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Verification, improvement and application of aerosol optical depths in China Part 1: Inter-comparison of NPP-VIIRS and Aqua-MODIS

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ABSTRACT

The objective of this study is to evaluate typical aerosol optical depth (AOD) products in China, which experienced seriously increasing atmospheric particulate pollution. For this, the Aqua–MODerate resolution Imaging Spectroradiometer (MODIS) AOD products (MYD04) at 10 km spatial resolution and Visible Infrared Imaging Radiometer Suite (VIIRS) Environmental Data Record (EDR) AOD product at 6 km resolution for different Quality Flags (QF) are obtained for validation against AErosol RObotic NETwork (AERONET) AOD measurements during 2013–2016. Results show that VIIRS EDR similarly Dark Target (DT) and MODIS DT algorithms perform worse with only 45.36% and 45.59% of the retrievals (QF = 3) falling within the Expected Error (EE, ± (0.05 + 15%)) compared to the Deep Blue (DB) algorithm (69.25%, QF ≥ 2). The DT retrievals perform poorly over the Beijing-Tianjin-Hebei (BTH) and Yangtze-River-Delta (YRD) regions, which significantly overestimate the AOD observations, but the performance is better over the Pearl-River-Delta (PRD) region than DB retrievals, which seriously under-estimate the AOD loadings. It is not surprising that the DT algorithm performs better over vegetated areas, while the DB algorithm performs better over bright areas mainly depends on the accuracy of surface reflectance estimation over different land use types. In general, the sensitivity of aerosol to apparent reflectance reduces by about 34% with an increasing surface reflectance by 0.01. Moreover, VIIRS EDR and MODIS DT algorithms perform overall better in the winter as 64.53% and 72.22% of the retrievals are within the EE but with less retrievals. However, the DB algorithm performs worst (57.17%) in summer mainly affected by the vegetation growth but there are overall high accuracies with more than 62% of the collections falling within the EE in other three seasons. Results suggest that the quality assurance process can help improve the overall data quality for MYD04 DB retrievals, but it is not always true for VIIRS EDR and MYD04 DT AOD retrievals.

1. Introduction

Atmospheric aerosol is the general term for solid and liquid particles dispersed evenly in the atmosphere, with aerodynamic diameters ranging from 0.001 to 100 μm. It features a not negligible role in the interactions between atmosphere and land surfaces, which can pose significant effects on sun radiation or scattering (Hatzianastassiou et al., 2007; Qian et al., 2007), atmospheric visibility (Charlson, 1969; Wang et al., 2009; Liu et al., 2012), local or global climate change (Levy et al., 2013; Penner et al., 2001; Roeckner et al., 2006; Ridley et al., 2015), especially for human health (Butt et al., 2016; Okuda et al., 2014; Zheng et al., 2014). Aerosol Optical Depth (AOD) has been widely used to describe the attenuation effect of aerosol on the light. With the development of satellite aerosol remote sensing, large-scale and long-time aerosol distributions can be extracted from visible channels with remote sensing images.

The MODerate resolution Imaging Spectroradiometer (MODIS) sensors on board the Terra (local solar time 10:30 a.m.) and Aqua (local solar time 1:30 p.m.) satellites have been viewing the entire earth surface since December 19, 1999 and May 4, 2002, respectively. MODIS includes 36 spectral bands ranging from 0.4 to 14 microns at three moderate resolutions at 250 m, 500 m and 1000 m with a good temporal resolution of 1–2 days. It has provided a long-time series of atmosphere, land and ocean products to allow better understandings of

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their interactions from local to global scales (Wei and Sun, 2017). MOD04 and MYD04 are the Terra and Aqua MODIS Level 2 daily global coverage AOD products at 10 km spatial resolution, which are generated based on the Dark Target (DT) (Kaufman et al., 1997a, 1997b; 2002; Levy et al., 2010) and the Deep Blue (DB) (Hsu et al., 2004, 2006; 2013) algorithms. Recently, the aerosol product has updated from Collection 5.1 (C51) to C6 with lots of improvements (Levy et al., 2013).

The Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suomi National Polar-Orbiting Partnership (Suomi NPP) spacecraft was successfully launched on October 28, 2011. It has a wide swath width of 3060 km at an 824 km sun-synchronous orbit (inclination = 98.7°) with a 1:30 p.m. local equator crossing time at ascending node. It includes five imaging resolution bands (I-bands) at 375 m spatial resolution, sixteen moderate resolution bands (M-bands) and one day-night band at 750 m spatial resolution that spans wavelengths from 0.41 to 12.5 microns with a temporal resolution of one day. It is improved upon a series of measurements initiated by the Advanced Very High Resolution Radiometer (AVHRR) and MODIS (Cao et al., 2013a, 2013b; Uprety et al., 2013). VIIRS provides a Level 2 daily global coverage aerosol product at a spatial resolution of 6 km and is one of the series Environmental Data Record (EDR) datasets. It is generated from a likely MODIS DT algorithm but with significant differences in the estimation of surface reflectance and assumption of aerosol types as well as other aspects (Jackson et al., 2013) and is public and available on May 2, 2012.

In recent years, China have suffered severe air pollution with significant contributions from both natural and anthropogenic particulate sources, especially for typical urban agglomerations including the Beijing-Tianjin-Hebei region, the Yangtze River Delta region and the Pearl River Delta region. They have suffered from varying degrees of air pollution with average of air polluted days of 43.2%, 23.9% and 10.5%, respectively reported by the China Environmental State Bulletin in 2016 (http://www.mep.gov.cn/hjzl/). Atmospheric particulates have been the primary pollutants affecting urban air quality, where $PM_{2.5}$ and PM_{10} dominated pollution days accounted for 80.3% and 20.4%, respectively (http://www.mep.gov.cn/hjzl/). However, atmospheric particulates (mainly for $PM_{2.5}$ and PM_{10}) are parts of atmospheric aerosols and previous studies showed that they exhibited really high correlations with and can be estimated by AOD retrievals derived from satellite images (Hu et al., 2014; Hsu et al., 2004; Li et al., 2015; Xin et al., 2014, 2016). Thus, objectively validate and compare the current operational AOD products is of great significance to provide users a more appropriate choice for better exploring the temporal and spatial variations of atmospheric aerosol concentrations as well as monitoring local or urban air pollution in China.

Nowadays, many researchers are focusing on evaluating the performance of different operational AOD products in China. Wang et al. (2010) examined the Terra and Aqua MODIS AOD products (C5, 10 km) against AOD ground observations from the Chinese Sun Hazemeter Network (CSHNET) over China from 2004 to 2007. Results showed that there are not significant differences for Angstrom exponent ranges, regional monthly averages and consistent negative or positive biases between them in each region over China. Tao et al. (2015) evaluated Aqua MODIS AOD products (C6, 10 km) with AERONET ground observations over China and found significant differences existed in DT and DB retrievals, where DT overestimated AOD but usually missed regional haze pollution. Nichol and Bilal (2016) evaluated and compared the Aqua MODIS Dark Target (DT) C6 AOD products at 3 km and 10 km against the ground AOD observations from the AErosol RObotic NETwork (AERONET) over Asian countries from 2002 to 2014. Results showed that 3 km DT retrievals are less reliable than 10 km DT retrievals. Xiao et al. (2016) evaluated the VIIRS EDR (6 km), Intermediate Product (IP, 750 m), Geostationary Ocean Color Imager (GOCI, 8 km), and Terra and Aqua MODIS (C6, 3 km) AOD products against ground observations from AERONET, Distributed Regional Aerosol Gridded Observation Networks (DRAGON)-Asia Campaign and handheld sunphotometers over urban areas in East Asia in 2012 and 2013. Results showed that VIIRS EDR and GOCI AOD products provided more accurate retrievals than VIIRS IP and MODIS AOD products. Wang et al. (2017) validated the VIIRS IP (750 m), MODIS Terra and Aqua (3 km) AOD products retrievals against ground CE-318 sun photometer measurements at Wuhan University station from 2014 to 2016 and found MODIS AOD products indicated higher correlations with lower Root Mean Square Errors (RMSE) and Mean Absolute Errors (MAE) than VIIRS IP AOD products. Moreover, researchers focus on evaluating the performance of Terra and Aqua MODIS C5 and C6 10 km AOD products against the ground-based AERONET AOD measurements and compared with AOD retrievals from their own algorithms over the Beijing-Tianjin-Hebei region in China (Bilal et al., 2014; Bilal and Nichol, 2015; Wang et al., 2017; Wei and Sun, 2017). Results showed that C6 DT AOD retrievals are slightly better than C5 DT retrievals due to the improvements of retrieval algorithm but they are much worse than C6 DB AOD retrievals.

