Evaluation and Comparison of MODIS Collection 6.1 and Collection 6 Dark Target Aerosol Optical Depth over Mainland China Under Various Conditions Including Spatiotemporal Distribution, Haze Effects, and Underlying Surface

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Abstract
Modifications such as degrading the retrieval quality of mixed pixels in the coastline area and revising surface characterization scheme have been made to the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6.1 Dark Target (DT) aerosol optical depth (AOD) product to address inaccuracy over urban areas. In this study, comprehensive evaluations of modifications to the MODIS C6.1 DT AOD product, in comparison with Collection 6 (C6), are conducted over mainland China under different spatial distributions, seasons, and air quality for the period 2010–2017, combined with validation against Aerosol Robotic Network (AERONET) AOD measurements. The preliminary result showed that the C6.1 DT AOD product in China displayed an overall good performance with high $R^2$ (0.87) and low root-mean-square error (0.23) against ground measurements. Moreover, the C6.1 DT AOD product was an overall improvement over C6, with greater correlation and lower uncertainty against ground measurements, especially for the North China Plain and Central China, although this was not the case for Western China. The improvement was also seasonal, being distinct in spring but less pronounced in winter, and negatively correlated with the level of air pollution. Furthermore, the analysis of DT AOD retrievals in different urbanized areas illustrated that the updated DT algorithm worked well in completely urbanized areas, where 97% of C6.1 DT AOD retrievals were an improvement over C6, while approximately 10% of C6.1 DT AOD retrievals were deteriorated in semiurbanized areas. Additionally, the DT AOD retrievals in areas with relatively low enhanced vegetation index and high surface reflectance were significantly improved, mitigating problems associated with the DT algorithm, further improving the reliability of MODIS DT AOD products.

Plain Language Summary
Modifications have been made to the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD) product to address inaccuracy over urban areas. This study evaluates the MODIS AOD product in comparison with the old version. Specifically, we evaluated products’ performance over mainland China under different spatial distributions, seasons, and air quality for the period 2010–2017. It was demonstrated that the updated AOD retrieval algorithm show a visible improvement in highly urbanized areas, as well as areas with relatively low enhanced vegetation index and high surface reflectance. However, because the surface reflectance scheme was trained over the continental United States, it could not effectively describe the complex surfaces in Eastern and Western China, and therefore, further improvement is required in this regard.

1. Introduction
As part of the atmosphere, aerosols, which are suspensions of solid particles or liquid droplets, are the most common condensate nodules of water droplets, ice crystals, and clouds; additionally, aerosols absorb and scatter solar radiation, participate in various chemical cycles, interact with the Earth’s energy budget directly and indirectly (Valsaraj et al., 2009; IPCC, 2013; Allen, 2015; del Aguila et al., 2018; Obregon et al., 2018;
Yang et al., 2019), and are hazardous to human health (Butt et al., 2017; Froehlich-Nowoisky et al., 2016; Gutierrez-Avila et al., 2018; Pacitto et al., 2018). Ground-based observation by CE-318 instruments is the traditional approach for measuring high-precision aerosol optical depth (AOD) and supports well-accepted atmospheric pollution studies but is limited by its low spatial resolution and high cost in terms of human, material, and financial resources (Che et al., 2009). Thus, satellite remote sensing, which continuously observes the Earth or atmosphere in detail, has the potential to overcome the shortcomings of ground-based observations and has previously been used to quantitatively retrieve AODs at regional and global scales (Kaufman, Tanré, et al., 1997; Kaufman, Wald, et al., 1997; Kaufman et al., 2005; Sun et al., 2017; Kumar et al., 2018; Lipponen et al., 2018).

AODs retrieved from Moderate Resolution Imaging Spectroradiometer (MODIS) are the most well-accepted aerosol products and are favored by researchers, with two AOD inversion algorithms for land and ocean, four-level quality assurances, approximately 1 day temporal resolution, and moderate spatial resolutions of 1, 3, and 10 km (Lyapustin et al., 2011; Hsu et al., 2013; Levy et al., 2016). Among them, AODs from the Dark Target (DT) algorithm are the first choice when all of the necessary data are available because of the superior explanation of ground aerosol over vegetated land surfaces (Sorek-Hamer et al., 2015; Bilal et al., 2016; Ma et al., 2016; Gong et al., 2017). The DT algorithm that was first proposed in 1997 used two midinfrareds (2.1 and 3.8 μm) to identify dark surface pixels and then estimated the reflectance of red and blue channels based on the statistical relationship of two and four times 2.1-μm reflectance, deriving AODs and the mass concentration of accumulation from the detected radiance (Kaufman et al., 1997a). DT in Collection 5 abandoned 3.8-μm channels and revised the aerosol model, aerosol lookup table, and the surface reflectance assumptions by introducing the normalized difference vegetation index (Levy et al., 2007). For Collection 6 (C6), all aspects of the retrieval algorithm were fine-tuned and updated; the spatial resolution was also improved to 3 km (Levy et al., 2013; Remer et al., 2013). At present, the latest version, Collection 6.1 (C6.1), of the DT aerosol product data sets over land has replaced the C6 online with modifications that degrade the quality of retrievals from coastal pixels to zero and modify surface reflectance assumptions when the urban percentage (UP) is larger than 20% (Gupta et al., 2016). The main improvement of MODIS C6.1 DT aerosol products lies on the DT aerosol retrieval algorithm over urban land surface, which focused on one of the DT retrieval issues, namely, the retrieval problem in urban bright surface. This modification is likely to bring significant improvements in DT aerosol products in urban regions with intensive artificial activities, supporting further studies on human health, which makes it significant to conduct a comprehensive evaluation.

