Validation and Accuracy Analysis of the Collection 6.1 MODIS Aerosol Optical Depth Over the Westernmost City in China Based on the Sun-Sky Radiometer Observations From SONET

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Abstract Toward the Kashi region in northwest of China, the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD) retrievals from Collection 6 (C6) MYD, Collection 6.1 (C6.1) MOD, and C6.1 MYD during 2016–2017 are compared with ground-based measurements from the Sun-sky Radiometer Network (SONET), and the first comprehensive evaluation of the Dark Target (DT) and Deep Blue (DB) retrievals with a 10-km spatial resolution in the latest C6.1 MYD AOD data set during 2016–2018 is presented. In general, C6.1 MYD AOD products (both of DT and DB algorithm) are the most effective in Kashi of the three collections, and there is an overall underestimation of DB AOD, while DT AOD that slightly outperformed DB AOD in Kashi is overestimated on the whole. As to the factors that influence the accuracy of MODIS AOD, for DB algorithm, the overestimations of the surface refflectance and Single Scattering Albedo that DB aerosol model assumed can cause underestimation of DB AOD retrievals over Kashi, while the ones for DT algorithm are opposite. Besides, the coarse dust particles with lower veracity are predominant in Kashi region, which illustrated that the errors of particle size assumption in C6.1 MYD DT and DB algorithms will make large inversion error of MODIS AOD. Moreover, whatever DB or DT algorithm, the accuracy of AOD is diminished as the aerosol loading increases. The more realistic aerosol models and surface characterizations are necessary during the process of generating the MODIS aerosol retrievals in Kashi region.

1. Introduction

Atmospheric aerosols are suspensions of fine solid particles or liquid droplets in air or another gas, also known as the particulate matter from both anthropogenic and natural processes (Tian et al., 2018). By interacting with solar and terrestrial radiation, while altering the properties and lifetime of cloud (Wang et al., 2019), aerosol can significantly affect the global and local ecological environments (Bilal et al., 2013; Colvile et al., 2001) and represents one of the largest uncertainties in climate researches (Climate change 2014, 2014). Aerosols in atmosphere are also primary pollutants, which reduced atmospheric visibility and affect transportation (Wang et al., 2017), while responsible for poor air quality and have negative impacts on human health (Butt et al., 2016; Pope & Dockery, 2006). Therefore, the impact of aerosol at the aspects mentioned above has drawn significant attention from researchers, and the collection of information about aerosol properties is crucial and principal.

Typically, AOD is defined as the measurement of light extinction by aerosols in the atmospheric column above the Earth’s surface (Van Donkelaar et al., 2010), which is the basic aerosol optical property and can be used to quantify the aerosol particles (He, Wang, Lin, Zhang, Bilal, & Wei, 2018; He, Wang, Lin, Zhang, Xia, et al., 2018; Holben et al., 2001) and can be retrieved from ground-based sun photometer and spaceborne satellite sensors (Wang et al., 2019). The application of aerosol studies at medium or large
scales is limited, owing to the relatively sparse distributions of traditional ground observation sites (Wei et al., 2019); it is difficult to satisfy the need to characterize the variability of regional aerosols in medium-large areas. The launch of passive satellite sensors, such as MODIS (Remer et al., 2008), Sea-Viewing Wide Field-of-View Sensor (Sayer et al., 2012), Advanced Very High Resolution Radiometer (Lee et al., 2009), Multi-angle Imaging SpectroRadiometer (Diner et al., 1998), Visible Infrared Imaging Radiometer Suite (Wei & Sun, 2017), Himawari-8 (Zhang et al., 2018), and any other sensors, provides great opportunities to solve this problem.

With 36 spectral channels and approximately 2,330 km wide, while extended from the visible to the thermal infrared (415–14,235 nm) with a temporal resolutions of 1 to 2 days and moderate spatial resolutions of 0.25, 0.5, and 1 km (Bilal et al., 2014; Bisht et al., 2005; Justice et al., 1998; King et al., 1992; Nichol & Bilal, 2016), the MODIS instrument onboard the Aqua and Terra satellites can generate aerosol products which help to understand the effects of aerosols at both global and regional scales (Qin et al., 2018; Qin et al., 2018). Despite the fact that the Terra and Aqua satellites have operated for more than a decade (Barnes et al., 2003), the enthusiasm of National Aeronautics and Space Administration (NASA) to upgrade the algorithms is still undiminished. From Collection 5.1 (C5.1) to C6, the MODIS Adaptive Processing System provides global AOD products over land at 10- or 3-km spatial resolutions based on the DT algorithm (Levy et al., 2007; Levy et al., 2013) and a 10-km spatial resolution based on the DB algorithm (Hsu, 2017; Hsu et al., 2013). In the fall of 2017, the MODIS C6.1 aerosol products were released based on major improvements in both aerosol retrieval algorithms and radiometric calibration. The C6.1 aerosol products are generated based on the new updated Level 1B calibrated radiance products, which includes additional calibration corrections developed by the NASA Ocean Biology Processing Group (OBPG) that were applied to the top-of-atmosphere (TOA) radiance product of the MODIS Characterization Support Team. The MODIS Characterization Support Team and Ocean Biology Processing Group corrections affect the sensor response and scan angle, the radiometric gain, and the polarization sensitivity (Jeong et al., 2011; Meister et al., 2014).

In addition, the MODIS sensor has now been in operation for around a decade longer than its design life, while the other general principles behind the C6.1 products are similar to those of C6 (Tian et al., 2018). The other descriptions of the newly modified algorithms are introduced in section 3.1. There are many studies conducting to evaluate the accuracies of MODIS AOD, and some researches demonstrated that the aerosol retrieval from satellites has large improvements and with high effectiveness (Li et al., 2013; Zhang et al., 2016). Meanwhile, other scholars think that there still are many uncertainties in satellite aerosol data sets (Li et al., 2009; Tao et al., 2015; Tao et al., 2017). However, numerous scholars have compared the MODIS AOD products to the observations from Aerosol Robotic NETwork (AERONET) or China Aerosol Robot Sunphotometer Network (Fan et al., 2017; Hsu et al., 2013; Sayer et al., 2014; Sayer et al., 2015; Tao et al., 2017; Wang et al., 2017; Wei et al., 2019; Xie et al., 2011; Yan et al., 2015), and most of their MODIS aerosol retrievals are from DT algorithm or DB algorithm of C5.1 and C6. Besides, the present studies mainly focus on the eastern coastal, the Beijing-Tianjin-Hebei Region as well as the whole of China, and overseas (Boiyo et al., 2017; Bouazziz et al., 2019; Tao et al., 2015; Tian et al., 2018; Wang et al., 2019), and due to the scarcity of aerosol observation, little research has been done on the region of northwestern China (Li et al., 2012; Tao, Chen, et al., 2017). Moreover, whatever the northwestern, the whole of China, or overseas, these existing researches mainly aim at the direct comparisons between satellite-derived AODs and ground measurements, or inter-comparison of the AOD products among MODIS and any other satellites while without analyzing the error source of them, or conduct the research of error analysis just for the older version or an individual algorithm. In addition, as C6.1 has only recently been released, detailed research on the new AOD products is rare, and more deep and comprehensive analysis is required.

In recent years, the aerosol effects have been diversified and significant in Kashi, a city that is located in central Eurasia, more specifically, in the western side of Taklamakan desert in Southern Xinjiang district of China, in which the high aerosol loadings are due to a combination of particulates from local anthropogenic emissions and long-range transport from the Gobi Desert (Kaufman et al., 1997). In Kashi, since the use of MODIS AOD products is necessary in environmental protection researches to estimate the air quality and conduct other relevant studies more effectively, it is important to evaluate the performance of MODIS AOD products and ensure their quality as well as examine the uncertainties of aerosol parameters desired for applications for Kashi. The surface observation of aerosol is the foundation of validating the MODIS AOD products, and the error of the MODIS aerosol retrievals compared to the ground-based
measurements can cause deviation in the estimation of air quality (Van et al., 2010). However, Kashi has poor measurement infrastructure and difficulties on ground-based instrument maintenance. Therefore, a sun-sky radiometer observation site located in Kashi was set up in November 2013 to provide aerosol products for satellite applications. In this study, we used Kashi measurements of SONET as baselines, compared the performance of MODIS AOD products from different collection (C6 MYD, C6.1 MOD, and C6.1 MYD AOD), and presented a first comprehensive evaluation of the latest C6.1 MYD AOD data sets in Kashi region during 2016–2018. The rest of this paper is structured as follows. Section 2 gives an overview of the study area while introduces the data and methodology. The comparison results and their uncertainties discussion are presented in section 3. Finally, section 4 provides the conclusion. It will be a pregnant supplement to the validation of C6.1 aerosol retrieval in northwestern China.

