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Special Section:
East Asian Study of Tropospheric Aerosols and Impact on Cloud and Precipitation

Key Points:

- Comprehensive evaluation of MODIS Deep Blue retrievals was conducted in deserts of East Asia with CARSNET observations
- MODIS Beep Blue retrievals obviously underestimates the dust loading in East Asia
- The large bias can be substantially improved by considering the unique characteristics of aerosol and surface in East Asia

Supporting Information:

- Supporting Information S1

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Evaluation of MODIS Deep Blue Aerosol Algorithm in Desert Region of East Asia: Ground Validation and Intercomparison

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Abstract The abundant dust particles from widespread deserts in East Asia play a significant role in regional climate and air quality. In this study, we provide a comprehensive evaluation of the widely used Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue (DB) aerosol retrievals in desert regions of East Asia using ground-based observations over eight sites of the China Aerosol Remote Sensing Network (CARSNET). Different from their well-characterized performance in urban and cropland areas around the globe, DB aerosol optical depth (AOD) retrievals exhibit underestimation across the deserts in East Asia. We found that 38%–96% of satellite values fall out of an expected-error envelope of $\pm(0.05 + 20\%AOD_{CARSNET})$, with the worst performance in Taklimakan Desert. In particular, DB retrievals erroneously give a nearly constant low values of 0.05 in Taklimakan Desert when AOD is below 0.5, which does not match with variation of moderate dust plumes. Comparison with Multi-angle Imaging SpectroRadiometer AOD shows that a similar underestimation is prevalent over the extensive deserts. Inversion of sky light measurements show that single scattering albedos of the yellow dust in East Asia are mostly below 0.9 at 440 nm, much lower than the “whiter” and “redder” dust models applied in the DB algorithm. On the other hand, overestimation of surface reflectance dominantly contributes to the significant low constant AOD values in MODIS DB retrievals in Taklimakan Desert. These large biases, however, can be substantially reduced by considering unique characteristics of aerosols and surface over the arid regions in East Asia.

1. Introduction

Mineral dust particles, one of the major components of tropospheric aerosols, play an important role in the Earth system in several different ways. Uplifted by the strong surface winds in deserts and semiarid areas, dust particles can be transported regionally and even globally as a result of atmospheric circulation (Uno et al., 2009; Yu et al., 2015). These elevated dust aerosols can alter radiation balance and modify cloud properties (Kim et al., 2005; W. Wang et al., 2010), exerting significant influences on regional rainfall and climate (Vinoj et al., 2014). When passing over urban/industrial areas, dust particles also impact tropospheric heterogeneous chemistry by providing a reactive surface (Li et al., 2014) and aggravate surface air quality (Tao et al., 2013). Furthermore, deposition of transported dust minerals into oceans influences biogeochemistry and carbon cycles by providing important nutrients to the marine ecosystem (Jickells et al., 2005).

The northwestern part of East Asia is dominated by widespread semiarid areas and deserts, contributing about half of the desert dust emissions of the world (Sun et al., 2001; Zhang et al., 1997). Carried by the prevailing westerly wind, large amounts of dust particles often travel downstream to the densely populated regions in eastern China (J. Wang et al., 2010), accompanying with intense dust-pollution interactions (Huang et al., 2008; Li et al., 2011). Besides a few intense dust storm events, prevalent dust plumes were found over eastern China during winter and spring with large spatial variations (Tao et al., 2012). To understand the role of airborne dust in regional air quality and climate, it is essential to quantify their amount and spatial variations.

Development of satellite sensors in recent years has enabled a daily detection of airborne dust globally from numerous perspectives (Hsu et al., 2006; Omar et al., 2009; Torres et al., 2007). In particular, active lidar measurements from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations

(CALIPSO) satellite provides unprecedented vertical information of dust particles in East Asia (Huang et al., 2007; Liu et al., 2008). However, CALIPSO detection is very limited in spatial and temporal coverage due to its narrow suborbital swath. By comparison, Moderate Resolution Imaging Spectroradiometer (MODIS) is one of the most widely used satellite sensors with near daily global coverage due to its wide swath (Levy et al., 2013). MODIS aerosol retrievals from the Deep Blue (DB) algorithm over bright surface such as desert areas provide substantial information concerning global dust activities and emission sources (Ginoux et al., 2012; Hsu et al., 2006). However, past studies with very limited ground-based validations suggested a large bias in MODIS aerosol retrievals in deserts of northwestern China (Li et al., 2012; Tao et al., 2015). To date, a comprehensive evaluation of MODIS DB aerosol products in the vast areas of deserts of East Asia is long overdue (Li et al., 2007; L. Wang et al., 2010), in part due to the lack of sufficient ground-based observations.

By using continuous ground-based observations from eight sites of the China Aerosol Remote Sensing Network (CARSNET) since 2003, this paper provides the first comprehensive evaluation of MODIS DB aerosol retrievals in arid regions of East Asia. Section 2 presents general information about the satellite and ground data used in this work. Section 3 compares MODIS aerosol data with ground observations and Multi-angle Imaging SpectroRadiometer (MISR) results, from which we identify major contributions to the uncertainties of MODIS DB aerosols retrievals over deserts. Section 4 provides summary and discussion of the findings.

2. Data and Methods

2.1. MODIS Deep Blue Aerosol Data Set

The MODIS sensors aboard the Terra satellite from 2000 and Aqua from 2002 measure reflected and emitted radiance of the Earth-atmospheric system with 36 bands in 0.4–14.4 μm. MODIS's wide swath (~2,330 km) enables a near daily global coverage, and its high spatial resolutions of 250–1000 m ensure a reliable cloud screening. MODIS Dark Target (DT) aerosol retrieval over land was first realized using a linear relationship of surface reflectance between visible and shortwave infrared bands in dense vegetation areas (Kaufman et al., 1997; Levy et al., 2013; Remer et al., 2005). To retrieve aerosol properties over bright surface such as deserts and some urban regions, the Deep Blue (DB) algorithm was developed to utilize precalculated surface reflectance database in near-UV blue bands, where surface reflectance is much lower than in other longer visible bands (Hsu et al., 2004). With derived surface reflectance and assumed aerosol optical models in look up tables, aerosol optical depth (AOD) and fraction of aerosol models or spectral single scattering albedos (ω) are determined by matching computed apparent reflectance with satellite observed spectral radiances.

The recent Collection 6 (C6) DB aerosol algorithm has undergone significant improvements and was extended to cover all cloud-free and snow/ice-free regions (Hsu et al., 2013). To reduce overscreened pixels caused by conservative filter in C5 DB cloud screening, brightness temperature at 11 and 12 μm and total precipitable water vapor were added in C6 version to relax previous criteria at 0.412 and 1.38 μm bands. The current DB algorithm considers a dynamic surface reflectance that depends on scattering angles and seasonal Normalized Differential Vegetation Index. And over known natural vegetation regions, a spectral relationship in surface reflectance between visible (0.47 and 0.65 μm) and 2.12 μm bands as that in DT algorithm is employed to derive surface reflectance. The DB algorithm retrieves AOD and fraction of two aerosol models with radiances in 412 and 470 nm bands (Hsu et al., 2004). During heavy dust events (retrieved AOD $>$ 0.7), satellite spectral radiances in three bands (412, 470, and 670 nm) are used to retrieve AOD and ω at 412 and 470 nm, simultaneously.