The new surface reflectance relationships between two visible bands (0.47 and 0.64 μm) and a shortwave infrared band (2.1 μm) were developed using the MODIS surface reflectance product (MOD09) and land cover-type data sets (MCD12Q1) over the continental United States (Gupta et al., 2016). The MOD09 surface reflectance product is generated using the 6S radiative transfer model, which requires AOD, water vapor, and ozone (Bilal, Nazeer, Nichol, Qiu, et al., 2019; Bilal, Nazeer, Nichol, Bleiweiss, et al., 2019; Liang et al., 2002; Vermote & Kotchenova, 2008). Thus, detailed studies of the DT C6.1 modification performance in other regions are needed. However, China, a country with the largest population, is suffering from severe haze pollution due to increasing urbanization and economic growth. Many previous studies have focused on China’s atmospheric pollution at the regional and national scales; within these studies, MODIS aerosol products are well accepted and most commonly used (Guo et al., 2016; Kamarul Zaman et al., 2017; Kang et al., 2016; Ma et al., 2019; You et al., 2015; Zhang, Ma, Xin, et al., 2018). It is important and necessary to conduct a detailed validation of the MODIS C6.1 DT aerosol product for China, where an aerosol varies greatly in horizontal and vertical dimensions because of the variations in terrain, complex climate affected by seasonal monsoon, and diverse aerosol sources (Cheng et al., 2016; Fan et al., 2019; Sheng et al., 2019; Sun et al., 2019). Previous studies evaluated and compared the performance of MODIS C6.1 and C6 AOD products against ground AERONET AOD measurements at global, national, regional, and city scales, considering ground elevation, season, and multiform underlying surface types (Bilal et al., 2018; Bilal, Nazeer, Nichol, Qiu, et al., 2019; Tian et al., 2018; Wang et al., 2019; Wei, Li, et al., 2019; Wei, Peng, et al., 2019). However, there is a gap in the research with regard to the evaluation of the strength of modification on the MODIS DT AOD product from C6 to C6.1, which is significant for providing a reference for future modifications. Therefore, it is essential to evaluate the strength of the modification on the MODIS DT AOD...
The paper aims to evaluate the modified MODIS C6.1 DT AOD products in comparison with C6 products in mainland China under various conditions, such as spatial distribution, season, and air pollution during the period 2010–2017, combined with validation against AERONET AOD measurements. Moreover, analysis of each retrieval in different degrees of urbanization is further conducted with surface reflectance and enhanced vegetation index (EVI). This study synthetically estimates MODIS C6.1 DT AOD products in China and provides recommendations for applications.

### 2. Data and Method

In this study, MODIS DT retrievals with a spatial resolution of 3 km in both C6.1 and C6 from the Terra satellite for the period 2010–2017 were collected. In addition, Level 2.0 of the AERONET Version 3.0 AOD data set was used as a reference. To perform further analysis, multiple data sets containing land cover type, surface reflectance, EVI, and air quality index (AQI) were also employed. All of the data sets used are listed in Table 1.

#### 2.1. MODIS DT AOD

Initially described by Kaufman et al. (1996), the MODIS DT algorithm has been constantly updated over the past 20 years, and the latest version, C6.1, was recently released on 15 October 2017 (Levy et al., 2007; Levy et al., 2013; Remer et al., 2013; Gupta et al., 2016). Based on the assumption between the visible bands and the shortwave infrared band, the AOD at 550 nm can be retrieved by a satellite-based atmospheric radiative transfer model, considering aerosol models, atmospheric models for gaseous components, geometrical conditions, and the directional effect of the target. The modified C6.1 DT AOD, developed from C6, focuses on urban surfaces and adds the UP calculated from the land cover type product, which updates the relationship between visible and shortwave infrared bands when the UP is greater than 20%. In the paper, the scientific data set named “Optical_Depth_Land_And_Ocean” was selected to gather the AOD products with a quality assurance of 3 over land. Since AODs from Aqua and Terra perform similarly (Livingston et al., 2014; Xie et al., 2015), and the 3-km AOD products have been generally used in more detailed studies at the regional scale, only the Terra DT AOD product with a spatial resolution of 3 km was used in this study. The MODIS AOD products as well as the subsequent MODIS auxiliary data are provided by the Level-1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (https://ladsweb.modaps.eosdis.nasa.gov/).

#### 2.2. Aerosol Robotic Network (AERONET)

The AERONET collaboration provides global measurements of AOD in eight spectral bands (http://aeronet.gsfc.nasa.gov), with low uncertainty (0.1–0.2) and high temporal resolution (15 min), by measuring spectral solar irradiance and sky radiance from a Sun photometer (Holben et al., 1998). AERONET measurements have been used to validate and correct the bias of satellite AOD retrievals (Almazroui, 2019; Che et al., 2018; Qin et al., 2017), due to its consistent international standardization of instruments, rigorous calibration and processing, globally distributed sites, and convenient data access. The AOD observations are divided among urban and rural regions.
into three types: Level 1.0 (unscreened), Level 1.5 (cloud screened), and Level 2.0 (cloud screened and quality assured) (Holben et al., 2001; Smirnov et al., 2000). In the paper, Level 2.0 of the AERONET Version 3.0 AOD data set was gathered from a total of 20 sites (Che et al., 2018; Eck et al., 2018; Wei, Li, et al., 2019). Additionally, aerosol measurements in Central China were provided by the Wuhan University, which have been used to analyze aerosol characteristic in previous studies (Zhang et al., 2016; Zhang, Ma, Gong, et al., 2018). The spatial distribution of these AERONET sites are shown in Figure 1. Since there is complex terrain from the western Tibetan Plateau and the desert to the eastern plain in China, it is essential to evaluate the modified MODIS C6.1 DT AOD product for different regions. Thus, all AERONET sites have been divided into five groups, listed in Table 2, namely, North China Plain (NCP), Yangtze River Delta (YRD), Pearl River Delta (PRD), Central China, and Western China.

### 2.3. Auxiliary Data

The land cover type data were extracted from the MODIS land cover type product (MCD12Q1), created from a supervised classification of Terra- and Aqua-MODIS reflectance data and provided global land cover maps with 500-m resolution at annual time steps for five legacy classification schemes (Friedl et al., 2010). The class named “urban and built-up area,” defined by the International Geosphere-Biosphere Program, was extracted and averaged to a 3-km resolution (equivalent to a 3-km MODIS DT AOD product resolution).