2. Data and Methodology

2.1. Data

2.1.1. MODIS Aerosol Products

No matter C6 or C6.1, all of the MxD04 (where O is for Terra and Y is for Aqua) aerosol products have 10-km MODIS aerosol data sets of DT retrievals, DB retrievals, and the merged products of DT and DB, while 3-km product data set only includes the retrievals from DT algorithm (Levy et al., 2013). To compare the performance of a variety of AOD products (the AOD of C6 MYD, C6.1 MOD, and C6.1 MYD) and analyze the differences between DT and DB retrievals over Kashi, the Level 2 MxD04 AOD products at 10-km spatial resolution from DT and DB of C6 MYD, C6.1 MOD, and C6.1 MYD with high quality (QA = 3 for DT and QA = 2, 3 for the DB algorithm) are all extracted. The reason why QA = 1 retrievals are not generally recommended for most scientific applications is that the applications such as data assimilation are very sensitive to high-magnitude outliers, and the validation by its nature may underestimate the error due to cloud contamination, both of which are expected to be more common in QA = 1 data (Hsu, 2017). Furthermore, in order to analyze the uncertainty of MODIS aerosol retrievals, the scientific data set (SDS) named “Surface_Refl ectance_Land” (LSR), “Deep_Blue_Spectral_Surface_Refl ectance_Land” (DB-SR), “Deep_Blue_Spectral_Single_Scattering_Albedo_Land” (DB-SSA), “Deep_Blue_Angstrom_Exponent_Land” (DB-AE), and “Aerosol_Type_Land” are also used (detailed information was shown in Table 1).

2.1.2. SONET Ground-Based Observations

The Kashi site (39.5°N, 75.93°E, 1,320 m a.s.l.) is located in Kashi Region in Xinjiang (Figure 1), the junction of Pamirs Plateau and Tarim Basin within central Eurasia, while east of China’s largest desert named

| Table 1 |
| --- |
| **Summary of Data Used in This Study** |
| **Product** | **Scientific data set (SDS)** | **Contents** | **Resolution** |
| C6.1 MOD04 L2, C6.1 MYD04 L2, C6 MYD04 L2 | Optical_Depth_Land_And_Ocean | Aerosol optical depth of DT algorithm over land (550 nm, QA = 3) | 10 km |
| C6.1 MYD04 L2 | Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimate | Aerosol optical depth of DB algorithm over land (550 nm, QA = 2 or 3) | 10 km |
| C6.1 MYD04 L2 | Surface_Refl ectance_Land | Estimated surface reflectance at 470, 660, and 2,130 nm | 15–30 min |
| Deep_Blue_Spectral_Surface_Refl ectance_Land | Deep Blue surface reflectance at 412, 470, and 660 nm for land | | |
| Deep_Blue_Spectral_Single_Scattering_Albedo_Land | Single scattering albedo at 412, 470, and 660 nm for land | | |
| Deep_Blue_Angstrom_Exponent_Land | Deep Blue angstrom exponent for land (412–470 nm for bright surfaces, 470–650 nm for vegetated surfaces) | | |
| Aerosol_Type_Land | Aerosol type: 1 = Continental, 2 = Moderate Absorption Fine, 3 = Strong Absorption Fine, 4 = Weak Absorption Fine, 5 = Dust Coarse | | |
| SONET | AOD | Aerosol optical depth (440 and 675 nm, Level 1.5) | 15–30 min |
| SSA | Single scattering albedo (440 and 675 nm) | | |
| AE (α) | Angstrom exponent (440–870 nm) | 60 min |
| VPSD | Volume particle size distribution with 22 bins for radius from 0.05 to 15.0 μm | 0.05°×0.05° |
| MCD12C1 | Land use cover | IGBP scheme | |
Taklimakan desert, and is the westernmost city in China. By geographical constraints, the Kashi region belongs to the warm temperate zone and continental drought climatic zone, which has four distinctive seasons, long illumination, the air temperature with annual and diurnal varying greatly, as well as the low precipitation and high evaporation. The gale, sandstorm, and dust weather often appear in spring and summer. The Kashi site is the westernmost site belonging to SONET, which provides systematic instrument maintenance, calibration, data processing, and quality control (Li et al., 2015).

The SONET is a ground-based CIMEL radiometer network, with the extension of multi-wavelength polarization measurement capability to provide long-term columnar atmospheric aerosol properties in China. The multi-wavelength polarized sun-sky radiometer CE318-DP, which is an automatic instrument for long-term continuous observation in the field, can measure both radiance and polarization at eight bands (0.34, 0.38, 0.44, 0.50, 0.67, 0.87, 1.02, and 1.64 μm) by combining filter wheels and the rotation of polarizer (Li et al., 2009), measured about every 15 min; the sky radiance is scanned following almucantar and solar principal plane geometry procedures approximately each hour in automatic mode (Holben et al., 1998), manufactured by the CIMEL Electronique in France employed by SONET (Li et al., 2018). Kashi site is one of the 16 automatic sites which is located in typical regions of China in SONET, and the instrument calibration is carried out once a year to ensure the data quality.

Aerosol optical and microphysical parameters of Kashi site are retrieved at 0.44, 0.67, 0.87, and 1.02 μm according to the algorithm of SONET, which is similar to AERONET. Moreover, the common record ratios of AOD products are above 95% in a joint SONET-AERONET data set during Dragon-Korus-AQ (2016) campaign (Holben et al., 2017), and the uncertainty of AOD is estimated to be about 0.01–0.02 (Holben et al., 1998). Besides, the average difference on SSA is slightly large, while differences of all other parameters are
less than or close to the AERONET nominal uncertainties. These suggest that the scientific data collection capabilities of SONET and AERONET are analogical, and uncertainty of SONET aerosol products is similar to AERONET products, which accuracies are quite high (Li et al., 2018). Thus, we can use the AOD observed by sun-sky radiometers from the SONET station of Kashi to validate MODIS aerosol retrievals in this region, which could compensate for the insufficient of the AERONET’s site distribution that is rare in northwest area of China.

The aerosol parameters including AOD (440 and 675 nm; Level 1.5, which is on the basis of Level 1.0 but selected by automatic cloud-screening algorithm), Ångström algorithm (\( \alpha \)) in 440–870 nm, SSA (440 and 675 nm), and volume particle size distribution with 22 bins for radius from 0.05 to 15.0 \( \mu m \) obtained from January 2016 to December 2018 at Kashi site are employed in this study. SONET instruments collect data in multiple wavelengths; we can know from the foregoing that all of which we employed are slightly different from the MODIS channel used (550 nm). Therefore, to compare with MODIS products, the parameters of the corresponding band are obtained by interpolation based on the following methods.

The ground-based AOD at 550 nm was interpolated using the \( \alpha \) (Wei et al., 2018), which is defined as shown in equation (1):

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

where \( \tau_1 \) and \( \tau_2 \) represent the available AOD measurements at the nearest wavelength \( \lambda \) of \( \lambda_1 \) (440 nm) and \( \lambda_2 \) (675 nm).

The surface observation of SSA at a wavelength of 550 nm \( \omega_{0.55} \) could be determined by a linear interpolation as follows (He et al., 2012):

\[
\omega_{0.55} = 0.55 \times \frac{\omega_{0.44} - \omega_{0.675}}{0.44 - 0.675} + \frac{\omega_{0.44} \times 0.675 - \omega_{0.675} \times 0.44}{0.675 - 0.44},
\]

where \( \omega_{0.44} \) and \( \omega_{0.675} \) represent the ground-based SSA at the nearest \( \lambda \) of 440 and 675 nm.

**2.1.3. MODIS Land Cover Type Product**

In order to ensure the calculation of surface reflectance of the DB algorithm that relate to the uncertainty analysis about surface reflectance, the MODIS Land Cover and Land Cover Dynamics product (MCD12C1), with the International Geosphere Biosphere Programme classification scheme (Loveland & Belward, 1997) in 2017 with good quality (the product which classifying believe degree is higher than 85%) is used.