The DB algorithm utilizes different fractions of two aerosol models to constrain aerosol optical properties in certain geographic regions. Two dust models with "whiter" color (ω = 0.98 and 0.99 at 412 and 490 nm, respectively) and "redder" color (ω = 0.91 and 0.95, correspondingly) are utilized in the deserts region. Smoke and sulfate models are selected to represent anthropogenic aerosols (Hsu et al., 2013). The DB retrieval is implemented for each single cloud-free pixel (at 1 km resolution near nadir and ~8 km at edge) and then averaged in 10 × 10 pixels. Quality assurance (QA) flag of DB AOD is determined by the number of retrieved AOD pixels and their standard deviation. Here we used Level two MYD04 aerosol products at 10 × 10 km spatial resolution and with high quality (QA = 2 or 3).

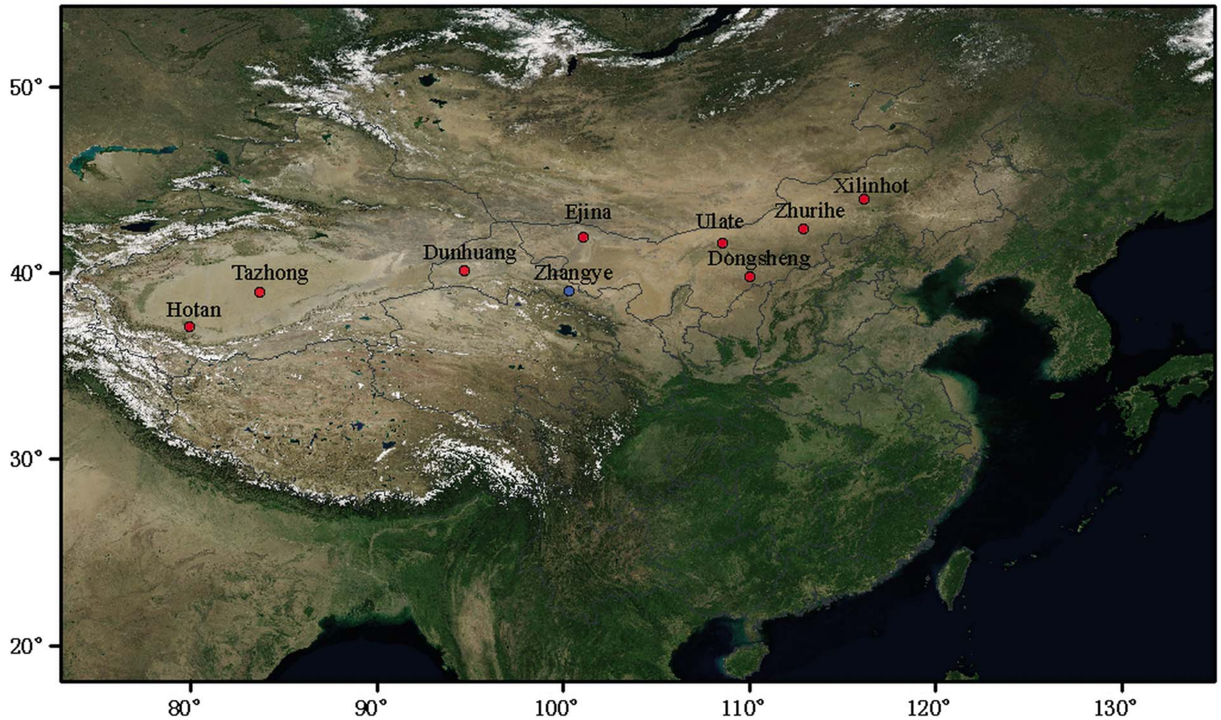

Figure 1. True color image of mainland of East Asia with locations of ground sites used. The red and green dots denote locations of CARSNET sites; the blue dot denotes AERONET site.

2.2. MISR Aerosol Data Set

The MISR instrument onboard Terra satellite measures radiation in four spectral bands (446, 558, 672, and 867 nm) with a swath width ~ 380 km from 9 different view angles including one nadir, four forward and four afterward (70.5°, 60.0°, 45.6, and 26.1°). With the measurements from these nine angles, the MISR aerosol retrieval algorithm first conducts an Empirical Orthogonal Function decomposition analysis to separate the atmospheric path radiance from its interaction with surface reflectance, and thereby, making aerosol retrieval insensitive to bright surface and capable of distinguishing mixtures of aerosol types (Diner et al., 2005). After radiometric calibration and geometric correction, MISR imaging data are resampled to a uniform resolution of 1.1 km, but aerosol retrieval is performed in a region of 17.6 km × 17.6 km. The operational (version 22) MISR aerosol algorithm contains 74 aerosol mixtures, which can be identified by matching their simulated radiances to satellite spectral radiances at top of atmosphere (TOA) (Kahn & Gaitley, 2015). In Level 2 swath data, total AOD of the passing mixtures is reported as "RegBestEstimateSpectralOptDepth." Past studies have consistently shown the good agreements of MISR AOD retrievals with ground-based measurements (Christopher & Wang, 2004; Liu et al., 2010; Martonchik et al., 2004; Xia et al., 2008).

2.3. CARSNET and AERONET Observations

AERONET (Aerosol Robotic NETwork) is a ground-based remote sensing aerosol network that provides continuous measurements and inversions of aerosol optical and microphysical properties (Dubovik et al., 2002; Holben et al., 1998). The CARSNET, established by the China Meteorological Administration in 2002, is a similar network in China that uses the same type of Cimel sun photometer (CE318) as AERONET. By now, CARSNET includes 50 sites throughout different land types of China (Che et al., 2015). Intercomparison results showed that CARSNET AOD had the same accuracy as the AERONET (Che et al., 2009). Meanwhile, CE318 instruments with more spectral bands as well as polarization measurements were added in later established CARSNET sites. Since CE318 does not measure at the 550 nm band, AOD at 550 nm was interpolated from AODs at 440 nm and 675 nm using Ångström exponent α, which is defined as