Although several validations and discussions among the current operational AOD products (especially for MODIS AOD products) have been conducted in China. However, they mainly focus on the direct comparisons between satellite-derived AODs and ground measurements at site or continental scale, single selected city (i.e., Beijing, Wuhan), typical region (i.e., Beijing-Tianjin-Hebei, Yangtze River Delta (He et al., 2010)) or surface type (i.e., urban, rural) using only the highest-quality (Quality assurance flag = 3) AOD retrievals. China has a vast land area and spans largely from East to West and South to North, covering abundant land use types. Sustained changes in the surface information, geographical locations, and characteristics of typical features may pose certain effects on the applicability of different aerosol retrieval algorithms. Moreover, to help monitor the urban air quality and provide real-time observations, in recent years, several new AERONET ground sites have been established in the local regions (i.e., Yangtze River Delta, Beijing-Tianjin-Hebei). Therefore, more comprehensively understand the performance of current aerosol products under the polluted background of China for different algorithms is needed.

MODIS and VIIRS are two main satellites, which provide long-time series of AOD products and can be very useful for aerosol and air quality studies, etc. However, evaluation and inter-comparisons studies between them over China are still few. Therefore, the objective of this study is to provide a more detailed evaluation and inter-comparison among MODIS and VIIRS AOD products over China. For this, the VIIRS EDR AOD at 6 km resolution and Aqua MODIS (MYD04) C6 DT and DB AOD products at 10 km resolution for different data-quality levels are collected over the period 2013–2016. Moreover, 22 AERONET ground observation sites located in the central, northeast, southeast and south of China over different land use types (i.e., urban, cropland and grassland), covering three typical regions, Beijing-Tianjin-Hebeiregion, Yangtze River Delta region and Pearl River Delta region are selected. Then the performance of VIIRS EDR and MODIS aerosol retrieval algorithms are validated and compared against AERONET AOD measurements at the site, local and continental scales, meanwhile, the effects of quality assurance, sensitivity of surface type to aerosol and seasonal variations on aerosol retrievals are also considered and discussed.

2. Datasets and methods

2.1. Satellite-derived aerosol optical depth products

2.1.1. MODIS aerosol retrieval algorithms over land

The MODIS contains two entirely independent DT algorithms over land and ocean. These are based on the empirically derived relationships between the surface reflectance among the blue (B3, 460 nm), red (B1, 660 nm) and short-wave infrared (SWIR, B7, 2130 nm) bands (B7/

B3 = 4, B1/B3 = 2), which are more stable over dark target surfaces (Kaufman et al., 1997a, 1997b). In order to improve the overall accuracy of retrievals over different land use covers, the estimation of surface reflectance has been improved via the parameters of Normalized Difference Vegetation Index (NDVI) calculated from SWIR bands ($NDVI_{SWIR}$) and scattering angles (Remer et al., 2007; Levy et al., 2010). It defined five typical aerosol types including dust, continental, weak absorption, moderate absorption and strong absorption aerosols, which are determined via the cluster analysis using the AERONET ground observations of aerosol optical parameters in a global map for each season. AOD retrieval is subsequently performed through the Look-Up Tables (LUT) approach. The official Expected Error (EE) of MYD04 DT AOD retrievals is ± (0.05 + 15%) over land (Levy et al., 2013). More detailed information about the retrieval algorithm can be found in (Kaufman et al., 1997a; 1997b; Levy et al., 2010, 2013).

The MYD04 DB algorithm is developed to retrieve AOD retrieval over bright land areas. The main difference between DT and DB algorithms is the estimation of surface reflectance, which the later one obtains the surface reflectance for visible bands from a pre-calculated seasonal land surface reflectance database created from the atmospheric corrected Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) surface reflectance products. It was first applied over bright deserts and obtained high retrieval accuracy (Hsu et al., 2004, 2006). Later several main improvements including surface reflectance estimation (adopt three approaches for estimating the surface reflectance over vegetated areas, urban, and arid and semiarid regions), aerosol model assumption and cloud screening schemes are made in the enhanced DB algorithm for producing the MODIS C6 aerosol products. The DB algorithm allows AOD retrieval for all dark and bright surfaces except those of oceans and snow/ice areas and the EE is ± (0.05 + 20%) over land (Hsu et al., 2013).

The Quality assurance Flags (QF) are stored in two Scientific Data Sets (SDSs) in MODIS AOD products named "Quality_Assurance_Land" and "Quality_Assurance_Ocean". It is the "Estimated quality flag of aerosol optical thickness" for land and the "Estimated quality of aerosol parameter of average solution" for ocean retrievals. Each QF corresponds to a certain number of bits and each bit corresponds to result of certain test. MODIS AOD products have four QFs including Poor (QF = 0), Marginal (QF = 1), Good (QF = 2) and Very Good (QF = 3) indicating an increasing data quality. High-quality data (QF = 3) account for approximately 60% and 25% of the valid retrievals over land and ocean, while marginal data (QF ≥ 1) accounts for about 85% and 98%, respectively (Levy et al., 2009, 2013). MODIS DT AOD retrievals with QF ≥ 1 over ocean and QF = 3 over land are strongly recommended for quantitative analysis by the MODIS aerosol team (Levy et al., 2009, 2013; Paul, 2017).

2.1.2. VIIRS aerosol retrieval algorithm over land

The VIIRS EDR AOD retrievals are generated based on a modified version of the Dark Target (DT) algorithm, which is similar to the MODIS C3 algorithm (Kaufman et al., 1997; TanrÉ et al., 1997). However, it is significantly different from that of MODIS over land. VIIRS algorithm computed the surface reflectance used the vector radiation transfer model (RTM) through the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) Version (V) 1.1 model (Kotchenova et al., 2006; Kotchenova and Vermote, 2007). The VIIRS apparent reflectances in the M1 (412 nm), M2 (445 nm), M3 (488 nm), M5 (672 nm), and M11 (2250 nm) bands are selected for AOD retrieval. AOD at 550 nm is retrieved using an empirically derived relationships between the surface reflectance in the blue (488 nm), red (672 nm) and SWIR (2250 nm) bands (M1/M5 = 0.513, M11/M5 = 1.788) (Jackson et al., 2013). Five candidate aerosol models including the dust, high-absorption smoke, low-absorption smoke, clean urban and polluted urban are selected. Then VIIRS aerosol retrieval is also performed through the LUT approach at the M-band pixel and provides a full set of aerosol parameters called the intermediate product (IP) at 750 m spatial resolution including AOD at 550 nm, Ångström exponent, and aerosol model. The AOD EDRs are generated by aggregating 8*8 IP retrievals with the spatial resolution of 6 km in a typical VIIRS granule. VIIRS EDR AOD product consists of AODs reported at 10 M-Bands from 412 nm to 2250 nm. More detailed information on aerosol retrieval algorithm can be found in [Dubovik et al., 2002; Jackson et al., 2013; Vermote and Kotchenova, 2008]. Similarly, QF is selected to determine the accuracy of the VIIRS EDR AOD product and provides three quality flags: Low (QF = 1), Medium (QF = 2) and High (QF = 3), indicating an increasing data quality. The highest quality (QF = 3) AOD retrievals are strongly recommended by the VIIRS aerosol team and the spatio-temporal coverage of high-quality VIIRS retrievals after data filtering is about 13.18% (Liu et al., 2014; Jackson et al., 2013; Wu et al., 2016).

2.2. AERONET AOD ground-measured measurements

AERONET is an international federation of ground-based aerosol networks and provides a long-term, continuous and accessible public database of globally distributed observations of spectral AOD, precipitable water and other AOD-dependent products ranging from 0.340 to 1.060 μm. The AOD ground-based measurements are computed for three data quality levels: Level 1.0 (unscreened), Level 1.5 (cloud-screened), and Level 2.0 (cloud-screened and quality-assured) with a low uncertainty of ∼0.01 and a high temporal resolution of 15 min (Holben et al., 2001; Smirnov et al., 2000). As the satellite-derived AOD retrievals are at the wavelength of 550 nm, therefore, AEORNET AOD at 550 nm is interpolated using Ångström Exponent to match with satellite AOD observations (Ångström, 1964; Sun et al., 2016; Wei and Sun, 2017). In this study, total 22 AERONET sites over land in China are collected for validation purposes (Fig. 1) and Table 1 provides the summary information.