The MCD12C1 is a global land cover type classification product, which provides the dominant land cover type as well as the sub-grid frequency distribution of land cover classes within each 0.05° cell (Friedl et al., 2010), at 5,600 m spatial resolution and yearly temporal resolution. A summary of data used in this study is provided in Table 1.

**2.2. Methodology**

Since SONET provides continuous AOD values at 15-min intervals of a point, while MODIS captures instantaneous AOD values of a larger region with a pixel size of 10 km \( \times \) 10 km, SONET and MODIS differ in terms of their spatial-temporal scales. Therefore, in order to take both of the spatial and temporal variabilities of aerosol distribution into account, SONET and MODIS measurements need to be co-located in space and time. The sample size is too small in a pixel of MODIS aerosol products, which is not conducive to better fitting. Besides, with the special climate, frequent winds, as well as the uniform underlying surface in Kashi, it is better to choose a larger sampling range. Therefore, in our study, in terms of spatial scale, the MxD04 AOD within a window size of 50 \( \times \) 50 km centered on SONET sites are selected, in which AOD is determined by the median of the nonzero values. In terms of temporal scale, the average SONET measurements within \( \pm 30 \) min of the times when the satellite passed overhead (10:30 local time for Terra while 13:30 local time for Aqua). The SSA, AE, surface reflectance, and land cover type are determined by the same method described above.
In order to analyze the validation results and uncertainties for the above data which is carefully matched, the evaluation statistic matrix that were calculated including the expected error (EE), which is derived from the two linear envelopes above and below the 1:1 line on a scatterplot that contains approximately one standard deviation of the matched point, is used here for the confidence envelopes of the retrieval algorithm over land to evaluate the quality of the MODIS AOD estimates (Wang et al., 2017), as shown in equation (3). The percentage of retrievals, falling within the envelope of EE (WEE), as compared to SONET AODs is given by equation (4). We also evaluated the extent of the overestimation and underestimation of MODIS aerosol products by percentages of collocations above EE (AEE) and below EE (BEE), respectively. The relative mean bias (RMB) indicates the overall bias of MODIS and SONET AOD, as shown in equation (5), while RMB < 1 and RMB > 1 represent underestimates and overestimates, respectively. The linear correlation coefficient (R) is a good indicator of the consistency between the SONET and MODIS AOD values, as shown in equation (6), and higher values of R indicate better agreement (Bilal & Nichol, 2015; Wei & Sun, 2017). Moreover, the root mean square error (RMSE), as shown in equation (7), the mean absolute error (MAE), as shown in equation (8), and the number of MODIS/SONET matchups (n) were counted and calculated synchronously.

\[
EE = \pm (0.05 + 0.15 \times \text{AOD SONET}),
\]

\[
WEE(\%) = \text{AOD SONET} - \frac{|\text{EE}|}{\text{AOD MODIS} - \text{AOD SONET}} + |\text{EE}|,
\]

where the AOD_{SONET} is AOD from SONET and AOD_{MODIS} is the retrieved value from MODIS.

\[
RMB = \frac{\sum_{i=1}^{n} (\text{AOD MODIS}(i) - \text{AOD MODIS}) (\text{AOD SONET}(i) - \text{AOD SONET})}{\sqrt{\sum_{i=1}^{n} (\text{AOD MODIS}(i) - \text{AOD MODIS})^2 \sqrt{\sum_{i=1}^{n}} (\text{AOD SONET}(i) - \text{AOD SONET})^2}}.
\]

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\text{AOD MODIS}(i) - \text{AOD SONET}(i))^2},
\]

\[
MAE = \frac{1}{n} \sum_{i=1}^{n} |\text{AOD MODIS}(i) - \text{AOD SONET}(i)|.
\]

### 3. Results and Discussion

#### 3.1. Performance of Different AOD Products in Kashi Region

Figure 2 provides the validation and accuracy differences for DT and DB aerosol retrievals of C6 MYD, C6.1 MYD, and C6.1 MOD against SONET AOD measurements at Kashi site from 2016 to 2017; the regression line is represented by the red solid line, the dashed lines (green) are EE bounds of the MODIS products, and the black solid line indicates the X = Y line. Meanwhile, Table 2 shows various statistical evaluation indicators between MODIS AOD for DT and DB algorithms of three collections and ground-based measurements.

For the C6 MYD AOD products, as shown in Figures 2a and 2d, as well as Table 2, no matter DT or DB algorithm, the R is generally high of MODIS AOD and SONET measurements (R = 0.964 and 0.910, respectively), and the data distribution is relatively concentrated (RMSE = 0.123 and 0.205, respectively). However, the fraction within the EE can be considered extremely low at only 13.08% and 15.52% correspondingly. With the MAE = 0.204 and 0.244, the RMB = 1.595 and 0.381. For the C6.1 MYD AOD products, as shown in Figures 2b and 2e, the R of MODIS DT, DB AOD and ground-based observations are 0.964 and 0.907, while WEE = 16.08% and 15.94%, RMSE = 0.123 and 0.203, MAE = 0.198 and 0.238, RMB = 1.596 and 0.388, respectively.

Through the statistical result above, we can see that there are some differences between the AOD products of C6.1 MYD and C6 MYD, and the differences will arise in the data sets as updates to the algorithms are made. For DT algorithm, from the initial version to C6, the major improvements of DT algorithm have been directed at improving the surface reflectance relationships among the bands of red, blue, and SWIR (Kaufman...
et al., 1997; Levy et al., 2007), and the improvements in C6.1 are no exception (Gupta et al., 2016), with the most important change was that the surface re
d reflectance estimation model for main urban surfaces was improved, and modified algorithm for aerosol retrieval over land surface when urban percentage is larger than 20% using a revised surface characterization (Gupta et al., 2016).

As for DB algorithm, four major improvements were introduced in C6.1: The first is called “heavy smoke detection,” which can address the over-screening issue while minimizing true cloud contamination. The second aspect is the artifact reduction in heterogeneous terrain. The third improvement is regarded as the improved surface modeling for elevated terrain. The last is the bug fixes and updated regional/seasonal aerosol optical models, in which several miscellaneous bugs were found and fixed and assumed aerosol optical models in some areas were updated based on biases identified from C6 validation work (Hsu, 2017; Wei et al., 2019).

Here, we compared the temporal trend of DT and DB retrievals between C6 and C6.1 with ground-based observations (Figures 3a and 3b), which shows the monthly bias between the two versions and SONET measurements during 2016–2017 in Kashi site. The black solid line denotes the 1:1 line, the green dashed lines are the EE lines, and the red solid line represents the regression line.

Figure 2. Density scatter plots of C6 MYD (a, d), C6.1 MYD (b, e), C6.1 MOD (c, f) AOD retrievals of DT (above) and DB (below) algorithms against SONET measurements during 2016–2017 in Kashi site. The black solid line denotes the 1:1 line, the green dashed lines are the EE lines, and the red solid line represents the regression line.

Table 2

|       | M     | n   | R     | k   | b     | RMSE | MAE | RMB | WEE (%) | AEE (%) | BEE (%) |
|-------|-------|-----|-------|-----|-------|------|-----|-----|---------|---------|---------|
| DT    | C6-MYD| 0.517 | 130 | 0.964 | 1.202 | 0.135 | 0.123 | 0.204 | 1.595 | 13.08 | 86.92   |
|       | C6.1-MYD| 0.550 | 143 | 0.964 | 1.224 | 0.124 | 0.123 | 0.198 | 1.596 | 16.08 | 83.92   |
|       | C6.1-MOD| 0.601 | 170 | 0.959 | 1.343 | 0.108 | 0.174 | 0.225 | 1.661 | 18.82 | 81.18   |
| DB    | C6-MYD| 0.228 | 232 | 0.910 | 0.624 | 0.095 | 0.283 | 0.280 | 0.337 | 17.65 | 82.35   |
|       | C6.1-MYD| 0.230 | 251 | 0.907 | 0.611 | 0.087 | 0.203 | 0.238 | 0.388 | 15.94 | 84.06   |

Note. The n is the number of MODIS/SONET matchups; R is the linear correlation coefficient; k and b are the slope and intercept of the linear fitting equation; RMSE is the root mean square error; MAE and RMB are the mean absolute error and relative mean bias; WEE, AEE, and BEE are the percentage of collocations that within EE, above EE, and below EE, respectively.
As can be seen from Figures 3a and 3b, whatever DT or DB, the monthly averaged AOD values of C6 and C6.1 in Kashi region had a nearly uniform temporal variation trend, with consistent rise and fall. Similarly, Figures 3c and 3d show that the monthly bias between C6.1 and SONET is close to zero slightly than the monthly bias between C6 and SONET, on the whole.