The surface reflectance data were extracted from the MODIS Level 3, 8-day composited surface reflectance product (MOD09A1), which estimates the surface spectral reflectance for each band after correction of the effects of atmospheric gases and aerosols. Since the reflectance at “Blue” channels are darker than at other two channels in the DT algorithm over bright surfaces (Che et al., 2018), the scientific data set “500 m Surface Reflectance Band 3: (459–479 nm)” was extracted to describe surface reflectance.

The EVI data were extracted from MODIS vegetation index products with a spatial resolution of 500 m at 16-day time steps (MOD13Q1) to provide a suite of science data sets describing the spatiotemporal variations of global vegetation activity. With the increased in sensitivity over high biomass areas, there was an improvement in monitoring capability and a reduction in atmosphere influences, and EVI was selected and extracted in this study to describe the surface vegetation condition.

Based on AQI data, the quality of air can be divided into four categories: clean, light haze, moderate haze, and heavy haze. AQI is used to describe how polluted the air is on account of six atmospheric pollutants measured at ground monitoring stations throughout each city, and a higher AQI indicates more serious...
pollution (Ministry of Environmental Protection of the People’s Republic of, 2016). All daily AQI data were downloaded from the China National Environmental Monitoring Centre website (http://www.cnemc.cn/).

2.4. Methodology

As AERONET provides a frequently repeated point observation, while satellites offer a snapshot of a certain region at a single time, studies generally conduct processing by temporally averaging AERONET measurements around the overpass time of the Terra satellite and spatially averaging the satellite retrievals over AERONET monitoring sites, mitigating the influence of aerosol variability. In this study, the averages of the AERONET observations within a half-hour of Terra overpass were calculated and compared with the averaged MODIS measurements (at least two) from a sampling window of 5 × 5 pixels (at least 20% pixels available) around the AERONET monitoring sites (Bilal & Nichol, 2015). As AERONET measurements at 550 nm are not provided, measurements were interpolated to 550 nm based on the Ångström exponent (\(\alpha\)) defined as follows:

\[
\alpha = \frac{\ln(\tau_1/\tau_2)}{\ln(\lambda_1/\lambda_2)}
\]

where \(\tau_1\) and \(\tau_2\) are the measurements at wavelengths \(\lambda_1\) and \(\lambda_2\), respectively. The nearest available pair of bounding wavelengths from AERONET, 675 and 440 nm, were used to calculate \(\alpha\). This spectral interpolation method inevitably introduces uncertainty, although this uncertainty is negligible.

A set of evaluation methods for statistical analysis were used to display how well the MODIS DT AOD matched observations from AERONET. The following evaluation methods were applied: (i) coefficient of determination \(R^2\), meaning a correlation of statistical relationship between the two data sets; (ii) the root-mean-square error (RMSE) calculated based on equation (2), which is a well-accepted evaluation metric of the difference between the two data sets; (iii) relative mean bias (RMB), the ratio of the two data sets as shown in equation (3), which is introduced as a simple indicator of overestimation or underestimation; and (iv) the expected error (EE), which is widely used to evaluate the performance of MODIS DT AOD.

| Region | Site          | N  | Mean | C6.1 | C6.1-W | R^2  | RMSE | RMB  | W  | A   | B   | UP  |
|--------|---------------|----|------|------|--------|------|------|------|----|-----|-----|-----|
| NCP    | AOE_Baotou    | 124| 0.2  | 0.22 | 0.7    | 0.09 | 1.11 | 69   | 23 | 9   | 0   | 0   |
|        | Beijing-CAMS  | 322| 0.34 | 0.6  | 0.83   | 0.3  | 1.78 | 17   | 83 | 0   | 1   | 0   |
|        | Beijing       | 354| 0.35 | 0.61 | 0.84   | 0.29 | 1.71 | 15   | 84 | 1   | 1   | 1   |
|        | Beijing_PKU   | 96 | 0.37 | 0.61 | 0.85   | 0.29 | 1.65 | 17   | 82 | 1   | 1   | 1   |
|        | Beijing_RADI  | 366| 0.4  | 0.63 | 0.88   | 0.27 | 1.56 | 21   | 78 | 1   | 1   | 1   |
|        | Lingshen      | 3  | 0.12 | 0.15 | 0.98   | 0.07 | 1.31 | 67   | 33 | 0   | 0   | 0   |
|        | Xingtai       | 8  | 0.36 | 0.41 | 0.97   | 0.09 | 1.14 | 88   | 13 | 0   | 0   | 0   |
|        | XiangHe       | 612| 0.48 | 0.57 | 0.95   | 0.18 | 1.19 | 72   | 27 | 1   | 0.22| 0.22|
|        | Xinglong      | 188| 0.18 | 0.2  | 0.86   | 0.09 | 1.07 | 85   | 11 | 4   | 0   | 0   |
| YRD    | NUIST         | 3  | 0.56 | 0.61 | 0.03   | 0.14 | 1.08 | 67   | 33 | 0.81| 0.81|
|        | Taihu         | 21 | 0.91 | 1.25 | 0.87   | 0.37 | 1.37 | 29   | 71 | 0   | 0   | 0   |
|        | Xuzhou        | 144| 0.6  | 0.77 | 0.91   | 0.22 | 1.28 | 48   | 52 | 0.5 | 0.5 |
| PRD    | HK_Hok_Tsui   | 5  | 0.73 | 0.75 | 0.99   | 0.08 | 1.03 | 80   | 20 | 0.08| 0.08|
|        | HK_PolyU      | 19 | 0.53 | 0.58 | 0.79   | 0.13 | 1.1  | 89   | 11 | 0.58| 0.58|
|        | HK_Sheung     | 27 | 0.49 | 0.5  | 0.96   | 0.07 | 1.02 | 96   | 4  | 0.17| 0.17|
|        | Zhongshan_Univ| 9  | 0.51 | 0.73 | 0.86   | 0.24 | 1.43 | 33   | 67 | 0.47| 0.47|
| Western China | Mt_WLG    | 17 | 0.11 | 0.12 | 0.17   | 0.06 | 1.05 | 88   | 6  | 0   | 0   | 0   |
|        | NAM_CO        | 5  | 0.05 | 0.11 | 0.71   | 0.06 | 2    | 60   | 40 | 0.14| 0.14|
|        | SACOL         | 126| 0.25 | 0.38 | 0.68   | 0.16 | 1.54 | 41   | 59 | 0   | 0   | 0   |
| Central China | Wuhan_Univ  | 84 | 0.69 | 0.84 | 0.82   | 0.22 | 1.22 | 57   | 43 | 0.61| 0.61|