3. Results and disscussion

In this study, the VIIRS DT AOD products at QF = All (including QF = 1, 2, 3) and QF = 3, MYD04 C6 DT AOD products at QF = All (including QF = 0, 1, 2, 3) and QF = 3, and MYD04 C6 DB AOD products at QF = All (including QF = 1, 2, 3) and QF ≥ 2 from 2013 to 2016 are collected for evaluation and comparison purposes over China. The average of at least two AERONET AOD measurements within ± 30 min of the VIIRS and Aqua–MODIS overpass times at each site is as AOD ground-based measurements. The AOD retrievals is averaged within a sampling window of 3 × 3 pixels (average of 9 pixels) for MODIS and 5 × 5 pixels (average of 25 pixels) for VIIRS with the same area of 30 km^2 centered on each AERONET site.

In order to quantitatively evaluate the accuracy of different AOD products, the Pearson product-moment correlation coefficient (R) based on the linear regression is selected to analyze the correlation between retrievals and measured values. The Expected Error (EE, Eq. (1)) of MODIS DT algorithm over land is obtained to evaluate the overall accuracy. Moreover, the Mean Absolute Error (MAE, Eq. (2)), Root-Mean-Square Error (RMSE, Eq. (3)) and Relative Mean Bias (RMB, Eq. (4)) are selected to evaluate the uncertainty in the aerosol retrievals:

$$EE = \pm(0.05 + 0.15 * AOD_{AERONET}) \tag{1}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} AOD_{Retrieval} - AOD_{AERONET} \tag{2}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (AOD_{Retrieval} - AOD_{AERONET})^2} \tag{3}$$

$$RMB = \frac{1}{n}\sum_{i=1}^{n} AOD_{Retrieval}/AOD_{AERONET} \tag{4}$$

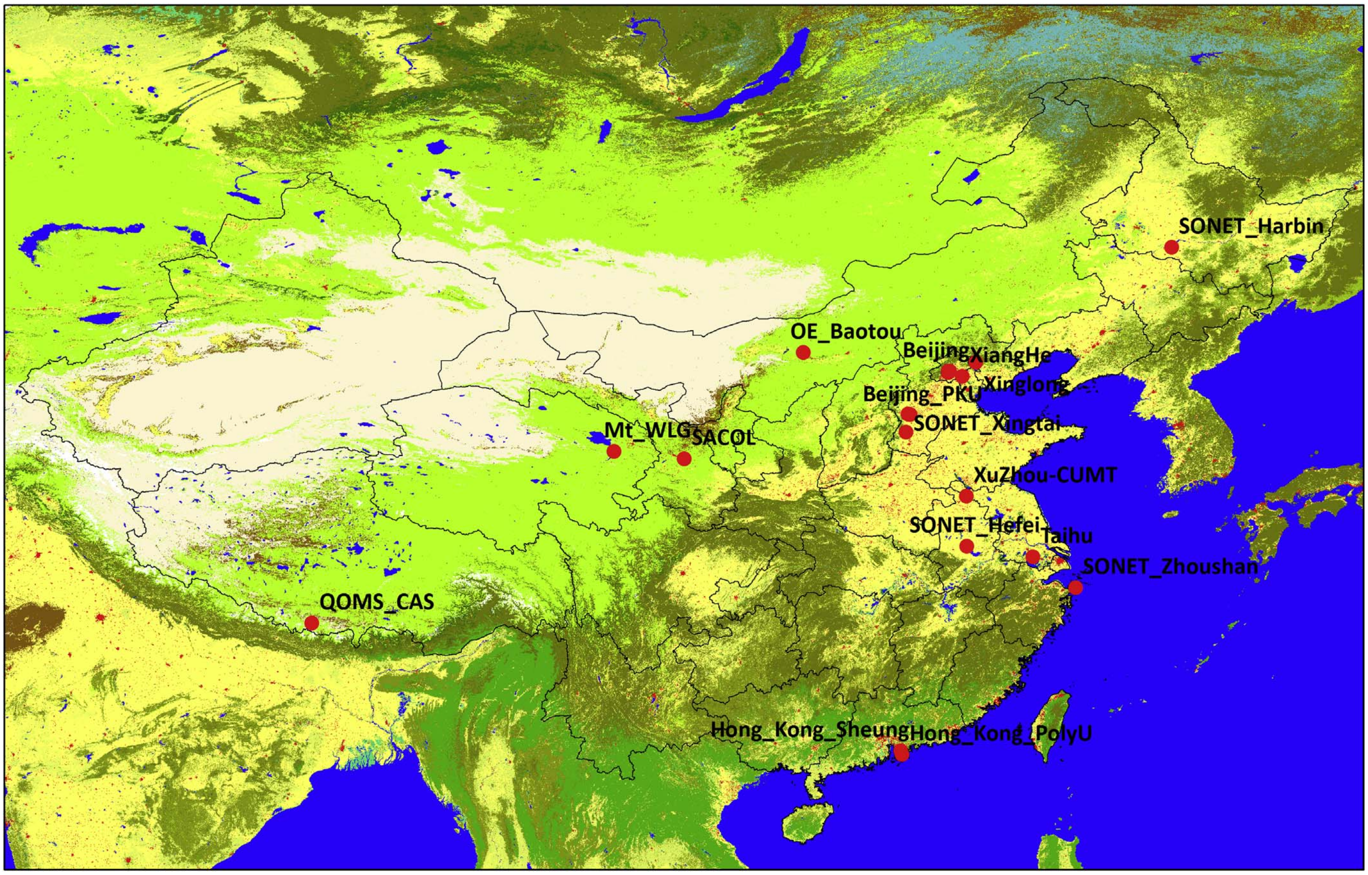

Fig. 1. Location of AERONET site in China and the background map is MOD12 Land use cover in 2013.

3.1. Performance of different AOD products at the site scale

Fig. 2 provides the validation and accuracy differences for VIIRS EDR DT, MYD04 DT and DB AOD products for different QF levels against AERONET AOD measurements at each site in China, and Tables S1–S3 show the accuracy statistics. X-axis refers to the sequential numbers of AERONET sites reported in Table 1 and the Y-axis (Difference) represents the numerical difference between the same evaluation indexes (R, RMSE, MAE or Uncertainly) for highest-quality (QF = 3 or ≥ 2) and all-quality AOD retrievals (QF = All). However, due to the differences of the retrieval algorithms and lengths of ground-based observations, etc., collected effective points for different sites show some differences. In this study, AOD retrievals at a site are considered as a "good" matching if more than 66% of them fall within the EE (Levy et al., 2010; Remer et al., 2013).

VIIRS EDR QF = All AOD retrievals show overall low accuracies at

Table 1
Detailed information of AERONET sites in China.

No.	Stations Name	Longitude	Latitude	Elevation	Land use	Periods
1	Beijing	116.381	39.977	92	Urban	2013/01–2016/12
2	Beijing_PKU	116.317	39.933	106	Urban	2016/06–2016/12
3	Beijing_RADI	116.379	40.005	59	Urban	2013/01–2016/12
4	Beijing-CAMS	116.310	39.992	53	Urban	2013/01–2016/12
5	Lingshan_Mountain	115.496	40.054	1653	Cropland	2014/05–2015/08
6	Shijiazhuang-CHEY	114.550	38.000	88	Urban	2013/12–2014/01
7	Shijiazhuang-SZF	114.458	38.017	158	Urban	2013/12–2014/01
8	SONET_Xingtai	114.360	37.182	29	Cropland	2016/04–2016/05
9	XiangHe	116.962	39.754	36	Cropland	2013/01–2016/12
10	Xinglong	117.578	40.396	970	Mixed Forest	2013/01–2014/11
11	SONET_Hefei	117.162	31.905	36	Cropland	2016/04–2016/06
12	SONET_Shanghai	121.481	31.284	84	Urban	2016/04–2016/06
13	SONET_Zhoushan	122.188	29.994	29	Cropland	2016/04–2016/06
14	Taihu	120.215	31.421	20	Wetland	2013/01–2016/12
15	Xuzhou-CUMT	117.142	34.217	59	Cropland	2013/06–2016/12
16	Hong_Kong_PolyU	114.18	22.303	30	Grassland	2013/01–2016/12
17	Hong_Kong_Sheung	114.117	22.483	40	Grassland	2013/01–2016/06
18	Mt_WLG	100.896	36.283	3816	Grassland	2013/01–2013/07
19	OE_Baotou	109.629	40.852	1270	Grassland	2013/09–2016/12
20	QOMS_CAS	86.948	28.365	4276	Grassland	2013/01–2016/12
21	SACOL	104.137	35.946	1965	Grassland	2013/01–2013/05
22	SONET_Harbin	126.614	45.705	187	Urban	2016/05–2016/06