We can know from the chart above that, compared with the C6 MYD aerosol products, there are more effective data, slightly reduced error, and growth of the percentage of retrievals that fall within the envelope of EE of C6.1 MYD; the remaining statistical indicators have changed a little. Overall, the effectiveness of C6.1 MYD AOD in Kashi region is a little higher than C6 MYD aerosol retrievals, but the difference is not very large, indicating that the improvement effect of the DT and DB algorithms are not significant in Kashi region.

There are two aerosol products for C6.1: C6.1 MOD and C6.1 MYD. For MOD AOD products, see Figures 2c and 2f. Compared to MYD, although the collocations ($n$) and the WEE (DT-WEE = 18.82%, DB-WEE = 17.65%) are higher than MYD, the C6.1 MOD AOD is relatively discrete, with comparatively large error (DT-MAE = 0.225, DB-MAE = 0.280; DT-RMB = 1.661, DB-RMB = 0.337). Overall, the retrievals of two algorithms from Aqua are better than those from Terra according to the aggregative indicators.
There could be many causes for these discrepancies between the aerosol retrievals of C6.1 MOD and C6.1 MYD, while MODIS Terra and MODIS Aqua processing are identical, and the symmetry of Terra and Aqua orbits should not lead to a consistent difference in retrieved AOD (Levy et al., 2018). Differences could arise from the differences in satellite overpass times (Terra at approximately 10:30 a.m. local time, while Aqua at approximately 1:30 p.m. local time). Therefore, it is possible that different aerosol statistics might arise, whether due to diurnal cycles of aerosol or clouds (leading to different sampling), or the differences in meteorological conditions (sunlight, air speed, radiation, diffusion conditions, atmospheric stability, and so on) between the morning and afternoon, which is convolved into the MODIS data. Apart from satellite overpass times, the calibration changes for Aqua MODIS are small (Levy et al., 2013); moreover, MODIS Aqua has been a better characterized and more stable instrument (Lyapustin et al., 2014). So we chose the aerosol data from Aqua rather than Terra, to evaluate the performance of aerosol retrievals. The validation results indicate that C6.1 MYD AOD products (both DT and DB algorithm) are comparable over Kashi region, which can be used in local climate studies and air quality assessment.

3.2. Evaluation of the AOD Retrievals in C6.1 MYD in Kashi Region

Based on the discussion about the performance of different AOD products in Kashi region in the section 3.1, we chose the C6.1 MYD aerosol retrievals during 2016–2018, compared and validated the accuracy of DT AOD and DB AOD in Kashi region with the units of all-year and four seasons, severally. The classification standard of four seasons is spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, January, and February).

3.2.1. Validation of the C6.1 MYD DT AOD Products

Figure 4 shows scatter plots of the AOD derived from C6.1 MYD DT against the AOD obtained from ground-based sun photometer measurements at the Kashi site in spring, summer, autumn, and all-year-round. Table 3 provides the statistical parameters of above. In Figure 4, the satellite retrievals and ground measurements exhibited good consistency of all time, with $R = 0.934–0.976$ and $\text{RMSE} = 0.047–0.273$. However, the C6.1 MYD DT AOD was largely overestimated, especially in all-year-round, spring.

Figure 4. Density scatter plots of C6.1 MYD DT AOD retrievals against SONET measurements in spring (a), summer (b), autumn (c), winter (d), and all-year-round (e) during 2016–2018 in Kashi site. The black solid line denotes the 1:1 line, the green dashed lines are the EE lines, and the red solid line represents the regression line.
and summer, with the AEE = 85.99%, 85.19%, and 91.61% for the three periods, respectively. The error is large (MAE = 0.232, 0.361, and 0.361; RMB = 1.618, 1.439, and 1.754). There is relatively high accuracy in autumn and winter, but the overestimate in some extent still existed (WEE = 40%, 80%; AEE = 60%, 20%). The DT algorithm retrieves aerosol properties over dense vegetated land and is not applied over scenes identified by internal tests as bright land surfaces (such as deserts, snow, and semiarid areas), as the swIR-to-visible surface reflectance relationship does not hold for these surface types (Sayer et al., 2014). However, due to snow/ice coverage in winter and part-time in autumn and early spring, which was masked by snow/ice mask step at the beginning of DT AOD retrieval algorithm (Xie et al., 2011), a long-term absence of DT retrievals can be observed in winter while partial data missing in spring and autumn, in which season the surface of the local regions is bright. Thus, the DT aerosol retrievals with the largest number appeared in summer (n = 155), while autumn and winter have few effective products (n = 20 and 5, respectively) of all time.

**3.2.2. Validation of the C6.1 DB AOD Products**

The evaluation of the C6.1 MYD DB products against Kashi SONET ground-based observations is presented in Figure 5. Table 4 shows the above related accuracy statistics at the Kashi SONET site.

| Time   | n     | R     | k     | b     | RMSE  | MAE   | RMB   | WEE (%) | AEE (%) | BEE (%) |
|--------|-------|-------|-------|-------|-------|-------|-------|--------|---------|---------|
| DT     | 207   | 0.968 | 1.311 | 0.115 | 0.168 | 0.232 | 1.618 | 14.01  | 85.99   | 0       |
| Spring | 27    | 0.976 | 1.366 | 0.060 | 0.273 | 0.361 | 1.439 | 14.81  | 85.19   | 0       |
| Summer | 155   | 0.959 | 1.310 | 0.135 | 0.137 | 0.229 | 1.754 | 8.39   | 91.61   | 0       |
| Autumn | 20    | 0.934 | 0.959 | 0.127 | 0.062 | 0.116 | 1.366 | 40.00  | 60.00   | 0       |
| Winter | 5     | 0.973 | 1.187 | 0.022 | 0.047 | 0.102 | 1.237 | 80.00  | 20.00   | 0       |

Note. The n is the number of MODIS/SONET matchups; R is the linear correlation coefficient; k and b are the slope and intercept of the linear fitting equation; RMSE is the root mean square error; MAE and RMB are the mean absolute error and relative mean bias; WEE, AEE, and BEE are the percentage of collocations that within EE, above EE, and below EE, respectively.
We can find through the charts above, no matter all-year-round or four seasons, that there is a systematic underestimation for DB retrievals over Kashi region; the DB AOD values under an expected error envelope of \( \pm (0.05 + 15\% \text{ AOD}_{\text{SONET}}) \) exceed 75% (BEE = 84.32%, 77.78%, 81.93%, 88.64%, and 95% in all-year-round and four seasons); all of the RMB are below 0.5, with the slopes of linear equation \( (k) \) under 0.7 and corresponding MAEs of 0.278, 0.404, 0.223, 0.209, and 0.275.

Although the DB algorithm was initially developed to obtain aerosol information over bright desert and vegetated surfaces like Kashi, the accuracy of DB retrievals in this region was found to be much lower than those in urban areas and croplands with a notable underestimation, which is consistent with the results of Tao et al. (Tao et al., 2015; Tao, Wang, et al., 2017).

### 3.2.3. Comparison of the Aerosol Retrievals Between DT and DB Algorithms

Combining the first two sections above (sections 3.2.1 and 3.2.2), we learned that there is an overall overestimation of C6.1 MYD DT AOD (BEE = 0), while C6.1 MYD DB AOD is underestimated by the whole (AEE = 0). Comparing the two algorithms, the total AOD coverage of the DB retrievals exceeds that of DT, with the number of DB collocations was almost 1.9 times those of DT, as the DB algorithm has been expanded to cover vegetated land surfaces and has able to retrieve AOD over complex and bright urban surfaces, which is more aligned with the underlying surface of Kashi region, while the DT algorithm retrieves aerosol properties over dense vegetated land and is not applied over scenes identified by internal tests as bright land surfaces. As for DB, the main factor resulting in a loss of AOD retrievals is the cloudy areas, where DB fails to retrieve AOD (Hsu et al., 2004; Hsu et al., 2013).

However, when it comes to \( R \), RMSE, MAE, and the fraction within the EE, the DT retrievals slightly outperformed DB in Kashi region with higher accuracy (whatever all-year-round or four seasons), and the slope of linear equation of AOD from C6.1 MYD DT and SONET ground-based measurements was more close to the one to one line.