Note. The correlation coefficients \(R^2\) were calculated at a significance level of \(p < 0.05\). \(N\) = number of matched points; \(W\) = the percentage within EE envelopes; \(A\) = the percentage above EE envelopes; \(B\) = the percentage below EE envelopes; \(UP\) = the urban percentage of a 3-km grid.
products; the EE of the DT algorithm over land with a spatial resolution of 3 km (Remer et al., 2013) is shown in equation (4). Matchups are classified into three types: one is above EE envelopes and indicates overestimation, the second is within EE envelopes and represents a correct estimation, and the last one is below EE envelopes and represents underestimation. A satisfactory performance of AOD product was concluded based on the highest value of $R^2$, lowest value of RMSE, lowest value of RMB, highest matches, and highest percentage within EE envelopes. To compare the performance of the two data sets, the threshold criteria are defined: If the relative difference is less than (a) 10% for the percentage of retrievals within EE envelopes, (b) 10% for $R^2$, (c) 5% for RMSE, and (d) 5% for RMB, then the two data sets are considered as performing similarly (Bilal, Nichol, & Wang, 2017).

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\text{AOD}_{\text{MODIS}} - \text{AOD}_{\text{AERONET}})^2}$$  \hspace{1cm} (2)

$$\text{RMB} = \frac{\text{AOD}_{\text{MODIS}}}{\text{AOD}_{\text{AERONET}}}$$  \hspace{1cm} (3)

$$\text{EE} = \pm (0.05 + 0.2 \times \text{AOD}_{\text{AERONET}})$$  \hspace{1cm} (4)

3. Results and Discussion

3.1. Overall Performance of C6.1 in Comparison to C6 Retrievals Over China

In total, 2,512 AOD matches were successfully collected from 20 AERONET sites over mainland China. Figure 1 shows the quantitative distribution of matches at each ground monitoring site during the experiment period. Sites with over 200 matches were mostly located in NCP, while PRD and Western China had less number of matches owing to the reduced quality assurance of retrievals in coastal pixels and problems pertaining to satellite AOD retrieval on snow-covered surfaces.

Figure 2a compares MODIS C6.1 DT AOD and AERONET AOD as matched data sets. The MODIS C6.1 DT AODs show good agreements with AERONET AODs, with high $R^2$ (0.87) and low RMSE (0.23). Majority of the AODs gathered ranged from 0 to 1, especially from 0 to 0.5, resulting in an AERONET mean of 0.4 and a C6.1 AOD average of 0.56. Nevertheless, most of matchups were distributed above the 1:1 reference line, resulting in an obvious overestimation, with an RMB of 1.41 and a high percentage of matchups above EE envelopes of 54%, which was greater than the percentage within EE envelopes (45%). Additionally, all averages of the AOD bias (MODIS − AERONET), shown as light blue boxes in Figure 2c, were above zero, and the averages were even above EE envelopes when the AOD was less than 0.8, suggesting that the C6.1 DT retrievals overestimated AOD compared to the ground measurements. Similar validation studies of the 10-km C6.1 DT AOD also reported the overestimated results for mainland China (Bilal, Nazeer, Nichol, Qiu, et al., 2019; Tian et al., 2018; Wang et al., 2019). Moreover, the verification experiments at the global scale showed that the monthly C6.1 DT AOD averages overestimated ground measurements by 25%, especially in Asia and western North America (Wei, Li, et al., 2019; Wei, Peng, et al., 2019). These results demonstrated the significant overestimation issue of the MODIS C6.1 DT AOD product due to underestimation of the surface reflectance and inappropriate aerosol schemes (Tian et al., 2018). To further study the overestimation performance under different aerosol loadings in detail, the RMBs (shown as red triangles and red curves) at intervals of 0.1 from the AERONET AOD were subsequently calculated (shown in Figure 2c). The declining RMBs (shown as the red curve) indicated that the overestimation depended to a certain extent on AOD. When AOD decreased, the overestimation increased, because the same uncertainty had a greater influence on low retrievals than on high retrievals. Furthermore, the deviation of retrievals, shown as the length of the light blue box, increased obviously when AOD increased, indicating a decrease in the stability of the MODIS C6.1 DT AOD product. To estimate the modified MODIS C6.1 DT AOD when comparing with C6, the MODIS C6 AOD product against AERONET AOD is validated (Figures 2b and 2d). As shown in Figures 2a and 2b, a clear clustering effect of matchups from C6 to C6.1 is evident, indicating the increased stability of the C6.1 DT AOD product. Additionally, statistical results showed that the percentage of matchups within EE envelopes increased by 13%, while RMSE (0.08) and RMB (0.16) decreased by 34% and 11%, respectively, indicating the improved ability of the C6.1 DT AOD product. Figures 2c and 2d display the RMB
and the boxplots of the AOD bias (MODIS \(-\) AERONET) against binned AERONET AOD with an interval of 0.1. In comparison with those of C6, the RMB as well as deviations of C6.1 for each AOD interval decreased, especially in case of low AOD loading. The node from above the EE line to within EE envelopes also decreased by 60% (from 1.2 in C6 to 0.75 in C6.1), demonstrating reduced overestimation in C6.1 over C6. The better performance of the C6.1 DT AOD product indicates that the C6.1 has a higher potential in terms of determining and describing atmosphere aerosols, due to a more appropriate surface reflectance scheme and significant mitigation of overestimation issues during low aerosol loadings. However, at high loading, large deviations of both versions are observed, indicating considerable uncertainty and instability for highly accurate retrievals; this can be likely attributed to the inept aerosol models in lookup tables (Bilal, & Nichol, 2017).