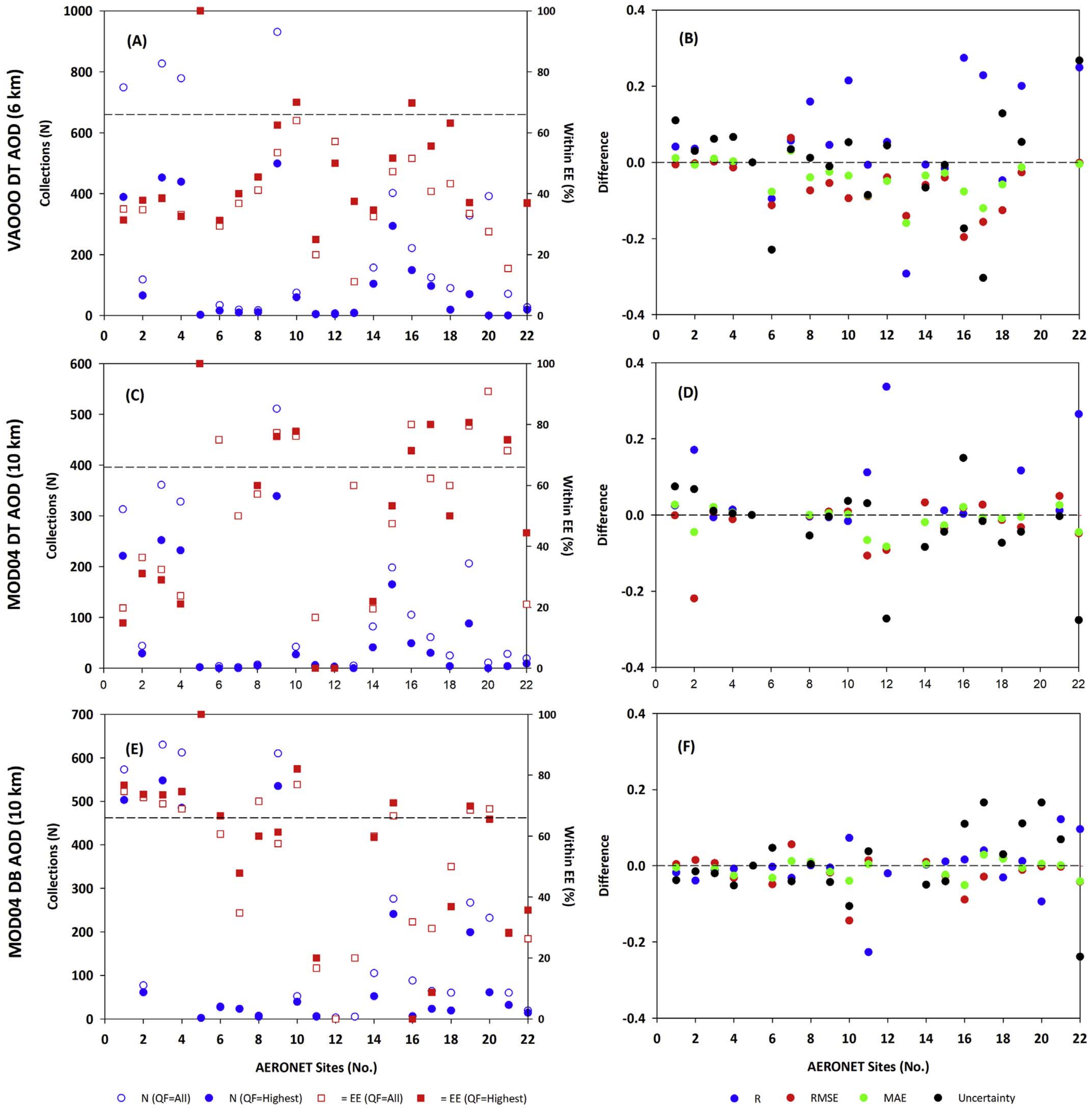

Fig. 2. Validation of VIIRS EDR (QF = All and 3), MYD04 DT (QF = All and 3) and DB (QF = All and ≥ 2) AOD retrievals at each AERONET site in China during 2013–2016. X-axis refers to the sequential numbers of AERONET sites reported in Table 1. Y-axis (Difference) represents the numerical difference between evaluation indexes for highest-quality and all-quality AOD retrievals.

all sites with less than 66% of collections falling within the EE. Especially, for three typical urban sites, Beijing, Beijing_RADI and Beijing-CAMS, although they have a large number of data collections of 749, 827 and 779, respectively. The AOD retrievals are seriously overestimated (RMB > 1.20) and only 34.98%, 38.57% and 33.12% of themfall within the EE with large MAE and RMSE errors greater than 0.29 and 0.21, respectively. For VIIRS EDR QF = 3 AOD retrievals, the number of data collections drops sharply by about 2.0 times (only AERONET sites with more than 20 effective AOD collections are involved in the calculation), especially for QOMS_CAS and SACOL sites, where the data collections decrease from 392 and 71 points to 0 point, respectively. However, the retrieval accuracies increase for 15 out of 20 sites with increasing correlations and decreasing MAE, RMSE and uncertainties. In contrast, accuracies decrease and only 31.36%, 37.88% and 38.41% of the collections fall within the EE with increasing MAE and uncertainties for Beijing, Beijing_RADI and Beijing-CAMS, noting that the numbers of data collections reduce to 389, 453 and 439, respectively. Similar to QF = All AOD retrievals, QF = 3 AOD retrievals show overall low accuracies with less than 66% of the retrievals falling within the EE in most sites (Fig. 2A and B).

The number of data collections for MYD04 DT QF = All AOD retrievals is approximately 2.2 times less than VIIRS EDR QF = All AOD