The reason for the accuracy differences between the DT and DB algorithms lies in the distinction in the selection of aerosol models and the assumption of surface reflectance (Sayer et al., 2014). As for the theory of surface reflectance determination, for the MODIS DT algorithm, all unsuitable pixels (e.g., the water, cloud, desert, and snow/ice), the darkest 20% and brightest 50% of pixels, within the retrieval box, were screened out and deselected (Tian et al., 2018). Moreover, the surface reflectance in the near-infrared and visible red band is a function of the vegetation index and scattering angle (Wang et al., 2017), which was parameterized based on a dynamic relationship between the infrared channel at 2.13 \( \mu \text{m} \) and the visible channels at 0.47 and 0.65 \( \mu \text{m} \) (Tian et al., 2018). Unlike DT, the MODIS DB algorithm was developed to retrieve aerosol properties over bright desert and vegetated surfaces. It performs retrievals at a 1 km resolution and then aggregates pixels to the 10 km retrieval box. These pixels are masked and screened to eliminate clouds and snow/ice surfaces (Hsu et al., 2013). For the remaining pixels, the surface reflectance has been updated as a function of season and scattering angle and has been determined comprehensively via the prior LSR database and normalized difference vegetation index values (Hsu et al., 2013). Thus, it leads to the accuracy differences between the DT and DB algorithms and helps to explain why the C6.1 MYD DB algorithm produces more AOD retrieval results.

Besides, the aerosol models of the two algorithms are also different, which of DT algorithm including fine particle and coarse aerosol models (Levy et al., 2007), that depended on the season and geolocation (Tian et al., 2018).
et al., 2018). But for the DB algorithm, the fraction of aerosol models is determined by matching computed apparent reflectance with satellite-observed spectral radiances, and the AOD is retrieved in 412 and 470 nm bands (Hsu et al., 2004), while during heavy dust events (retrieved AOD > 0.7), satellite spectral radiances in three bands (412, 470, and 670 nm) are used to retrieve AOD. The DB algorithm utilizes different fractions of two aerosol models to constrain aerosol optical properties in certain geographic regions. Two dust models with “redder” color and “whiter” color are utilized in the desert region, of which the lookup table is composed of radiances for dust models that are chosen to represent variations in the redness of different dust sources. The DB algorithm basically determines \( \tau_a \) and the redness of the dust aerosol (i.e., the ratio of “whiter” dust to “redder” dust) simultaneously by matching the measured radiances with those in the table, and the SSA for the two wavelengths is then derived from this ratio (Hsu et al., 2004). At the same time, smoke and sulfate models are selected to represent anthropogenic aerosols (Hsu et al., 2013; Tao, Chen, et al., 2017). Comparatively speaking, the DT retrievals that slightly outperformed DB in Kashi might be due to the aerosol models and surface reflectance and that the DT algorithm adopted is more appropriate for this region.

3.3. Uncertainty Analysis

Generally speaking, there are many factors that influence the accuracy rating of the MODIS AOD, such as the surface reflectance estimation and the assumptions in aerosol model, which has been reported in previous studies (Huang et al., 2016; Sayer et al., 2013, 2014). Besides, the quality of the AOD products is also affected by pollution level, land cover type, as well as the terrain and altitude of study area. In this section, we explore the possible sources of AOD error in Kashi from the aspects of land surface reflectance, aerosol model, and aerosol loading.

3.3.1. Uncertainty Related to Surface Reflectance

The key factor in aerosol retrieval is the separation between the land surface and aerosol reflectance (Li et al., 2013). As described in the section 3.2, over land, the methods to estimate surface reflectance of DT and DB algorithms (the corresponding data sets are LSR and DB-SR, respectively) are different, which determines the retrieval accuracy of AOD for the most part. Thus, there is no doubt that the accuracy of surface reflectance estimation is of considerable importance. Studies have shown that errors in surface reflectance estimates are magnified, becoming 10 times larger, when applied to the retrieval of AOD (Munchak et al., 2013). To explore the uncertainty related to the accuracy of surface reflectance estimation, the DT AOD samples were classified into three intervals based on LSR, specifically 0–0.05 and 0.05–0.1, and greater than 0.1. We can see from Figure 6 and Table 5 that the DT algorithm displays comparatively higher accuracy and reliability in the 0–0.05 LSR interval when it is used for dark target areas, in which 40% of the DT samples fall within the EE while 60% of the samples are above it over areas, where MAE = 0.084 and RMSE = 0.034. As LSR increases, the AOD retrieval accuracy of DT decreases gradually, and the fraction of the DT samples that fall within the EE decreases to 15.15% in the LSR interval of 0.05–0.1, whereas the fraction of the DT samples above the EE is 84.85%; meanwhile, the MAE grows to 0.244 in the corresponding interval. The product accuracy of DT reaches a minimum for areas with LSR values larger than 0.1; in such areas, just 8.57% of the DT samples fall within the EE; the samples that fall above the EE reach up to 91.43%, and...
MAE = 0.263, RMSE = 0.140. From the perspective of 2016–2018 as a whole, all of the data support the conclusion that DT AOD retrievals are overestimated in all of the intervals, and the overestimates of MODIS DT AOD become more pronounced while the error increases gradually, along with the increase of LSR. The overestimation of MODIS DT AOD retrievals over Kashi is due to underestimation of the surface reflectance in the corresponding channels.

### Table 5

| LSR       | n   | R    | k     | b     | RMSE | MAE  | RMB  | WEE (%) | AEE (%) | BEE (%) |
|-----------|-----|------|-------|-------|------|------|------|---------|---------|---------|
| 0 – 0.05  | 5   | 0.854| 1.075 | 0.073 | 0.034| 0.084| 1.548| 40.00   | 60.00   | 0       |
| 0.05 – 0.1| 33  | 0.893| 1.307 | 0.147 | 0.161| 0.244| 1.776| 15.15   | 84.85   | 0       |
| > 0.1     | 35  | 0.978| 1.296 | 0.142 | 0.140| 0.263| 1.644| 8.57    | 91.43   | 0       |

*Note.* The n is the number of MODIS/SONET matchups; R is the linear correlation coefficient; k and b are the slope and intercept of the linear fitting equation; RMSE is the root mean square error; MAE and RMB are the mean absolute error and relative mean bias; WEE, AEE, and BEE are the percentage of collocations that within EE, above EE, and below EE, respectively.

**Figure 7.** Evaluation result of C6.1 MYD DB AOD retrievals in (a) 0 < DB‐SR ≤ 0.05, (b) 0.05 < DB‐SR ≤ 0.1, (c) 0.1 < DB‐SR ≤ 0.15, and (d) DB‐SR > 0.15 during 2016–2018 in Kashi site. The meaning of the lines is same with Figure 6.
Consistent with the reasons mentioned above, the DB AOD samples were classified into four intervals based on DB-SR, which are 0–0.05, 0.05–0.1, 0.1–0.15, and greater than 0.15, respectively. Combined with Figure 7 and Table 6, we can know that 33.33% of the DB samples fall within the EE, while 66.67% of the samples are below it over areas with reflectance lower than 0.05, where MAE = 0.147 and RMSE = 0.144. As DB-SR increases, the AOD retrieval accuracy of DB decreases gradually. The fraction of the DB samples that fall within the EE decreases to 27.12%, 9.26% in the DB-SR interval of 0.05–0.1 and 0.1–0.15, whereas the fractions of the DB samples below the EE are 72.88% and 90.74%; meanwhile, the MAE grows to 0.235 and 0.313 in the corresponding two intervals. In particular, over high reflectance areas (DB-SR > 0.15), where just 8.6% of the DB samples fall within the EE, the BEE reaches up to 91.4%, with MAE = 0.325, RMB = 0.367.

Table 6

| DB-SR     | n   | R   | k   | b   | RMSE | MAE   | RMB   | WEE (%) | AEE (%) | BEE (%) |
|-----------|-----|-----|-----|-----|------|-------|-------|---------|---------|---------|
| 0–0.05    | 9   | 0.94| 0.366| 0.016| 0.144| 0.147 | 0.427 | 33.33   | 0       | 66.67   |
| 0.05–0.1  | 59  | 0.799| 0.336| 0.006| 0.251| 0.235 | 0.354 | 27.12   | 0       | 72.88   |
| 0.1–0.15  | 108 | 0.927| 0.562| −0.085| 0.279| 0.313 | 0.398 | 9.26    | 0       | 90.74   |
| >0.15     | 93  | 0.910| 0.617| −0.128| 0.266| 0.325 | 0.367 | 8.60    | 0       | 91.40   |

Note. The n is the number of MODIS/SONET matchups; R is the linear correlation coefficient; k and b are the slope and intercept of the linear fitting equation; RMSE is the root mean square error; MAE and RMB are the mean absolute error and relative mean bias; WEE, AEE, and BEE are the percentage of collocations that within EE, above EE, and below EE, respectively.