To examine the spatial difference between C6.1 and C6 DT AODs, their retrievals over China for 2010–2017 were selected and averaged; the difference between C6.1 and C6 could be represented using the value obtained by subtracting the C6 mean retrieval from the C6.1 mean retrieval. As shown in Figures 3a–3c, almost all values for C6.1 less than those for C6 were distributed in the east and south of China, and large differences were observed in urban agglomerations, such as Beijing and Guangzhou. The spatial distribution of the negative value of the difference showed a good consistency with the urban surface distributions (Figure 3d), indicating an overall decline of AOD retrievals in C6.1 from C6 in urban areas, which, to a certain extent, mitigates the overestimation from urban areas. According to the C6.1 DT algorithm, the surface reflectance relationships at UP < 20% are divided into four grades based on the UP and EVI. The larger the

Figure 2. (a, b) Frequency scatterplots of MODIS (C6.1 and C6) AOD retrievals against AERONET AOD observations at 550 nm over China. The linear regression is shown as a solid red line. The boundary lines of the EE are shown in the dashed lines, and the solid black line is a 1:1 line for reference. (c, d) Box charts of AOD bias (MODIS \(-\) AERONET) versus binned AERONET AOD over China with an interval of 0.1. The zero bias and the boundary lines of the EE are shown as the blue dash lines. For each box whisker, the middle line, blue squares, and upper and lower hinges represent the AOD bias median, average, and 25th and 75th percentiles, respectively. The gray whiskers extend to 1.5 times the interquartile range (IQR). The red triangles represent the relative mean bias versus the binned AERONET AOD with an AOD interval of 0.1. The red solid line is the fitting curve for the red triangles.
The 2010–2017 mean AOD retrievals of (a) C6.1, (b) C6, (c) C6.1 – C6, and (d) urban land cover distributions over China.

Moreover, due to the complex geography, changing climate, and variable human activities, observable differences in region distribution, season, and air quality condition in the performance of the C6.1 DT AOD product in China can be noted; these have been either rarely or partially considered in previously reported studies. Bilal et al. (2018) and Wei, Li, et al. (2019), Wei, Peng, et al., (2019) respectively evaluated the MODIS AOD products in the global scale to understand the overall performance of products in each continent. Tian et al. (2018) assessed the seasonal performance of MODIS AOD products in Beijing, and Bilal, Nazeer, Nichol, Qiu, et al. (2019) analyzed the monthly variation of the fused MODIS AOD products in Beijing-Tianjin-Hebei; both supported their practical application in local regions. Therefore, in this study, evaluations of the MODIS C6.1 DT AOD product were conducted from the perspectives of season, air quality, and spatial distribution and compared with those of the C6 product. The validation results of C6.1 DT AOD products in different regions are shown in Figure 4. All C6.1 DT AOD products in each region showed good performance, with $R^2$ ranging from 0.73 to 0.9 and RMSE ranging from 0.13 to 0.25. PRD had the best validation results, with over 80% of matchups falling within EE envelopes, along with the lowest RMB of 1.11, the lowest RMSE of 0.13, and a relatively high $R^2$ of 0.84. Nearly half of the matchups in PRD were collected from the HK_Sheung station located in a rural area and surrounded by vegetation; as a result, good retrievals were obtained from this region. For the regions of NCP, YRD, and Central China, the C6.1 DT AOD retrievals agreed well with ground measurements, with all $R^2$ values being over 0.8 and all RMSE values being lower than 0.25, indicating the good performance of C6.1 AOD products in these regions. However, the percentage of normal matchups was only approximately 50%, and the RMB ranged from 1.22 to 1.44, showing the overestimation of C6.1 AOD, which was in agreement with other validation
Figure 4. Validation results of MODIS (C6.1 and C6) DT AOD retrievals over different regions (NCP, PRD, YRD, Western China, and Central China) of China. The linear regression, the boundary lines of the EE, and the 1:1 line for references are shown as a solid magenta line, dash green lines, and a solid green line, respectively, in the first two columns. And the triangles, solid line, and gray dashed line in the third column are the measured values of the relative mean bias, the fitting curve of the measurements, and the reference line, respectively.
results in NCP (Bilal, Nazeer, Nichol, Qiu, et al., 2019; Tian et al., 2018). The statistical relation between RMB and aerosol loading (shown as red curves of decline trend) indicates that the overestimation was obvious with low aerosol loading. The main reason for this observation is that the underestimation of surface reflectance from bright targets has a greater effect on retrievals during low aerosol loading than during high aerosol loading (Mhawish et al., 2017). In contrast, the retrievals in Western China did not perform well, with $R^2$ being only 0.73 and the slope of the regression lines being 1.26, that is, much greater than 1. Almost all the matchups were above the reference line of 1:1, and the overall RMB of 1.52 was greater than for all the other regions. These results demonstrate a distinct overestimation of C6.1 DT AOD products in Western China, due to an underestimation of the surface contribution. As the AERONET sites in Western China are located on the rugged Tibetan Plateau or near inland lakes with an elevation of greater than 1,900 m, the bidirectional reflectance distribution function effect is obvious, which likely generates an underestimation of the surface reflectance, causing an overestimation of the aerosols. Referring to related studies, similar significant overestimation results with few successful retrievals and small proportion of retrievals falling within EE lines were also noted in Africa and other bare lands of the world (Farahat 2019; Wei, Li, et al., 2019). When compared to the C6 AOD product, the modified product also had obvious spatial differences. In Western China, there was hardly a change between the two versions, and the overestimation issue was observed, indicating that the MODIS DT algorithm needs to be further improved for this region. Apart from no modification for Western China, C6.1 DT AOD products were modified to varying different degrees for other regions. The modification was slight for YRD and PRD and was such that all matchups moved down slightly, with a reduction of RMB by less than 5%. Because of the complex nature of the underlying surface, which consists of urban areas, hills, farming land, coastline, and water in these two regions, and because it is different from the underlying surface of inland areas such as the continental United States, the river delta could not be properly described by the updated surface reflectance scheme trained from observations in the continental United States. Nevertheless, optimal modification was displayed in NCP and Central China, which are two typical inland regions in China. The difference in RMSE is observed to be 34% and 18% over NCP and Central China, respectively, when C6.1 DT AOD was compared to C6, combined with the difference in the percentage of retrievals within EE envelopes up to 13% and 43%, as well as the difference in RMB up to 13% and 7%, respectively. For each RMB at an interval of 0.1, sharp declines were observed during low aerosol loading; the decline in RMB ranged from 0.1 to 0.57 in NCP and from 0.21 to 0.5 in Central China when AERONET AOD was smaller than 1. This demonstrates that the modified surface scheme is applicable to inland regions of China, and the MODIS DT algorithm overestimation issue in inland of China has been significantly mitigated.

