Validation of MODIS C6 Aerosol Optical Depth in China

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Abstract. The accuracy of MODIS Collection 6 (C6) aerosol optical depth (AOD) products in China is validated by using AERONET (Aerosol Robotic Network) ground observation data. The scatter plots and linear fitting results of each ground site are obtained, and the research area is divided into five parts. Analyzed the retrieval effects of MODIS C6 AOD products in different areas. The results show that: (1) In North China and Southeastern coastal, the difference between MODIS and AERONET AOD is small, and the retrieval accuracy is good. (2) The Northwest and Central and Eastern are uncertain due to the diversity of topography and landforms. (3) The accuracy of the Qinghai-Tibet Plateau is poor and there is a serious overestimation. Compared with the previous MODIS version of AOD products, the accuracy of C6 products in various regions of China has been significantly improved, which can provide data support for aerosol spatial-temporal distribution and atmospheric particulate matter retrieval research.

1. Introduction
Aerosols are usually solid or liquid particles suspended in the atmosphere with a particle size ranging from $10^{-2}$ to $10^{3} \mu m$. They are important components of the earth atmospheric environment system. They can not only affect the radiation balance of the earth atmosphere system [1], but also cause significant harm to the environment and human health [2]. Aerosol optical depth (AOD) is one of the most important parameters of aerosols, and it is also a physical quantity to characterize atmospheric turbidity [3]. The conventional monitoring method of AOD is observation of ground monitoring station, which has the advantages of high accuracy and continuous time. However, the limited number of ground stations and nonuniform spatial distribution make it impossible to obtain a wide range of AOD spatial distribution. With the development of satellite remote sensing technology, retrieving aerosols by remote sensing has the characteristics of large scale and continuity, which can effectively make up for the shortcomings of conventional monitoring methods. Moderate-Resolution Imaging Spectroradiometer (MODIS) carried by Terra and Aqua satellites is widely used in aerosol retrieval because of its wide coverage, high spatial resolution and short revisit period [4].

MODIS aerosol algorithm has experienced more than 20 years of development, and six versions have been published successively. There are two kinds of algorithms in the product, Dark Target (DT) and Deep Blue (DB) [5]. Many scholars have done a lot of verification work on the applicability of MODIS AOD products in China. By comparing the accuracy of C4 and C5 products and evaluating their applicability in China, Zhou et al. [6] show that the method of determining ground reflectance adopted by the new version of products is feasible in areas with good vegetation coverage and has
poor effect in areas with high reflectance. Wang et al. [7] verified the accuracy of C5 products in China, and analyzed the reasons of retrieval errors in different regions. Yang et al. [8] compared the accuracy and applicability of C5 and C6 products in several typical areas of China, proving that C6 version is better than C5 as a whole.

Due to the short release time of C6 products, there is a lack of extensive verification work in China. In this study, 20 AERONET sites were used to validate MODIS C6 AOD products, which were divided into five regions to analyze the inversion effect of C6 products in different regions.

2. Datasets

2.1. MODIS AOD Products

MODIS C6 AOD data is downloaded from the LAADS (Level-1 Atmosphere Archive & Distribution System) website (https://ladsweb.nascom.nasa.gov/). The product code is MOD04 and MYD04 (MOD stands for Terra star, MYD stands for Aqua star). The data space ranges from 72° to 136° east longitude and 18° to 54° north latitude. The time span is from January 1, 2006 to December 31, 2015. The spatial resolution is 10 km. Downloaded the daily AOD data and extracted the DT and DB combined data sets.

2.2. AERONET AOD Data

AERONET is a global ground-based aerosol monitoring network established jointly by NASA and French National Centre for Scientific Research (CNRS). AERONET provides long-term, continuous and open aerosol optical characteristic data with aerosol inversion accuracy of 0.01-0.02 and time resolution of 15 minutes. It is widely used to verify and evaluate aerosol optical characteristic parameters from satellite inversion [9].

AERONET AOD products include three levels: level 1, level 1.5 and level 2. Level 1 products have not been screened by cloud removal and correction, level 1.5 have been screened by cloud removal but not finally corrected, and level 2 products have been screened and corrected to ensure their data quality. This study downloaded the level 2 products of all sites in China.