Figure 8. The land cover type spatial distribution of Kashi region in 2017. The black pentagram represents Kashi site and the inner solid box is 50 km × 50 km boundary for satellite-ground collocation.
In order to ensure the calculation of surface reflectance of the DB algorithm, Hsu et al. (2013) used the MCD12C1 to separate pixels into three categories: (a) arid and semiarid regions, (b) general vegetation, and (c) urban/built-up and transitional regions (Friedl et al., 2002). The land cover type of the region of Kashi SONET site and its surrounding in 2017 has been extracted based on MCD12C1 (Figure 8), an area of 50 × 50 km which centered around the Kashi SONET site appeared in the inner solid box, and we find that 46.1% of the region was barren or sparsely vegetated, 45.4% was croplands while 8.5% was savannas. That is to say, more than 90% of the study area belongs to arid and semiarid regions, for these regions, the Deep Blue Surface Database method is used in C6.1 MYD for determining the surface reflectance (Hsu et al., 2013).

Based on these results, from the perspective of 2016–2018 on the whole, the DB AOD retrievals are underestimated in all of the intervals, and the negative AOD bias increases obviously with DB-SR increases in Kashi. In consideration of the surface reflectance in DB algorithm, which was depended on a clear-scene database based upon its geolocation (Hsu et al., 2006), even in a clear-scene, it could be calculated incorrect without taken the atmospheric effect into account, which leads to the overestimation of DB-SR stored in the database (Xie et al., 2011) and the large underestimation of DB retrievals.

To sum up, although the C6.1 DT and DB algorithms improved the estimation of surface reflectance, there is still a serious underestimation/overestimation issues over Kashi region, and the performances of all data sets decrease gradually as LSR/DB-LR increases, indicating that the accuracy must be improved in Kashi areas.

3.3.2. Uncertainty Related to Aerosol Model

Except for surface reflectance estimation, the assumptions in aerosol model that include SSA, aerosol types, particle size, and any other aerosol parameters are also important factors in the retrieval of AOD, which would affect the accuracy of AOD retrievals directly.

3.3.3. SSA

We contrast the SSA of SONET actual measurements (SSA_{SONET}) and the extraction results from C6.1 MYD DB-SSA data set directly (SSA_{DB}), as shown in Table 7.

It can be found that the DB-SSA is on the high side in comparison to the ground-based observations in spring (SSA_{DB} = 0.953, SSA_{SONET} = 0.912), summer (SSA_{DB} = 0.950, SSA_{SONET} = 0.937), autumn (SSA_{DB} = 0.915, SSA_{SONET} = 0.911), and winter (SSA_{DB} = 0.924, SSA_{SONET} = 0.917), while with SSA_{DB} = 0.925 and SSA_{SONET} = 0.915 in all-year-round. Particularly in spring, there is a difference between MODIS DB-SSA retrievals and SONET measurements, with the largest difference value of 0.041.

In addition, there are two dust models with “redder” color (ω = 0.910 and 0.950, respectively) and “whiter” color (ω = 0.980 and 0.990 at 412 and 490 nm, correspondingly) are utilized in the deserts region in the MODIS DB algorithm (Tao, Chen, et al., 2017). The SSA of SONET Kashi ground-based observations was compared with that of two dust models in MODIS DB algorithm, both of which were interpolated to the band of 550 nm (Table 8), and the result showed that the assumed values of two dust models (ω ≈ 0.998 and 0.981, respectively) in MODIS DB algorithm, which is much higher than ground-based SSA. Moreover, with the result of Tao, Chen, et al. (2017) research, which compared with the strong scattering white and red dust, dust particles in East Asia tend to appear yellow. The above were large enough to indicate that the scattering ability of aerosol particles in Kashi region has been obviously overestimated in DB dust models.

3.3.3.1. Aerosol Types

The aerosol types used in the satellite data retrieval over land at a resolution of 10 km in the scientific data set (SDS) named “Aerosol_Type_Land” of the MODIS DT aerosol products, which are obtained via the cluster analysis of AERONET aerosol parameters, including fine aerosol types (weak absorbing, moderate absorbing, and strong absorbing fine types), continental, and dust (Wang et al., 2017), their corresponding SSA is

| Table 7 | Comparison of the SONET Measured SSA With C6.1 MYD DB-SSA During Four Seasons and All-Year-Round in Kashi Region |
|---------|-------------------------------------------------|
|         | SONET | C6.1 MYD DB |
|         | 412 nm | 490 nm | 550 nm | 550 nm |
| Spring  | 0.912  | 0.953  |       |       |
| Summer  | 0.937  | 0.950  |       |       |
| Autumn  | 0.911  | 0.915  |       |       |
| Winter  | 0.917  | 0.924  |       |       |
| All-year-round | 0.915 | 0.925  |       |       |

| Table 8 | Comparison of the SSA in Two Dust Models of DB Algorithm With the SONET Observations |
|---------|---------------------------------------------|
| MODIS DB | SONET |
| 412 nm | 490 nm | 550 nm | 550 nm |
| “White” color | 0.980 | 0.990 | 0.998 | 0.915 |
| “Redder” color | 0.910 | 0.950 | 0.981 | 0.915 |
shown in Table 9. We can know from the aerosol types of Kashi region (Table 10) that, during 2016–2018, the aerosol type was highly absorption in summer, while it show up as moderately absorption most of the time (93.23%, 95.67%, and 90.57%), and a few moments of continental (6.77%, 4.33%, and 9.43%) in spring, autumn, and winter, respectively. Thus, we identify the SSA of DT algorithm in Kashi region, which is determined by the aerosol types extracted from C6.1 MYD. To compare the difference of SSA between the SONET measurements and DT retrievals, the seasonal average SSA from the Kashi SONET site and what is used in the DT retrievals from the aerosol types mentioned above, both of which are at 550 nm band, were obtained (Table 11). The seasonal averages of SSA from the SONET data were 0.912, 0.937, 0.911, and 0.917 from spring to winter, while the average DT-SSA with the weighted arithmetic was respectively 0.918, 0.920, 0.919, and 0.917 during four seasons. We can find that, compared to the actual measurements, the MODIS DT-SSA present the following characteristics: much severely low in summer, a little bit low during winter, while higher in spring and autumn (it is probably due to the frequently appeared dust weather in Kashi region during spring and autumn; the measured SSA was affected by near-surface dust particles). The retrieved AOD from MODIS DT algorithm is often biased due to the uncertainties associated with the employed aerosol types (Levy et al., 2007), which introduced the low SSA and led to overestimate the DT AOD.

### 3.3.3.2. Particle Size

The retrieved particle size distributions are divided into 22 bins, with radii from 0.05 to 15 μm. Seasonal mean variations of the size distributions at Kashi site are shown in Figure 9, and corresponding parameters during four seasons and all-year-round, which include volume concentrations (Vf and Vc), central radii (Rf and Rc), and variances (σf and σc) of bimodal log-normal function of fine-mode and coarse-mode, respectively (Dubovik et al., 2006), as well as the AE are listed in Table 12.

We can see that, all of the AE (0.300), FMF (0.261), and Vf (0.02 μm³/μm²) in spring are the lowest of the four seasons, while the mean volume of coarse particles in spring (0.40 μm³/μm²) is much higher than other seasons, which indicate that the spring particles are the coarsest. This might be due to the special climatic background of Kashi region. Related researches (Wang et al., 2003; Xinjiang, S.F.M, 1986) show that the sandstorm of Kashi mainly concentrated in March to May (sandstorm days accounted for about 80% of the year). Besides, cold air is frequent and the wind speed is high in Northwest China, and with the addition of vegetation, bare, and loose soil of Kashi region, the severe sandstorms are easy to come up. Moreover, Kashi is also adjacent to the Taklamakan desert, the cross-over mountain gale and east irrigation phenomenon would appeared when the cold air comes, so that the dust is more obvious (Xinjiang, S.F.M, 1986), all of the mentioned above could somewhat increase the particulate size.