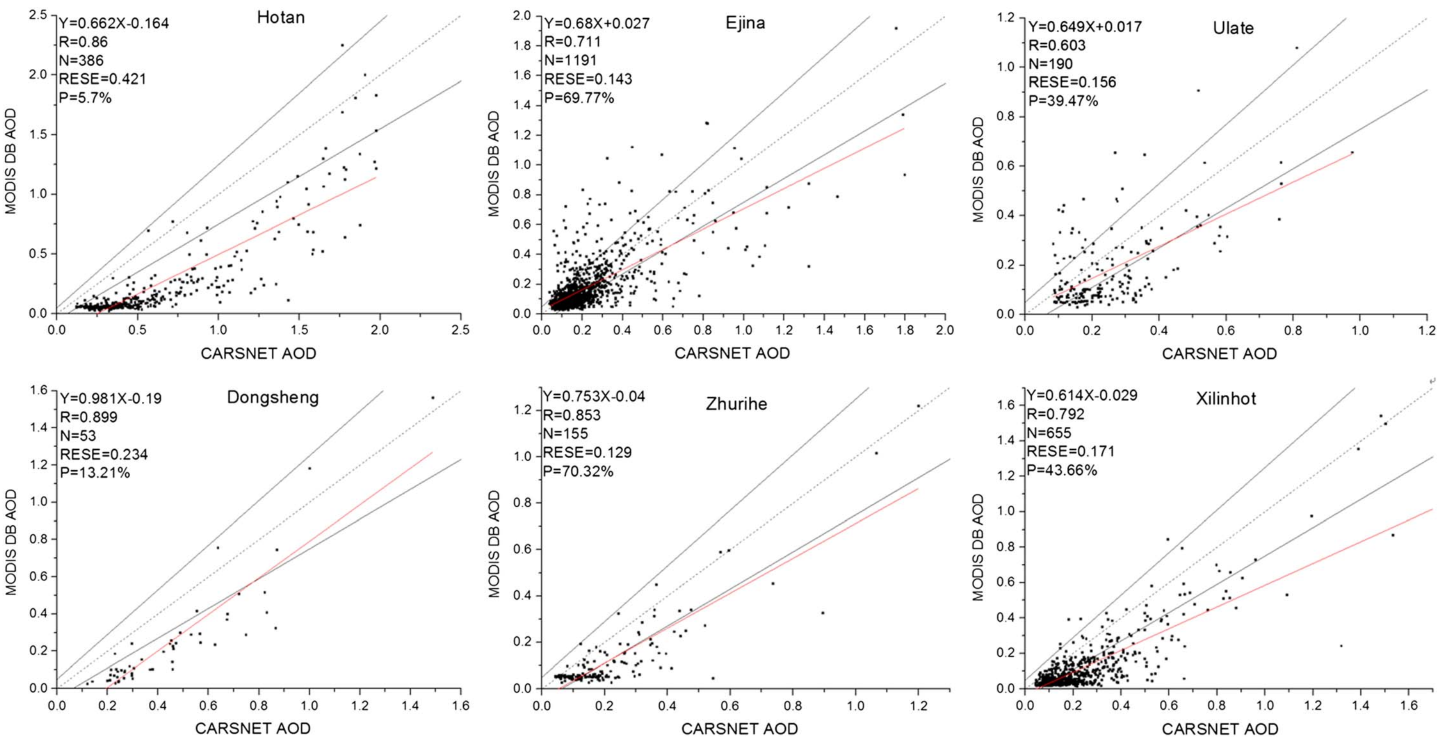

Figure 2. Comparison between MODIS DB AOD of high quality and CARSNET observations. *P* denotes percent of DB retrievals within the expected error envelope of ±(0.05 + %20AOD$_{CARSNET}$).

$$\alpha = -\frac{\ln(\tau_1/\tau_2)}{\ln\lambda_1/\lambda_2}$$

τ_1, τ_2 are AODs at 440 nm and 675 nm bands (λ_1 and λ_2) in CE318 measurements.

Figure 1 illustrates locations of the CARSNET and AERONET sites used in this study and topography of the mainland of East Asia. Over the widespread deserts and arid region in northwestern part of East Asia, continuous observations were obtained from 2003 to 2005 in Hotan, Ulate, Dongsheng, and Zhurihe sites, and from 2003 to 2012 in Ejina and Xilinhot sites except temporary interruptions for instrument calibration. Despite a short observation time of 3 months in 2008, daily aerosol size distribution and single scattering albedos from AERONET Level 2 inversions in Zhangye were used. Similar inversions with a much longer observation during 2012 and 2013 at the CARSNET site of Dunhuang were also available. MODIS Level 2 DB AODs of high quality in 5 × 5 pixels centered over each selected site were averaged to compare with the mean value of ground-based observations within ±30 min of the satellite overpass time (Ichoku et al., 2002). Similarly, 3 × 3 pixels of MISR AODs were selected for the comparison.

3. Results

3.1. General Performance of DB Aerosol Retrievals in Arid Region of East Asia

Figure 2 shows comparison between MODIS DB AOD and ground-based observations in arid region of East Asia. Although the DB algorithm was initially developed for obtaining aerosol information over bright surfaces, accuracy of DB retrievals in this region was found to be much lower than those in crop lands and urban areas with a notable underestimation (Tao et al., 2015). It is worth noting that the performance of the DB algorithm exhibits geographic differences in these deserts. About 90% of the DB AOD values in the Taklimakan Desert and ~30%–80% in the Gobi deserts fall out of an expected error envelope of ±(0.05 + 20%AOD$_{CARSNET}$). Best performance of DB retrievals is over Ejina site in Gobi deserts with ~70% of AOD values within the expected error range, but large bias exists in some cases. There is a systematic underestimation for DB retrievals over all studied sites, especially during high-AOD conditions. In addition, a few notable overestimation cases appear in low-AOD conditions in Ejina and Ulate sites.

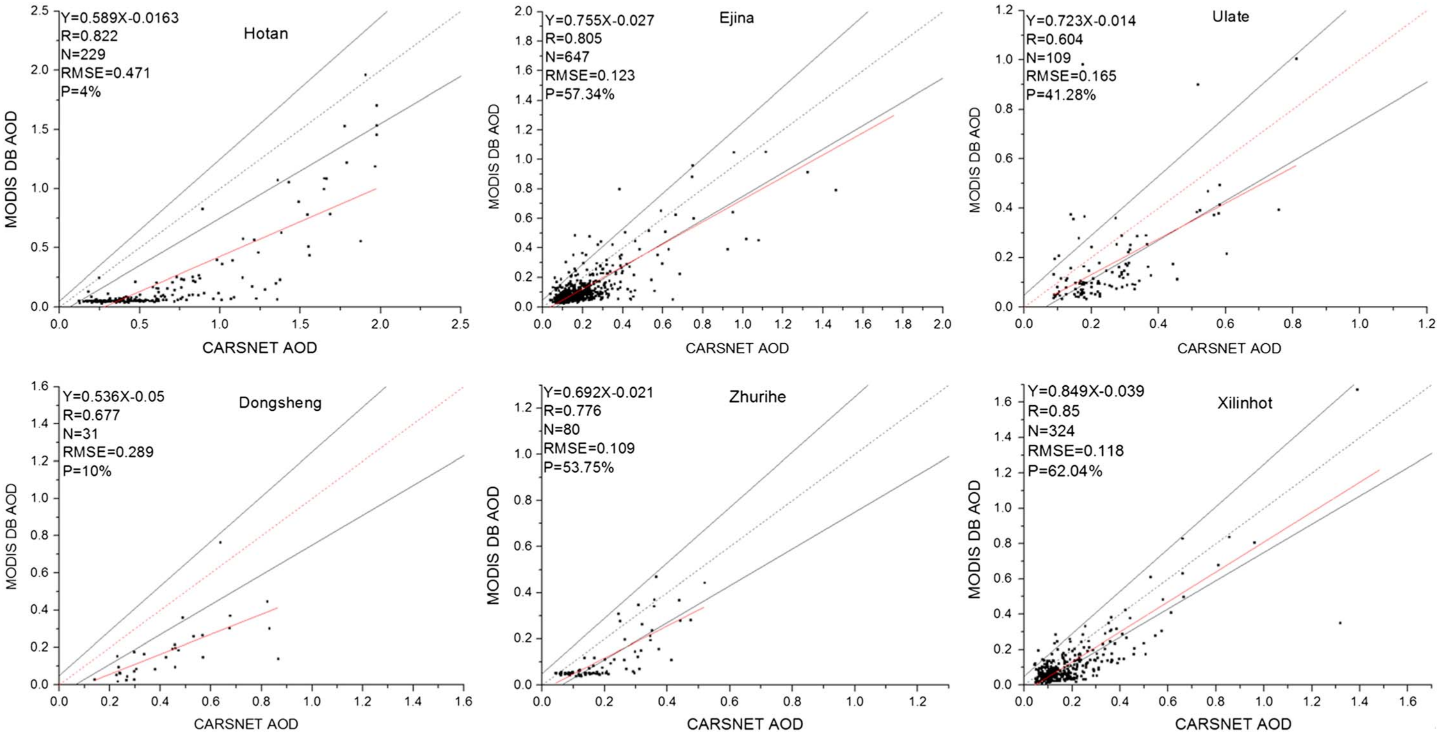

Figure 3. Same with Figure 2 but with single collocated MODIS AOD pixel used.