As shown in Figure 5, the seasonal performance of C6.1 DT AOD products had a similar $R^2$ range from 0.9 to 0.82, with a relatively high $R^2$ in warm seasons (summer and autumn), and a slightly lower $R^2$ in cold seasons (winter and spring). Although the number of matchups in winter was only an eighth of those for the other seasons due to the problem with regard to the MODIS DT algorithm over snow or ice surfaces, the C6.1 DT AOD product in winter had an optimal validation result, with a higher ratio of normal matchups (67%), lower RMSE (0.11), and a relatively low overestimation (1.21). Since the rigorous mask algorithm discarded pixels with high reflectance in winter, there were less pixels remaining from a bright target, decreasing the uncertainty of the surface reflectance scheme when describing the surface, which resulted in C6.1 DT AOD products performing better in terms of the percentage within the EE, RMSE, and RMB (Martins et al., 2002; Li et al., 2005). With enough matchups, summer and autumn showed slightly better validation results against ground measurements than did spring. In comparison with that in spring, the $R^2$ in the warm seasons was slightly higher by 6% and 8%, while the RMSE was lower by 12% and 28% for summer and autumn, respectively, and the regression lines were closer to the reference line. As the primary dark target in the DT algorithm, vegetation varies with season due to its phenological cycle and flourishes in the warm seasons. This results in a larger percentage of dark target on the surface in the warm seasons, which is an advantage in terms of AOD retrieval, resulting in less uncertainty and improved performance of MODIS C6.1 DT AOD products in warm seasons. The modification of the C6.1 DT AOD product in comparison with C6 also varied with season. The modification in C6.1 was significant in spring, with a difference in $R^2$, RMSE, RMB, and the percentage of retrievals within EE lines being up to 12%, 26%, 12%, and 17%, respectively, when compared to those of C6, resulting in a clearer accumulation of matchups with C6.1. As shown in Figure 5c, RMB
decreased dramatically when AOD was less than 1, and the maximum decrease reached 22%, resulting in a decrease of 12% in the overall RMB. This was because the obvious overestimation caused by the large percentage of bright pixels in spring can be well remitted by improving the surface relationship assumption of the urban target. In contrast, the modification decreased fractionally in the warm seasons. The difference in $R^2$, RMSE, RMB, and the percentage of retrievals within EE lines were recorded to be 6%, 22%, 8%, and 17%/9%, respectively, in summer/autumn when C6.1 AOD was compared to C6. As the

![Figure 5](image-url)
percentage of bright surface contribution slightly decreases in the warm seasons, the remission of overestimation from the bright surface decreased slightly. However, the difference in winter was barely noticeable; the maximum difference in RMB was only 7%, which was due to the reduced number of pixels of bright target to be revised after the good mask effect. In contrast with the obvious modification during low aerosol loading in other seasons, there was less modification of C6.1 DT AOD during low aerosol loading in winter, possibly due to the lower retrievals from the non-urban surface.

Further validation experiments under different air quality conditions were conducted, as shown in Figure 6. The C6.1 DT AOD retrieval is dependent on the air pollution level; on clean days, the C6.1 AOD retrieval performs poorly, with bad correlation \((R^2 = 0.56)\), a low slope of regression line \((0.92)\), and a low ratio of matchups within EE envelopes \((42\%)\), as well as serious overestimation \((RMB = 1.81)\) against the ground observations. The matchups were dispersedly distributed above the EE envelopes, leading to a high RMSE \((0.22)\) when most of AODs were less than 0.5. As the signals received by satellites from the top of the atmosphere are dominated by the ground contribution during clean days, the inaccuracy of surface assumptions will introduce a large relative uncertainty to atmospheric aerosol retrievals, leading to poor validation results. At the same time, the elevated aerosol levels may magnify the difference between satellite retrievals and ground measurements during clean days due to different measuring ranges between MODIS and AERONET AOD (Tsai et al., 2011). When the air quality worsened to the next level, the \(R^2\) grew significantly, by 50%, to 0.84. The matchups were clustered tightly around EE envelopes, resulting in a 19% reduction in RMB. The slope of the regression lines improved, from 0.92 to 1.1, mitigating the overestimation with low aerosol loading to some extent; however, this brought some overestimation to high aerosol loading values. As air quality worsened further, resulting in heavy haze, more optimal validation results were observed: \(R^2\) increased to 0.91, the RMB decreased to 1.23, and the percentage of retrievals within EE envelopes increased to 56%. As the surface contribution becomes less important on haze days, the retrievals can tolerate relatively high uncertainty from assumptions about surface reflectance (Li et al., 2013); thus, the retrievals are closer to ground measurements, resulting in a more optimal performance of C6.1 DT AOD products during the haze period. However, the decrease in the number of matchups and increase in the RMSE on heavy haze days have indicated that the MODIS C6.1 DT algorithm and cloud masking algorithm still need further improvement for the latter. The difference between the modified MODIS C6.1 DT AOD and C6 also varies with air pollution levels. During clean days, a significant improvement was shown: The \(R^2\) grew by 30%, the overall RMB decreased by 13%, and the RMSE was reduced by 21% when the average of AERONET AOD was only 0.2. As the air quality worsened, the \(R^2\) grew by 11%, 6%, and 3%; the RMB decreased by 7%, 7%, and 6%; and the RMSE decreased by 24%, 22%, and 21%. These results illustrate that the modification was negatively correlated with the pollution level. As top-of-atmosphere reflection received by the satellite mainly comes from ground contributions during the no-haze period, the same correction in the surface reflectance scheme can make a distinct difference to the final retrieval. Yet the surface contributions become less important as air quality worsens, and the modification of the surface reflectance scheme had less influence on the final retrievals. In brief, C6.1 DT AOD performs better during the haze period than during the no-haze period, whereas the modified C6.1 DT AOD performs worse than C6 when the air quality worsens.