On the contrary, during winter, fine-mode aerosol dominates the size distribution with the highest AE (0.752), FMF (0.623), and Vf (0.05 μm³/μm²) in the four seasons. This fine particle pollution is closely associated with the pollutant discharge which is caused by coal-combustion during winter heating period, steady weather conditions, and poor diffusion conditions in Kashi. The volume median radius of fine mode is not affected by seasonal changes, which is equal to 0.13 μm throughout the year consistently. However, the volume median radius of coarse mode in summer is 2.15 μm, which are larger than that in other three seasons. This is likely on account of high humidity that result from the main flood season and high temperature period in Xinjiang during summer, which together make the diffusion more difficult (Yang et al., 2017). Compared to the three seasons above, all of the various parameters in autumn are comparable, with AE = 0.682, FMF = 0.578, Vf = 0.03 μm³/μm², Ve = 0.22 μm³/μm², and Rc = 2.07 μm, respectively.

Based on Table 12 and the analysis above, the regularity that FMF and Vf would change as AE changed (the FMF and Vf became

### Table 9

| Aerosol type   | SSA (550 nm) |
|----------------|-------------|
| Continent      | 0.890       |
| Weak absorbing | 0.950       |
| Moderate absorbing | 0.920   |
| Strong absorbing | 0.870     |
| Dust           | 0.950       |

### Table 10

| Season          | Moderate absorbing | Continental |
|-----------------|--------------------|-------------|
| Spring          | 93.23              | 6.77        |
| Summer          | 100                | 0           |
| Autumn          | 95.67              | 4.33        |
| Winter          | 90.57              | 9.43        |
higher when AE increased, whereas the FMF and $V_f$ got lower) has been discovered. Thus, we could develop the study of the uncertainty related to aerosol particle size, represented by AE of the Kashi SONET site. According to the AE of four seasons and all-year-round, the average AE is between 0.300 and 0.752, and taking the frequency distribution of the Angstrom exponent (Figure 10) into account, we divided the aerosol particles into three compartments, $AE \leq 0.3$ (biggish-dust-dominated case), $0.3 < AE \leq 0.8$ (coarse-mode-dominated case), and $AE > 0.8$ (fine-mode-dominated aerosols), and then discuss the performance of DT and DB AOD products in Kashi respectively for each interval, as shown in Figure 11 and Table 13.

We can learn from Figure 11 and Table 13 that, combining all the statistical parameters, whatever for DT or DB algorithm, the MODIS AOD retrievals for fine-mode-dominated case ($AE > 0.8$) were most effective of the three, appeared as the higher $R$ ($R = 0.952$ for DB while $R = 0.977$ for DT), the RMB which is more closer to 1 (DB-RMB = 0.478, DT-RMB = 1.527), the lower MAE (DB-MAE = 0.261, DT-MAE = 0.199), and fitting straight line is more closer to the 1:1 line; to be specific, the corresponding aerosols that in the interval of $AE > 0.8$ are likely dominated by small particles such as smoke or industrial pollution or fine mode dominated under conditions of high humidity (Sayer et al., 2014). For coarse-mode-dominated case ($0.3 < AE \leq 0.8$), the situation is reversed, with the accuracy of MODIS AOD in Kashi is very low, particularly the DB AOD products, with a low $R$ (0.610), a fitting straight line which is far from the 1:1 line, lower RMB (0.247) and WEE (13.25%), while the statistical parameters of DT algorithm are $R = 0.941$, RMB = 1.727, and WEE = 10.83%, respectively. The aerosols corresponding to this area are likely dominated by mineral dust or a mixture of fine- and coarse-mode aerosols, chief of all are coarse-mode aerosols. In addition, combined with the comparison of the DB-AE with the AE derived from CE318 observations in Figure 12, it can be discovered that the

| Table 11 |
|-----------------|-----------------|-----------------|-----------------|
| The SSA at 550 nm Band of Each Season in Kashi Region During 2016–2018 | | |
| | SONET | C6.1 MYD DT |
|-----------------|-----------------|-----------------|-----------------|
| Spring | 0.912 | 0.918 |
| Summer | 0.937 | 0.920 |
| Autumn | 0.911 | 0.919 |
| Winter | 0.917 | 0.917 |

Figure 9. Average volume size distribution of Kashi aerosol particles throughout the different seasons.
smallest difference between the two AE appeared in winter, and as stated before, the particles are the smallest in winter of all seasons. From these we can infer that the accuracy of AE and AOD retrievals from C6.1 MYD for the fine-mode-dominated situation is superior to the coarse-mode-dominated case. However, the combination of VSPD (concentrate mainly between 1.302 and 5.061 during four seasons and all-year-round, as coarse particles) and AE (90% of AE were concentrating upon 0 to 1 that coarse particle dominated) in Kashi site shows predominant coarse dust particles (Figures 9 and 10), particles mainly distributed in the AE between 0.3 and 0.8, and the averages of four seasons and all-year-round were all sitting here. Moreover, due to the special geographical and climatic conditions in Kashi region, the particle size varies dramatically and with significant difference during four seasons.

Besides, we compared the DB-AE (AEDB) with the AE derived from CE318 observations (AESONET), as shown in Figure 12, and found that there is a big gulf between those two parameters. The average AE of MODIS DB is much higher than that of SONET in spring (AEDB = 0.724, AESONET = 0.259), summer (AEDB = 1.028, AESONET = 0.454), autumn (AEDB = 1.080, AESONET = 0.628), and all-year-round (AEDB = 0.884, AESONET = 0.494), which may also confirm the inaccuracy of the aerosol models in MODIS DB algorithm in Kashi region. It also illustrated the particle size that aerosol models assumed is much smaller than that should be, which causes a higher scattering phase function in Kashi and can contribute to underestimation of the aerosol loading.

Therefore, some errors exist in C6.1 MYD DT and DB algorithms that about the assumption of particle size in Kashi region leads to the MODIS AE having a big difference with the ground observations; moreover, the particle size will directly affect the scattering, absorption, and any other abilities of aerosols and then make large inversion error of MODIS AOD.

### 3.3.4. Uncertainty Related to Aerosol Loading

We can find from the variation tendency of mean AOD bias, which is shown in Figure 13 and Table 14 that, in general, all data sets worsen as the aerosol loading increases. For slightly polluted cases (AOD ≤ 0.5), in which aerosol products are mainly concentrated in, the percentage of available products are 75.58% and

![Figure 10](https://example.com/figure10.png)

**Figure 10.** Frequency distribution of the Angstrom exponent during 2016–2018 over Kashi region.

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### Table 12

| AE       | FMF | V_f (μm^2/μm^3) | V_c (μm^2/μm^2) | R_f (μm) | R_c (μm) | σ_f | σ_c |
|----------|-----|-----------------|-----------------|----------|----------|-----|-----|
| Spring   | 0.300 | 0.261 | 0.02 | 0.40      | 0.13 | 1.95 | 0.58 | 0.63 |
| Summer   | 0.489 | 0.278 | 0.02 | 0.15      | 0.13 | 2.15 | 0.50 | 0.64 |
| Autumn   | 0.682 | 0.578 | 0.03 | 0.15      | 0.13 | 2.07 | 0.51 | 0.65 |
| Winter   | 0.752 | 0.623 | 0.05 | 0.22      | 0.13 | 2.10 | 0.51 | 0.62 |
| All-year | 0.500 | 0.361 | 0.03 | 0.23      | 0.13 | 2.08 | 0.52 | 0.63 |

*Note. AE is the angstrom exponent; FMF is fine-mode fraction; V_f and V_c are volume concentrations; R_f and R_c are median radii; σ_f and σ_c are standard deviations of fine and coarse modes.*
80.68% of DB and DT algorithms. DB retrievals show negative biases during $-0.332$ to $-0.023$, while the DT retrievals show positive biases with the MAE = $0.178$ – $0.201$, for AOD $\leq 0.5$, the mean MAEs are $-0.170$ and $0.190$ of DB and DT, respectively, during which the error is relatively small and the effectiveness is high. For moderately polluted cases (0.5 < AOD $\leq 1.0$), with the increase of aerosol loading, the n of DB and DT are reduced (14.39%, 11.59% of all retrievals), DB retrievals still show large negative biases with the average around $-0.466$, while the DT biases become more positive (mean MAE = 0.270) as AOD increases. For heavily polluted cases (AOD > 1), all data sets have large biases, the mean MAE of DB and DT reach up to $-0.818$ and $0.614$, the percentage of available AOD products merely is 10.03% and 7.73% of DB and DT algorithms within this interval. At the same time, the number of DT retrievals is much less than that of the DB retrievals, yet the DB retrievals show large underestimations. It indicates that aerosol retrievals under high load conditions still face great challenges, which is in accordance with the results of previous studies (Wang et al., 2019; Wei et al., 2018).