Surprisingly, MODIS DB AOD is nearly a constant value around 0.05 when CRASNET AOD is below 0.5 at most sites except Ejina and Dongsheng (Figure 2), which is an obvious artifact. The very low AOD ~ 0.05 could be derived when the observed TOA reflectance is equal or lower than the calculated value for AOD = 0. To examine the influence of spatial average on this artifact, MODIS Level 2 10 km AOD from each single pixel

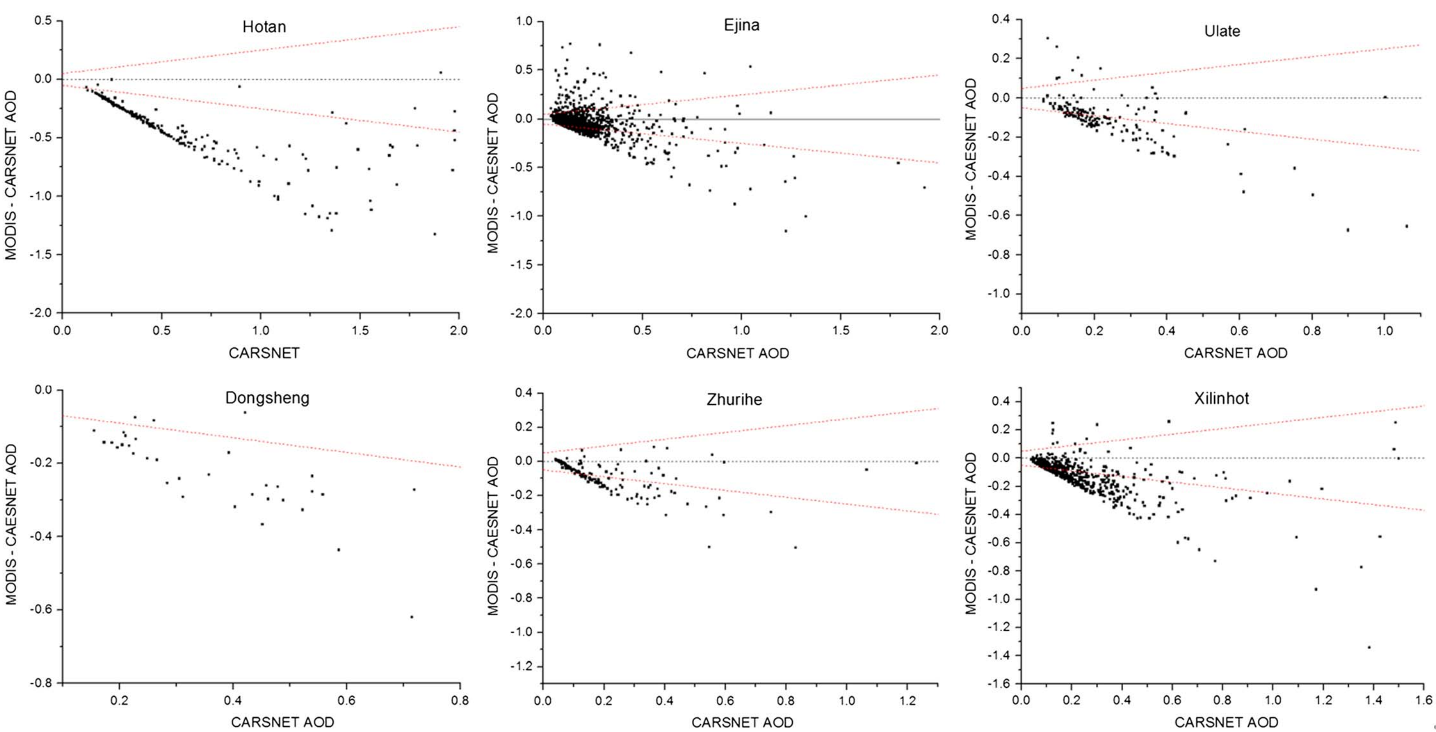

Figure 4. Difference of MODIS DB and CAESNET AOD as a function of CARSNET AOD.

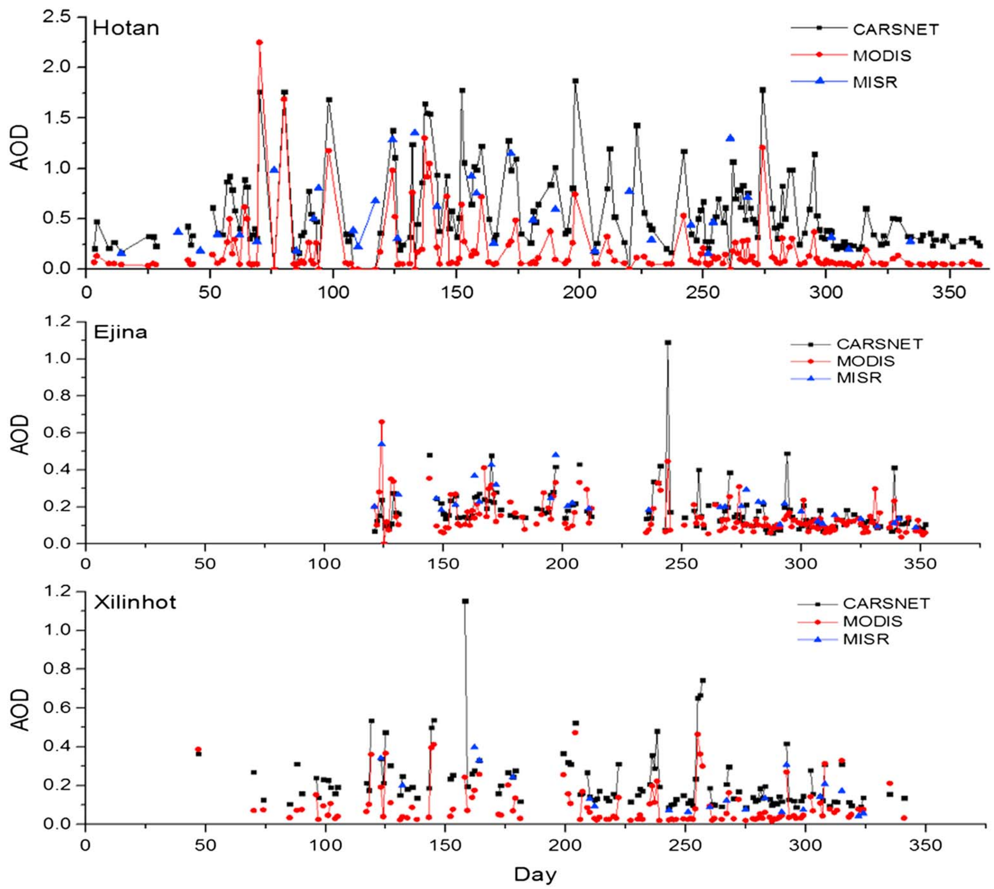

Figure 5. Comparison of collocated DB AOD, MISR AOD, and CARSNET results in Hotan, Ejina, and Xilinhot during 2004, respectively.

centered on each ground site was compared with the measured AOD at the corresponding site (Figure 3), but the comparison showed no considerable changes in performance of the DB retrievals. Therefore, average of 5 × 5 MODIS 10 km AOD pixels in Figure 2 has negligible impact on frequent occurrence of very low retrieval values. On the other hand, cases of overestimation for DB results over Ejina and Ulate decline significantly when a single AOD pixel was used in the ground validation, indicating that dust events in other pixels of the 5 × 5 10 km scope can lead to some abnormal high AOD values.

