Y = 0.86X + 0.07$, and difference compared with the midline of $Y = X$ reaches 0.14. The RMSEs for both MAM and DJF all are relatively small, with values of 0.17 and 0.18, respectively.

For long-term AOD characteristic analysis, accuracy evaluation of the yearly retrieval result is more important. Table 2 shows that within two decimal places, the relative errors for the yearly average data of OBEM and CSHNET in 2006–2010 all are less than 5.00%. The smallest value of 0.00% occurred in 2009, and the largest value of 3.85% occurred in 2010. The largest average AOD values for OBEM and CSHNET all appeared in 2006, with values of 0.57 and 0.59, respectively. Xu et al. (2015) illustrated that the yearly average AOD for 2006 was significantly higher than those of the other 4 years (2007–2010) as well. The smallest values of 0.51 for OBEM and CSHNET all occurred in 2009. Therefore, the yearly retrieval datasets are also acceptable.

**Model Application—Long-Term Variation of AOD at 500 nm over Beijing**

Based on the above analysis, the OBEM retrieval result is reliable and acceptable for revealing the variation characteristics of AOD at 500 nm. Fig. 6 gives the monthly variation of 500 nm AOD (Fig. 6(a)) and irradiance (Fig. 6(b)) in 1993–2010. The AOD variation obviously presents significant inter-annual cycle characteristics over the Beijing region and a unimodal or a bimodal distribution over the course of a year, among which peak values are primarily found in MAM and JJA, and the valley values are found in SON and DJF. In analyzing AOD variations
in 14 different background stations, Xu et al. (2015) also found that in most regions of China, the AOD values for MAM and JJA all are larger than those of SON and DJF. The largest monthly AOD value of 1.08 occurred in May 2003 and June 2007, and the smallest value of 0.20 occurred in December 2007 during the 18 years of 1993–2010. The AOD in 2007 fluctuated remarkably, with a range of 0.20–1.08, and the AOD variation in 2001 showed the weakest fluctuation, with an AOD range of 0.44–0.76. The irradiance fluctuated severely, and it's related to the seasonal differences of light distribution and the atmospheric extinction effect.

Comparing the monthly average values in 1993–2005 (red line in Fig. 7(a)) with those of 2006–2010 (green line in Fig. 7(a)), except for June, August and September, the values for 1993–2005 all are greater than those of 2006–2010. The difference in March is the most obvious, reaching a gap of 0.18 and mainly associated with the decrease in MAM dust events (Wang et al., 2017). In the entire variation (blue line in Fig. 7(b)), the AOD presents an unimodal shape. Peak value of 0.79 occurs in April, which is contributed by the frequent strong dust events. Statistics for the annual and seasonal average AOD in 1993–2010 (table in Fig. 7(b)) shows that the annual mean value is 0.58 ± 0.03. Among the 4 seasons, AOD of 0.70 in MAM is the largest and that these values decrease with the order of JJA (0.64), SON (0.51), and DJF (0.46). In common sense, irradiance of JJA should be higher than the other three seasons over Beijing. While the observational irradiance for 1993–2010 (Fig. 7(b)) has two peaks and the valley value is in JJA. Comparing with MAM, the aerosols exhibit similar extinction effect (AODMAM: 0.70; AODJJA: 0.64). So we can come to a principal conclusion that, except for the relatively higher AOD, the clouds developed by severe convection and high humidity also have strong extinction effect on weakening the solar light in this season. In ideal clear MAM and SON, the received irradiances are the same, but Fig. 7(b)

Fig. 5. Seasonal comparison for AOD values between observation data of CSHNET and OBEM retrieval results over Beijing site (solid thick line represents the linear fit of the daily data; dashed line represents Y = X; dotted line represents Y = 1.15X ± 0.05).

Table 2. Comparison of the yearly average AOD between observation data of CSHNET and OBEM retrieval results at the Beijing site.

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSHNET</td>
<td>0.59</td>
<td>0.53</td>
<td>0.56</td>
<td>0.51</td>
<td>0.52</td>
</tr>
<tr>
<td>OBEM</td>
<td>0.57</td>
<td>0.52</td>
<td>0.54</td>
<td>0.51</td>
<td>0.54</td>
</tr>
<tr>
<td>Relative error</td>
<td>3.39%</td>
<td>1.89%</td>
<td>3.57%</td>
<td>0.00%</td>
<td>3.85%</td>
</tr>
</tbody>
</table>
Fig. 7. Monthly average of 500 nm AOD for 1993–2005 (red line in (a)), 2006–2010 (green line in (a)) and 1993–2010 (blue line in (b)). Red line in (b) represents the variation of monthly average irradiance for 1993–2010. Table in (b) gives the statistics for annual and seasonal average AOD.

Fig. 8. Long-term variation for yearly average of retrieved 500 nm AOD (a) and irradiance (b) during 1993–2010. shows that the MAM peak is obviously higher than the SON peak and the aerosol loading in SON is lower, hence cloud extinction effect in SON is very significant as well.

Xu et al. (2015) retrieved the 750 nm AOD in the period 1993–2012 using the traditional broadband extinction method and found that the AOD exhibited a downward trend for the past 20 years in Beijing. Two peaks existed in 2003 and 2006, among which the AOD in 2006 was relatively high, with a value of approximately 0.60. Che et al. (2015) analyzed the 440 nm AOD variation of the Beijing site belonging to CARSNET for the duration of 2002–2013 and also noted that the AOD decreased year by year. Fig. 8 shows the yearly average values of retrieved 500 nm AOD (Fig. 8(a)) and irradiance (Fig. 8(b)) in 1993–2010. It is obvious that the retrieval result commendably presents the AOD downward trend, with a fitting equation of $Y = -0.0058X + 0.6998$. The smallest AOD of 0.51 occurred in 2009, and the largest AODs of 0.63 were noted in 1993 and 1996. Because the AOD value decreased with the increase in monitoring channels, the OBEM retrieval datasets were lower than those of Che et al. (2015) and higher than those of Xu et al. (2015). As is shown in Fig. 8(b), the irradiance also exhibited a downward trend during 1993–2010. Zheng and Zhang (2013) found the total-cloud amount was increasing in this period. So the extinction effect of cloud was the major factor on weakening the solar light.

**CONCLUSION**

With the application of the cloud-screening module and the aerosol modal adjustment module, the OBEM is more accurate and reliable in retrieving the AOD database of 500 nm and is favorable for docking with the current 500 nm AOD datasets monitored by satellite and ground-based instruments. What's more, OBEM is assuredly feasible to reconstruct the historical 500 nm AOD database and implement the homogenization for observational wavelength of AOD. The AOD for 1993–2010 retrieved by OBEM
shows that this value presents significant inter-annual cycle variation in Beijing. Affected by frequent dust events, the highest AOD occurred in MAM, whereas the lowest value was noted in DJF. In the past 18 years of 1993–2010, the AOD exhibited a slight downward trend. Cloud extinction effect is especially significant in JJA and SON and the long-term variation of irradiance also decreased due to the extinction of increasing total-cloud amount, so it was obviously more important to remove the cloud contamination in the process of retrieving AOD with direct solar radiation.

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