3. Methods

3.1. Wavelength Matching

The central wavelengths of MODIS aerosol products are 470, 550 and 660 μm. In this study, 550 μm AOD data are extracted, while the central wavelengths of AERONET AOD products are 340, 380, 440, 500, 670, 870 and 1020 μm. There is no corresponding wavelength with MODIS. Therefore, it is necessary to use formula (1) to interpolate AERONET data to obtain AOD at 550 μm [10].

$$AOD_{\lambda'} = AOD_{\lambda_1} \cdot (\lambda'/\lambda_1)^{-\alpha_{\lambda_1-\lambda_2}}$$

In the formula, $\lambda_1$, $\lambda_2$ is wavelength, $\lambda'$ between $\lambda_1 \sim \lambda_2$. $\alpha_{\lambda_1-\lambda_2}$ is the Angström wavelength index at $\lambda_1 \sim \lambda_2$. In this study, the AOD values at 550 μm are obtained by interpolating the AOD values at 500 μm and the wavelength index at 440–670 μm provided by AERONET products.

3.2. Spatio-Temporal Matching

MODIS AOD products are instantaneous surface data with a resolution of 10 km. AERONET AOD products are AOD values continuously observed at the site location. The spatial matching principle of the two products is to select a certain range of MODIS data with AERONET site location as the center and take them as the mean, while the time matching principle is to take the observation time of MODIS products as the criterion, and select the AERONET data in a certain time range before and after, and then take the mean. In this study, the AERONET site is used as the center of the 3 × 3 pixel range of MODIS data to take the mean, and it is matched with the AERONET mean data of 30
minutes before and after the MODIS satellite transit. According to this principle, 20 sites can be matched, and the distribution of matching sites is shown in Figure 1.

Figure 1. Distribution of AERONET Sites with Completed Matching of Research Areas. A: North China. B: Northwest. C: Qinghai-Tibet Plateau. D: Central and Eastern. E: Southeast Coast.

4. Results and Discussion

4.1. Site matching results

The matching results are expressed by linear fitting equation which is expressed by formula (2).

\[
AOD_{\text{MODIS}} = s \cdot AOD_{\text{AERONET}} + i \tag{2}
\]

The slopes and intercepts of fitting straight lines are represented by \( s \) and \( i \) in the formula. The correlation coefficient (R) and the Root Mean Square Error (RMSE) are also the statistics of the evaluation results. In addition, Expected Error (EE) interval is an important parameter for judging the accuracy of MODIS AOD products. The more matching points in EE interval, the better the quality. The EE interval of DT and DB AOD products in MODIS C6 version is \((0.05 \pm 0.15)\) \(AOD_{\text{AERONET}}\), \((0.05 \pm 0.2)\) \(AOD_{\text{AERONET}}\) [11]. Because this research adopts DT and DB combined products, so selected \((0.05 \pm 0.2)\) \(AOD_{\text{AERONET}}\) as EE interval to unify standards. The matching scatter plot of each site is shown in Figure 2. The red line is the fitting line, the black dotted line is \( y = x \), it is the fitting line when \( AOD_{\text{MODIS}} = AOD_{\text{AERONET}} \) assumed, the blue dotted line is the EE line, and \( N \) is the number of matching points. As can be seen from the figure, MODIS and AERONET AOD show a good correlation at most stations. The fitting line lies between EE lines, but the distribution of matching points, slope and intercept of each site are quite different. In order to observe the correlation between them more accurately, Table 1 lists the detailed statistical parameters of each site.
Figure 2. Matching Spot Map of MODIS and AERONET AOD for Research Area Sites.

In the Table, "M-A" indicates the subtraction between the mean value of MODIS and AERONET AOD of the site. ">EE", "EE" and "<EE" indicate the percentage of matching points larger than EE interval, within EE interval and less than EE interval in total matching points. Statistical results of each site show that: 9 sites of MODIS AOD is overestimated, among which Hefei, QOMS_CAS and Taihu sites are overestimated seriously, with 50%, 48% and 56% matching points higher than EE interval respectively. 11 sites are underestimated, among which Dunhuang_LZU, Jingtai and Lanzhou_City sites are underestimated seriously, with 53%, 95% and 90% points lower than EE interval respectively. Using R as the criterion, 15 sites exceeded 0.8, reaching strong correlation, 3
sites ranged from 0.6 to 0.8, reaching moderate strong correlation, 2 sites was below 0.3, which was weak correlation.