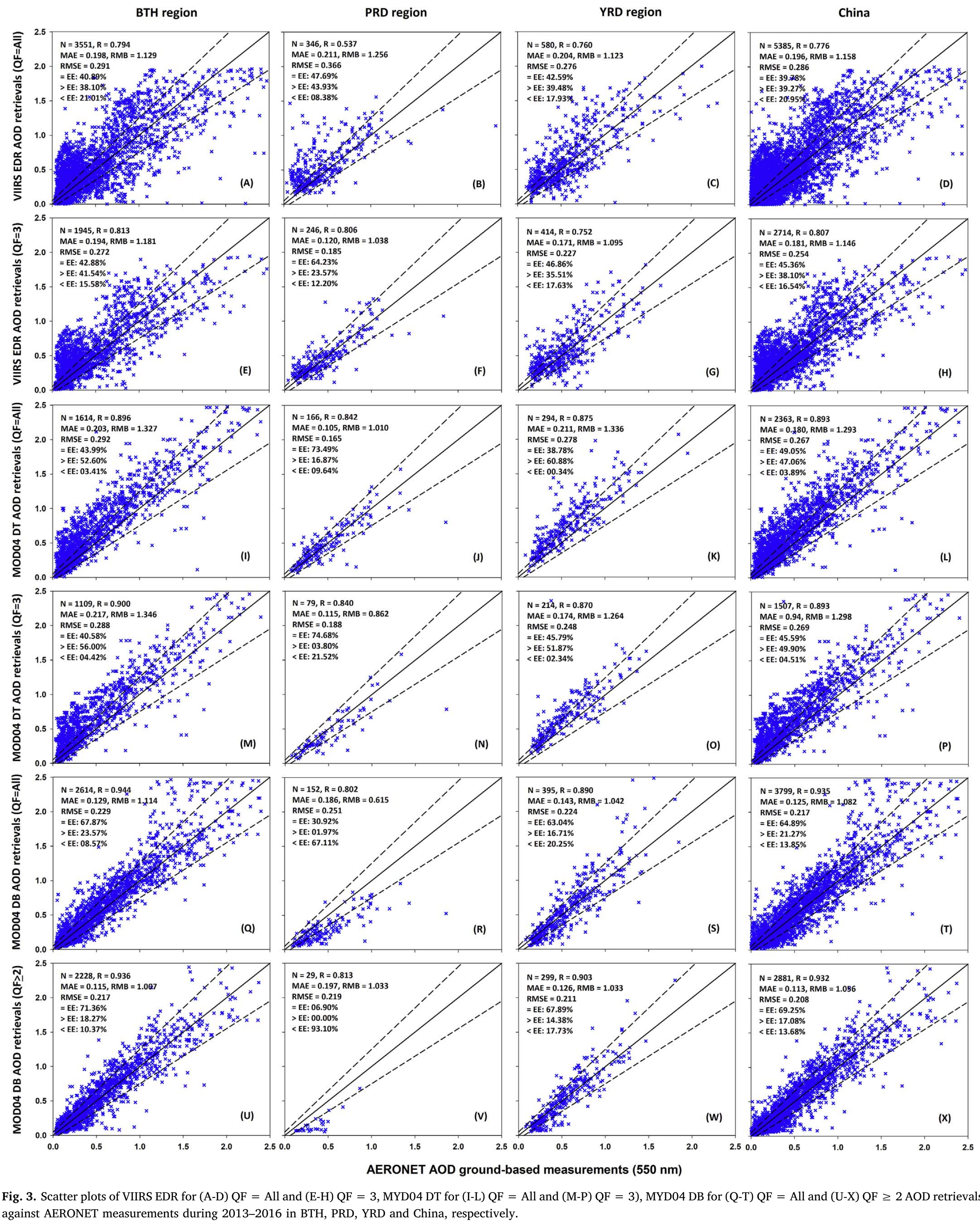

Fig. 3. Scatter plots of VIIRS EDR for (A-D) QF = All and (E-H) QF = 3, MYD04 DT for (I-L) QF = All and (M-P) QF = 3), MYD04 DB for (Q-T) QF = All and (U-X) QF ≥ 2 AOD retrievals against AERONET measurements during 2013–2016 in BTH, PRD, YRD and China, respectively.

retrievals. Especially for the QOMS site located in deep Tibetan Plateau, where 90% of retrievals out of 11 collections are within the EE for MYD04 DT, yet 27.55% of 392 collected retrievals fall within the EE for VIIRS EDR. However, after quality controls, no data is obtained at this site, indicating poor accuracies for both AOD datasets over plateaus in southwestern China. The accuracies vary greatly at different sites, where only eight sites match good performance with more than 66% of the collections falling within the EE. Beijing, Beijing_RADI and Beijing-CAMS, with more than 300 data collections, show low accuracies with only 19.81%, 32.41% and 23.78% of the collections falling within the EE with large MAE ~ 0.222–0.283, RMSE ~ 0.304–0.361 values compared to VIIRS EDR AOD retrievals, resulting in a seriously average overestimation uncertainty of 41%–64% (RMB = 1.410–1.638). In contrast, for Xianghe site located in the suburbs close to croplands, a large number of points (931) are collected and 77.30% of the retrievals fall within the EE with low MAE ~ 0.105 and RMSE ~ 0.181, causing an average of only 8.9% overestimation uncertainty. After quality controls, the data collection reduces by approximately 1.7 times and most sites show decreasing accuracies with increasing MAEs and uncertainties, especially for above urban sites. There are only 14.93%, 28.97% and 21.12% of the collections falling within the EE with increasing MAEs and uncertainties for Beijing, Beijing-RADI and Beijing_CAMS sties, respectively (Fig. 2C and D).

The number of collections for MYD04 DB (QF = All) AOD retrievals is approximately 1.54 times more than that of MYD04 DT (QF = All) AOD retrievals, but 1.50 times less than VIIRS EDR (QF = All) AOD retrievals. The DB retrievals are well correlated with AERONET AOD measurements (R = 0.751–0.992), and about half of the sites show high accuracy with more than 66% of the retrievals falling within the EE. Especially, there are 74.69%, 70.63% and 68.85% of the retrievals falling within the EE for Beijing, Beijing_RADI and Beijing-CAMS sites, which are approximately 2.7 and 2.1 times better than MYD04 DT and VIIRS EDR AOD products, respectively. After quality controls, the numbers of the collections overall decrease but with improved accuracies at most sites. It is apparent that more than half of the sites show high accuracies with more than 60% of the collections falling within the EE. However, there are still some individual sites with lower accuracies for the DB algorithm compared to the DT algorithm over densely vegetated or coastal areas (Fig. 2E and F).

Previous studies selected and recommended the highest-quality VIIRS and MODIS AOD products for aerosol studies (Liu et al., 2014), and through the above analysis, we found that with QF increasing, the accuracies do overall improve in most sites in China for MYD04 DB AOD retrievals, which can support this recommendation. However, this recommendation is not always appropriate for VIIRS EDR and MYD04 DT AOD products, especially for several typical urban sites (i.e. Beijing, Beijing_RADI, Beijing-CAMS) where the accuracies ddo not improve for increasing QF AOD retrievals, and the numbers of data collection significantly decrease over these sites. Therefore, QF may not be an useful and right diagnostic to study the spatial or temporal variations of aerosol in such areas. Moreover, comparison results showed that MYD04 DB AOD product exhibits overall better performance with lower MAE, RMSE and RMB errors than MYD04 DT and VIIRS EDR AOD products at most sites in China.

3.2. Performance of different AOD products over local regions

Beijing-Tianjin-Hebei (BTH), Yangtze-River-Delta (YRD) and Pearl-River-Delta (PRD) regions are three typical clusters of urbanized areas in China. Due to special regional, economic and polluted background, they have been the hotspots for AOD retrieval and related aerosol studies, moreover, relevant domestic organizations also regard them as typical areas to monitor and reflect the general air pollution in China. Therefore, investigate the applicability of current AOD products in such typical regions can help more accurately monitor the air quality and is also of great importance for their ecological protection. In this study, the BTH region includes ten AERONET sites ranging from site numbers (No.) 1 to 10 in Table 1, and the YRD region includes five AERONET sites ranging from No.11 to 15. The PRD region mainly includes the Hong_Kong_PolyU and Hong_Kong_Sheung sites located in Hong Kong. Fig. 3 shows the validation of VIIRS EDR (QF = All and QF = 3), MYD04 DT (QF = All and QF = 3) and DB (QF = All and QF ≥ 2) AOD retrievals against AERONET AOD measurements over three typical regions in China during 2013–2016 and statistical summary of validation is given in Table S4.

The BTH region is located in the central China and centered on the city of Beijing. There are a large number of 3551, 1614 and 2614 retrievals observed over this region by VIIRS EDR, MYD04 DT and DB algorithms, respectively. Statistical data show that approximately 10.56%, 13.26%, 16.07% of VIIRS EDR,MYD04 DT, and DB retrievals, respectively, exhibit high AOD values greater than 1.0, indicating severe air pollutions in BTH region. After quality controls, although the overall accuracy increases with decreasing MAE, RMSE and RMB values, there are overall low accuracies for both VIIRS EDR QF = All and QF = 3 AOD retrievals with only 40.89% and 42.88% of the collections falling within the EE, showing large overestimation uncertainties (RMB = 1.129–1.181). The data collections of MYD04 DT AOD products reduced by about 2.2 times than VIIRS EDR and only 43.99% of the QF = All retrievals fall within the EE with large MAE, RMSE and RMB values. Moreover, after quality controls, the accuracy decreases with increasing MAE and uncertainties. However, MYD04 DB retrievals show the highest correlation against AERONET AOD measurements (R = 0.944) with lowest RMSE, MAE and RMB errors than both VIIRS EDR and MYD04 DT AOD products. With increasing QF, the data quality gets improved from 67.87% to 71.36% with low MAE ~ 0.115, RMSE ~ 0.217 and RMB ~ 1.077 values. Our results suggest the DT algorithm is unsuitable for BTH region, which seriously over-estimates the AOD loadings. In contrast, the DB algorithm exhibits overall high accuracy and significantly reduces the estimation uncertainty, thus, the DB retrievals (QF ≥ 2) are recommended for air quality or aerosol studies in BTH region.