Figure 4 shows difference of MODIS-CARSNET AOD as a function of CARSNET AOD. It can be seen that the negative bias of DB retrievals increases almost linearly with the increase of aerosol loading, especially in low-AOD conditions. The worst accuracy of DB retrievals appears in Hotan in Taklimakan Desert with biases ranging from −80–100% when AOD < 1.0 to −30–50% in high-AOD conditions. Ground validation of DB AOD in Tazhong site exhibited similar performance (Tao et al., 2015). Although DB retrievals in other sites except Dongsheng perform better when AOD is low, substantial negative bias still exists in high-AOD cases. Unlike the concentrated scatters in low-AOD conditions, the deviation between MODIS and CARSNET AOD spreads out when aerosol loading gets high, which can be caused by incorrect assumption of aerosol optical properties. Besides, difference in selection of 5 × 5 pixels and single MODIS pixel can partly explain the scattered deviation (Figures 2 and 3).

3.2. Comparison of MODIS and MISR Aerosol Retrievals

To further examine the uncertainties of DB retrievals, Figure 5 shows comparison of collocated MODIS and MISR AODs over three CARSNET sites located in different desert areas of East Asia. Ground observations in Hotan show frequent heavy dust events in the southwestern part of Taklimakan Desert with AOD > 1.0. Although aerosol loading ranges from background AOD of 0.25 to high values of 1.5, most of MODIS results are at low values around 0.05. This persistent low values of MODIS AOD are also found over Xilinhot site. In contrast, MISR AOD values are generally at the same level with CARSNET observations, indicating that

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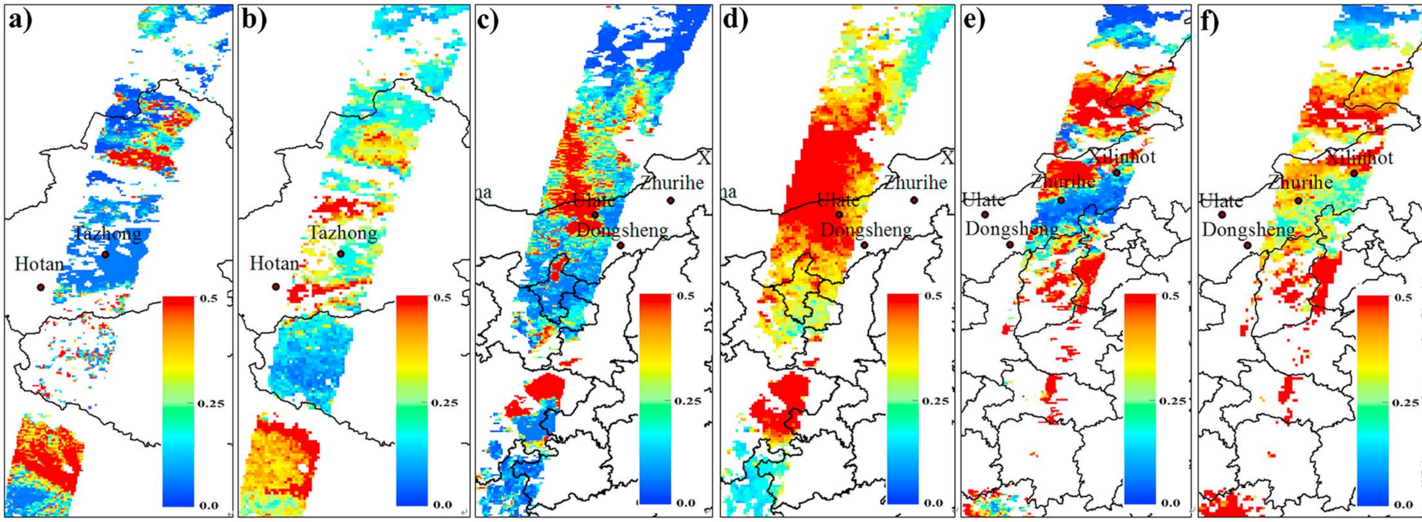

Figure 6. (a, c, and e) MODIS and (b, d, and f) MISR AOD on 14 and 21 May and 10 June 2004, respectively.

aerosol retrieval algorithm could be the primary cause of this large difference. The aerosol loading in Ejina and Xilinhot sites is much lower than that in Hotan, with most AOD values below 0.4 with a background AOD of about 0.1. These two sites are located at the edge of the Gobi deserts, and apart from main downstream pathways of the dust events (Tao et al., 2012). While MISR products slightly overestimate the aerosol loading sometimes in Ejina, MODIS retrievals agree well with CARSNET AOD.

Figure 6 shows typical results of MODIS and MISR AOD in the arid areas of East Asia. Large spatial differences exist between retrieved aerosol loading from MODIS and MISR algorithms. MODIS DB retrievals give very low

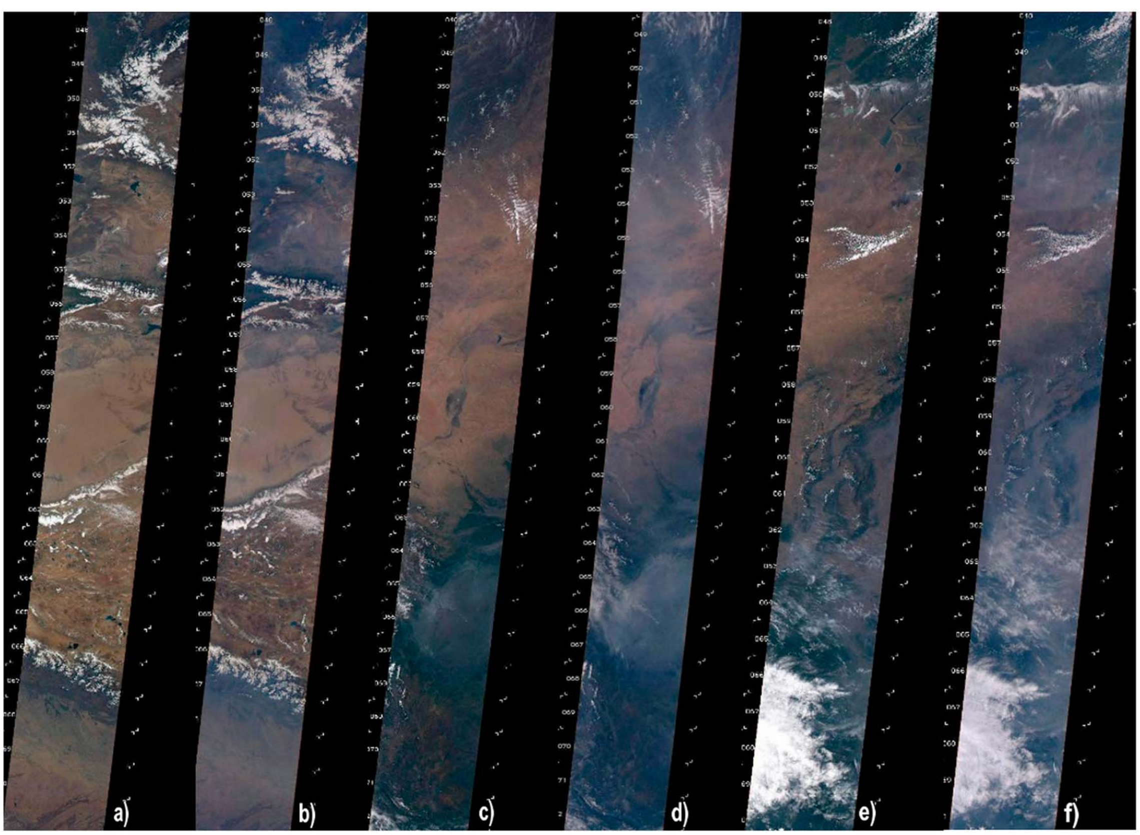

Figure 7. MISR true color image at (a, c, and e) nadir and (b, d, and f) 70° forward view angle on 14 and 21 May and 10 June 2004, respectively.