Figure 11. Evaluation result of C6.1 MYD DB (above) and DT (lower) AOD retrievals in (a, d) AE $\leq 0.3$, (b, e) 0.3 < AE $\leq 0.8$, and (c, f) AE > 0.8 during 2016–2018 in Kashi site. The black solid line denotes the 1:1 line, the green dashed lines are the EE lines, and the red solid line represents the regression line.

Table 13

|               | AE $\leq 0.3$ | 0.3 < AE $\leq 0.8$ | AE > 0.8 |
|---------------|--------------|---------------------|----------|
| $n$           | 152          | 151                 | 86       |
| $R$           | 0.898        | 0.610               | 0.952    |
| $k$           | 0.604        | 0.122               | 0.745    |
| $b$           | -0.10        | 0.04                | -0.13    |
| RMSE          | 0.326        | 0.208               | 0.198    |
| MAE           | 0.336        | 0.229               | 0.261    |
| RMB           | 0.435        | 0.247               | 0.478    |
| WEE (%)       | 19.74        | 13.25               | 12.79    |
| AEE (%)       | 0            | 0                    | 0        |
| BEE (%)       | 80.26        | 86.75                | 87.21    |

Note. The $n$ is the number of MODIS/SONET matchups; $R$ is the linear correlation coefficient; $k$ and $b$ are the slope and intercept of the linear fitting equation; RMSE is the root mean square error; MAE and RMB are the mean absolute error and relative mean bias; WEE, AEE, and BEE are the percentage of collocations that within EE, above EE, and below EE, respectively.
Figure 12. Comparison of the SONET measured AE with C6.1 MYD DB-AE during four seasons in Kashi region.

Figure 13. Box plots of AOD bias for MODIS C6.1 MYD DT (red) and DB (blue) AOD retrievals against SONET AOD measurements as a function of aerosol loading. The black horizontal dotted line represents the zero bias. In each box, the middle, lower, and upper horizontal lines represent the AOD bias median, and 25th and 75th percentiles, respectively.
4. Conclusion

This study validated and compared the performance of MODIS AOD retrieval products from three different collections (C6 MYD, C6.1 MOD, and C6.1 MYD) using ground-based measurements from the SONET data set over Kashi region in the northwest of China during 2016–2017 and presented a first comprehensive evaluation of the DT and DB retrievals with a 10-km spatial resolution in the latest C6.1 MYD AOD data set in this region during 2016–2018. The results showed as follows.

Compared with the C6 MYD aerosol retrievals, the effectiveness of C6.1 MYD AOD in Kashi region is a little higher, with more effective data, slightly reduced error, and growth of the percentage of retrievals which falls within the envelope of EE, but the difference is not very large, indicating that the improvement effect of the DT and DB algorithms in new collection is not significant in Kashi region. Besides, the retrievals of two algorithms from Aqua (C6.1 MYD) are better than those from Terra (C6.1 MOD) according to the aggregative indicators, and these discrepancies mainly result from satellite overpass times as well as the better characterized and more stable instrument of MODIS Aqua. Overall, the validation results indicate that C6.1 MYD AOD products (both DT and DB algorithms) are comparable over Kashi region, which can be used in local climate studies and air quality assessment.

For C6.1 MYD aerosol retrievals in Kashi region, there is an overall overestimation of DT AOD (BEE = 0), while DB AOD is underestimated on the whole (AEE = 0); the accuracy of DB retrievals in Kashi region was found to be much lower than those in urban areas and croplands with a notable underestimation. Comparing the two algorithms, the total AOD coverage of the DB retrievals exceeds that of DT, with the number of DB collocations almost 1.9 times than those of DT, as the underlying surface that the two algorithms focused is different, of which the DB algorithm act on is more aligned with the underlying surface of Kashi region. However, when it comes to statistics, the DT retrievals slightly outperformed DB in Kashi region with a higher accuracy. Comparatively speaking, the DT retrievals that slightly outperformed DB in Kashi might be due to the aerosol models and surface reflectance and that the DT algorithm adopted is more appropriate for this region.

As to the uncertainty of C6.1 MYD aerosol retrievals in Kashi region, all of the land surface reflectance, aerosol model, and loading are contributive. Above all, although the C6.1 DT and DB algorithms improved the estimation of surface reflectance, there is still a serious issue over Kashi region that the overestimation/underestimation of MODIS DT/DB AOD retrievals over Kashi is due to underestimation/overestimation of the surface reflectance in the corresponding channels, and the performances of all data sets decrease gradually as LSR/DB-LR increases. Second, the assumptions in aerosol model would also affect the accuracy of AOD retrievals directly. For SSA, compared to that of SONET actual measurements, whatever the extraction results from C6.1 MYD DB-SSA data set directly or the assumed values of two dust models in MODIS DB algorithm, all of the DB-SSA are on the high side. Toward the aerosol types, which are extracted from C6.1 MYD and determined in the DT-SSA, we find that the DT-SSA is lower during summer and winter, while a bit high in spring and autumn. The uncertainties of the employed aerosol types could introduce low SSA. It is worthwhile to note that if higher/lower SSA values are used in the AOD retrievals, the MODIS AOD should have more severe underestimation/overestimation of DB and DT algorithms if the surface reflectance is perfect. With respect to the particle size, we find that the spring particles are the coarsest of the four seasons, while fine-mode aerosol dominates the size distribution during winter. Besides, the volume median radius of coarse mode in summer is larger than that in other three seasons, and all of the various parameters in autumn are comparable. The MODIS AOD retrievals for fine-mode-dominated case were most effective of the three, while

| Table 14 |
|-----------------|
| The Mean Bias for MODIS C6.1 MYD DB (Above) and DT (Lower) AOD Retrievals Against SONET AOD Measurements in Different Intervals of Aerosol Loading |
| SONET AOD | 0–0.1 | 0.1–0.2 | 0.2–0.3 | 0.3–0.4 | 0.4–0.5 | 0.5–0.6 | 0.6–0.8 | 0.8–1 | 1–1.5 | 1.5–2 | >2 |
| DB | n | 30 | 95 | 68 | 65 | 36 | 22 | 21 | 13 | 10 | 10 |
| Mean bias (−) | 0.023 | 0.093 | 0.192 | 0.237 | 0.332 | 0.386 | 0.482 | 0.576 | 0.736 | 0.895 | 0.899 |
| DT | n | 13 | 71 | 41 | 26 | 16 | 7 | 11 | 6 | 11 | 3 |
| Mean bias (+) | 0.181 | 0.201 | 0.184 | 0.178 | 0.179 | 0.310 | 0.230 | 0.298 | 0.502 | 0.802 | 0.943 |

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for the coarse-mode-dominated case, the situation is reversed, with the accuracy of MODIS AOD in Kashi is very low. However, the combination of VSPD and AE in Kashi site shows predominant coarse dust particles, particles mainly distributed in the AE between 0.5 and 0.8, and the averages of four seasons and all-year-round were all sitting here. Moreover, as the AE of MODIS DB is much higher than that of SONET, it illustrated that the particle size that aerosol models assumed is much smaller than that should be, which causes a higher scattering phase function in Kashi. Therefore, some errors exist in C6.1 MYD DT and DB algorithms that about the assumption of particle size in Kashi region, which will directly affect the scattering, absorption, and any other abilities of aerosols and then make large inversion error of MODIS AOD. Finally, all data sets of the mean AOD bias become worsen as the aerosol loading increases. For slightly polluted cases (AOD ≤ 0.5), in which aerosol products are mainly concentrated in, the error is relatively small and the effectiveness is high. For moderately polluted cases (0.5 < AOD ≤ 1.0), with the increase of aerosol loading, DB retrievals still show large negative biases, while the DT biases become more positive. For heavily polluted cases (AOD > 1), all data sets have large biases. It indicates that aerosol retrievals under high load conditions still face great challenges.

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