In general, the C6.1 DT AOD product is more suitable for most of China, with the exception of Western China, in the winter and warm seasons, and during haze periods. In comparison with that in C6, an obvious decline was observed in the C6.1 DT retrievals in urban areas of Eastern and Southern China, mitigating the overestimation issue from urban surfaces, while it needs to be improved in Western and Northern China. Moreover, the C6.1 DT AOD products are a distinct improvement over the C6 AOD products in NCP and Central China during spring and the no-haze period.

### 3.2. Evaluation of C6.1 and C6 Retrieval Accuracy in Surface Areas With Different Degrees of Urbanization

#### 3.2.1. Evaluation of the Modified of C6.1 With Different Urbanized Surfaces

In previous research, the correlation between C6.1 and C6 was calculated for differently urbanized surfaces, and the conclusion was drawn that the strength of the modification from C6 to C6.1 increased as the urban proportion increased, but no description was provided of whether the modification is beneficial or deteriorating under different degrees of urbanization (Wang et al., 2019). In this section, the retrieval of each
matchup is further evaluated by comparison with AERONET measurements in surface areas with different degrees of urbanization, which deserved more attention in practical application. All the matchups have been divided into four groups: completed urbanization (UP = 1), moderate urbanization (UP ~ 0.5), low urbanization (UP ~ 0.2), and no urbanization (UP = 0). The modification to C6.1 DT AOD over C6 was represented by the value defined as $M = I_{6.1} - I_6$, where $I_{6.1}$ ($I_6$) was the inverse of the difference between C6.1 (C6) and the AERONET AOD. A positive value for $M$ indicates that the C6.1 retrieval was

Figure 6. Validation results of MODIS (C6.1 and C6) AOD retrievals under different air quality conditions. The linear regression, the boundary lines of the EE, and the 1:1 line for references are shown as a solid magenta line, dash green lines, and a solid green line, respectively, in the first two columns. And the triangles, the solid line, and gray dashed line in the third column are the measured values of the relative mean bias, the fitting curve of the measurements, and the reference line, respectively.
improved compared to the C6 retrieval, while a negative value for \( M \) indicates that the C6.1 retrieval worsened. As shown in Figure 7, the modification of C6.1 DT AOD from C6 varied with urbanization. With an increase in urbanization, the percentage of the improved retrievals in C6.1 grew from 8% to 97%, while the percentage of no-updated retrievals was reduced from 87% to near 0. However, the percentage of the deteriorated retrievals in C6.1 compared with C6 was higher in areas of moderate urbanization (11%) and low urbanization (9%), followed by no urbanization (5%); it was lowest in completed urbanization (2%). In areas with completed urbanization, the accuracy of almost all retrievals was improved, and about 2% of retrievals worsened due to a tiny fraction of underestimation caused by overcorrection of the surface contribution. In areas with no urbanization, the statistical results were almost the opposite: 87% of C6.1 retrievals were the same as the C6 retrievals, while the improved retrievals of the rest were only slightly higher than the deteriorated ones. The changes to C6.1 DT AOD over C6 in areas with no urbanization were due to the average smoothing effect that occurred when matching processing was performed, such that the matchups from nonurbanized sites also contained different urbanized values, resulting in better or worse averages. In semiurbanized areas (moderate and low urbanization), the deteriorated percentage of C6.1 AOD from C6 became nonnegligible at around 10%. In mixed areas containing urban and one or more other features, the surface reflectance relationship for each category varied, making it difficult to describe the overall areas in a uniform manner such that a certain proportion of deteriorated retrievals were inevitable. Future versions of the surface reflectance scheme in the MODIS DT algorithm for semiurbanized areas may require more consideration.

3.2.2. Improvement From C6 to C6.1 With Different EVI and Surface Reflectance

In this section, we focus on the modification of the C6.1 DT AOD product related to two important factors, that is, the surface reflectance and EVI, influencing the aerosol inversion over areas with different degrees of urbanization. Figure 8 shows the variation of the improvement of C6.1 DT AOD retrievals from C6 with an EVI. In completely urbanized areas, the EVI had a concentrated and narrow range from 0.02 to 0.26, indicating underlying stable surface conditions. In moderately urbanized areas, the EVI range grew slightly wider, from 0.04 to 0.34, but was still relatively concentrated, indicating the dominant role of the urban surface. In contrast, the EVI in low-urbanization areas was dispersed, with a wide range from 0.02 to 0.48, although there was still partial accumulation from 0.1 to 0.26. Most of the EVIs in nonurbanized areas were evenly distributed between 0.08 and 0.28, with the rest sporadically distributed between 0.3 and 0.52, due to a mixture of various land cover types other than urban. The percentage of dark blue area was distinctly higher in highly urbanized areas, meaning that the improvement in C6.1 became more obvious along with an increase in urbanization; this agreed with other research that showed that the performance of C6.1 DT AOD is much improved over urban areas due to obvious modification in surface reflectance schemes compared to that of nonurbanized areas.