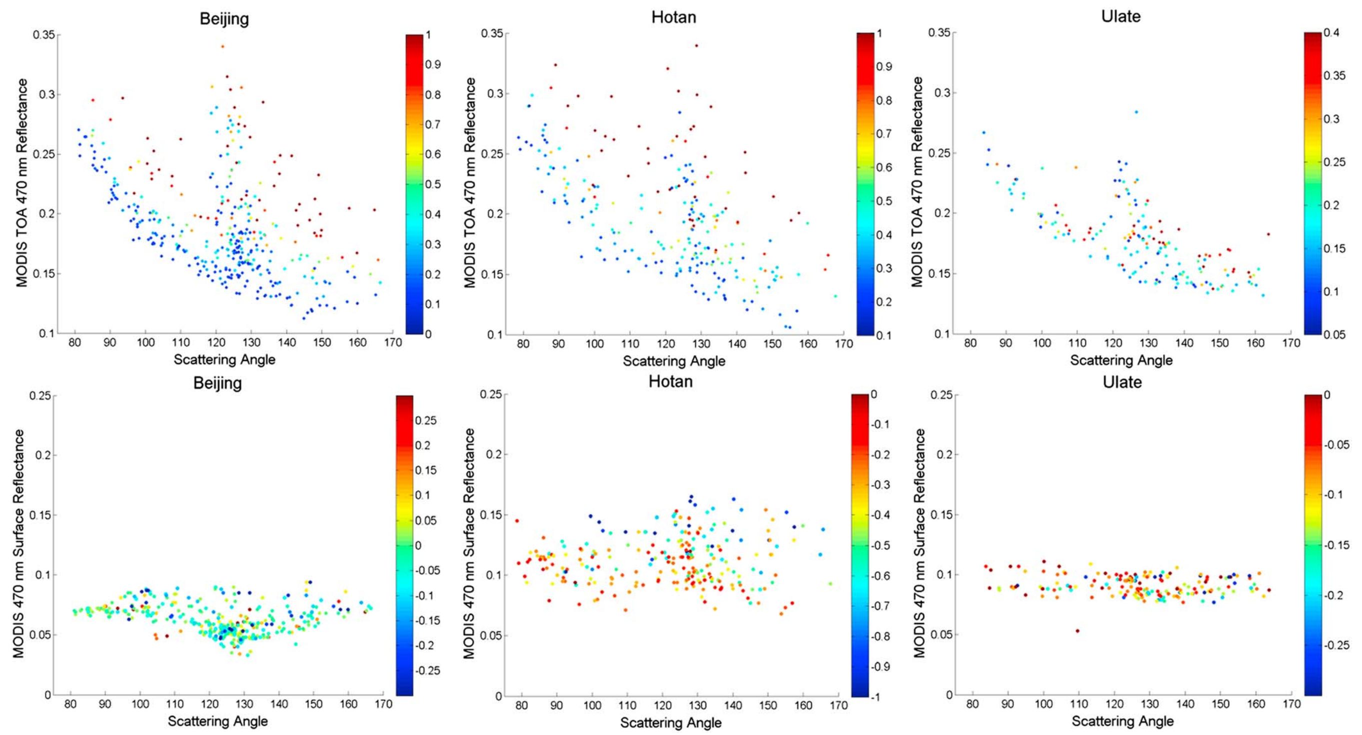

Figure 8. (top) Variations of MODIS apparent reflectance at TOA for 470 nm with scattering angles from 2003 to 2005: the color bar denotes ground observed AOD; (bottom) estimated MODIS surface reflectance at 470 nm with scattering angles from 2003 to 2005: the color bar denotes errors of MODIS DB AOD.

aerosol loading (AOD < 0.1) in the Taklimakan Desert and high loading (AOD > 0.5) in the mountain regions to the north of the desert on 14 May 2004 (Figure 6a). However, MISR results in Figure 6b reveal clear dust events in the north and south of the Taklimakan Desert with AOD > 0.5 and relatively lower aerosol loading in the mountain regions to the north. Most likely, the constant low values of DB retrievals, as identified in the comparison with CARSNET AOD, exist over the entire Taklimakan Desert. In the meantime, MODIS DB tends to overestimate aerosol loading over vegetation areas of the mountains, where surface reflectance is estimated using spectral relationships. Similar situations occur in the middle and west part of the Gobi deserts. It should be stated that MODIS DB AOD can reflect the heavy loading of dust events in the desert regions of East Asia (Figure 6d). During 10 June 2004 in the biomass burning season, DB AOD is even higher than MISR results to the north of Zhurihe (Figures 6e and 6f).

MISR true color images with different view angles provide a direct view of the dust events in Figure 6. Although it seems clean at nadir over the bright surfaces, oblique view of MISR accentuates the appearance of dust plumes due to increased forward scattering and atmospheric path length (Figure 7). Figures 7d and 7f show obvious floating dust over the Gobi deserts, giving a visible evidence for considerable amount of airborne dust over the deserts in East Asia. Unlike the severe dust storms, such dust plumes are not noticeable but more frequent, which is usually detected in upper part of the haze layer in eastern China (Tao et al., 2012).

3.3. Uncertainties of MODIS DB Aerosol Retrieval in Desert Region of East Asia

The assumptions in aerosol model and surface reflectance estimation are both crucial in satellite retrievals, which are the primary sources of satellite AOD errors. Considering the distinct differences between performance of MODIS DB retrievals in urban/cropland and deserts regions as well as among the desert sites themselves, Figure 8 shows comparison of MODIS TOA reflectance and estimated surface reflectance (ESR) as a function of scattering angle at 470 nm in Beijing, Hotan, and Ulate. Despite a similar angular variability over those three sites, TOA reflectance in Beijing is more sensitive to AOD at any given scattering angles; an obvious linear relationship can be found when AOD < 0.5. This can be explained by lower surface reflectance (~0.07) in Beijing than in deserts (~0.1). Compared with the concentrated ESR values in Beijing and Ulate, surface reflectance in Hotan varies dramatically, which could be caused by large spatial and seasonal