Table 1. Comparative statistical parameters of each site in research area.

| Site                | N   | M-A      | s      | i      | R   | RMSE | >EE (%) | EE (%) | <EE (%) |
|---------------------|-----|----------|--------|--------|-----|------|---------|--------|---------|
| Beijing             | 1283| +0.129   | 1.05   | 0.11   | 0.915| 0.245| 38      | 60     | 2       |
| Xianghe             | 1245| +0.096   | 1.05   | 0.07   | 0.954| 0.215| 31      | 67     | 2       |
| AOE_Baotou          | 42  | -0.041   | 0.54   | 0.04   | 0.788| 0.084| 2       | 79     | 19      |
| SACOL               | 674 | -0.027   | 0.75   | 0.05   | 0.693| 0.147| 16      | 56     | 28      |
| Jingtai             | 43  | -0.308   | 0.44   | -0.05  | 0.715| 0.34  | 2       | 2      | 95      |
| Lanzhou_City        | 58  | -0.495   | 0.17   | 0.14   | 0.275| 0.551| 10      | 0      | 90      |
| Zhangye             | 26  | -0.006   | 0.95   | 0.01   | 0.833| 0.144| 12      | 77     | 12      |
| Dunhuang_LZU        | 30  | -0.159   | 0.7    | -0.01  | 0.871| 0.249| 3       | 43     | 53      |
| QOMS_CAS            | 62  | +0.1     | 0.21   | 0.14   | 0.05 | 0.164| 48      | 50     | 2       |
| Hangzhou-ZFU        | 25  | -0.103   | 0.88   | -0.01  | 0.977| 0.147| 0       | 68     | 32      |
| Hefei               | 74  | +0.188   | 1.4    | -0.06  | 0.886| 0.32  | 50      | 47     | 3       |
| NUIST               | 13  | +0.02    | 0.87   | 0.13   | 0.939| 0.139| 15      | 85     | 0       |
| Shouxian            | 56  | -0.016   | 0.87   | 0.06   | 0.903| 0.15  | 11      | 79     | 11      |
| Taihu               | 196 | +0.222   | 0.97   | 0.24   | 0.82 | 0.346| 56      | 42     | 3       |
| Hong_Kong_Hok       | 63  | -0.025   | 0.84   | 0.05   | 0.951| 0.086| 2       | 96     | 2       |
| Hong_Kong_POL       | 118 | -0.042   | 0.86   | 0.03   | 0.942| 0.113| 3       | 89     | 8       |
| Hong_Kong_She       | 39  | +0.027   | 0.91   | 0.09   | 0.913| 0.132| 10      | 87     | 3       |
| Chen-Kung_Univ      | 411 | +0.108   | 0.95   | 0.13   | 0.88 | 0.188| 39      | 57     | 4       |
| Taipei_CWB          | 273 | -0.048   | 0.82   | 0.02   | 0.877| 0.129| 5       | 77     | 18      |
| Kaiping             | 17  | +0.053   | 0.96   | 0.07   | 0.954| 0.089| 12      | 82     | 6       |

4.2. Regional accuracy analysis

According to the distribution of each site and fitting scatter map, it is observed that the sites with similar geographical location have similar inversion effects. It is helpful to get the overall inversion effect of MODIS C6 AOD products in a larger area by analyzing the sites with similar locations as a whole. According to the distribution of AERONET site, the research area is divided into five parts: North China, Northwest, Qinghai-Tibet Plateau, Central and Eastern and Southeast Coast. As shown in Figure 1, the five parts are marked “A”, “B”, “C”, “D” and “E”.