The PRD region is located in the Southern China, centered on the cities of Shenzhen and Hong Kong. Only 346, 166 and 152 of AOD retrievals are collected from VIIRS EDR, MYD04 DT and DB products, respectively. Air quality is overall good in PRD region with more than 90% of the collections showing low AOD values less than 1.0. VIIRS EDR AOD retrievals show low agreements with AERONET AODs as 47.69% and 43.93% of the retrievals are within and above the EE, respectively. After quality controls, the percentage of retrievals within the EE increases to 64.23% with an increasing correlation of 0.806 and lower MAE, RMSE and RMB errors of 0.120, 0.185 and 1.038, respectively. MYD04 DT AOD retrievals agree well with AERONET AOD measurements (R = 0.842) as 73.49% of the retrievals are within the EE with low MAE ~ 0.105 and RMSE ~ 0.165 errors, leaving only an average overestimation uncertainty of 1%. However, after quality controls, the number of data collections decreases by more than two times, and the MAE, RMSE values and underestimation errors increase. MYD04 DB AOD retrievals show worse performance with only 30.93% and 67.11% of the retrievals are within and below the EE, respectively, with larger MAE and RMSE errors than the DT AOD retrievals. Moreover, after quality controls, the number of collections and the overall accuracy significantly decrease, moreover, the DB algorithm seriously underestimates the aerosol loadings with 93.10% of the retrievals falling below the EE. These results suggests poor performance of the DB algorithm over the PRD region. On the contrary, the DT algorithm shows good performance with small errors and can better reflect the AOD distributions over the region, therefore, VIIRS EDR retrievals (QF = 3) or MYD04 DT retrievals (QF = All) are recommended for air quality studies in the PRD region.

The YRD region is located in the southeast coastal area of China centered on the city of Shanghai. There are 580, 294 and 395 collections obtained from VIIRS EDR, MYD04 DT and DB products, respectively. The VIIRS QF = All AOD retrievals show an overall low accuracy with only 42.59% of the retrievals falling within the EE. For highest quality flag, the accuracy of the retrievals improves to 46.86% with decreasing MAE (0.204 to 0.171) and RMSE (0.276 to 0.227) errors. The MYD04 DT AOD retrievals provide about two times of AOD collections less than the VIIRS EDR, and show worse performance with only 38.78% of the retrievals falling within the EE, causing a high average overestimation uncertainty of 33.6% (RMB = 1.336). After quality controls, through the accuracy overall improves (45.79%) with decreasing MAE ~ 0.174, RMSE ~ 0.248 and RMB ~ 1.264 errors, the MYD04 DT algorithm still seriously overestimates the AOD loadings in YRD region with 51.87% of the retrievals falling above the EE. However, MYD04 DB retrievals shows a high consistency with AERONET AOD measurements (R = 0.890) and approximately 63.04% of the collections meet the EE requirement with low MAE and RMSE values. With QF increasing, the accuracy improves to 67.89% with decreasing MAE ~ 0.126, RMSE ~ 0.211 and RMB ~ 1.033 errors, causing only an average overestimation uncertainty of less than 4%. These results suggest that the DT algorithms show overall poor applicability and seriously overestimates the AOD loadings. However, the DB algorithm significantly improves the performance of retrievals and reduce the uncertainty, therefore, the DB retrievals (QF ≥ 2) are recommended for air quality studies in YRD region.

We collected 5385, 2363 and 3799 AOD retrievals for all quality flags from VIIRS EDR, MYD04 DT and DB AOD products, respectively during 2013–2016 over China. VIIRS EDR AOD retrievals (QF = All) show an overall low agreement with AERONET AOD measurements and only 39.78% of the retrievals fall within the EE with large MAE ~ 0.196 and RMSE ~ 0.286 values. After quality controls, there are 45.36% of 2714 AOD collections falling within the EE with decreasing MAE ~ 0.181, RMSE ~ 0.254 and RMB ~ 1.146 values. However, they show high overestimations with more than 38% of the retrievals falling above the EE, which indicates that the VIIRS EDR retrievals show overall low performance in China. MYD04 DT AOD retrievals (QF = All) are approximately 2.28 times less than VIIRS EDR retrievals, but they are well correlated (R = 0.893) with AERONET AOD measurements with 49.05% of the collections falling within the EE and 47.06% of them falling above the EE, causing a similar high average overestimation uncertainty of 29% (RMB = 1.293). For DT QF = 3 AOD retrievals, the number of data collections decreases by 1.57 times and the percentage of AOD retrievals within the EE decreases while the percentage above the EE increases. Overall, the DT AOD retrievals show high overestimation errors and poor performances in China which are similar to VIIRS EDR AOD retrievals. The DB AOD retrievals perform best with 64.89% of 3799 AOD collections are within the EE with the smallest MAE ~ 0.125 and RMSE ~ 0.217 values than both the VIIRS EDR and MYD04 DT AOD products. ForDB QF ≥ 2 product, 2881 effective points are collected which are well correlated with AERONET AOD (R = 0.932), and 69.25% of them are within the EE with decreasing MAE ~ 0.113 and RMSE ~ 0.208 values.

3.3. Adaptability of different AOD products over surface types

Aerosol retrieval over land is much more difficult because the surface reflectances show obvious irregular characteristics for different land covers, which is hard to be accurately determined. However, surface reflectance estimation has been the most essential issue affecting the retrieval accuracy using remote sensing technology. Previous showed that 1% estimation errors in the surface reflectance can lead to 10% errors in AOD retrieval (Kaufman et al., 1997a). Therefore, different aerosol retrieval algorithms are designed to improve estimations of surface reflectance over different land use types, where DT and DB algorithms are two of the most typical algorithms. To explore the adaptability of VIIRS and MODIS aerosol retrieval algorithms over different underlying surfaces, AERONET sites are divided into two typical vegetated land use types, cropland (6 sites) and grassland (6 sites), along with urban (8 sites), which are extracted through the MOD12Q1 Land Cover product at 1 km spatial resolution in 2013. Fig. 4 illustrated the validations of VIIRS EDR and MYD04 AOD products at different QF levels against AERONET AOD measurements over cropland, grassland and urban areas in China during 2013–2016 and Table S5 shows the accuracy statistics.

There are a total of collected 1366, 729 and 906 AOD retrievals over cropland during 2013–2016 in China for VIIRS EDR, MYD04 DT and DB products. It is easy to find that AOD retrievals exhibit overall high correlations with AERONET AOD measurements (0.846–0.943) with 51.17%, 68.45% and 60.04% of them falling within the EE, respectively, indicating good performances over the cropland. After quality controls, the numbers of the collections reduce to 818, 516 and 788, and the accuracies of the retrievals get improved with 58.07%, 68.22% and 64.09% of the collections falling within the EE, along with decreasing MAE (0.142, 0.119 and 0.137), RMSE (0.208, 0.184 and 0.238) and estimation uncertainties for VIIRS EDR, MYD04 DT and DB algorithms, respectively. In general, MODIS DT and DB algorithms overall overestimate the AOD loadings with approximately 26%–33% of the retrievals falling above the EE, whereas the VIIRS algorithm shows similar overestimation (19%–22%) or underestimation (22%–28%) errors over cropland in China.

For grassland, we have collected a total of 1227 points for VIIRS EDR product and there is a low consistency between the retrievals and AERONET AOD measurements (R = 0.538) with only 35.29% of them falling within the EE and large RMSE ~ 0.281, MAE ~ 0.186 errors. With QF increasing, the number of data collections sharply reduces by about 3.7 times but the accuracy significantly improves with 58.33% of the retrievals falling within the EE, showing descreasing RMSEof 0.172 and MAE of 0.114 values. MYD04 DT retrievals agrees well with AERONET AODs (R = 0.875) and 75.92% of 436 collections fall within the EE with small RMSE ~ 0.128 and MAE ~ 0.076 errors. After quality controls, the percentage of retrievals within the EE increases to 77.14% but with sharply reduced (by about 2.5 times) data collections and increasing RMSE, MAE and estimation uncertainty. MYD04 DB product provides about 1.8 times of AOD retrievals more than MYD04 DT product and it shows a high correlation with AERONET AODs (R = 0.760) and 56.68% of them fall within the EE. With QF increasing, the retrievals reduce by about 2.3 times and the accuracy only increases by about 1% with slight decreasing RMSE and MAE errors. However, the DB algorithm seriously underestimates the AOD loadings with 28–33% of the retrievals falling below the EE over grassland in China.