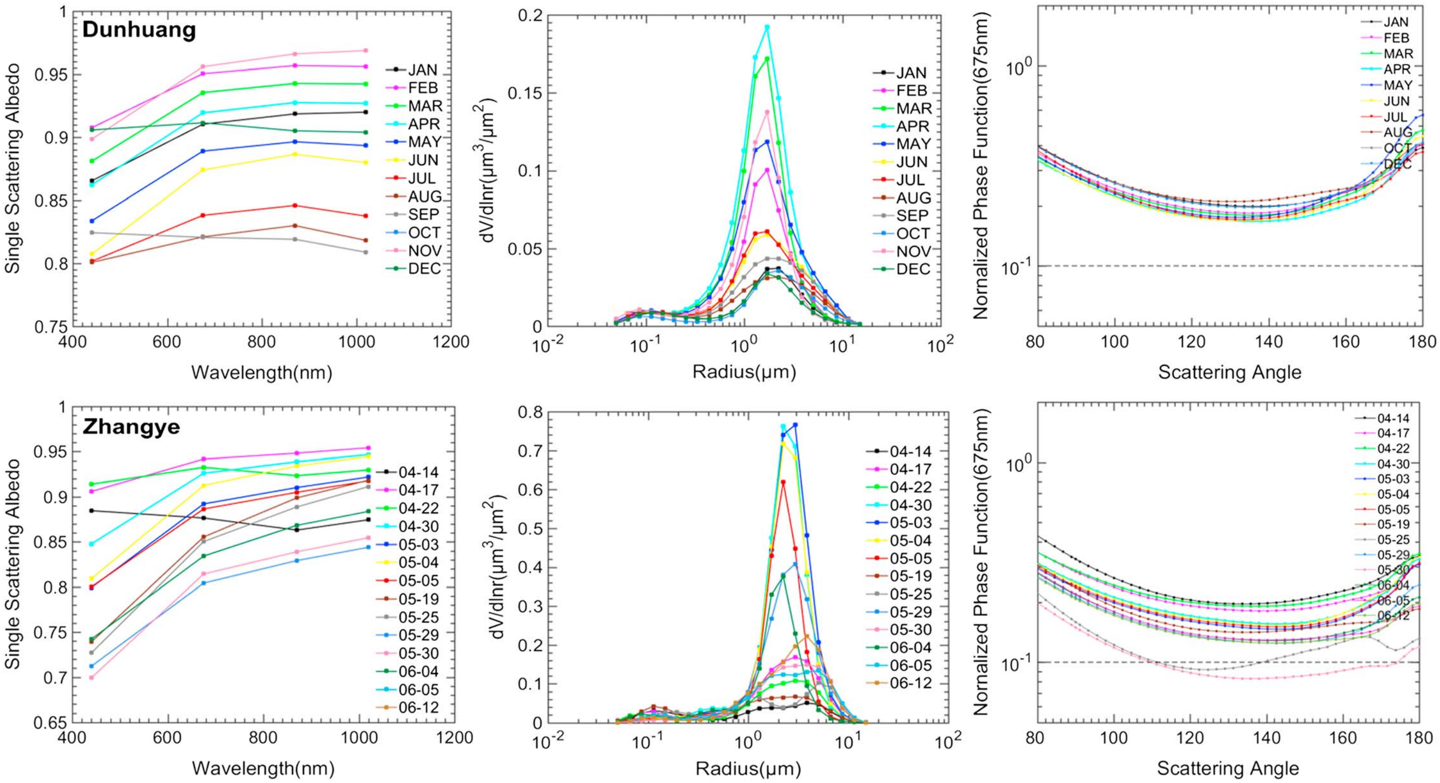

Figure 9. Monthly average of aerosol single scattering albedos, volume size distribution, and scattering phase function at 675 nm that retrieved from ground observations in CARSNET site of (top) Dunhuang and corresponding daily values in AERONET site of (bottom) Zhangye.

variations of surface covers in the surrounding areas. Retrieval errors of DB AOD exhibit weak dependence on ESR in Beijing and Ulate. However, negative AOD bias increases obviously with ESR in Hotan, indicating an overestimation of surface reflectance, which especially leads to underestimation of DB retrievals in low-AOD conditions. The same contrast also exists at 412 nm (Figure S1 in the supporting information), except higher TOA reflectance and lower ESR.

The source of retrieval errors could be empirically identified from the statistical relationship of bias and magnitude. As shown in Figure 2, the intercept of linear fit of satellite retrieved and ground observed AOD values cloud reflect static errors in surface reflectance estimation, and the slope is regulated by systematic deviations more likely caused by assumed aerosol models. Each aerosol model is characterized by a single scattering albedo and a scattering phase function, which are determined by aerosol particle size distribution and refractive index. Figure 9 shows aerosol optical and scattering properties in Dunhuang and Zhangye. The single scattering albedos at 440 nm range between 0.70 and 0.91 at these two sites with an average values of ~0.85, which is much lower than assumed values in the two dust models ($\omega \approx 0.925$ and 0.983 at 440 nm, respectively) in MODIS DB algorithm (Hsu et al., 2004). Compared with the strong scattering white and red dust, dust particles in East Asia tend to appear yellow (Figure 7), the scattering ability of which have been obviously overestimated in DB dust models.

Particle volume size distributions in Dunhuang and Zhangye sites show predominant coarse dust particles (Figure 9). Despite large variations in the fraction of coarse mode volume, monthly scattering phase function at 675 nm in Dunhuang is relatively concentrated and is at similar level with that used in DB algorithm (Hsu et al., 2004), except much higher values in 170–180° (detailed comparison in Figure S2). It is worth noting that the scattering function in Dunhuang is slightly higher than in DB dust model between 120 and 160°, which can contribute to underestimation of the aerosol loading. In contrast, daily scattering phase function in Zhangye during spring is much scattered and lower than in Dunhuang, with notable larger particle size. Despite some difference in aerosol properties of different areas, the overall negative errors of DB retrievals indicate prevalent overestimation of the scattering ability of dust particles in East Asia from combined contribution of assumed particle size and single scattering albedos in DB dust model (Figure 2).