(1) North China

Including two sites, Beijing and Xianghe. The mean R of the two sites is 0.934 and RMSE is 0.230, indicating a high correlation. The difference between MODIS and AERONET mean value is +0.112, indicating that MODIS inversion is overestimated. The percentage of matching points in EE interval is 60%, 67%. 38% and 31% fall above the EE interval, and the fitting line in EE interval, it shows that the overestimation is not serious. Generally speaking, there is little difference between MODIS AOD products and ground observations in North China, and the inversion accuracy is better.

(2) Northwest

From east to west, the sites are AOE_Baotou, SACOL, Jingtai, Lanzhou City, Zhangye and Dunhuang_LZU. The R means of the sites is 0.696, RMSE is 0.252, and the correlation is only moderately strong. The subtract between their mean values is -0.173, and all the sites are negative, indicating that MODIS AOD products are generally undervalued in the Northwest region. Jingtai,
Lanzhou City and Dunhuang LZU sites are seriously underestimated. However, AOE Baotou and Zhangye sites show good inversion results. Northwest China belongs to arid and semi-arid landform, MODIS AOD is mainly obtained by DB algorithm. Therefore, it can be concluded that the applicability of C6 DB algorithm in arid and semi-arid areas of China is uncertain.

(3) Qinghai-Tibet Plateau
There is only one site in the region. AOD inversion accuracy is poor and there is a serious overestimation phenomenon. Because of the plateau, the pollution degree is relatively small, and the mean value of AOD observed on site is only 0.052, which indicates that MODIS AOD is seriously overestimated in low AOD area.

(4) Central and Eastern
The regional sites are Taihu, Hangzhou-ZFU, NUIST, Hefei and Shouxian respectively. Taihu and Hefei sites are seriously overestimated, 56% and 50% of the matching points are located above the EE interval respectively. Hangzhou-ZFU, NUIST and Shouxian have high accuracy, which indicates that MODIS AOD also has uncertainty in the Central and Eastern of China.

(5) Southeast Coastal
Six sites are included: Taipei_CWB, Chen-Kung Univ, Hong_Kong_Hok_Tsui, Hong_Kong_PolyU, Hong_Kong_Sheung and Kaiping. According to scatter plots and statistical data, it is shown that except Chen-Kung Univ site, which has a slight overestimation (39% of the points are above the EE interval), the inversion accuracy of the other sites is higher. It can be seen that MODIS AOD inversion algorithm has strong applicability in this region.

4.3. Contrast with earlier versions
To compare the inversion effect of MODIS C6 AOD products with previous versions, the percentage of matching points in EE interval is taken as an index, and the results are shown in Table 2.

It can be seen that compared with version 4 and C5, the percentage of C6 in EE interval in each region has increased. The accuracy of C6 AOD product is much better than that of previous version. The inversion effect is good in the eastern region. Although the inversion effect is general in the western region, it still improves to a certain extent compared with the previous version.

Table 2. Comparison of inversion effects of different versions of MODIS AOD products.

| version | region     | North China | Northwest | Middle East | Qinghai Tibet Plateau | Southeast coast | Reference |
|---------|------------|-------------|-----------|-------------|-----------------------|-----------------|-----------|
| C4      | North China | 54          | 27        | 62          | 38                    | 51              | [12]       |
| C5      | North China | 56          | 45        | 57          | -                     | 76              | [7]        |
| C6      | North China | 64          | 45        | 64          | 50                    | 81              | This research |

5. Conclusion
(1) The comparison of MODIS and AERONET AOD data shows that 9 sites are overestimated, of which 3 sites are seriously overestimated. 11 sites are underestimated, of which 3 sites are seriously underestimated. From the R point of view, 15 sites reaching strong correlation, 3 sites belonging to medium-strong correlation, and 2 sites was weak correlation.

(2) The site is divided into five regions according to its distribution. The results show that there is little difference between MODIS AOD products and AERONET observations in North China and Southeastern coastal, and the inversion accuracy is high. The Northwest and Central and Eastern are uncertain due to the diversity of topography and landforms. The AOD values in Qinghai-Tibet Plateau are relatively low, MODIS AOD is seriously overestimated.
(3) Compared with MODIS C4 and C5 AOD products, the accuracy of C6 in China has been significantly improved, which can be used as basic data to provide data support for aerosol spatial-temporal distribution and atmospheric particulate matter inversion research.

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