We have collected 2560, 1074 and 1965 points over urban areas during 2013–2016 in China for VIIRS EDR, MYD04 DT and DB AOD products. The VIIRS DT algorithm retrieves aerosol with the maximum number of days but the retrievals show low consistency with AERONET ground-based observations. Only 35.59% of the retrievals fall within the EE with large RMSE ~ 0.303, MAE ~ 0.216 values. With QF increasing, the overall accuracy decreases with only 34.53% of 1396 AOD retrievals falling within the EE, showing similar large RMSE ~ 0.297, MAE ~ 0.222 values. Both two quality-level AOD retrievals show obvious overestimations with more than 47% of them falling above the EE. Compared to VIIRS EDR retrievals, MYD04 DT retrievals show worse performance with only 26.16% of them falling within the EE and larger RMSE ~ 0.337, MAE ~ 0.256 and estimation uncertainty. After quality controls, the overall accuracy decreases with 22.73% of total 748 collections falling within the EE and large RMSE ~ 0.328, MAE ~ 0.272 errors. The MYD04 DT algorithm significantly overestimates the AOD loadings (RMB = 1.494) with more than 71% of the retrievals falling above the EE. However, MYD04 DB retrievals (1965 points) agree better with AERONET AOD measurements (R = 0.939) and 71.60% of them fall within the EE with smaller RMSE ~ 0.216, MAE ~ 0.120 values, and after quality controls, the overall accuracy overall increases with decreasing RMSE ~ 0.209, MAE ~ 0.107 values, causing an average low overestimation uncertainty of less than 5%.

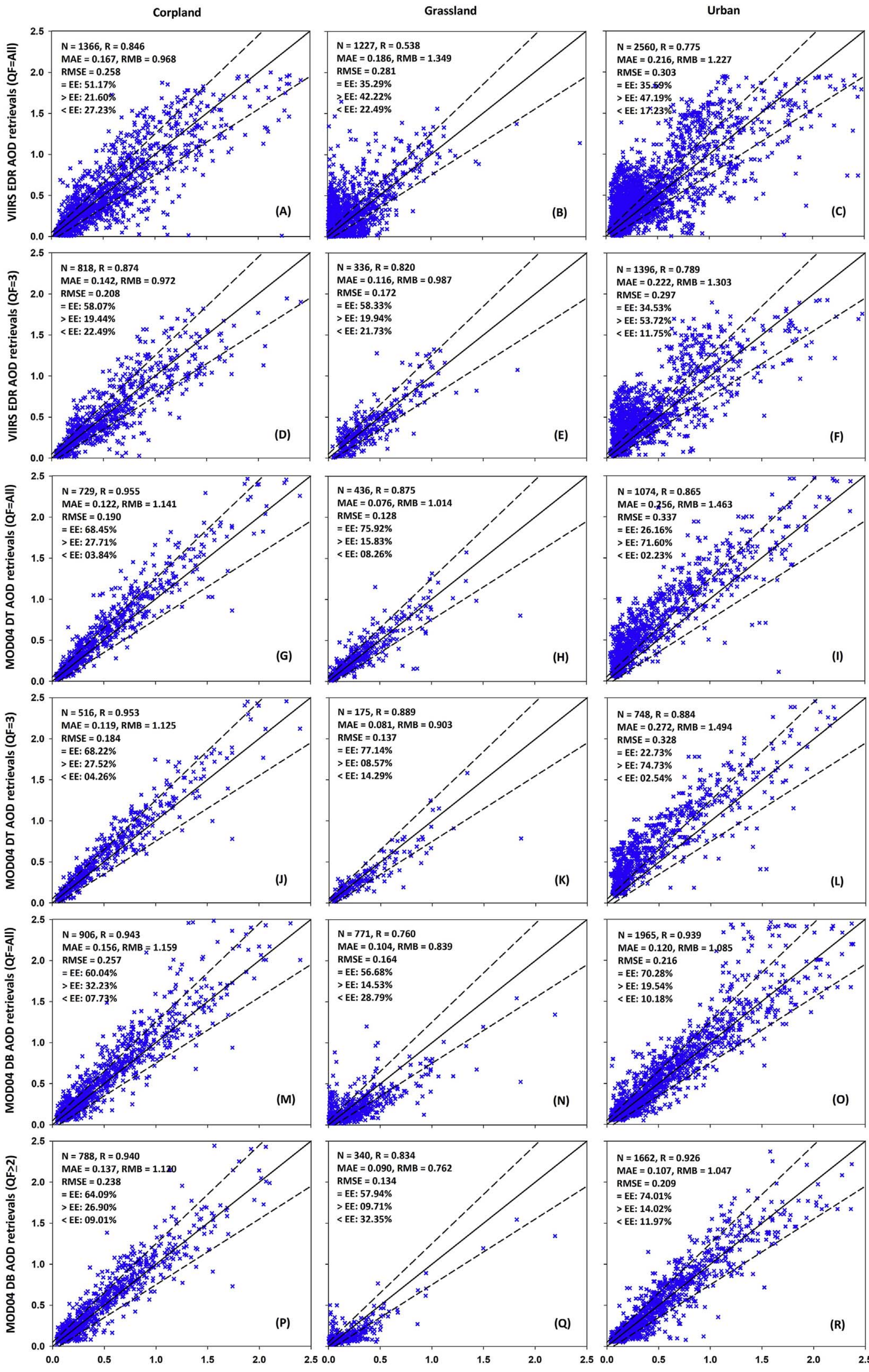

Fig. 4. Scatter plots of VIIRS EDR (QF = All and QF = 3), MYD04 DT (QF = All and QF = 3) and DB (QF = All and QF ≥ 2) AOD retrievals against AERONET AOD ground-based measurements over different land types in China during 2013–2016. The dashed lines = EE lines and black solid line = 1:1 line.

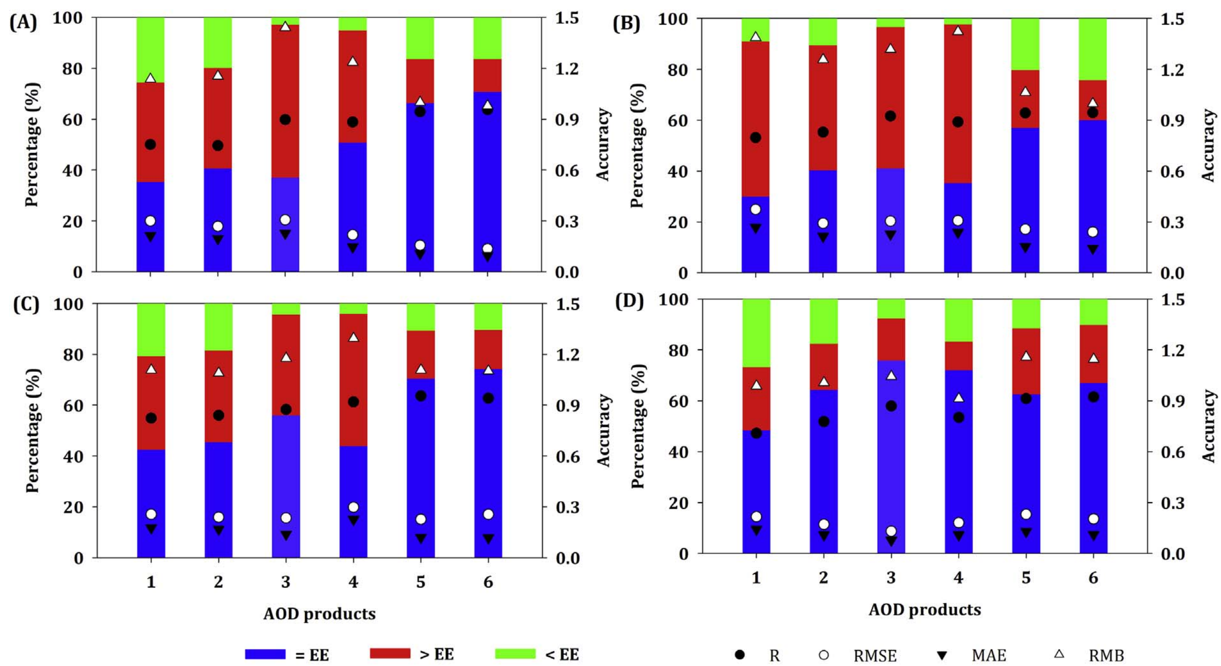

Fig. 5. Validation of VIIRS EDR, MYD04 DT and DB AOD retrievals at each AERONET site for spring (A), summer (B), autumn (C) and winter (D) in China during 2013–2016. Where X-axis 1-6 represents six AOD products for VIIRS EDR (QF = All), VIIRS EDR (QF = 3), MYD04 DT (QF = All), MYD04 DT (QF = 3), MYD04 DB (QF = All) and MYD04 DB (QF ≥ 2), respectively.