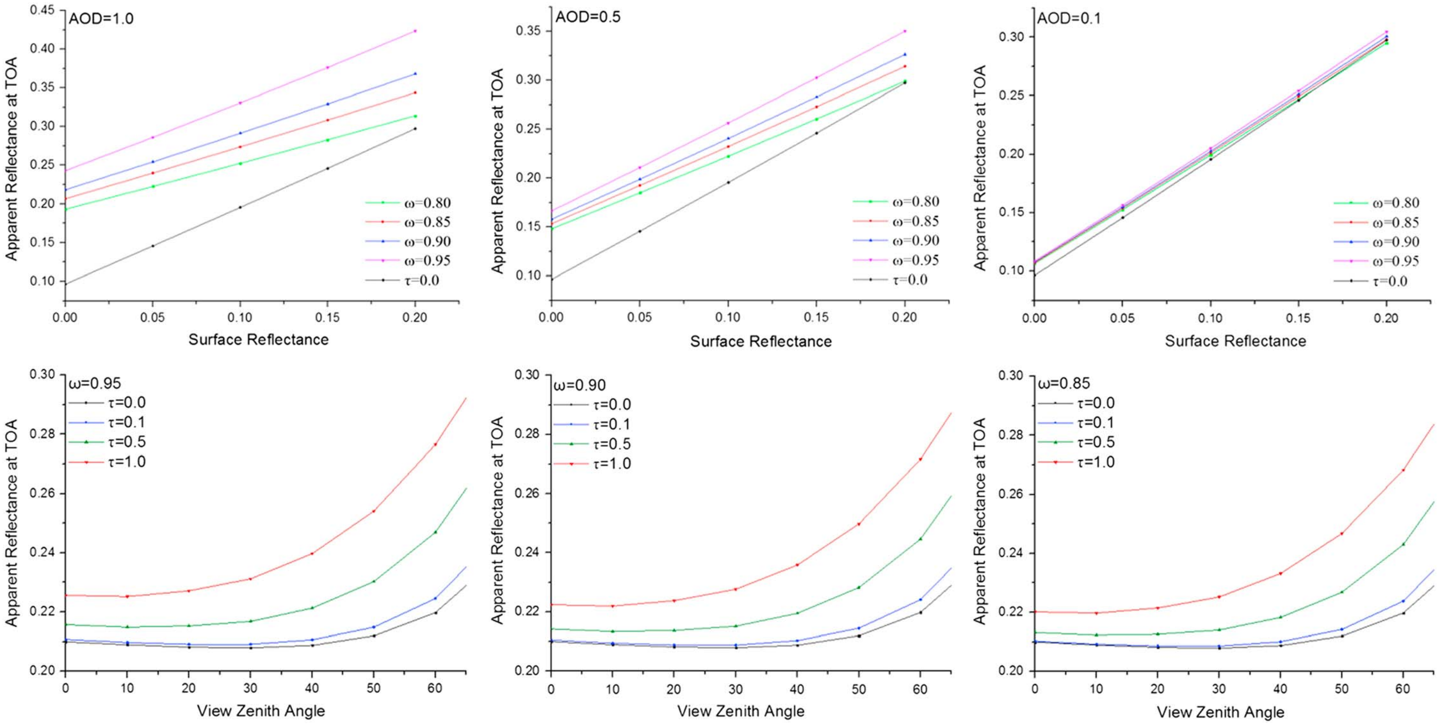

Figure 10. (top) Simulated apparent reflectance at 470 nm with increased surface reflectance at AOD (τ) = 1.0, 0.5, and 0.1 and (bottom) apparent reflectance with increased view zenith angles at ω = 0.95, 0.90, and 0.85. The corresponding sun zenith angle, satellite view angle, and relative azimuth is 30°, 35°, and 100°, respectively.

To further examine the error sources of MODIS aerosol retrievals in bright surfaces, TOA reflectance as a function of surface reflectance at 470 nm and aerosol single scattering albedos was simulated by a vector radiative transfer model with phase function from AERONET inversions in Dunhuang (Wang et al., 2014). As shown in Figure 10, low single scattering albedos can largely decrease the TOA reflectance but have no obvious

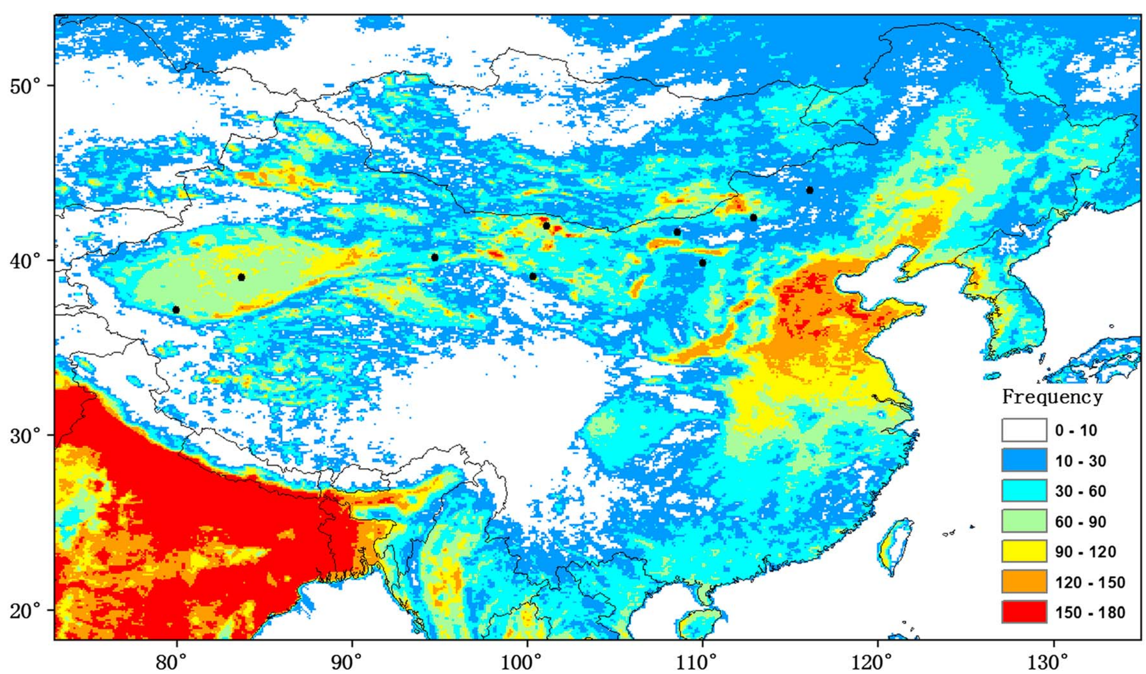

Figure 11. Annual frequency of C6 MODIS DB AOD $>$ 0.3 in 2015.

influence on sensitivity to increase of aerosol loading with surface reflectance <0.15, even ω = 0.80. On the other hand, TOA reflectance is sensitive to dust events in bright surface such as Taklimakan Desert with surface reflectance at 470 nm < 0.15 mostly except very clean conditions (AOD < 0.1) with low view zenith angles (e.g., <40°). Thus, MODIS DB retrievals in the deserts of East Asia could be potentially improved in principle. Considering the minor influence of low single scattering albedos and bright surface on sensitivity of TOA reflectance to aerosol loading in deserts of East Asia, the consistent low constant values in the DB retrieval during moderate dust events can mainly result from overestimation of surface reflectance (Figures 2 and 8). With the increase of dust loading, deviation of the assumed dust models dominates the system errors of DB retrievals.

Figure 11 displays annual frequency of MODIS DB AOD > 0.3 over East Asia. Although DB retrievals exhibit widely strong underestimation over deserts, numerous hotspots with active dust events were found in Taklimakan Desert and Gobi deserts with more than 100 days that AOD of dust particle exceeds 0.3. Considering the serious deviation of DB AOD, the frequent dust plumes in East Asia as well as their influence on regional climate and air quality could have been overlooked. In addition, the surface reflectance database derived from almost 10 years satellite data may not be sensitive to spatial variations of dust sources. However, so far, there are still few ground measurements concerning optical and physical properties of the airborne dust across the extensive deserts in East Asia. To accurately retrieve the dust loading, more quantitative laboratory and field studies are needed to constrain the unique aerosol and surface properties.

4. Conclusions

The extensive deserts in East Asia contribute to almost half of desert dust emission of the world. Elevated dust plumes are prevalent, exerting widely influence on downstream eastern China with a large population. In this study, we present a comprehensive evaluation of C6 MODIS DB aerosol retrievals in desert regions of East Asia based on ground observations in CARSNET. Evident underestimation of satellite retrievals was found in all the sites with most values falling out the expect error envelop ± (0.05 + 20%$AOD_{CARSNET}$). MODIS DB AOD persists constant low values around 0.05 in some regions such as the Taklimakan Desert when AOD is below 0.5. Intercomparison with MISR retrievals shows that such underestimation exists in most parts of the widespread deserts in East Asia.

The scattering ability of airborne dust over East Asia has been largely overestimated in the dust models of DB algorithm. The average values of single scattering albedos in Dunhuang and Zhangye is ~0.85 at 440 nm, which is much lower than those assumed in DB dust models. The slightly higher scattering phase function due to smaller particle size also partly contributes to the negative bias. Close connections between the increase of estimated surface reflectance and retrieval errors in Taklimakan Desert demonstrate overestimation of surface reflectance, leading to invalid low constant retrieval values in moderate aerosol loading (AOD < 0.5). Generally, radiative transfer simulations show that the bright surface and low single scattering albedos of the yellow dust over East Asia have no distinct limitation on DB retrievals except very clean conditions (AOD < 0.1) at low view angles. Therefore, MODIS DB retrieval can be improved by applying more realistic aerosol models and surface characterization over East Asia based on more ground measurements.

Acknowledgments
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