Figure 7. The frequency of modification performance of C6 under different degrees of urbanization. Green represents the percentage of the improved retrievals for C6.1 in comparison with C6; blue represents the percentage of C6.1 to C6 with the same retrievals; red represents the percentage of the deteriorated retrievals in C6.1 in comparison with C6.
C6 DT AOD (Wang et al., 2019; Wei, Li, et al., 2019). The magenta fitting curve lines display a significant and relatively low single peak in the distribution tendency, indicating that the improvement in C6.1 was different even though the UP was the same, and the new DT algorithm successfully improved its performance with a relatively low EVI. Similarly, the significant improvements of the DT algorithm in moderately vegetation index were also demonstrated in the Beijing-Tianjin-Hebei region (Bilal, Nazeer, Nichol, Qiu, et al., 2019).

Since the previous DT algorithm already had good aerosol inversion performance with high vegetation index, there was no obvious improvement from C6 to C6.1. Nevertheless, there was still an overestimation in C6.1 DT AOD products when the EVI was low, illustrating that the new DT algorithm cannot find an ideal solution to the inversion problem with a low EVI.

The improvement in C6.1 retrieval over C6 also varied with surface reflectance, as shown in Figure 9. The latter ranged widely from 0.04 to 0.17 in areas of high urbanization, while most of the reflectance was between 0.04 and 0.11 in areas of low urbanization; this indicated that the high surface reflectance values come mainly from the former. There was a single peak distribution tendency in semurbanized areas, and an obvious improvement appeared when the surface reflectance was relatively high. This demonstrates that the C6.1 DT algorithm is well revised when surface reflectance is relatively high. However, the retrievals from areas where surface reflectance is relatively low had less improvement, because the performance was already good. The retrievals from the high reflectance areas might also improve slightly due to other bright surfaces, such as deserts, that cannot be properly described by a surface scheme trained using mixed areas that included urban surfaces and vegetation. However, there is a bimodal distribution tendency in completely urbanized and nonurbanized areas, because there are two sets of regression coefficients officially set to express the relationship between visible and shortwave infrared channel in the former and the latter, respectively, corresponding to the two peaks. This indicates that each surface relationship obtained good results and that the C6.1 DT algorithm perfectly alleviated the overestimation issue associated with relatively high surface reflectance in high urbanization areas. For reference, previous work also reported that C6.1 DT algorithm significantly improved in areas of high and low surface reflectance in Beijing (Tian et al., 2018). Nevertheless, there was little improvement in DT C6.1 AOD products over nonurbanized areas because few pixels met the requirements for updating. Moreover, the surface reflectance with the maximum improvement gradually increased with the increase in UP, demonstrating that the obvious mitigation of the overestimation issue in DT AOD retrievals was observable over highly urbanized areas. This further improves the reliability of MODIS DT AOD products in urban areas.

4. Conclusions

In this study, the MODIS C6.1 DT AOD product was evaluated in detail over mainland China in various conditions with regard to spatial distribution, seasons, and air quality for the period 2010–2017. The conclusions are as follows.

The overall validation of the MODIS C6.1 AOD product in China indicates good performance, with a high $R^2$ (0.87) and low RMSE (0.23) against ground measurements, and an obvious overestimation during low aerosol loading. Apart from a significant overestimation in Western China, the DT retrievals in C6.1 show higher correlation to ground measurements in PRD, NCP, YRD, and Central China. The retrievals in C6.1 performed best in winter, followed by summer and autumn, and relatively poorly in spring. Additionally, the
retrievals after strict cloud masking performed better during the haze period than during the no-haze period. This indicates that C6.1 DT AOD products are suitable for most of China and during the haze period after a more accurate cloud detection.

In comparison with the MODIS C6 DT AOD, the latest C6.1 AOD product is improved with higher correlation and lower uncertainty against ground measurements. However, there was a spatial variation in the difference between C6.1 and C6: An overall decline in DT retrievals was observed in the south and east where more large-scale urban agglomerations are accumulated, while the modified C6.1 does not achieve the desired effect in northwest China. Moreover, C6.1 improved significantly in NCP and Central China, slightly in the YRD and PRD, and hardly in Western China, indicating that the updated DT algorithm was only optimal in inland areas consisting of vegetation and urban areas, was moderate in river deltas, and had little effect in high-altitude areas with deserts, cities, and little vegetation. In terms of seasonal performance, the retrievals for C6.1 improved greatly in spring, followed by summer and autumn, and hardly changed in winter, indicating that the modification performed better during the period when vegetation is flourishing compared to when the latter is growing. Furthermore, the improvement from C6 to C6.1 showed a negative correlation with the level of air pollution, demonstrating that the modification works better during the no-haze period than during the haze period.

Further analysis of each area in areas with different degrees of urbanization illustrates that the updated DT algorithm works well in completely urbanized areas, with a 97% improvement rate, and has a 10% deterioration rate in semurbanized areas, and has an 87% invariability rate in nonurbanized areas. Moreover, the improvement analysis of C6.1 based on the EVI indicated that problems with the MODIS DT AOD retrievals in areas of low vegetation coverage have been revised to some extent. Furthermore, the improvement analysis of C6.1 based on surface reflectance demonstrated that the problems of the DT algorithm with regard to low surface reflectance for areas of semurbanization, and lower and higher surface reflectance for completely urbanized and nonurbanized areas, respectively, have been mitigated. These results demonstrate that the regression relationship in the surface scheme has been revised commendably, further improving the accuracy of MODIS C6.1 DT AOD products.

Acknowledgments
This study was supported financially by the National Key R&D Program of China (2017YFC0212601 and 2016YFC0200900), Hubei Provincial Natural Science Foundation of China (No. 2016CFB620), National Natural Science Foundation of China (41571344), and the China Postdoctoral Science Foundation (2015M572198). The data used are available from the Level-1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (https://ladsweb.modaps.eosdis.nasa.gov/), AERONET Web (http://aeronet.gsfc.nasa.gov/), and the China National Environmental Monitoring Centre website (http://www.cnemc.cn/). We would like to thank the investigations for providing scientific data and maintaining websites.

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