3.4. Influence of seasonal variations on different AOD products

Different surface types exhibit different characteristics in different seasons. The vegetation shows obvious seasonal variations where its surface reflectance can vary lot in the growing seasons but keep unchanged for a long period in winter. However, bright areas (i.e. urban, desert and bare land) show lower seasonal variations as well as weaker effects of surface Bidirectional Reflectance Distribution Function (BRDF) compared to vegetation. The surface reflectance of bright areas are much higher than that of vegetation in visible channels, but are not significantly variant with time (Hsu et al., 2013). Therefore, to better understand the adaptability of different AOD retrieval algorithms over different seasons, we collect AOD retrievals fromVIIRS EDR , MYD04 DT and DB AOD products and explore their performance in each season in China. Fig. 5 plots the VIIRS EDR (QF = All and QF = 3), MYD04 DT (QF = All and QF = 3) and DB (QF = All and QF ≥ 2) AOD retrievals against AERONET AODs at each season in China during 2013–2016 and Table S6 shows the accuracy statistics.

For VIIRS EDR AOD product, 1362, 1124, 1483 and 1416 points are collected for four seasons, and they show overall low accuracies with only 35.39%, 30.16%, 42.62% and 48.66% of the collections falling within the EE. With QF increasing, the numbers of collections dropped sharply to 731, 711 and 928 for spring, summer and autumn, and it significantly decreases by approximately 4 times (344 collections) in winter. With QF increasing, the accuracies overall increase with 40.77%, 40.51%, 45.58% and 64.53% of the collections meeting the EE acquirements and decreasing MAE, RMSE, estimation uncertainties for four seasons, respectively. It indicates that QF controls can help improve the overall quality of AOD product in season scales. However, VIIRS DT algorithm seriously overestimates the AOD loadings with 18–62% of the collections falling above the EE, especially for summer. In contrast, it exhibits a higher accuracy in winter with lower MAE ~ 0.110, RMSE ~ 0.171 and RMB ~ 1.007 errors than other three seasons.

There are 755, 559, 758 and 292 effective collections obtained from MYD04 DT (QF = All) AOD product and they show overall increasing accuracies with decreasing MAE, RMSE and overestimation uncertainties for four seasons. However, although minimum observations, AOD retrievals agree well with AERONET AOD measurements with approximately 76.03% of them falling within the EE and low MAE ~ 0.078 and RMSE ~ 0.131 errors, causing only 4.4% overestimations in winter. After quality controls, the numbers of data collections obviously decreased to 539, 463, 415 for spring, summer and autumn, respectively, especially for winter, it reduced by more than 3 times and only 90 effective points are collected. With QF increasing, only the accuracy in spring increases, in contrast, the accuracies for summer, autumn and winter decreases and 35.42%, 44.10% and 72.22% of the collections meet the EE acquirements with increasing MAE and RMSE errors. In general, the DT algorithm significantly overestimates the AOD loadings with 39–63% of the collections falling above the EE in the spring, summer and autumn. However, it performs better with lower estimation errors but less AOD retrievals available in winter than other three seasons. Our results also show that QF controls do not work well for DT AOD products and is not suitable for aerosol analysis of seasonal variations in China.

We collected more AOD retrievals with a total numbers of collections of 999, 621, 989 and 1191 for four seasons from MYD04 DB product than MYD04 DT product, but overall less than VIIRS EDR product. MYD04 DB AOD retrievals show overall high accuracies with approximately 66.47%, 57.17%, 70.68% and 62.72% of the collections falling within the EE for spring, summer, autumn and winter, respectively. With QF increasing, the numbers of data collections reduce to 810, 382, 781 and 908 and the data qualities of AOD retrievals obviously increase with 70.86%, 60.21%, 74.39% and 67.18% of the collections meeting the EE requirements with low MAE (0.096–0.145), RMSE (0.135–0.256), RMB (0.979–1.145) for four seasons, respectively. However, the MYD04 DB algorithm performs worse in summer than other three seasons mainly due to the effects of disturbance of vegetation changes. In general, MYD04 DB AOD product shows similar accuracy to VIIRS and MYD04 DT products in winter but performs much better in other three seasons.

3.5. How do surface reflectance and quality assurance affect aerosol retrieval accuracy

To quantitatively explore the sensitivity of AOD variations to land

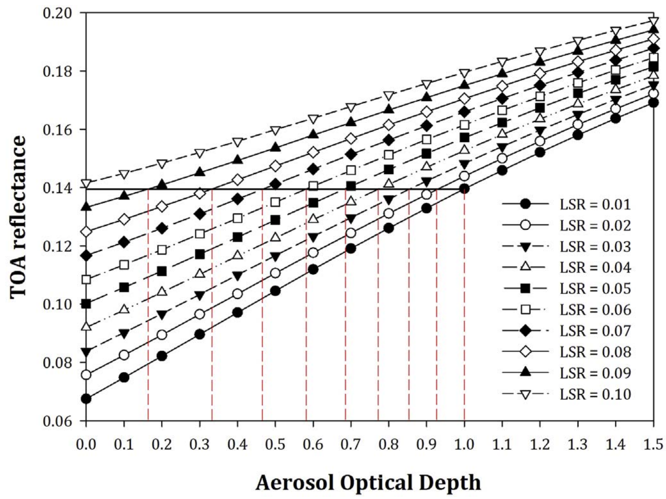

Fig. 6. Sensitivity of AOD to TOA reflectance in the blue band (0.47 μm) under different surface conditions.

surface types, we simulated the relationships between AOD and top-of-atmosphere (TOA) reflectance under wide range of surface conditions (0.01–0.10 at an interval of 0.01) using the MODIS blue channel (0.47 μm) through the MODTRAN (MODerate spectral resolution atmospheric TRANsmittance algorithm and computer model) (Fig. 6). In the simulations, we assume solar zenith angle, satellite zenith angle and relative azimuth angle as 20°, 10° and 100°, respectively. Previous studies showed that the blue-band LSRs are generally low with more than 90% of the pixels less than 0.10, indicating the simulated surface conditions can cover most surface types over land (Wei and Sun, 2017).

The strong linear relationship demonstrates that the TOA reflectance responds to an increase with increasing AOD variations. For dark target areas (i.e. vegetation, soil and water) with approximately LSR values less than 0.04 (Sun et al., 2016), the sensitivity of aerosol to change of TOA reflectance is overall high with large slopes ranging from 0.058 to 0.069 ($R^2 > 0.99$). The TOA reflectance received by the satellites comes from both atmosphere and surface and base on the atmospheric radiative transfer equation, TOA reflectance increases with decreasing LSRs, dominated by the atmospheric path reflectance. This is the foundation of the DT algorithm, thus, Kaufman et al., explores the stable and almost fixed relations between surface reflectance among visible and SWIR channels and realizes high-precision aerosol retrieval in dark target areas. Along with increasing LSR, especially for bright areas (i.e. urban, desert and bare land) with high LSR values greater than 0.07, atmospheric contribution to the TOA reflectance decreases and the influence of AOD changes on the TOA reflectance is decreasing with small slopes ranging from 0.038 to 0.048, complicating the AOD retrieval. However, the relationship demonstrates that the TOA reflectance still increase with the AOD increasing when the surface reflectance is much higher than that for the dark target surfaces, moreover, there is no stable relationships between visible and SWIR bands, which is the foundation of the DB algorithm (Hsu et al., 2004). Building a prior database using existed high-quality surface reflectance products to provide surface reflectance at visible wavelengths is the core content of the DB algorithm, which allows high-precision aerosol retrieval over bright areas. In general, the sensitivity of aerosol to TOA reflectance reduces by about 34% when the surface reflectance increases by 0.01. Moreover, our simulations also show that when the surface reflectance is low (< 0.04), 0.01 estimation errors can lead to less than 0.1 errors in AOD retrieval, however, with the increase of surface reflectance (> 0.07), with the same 0.01 estimation errors, the AOD retrieval error increases more than 0.15. Thus, it is no doubt that the accuracy of surface reflectance estimation is most crucial for AOD retrieval and it also better explains the accuracy difference between two different algorithms on different surface types.

The Run-Time Quality Assurance (QA) Plan over land for MODIS AOD products uses multiple individual QA tests to assess and estimate the overall quality confidence of the AOD retrievals. The QA test tasks mainly include the "semi-bright surface" test ($\rho_{2.11} > 0.25$), possible "thin cirrus" test ($\rho_{1.38} > 0.01$), "water" test, "fitting error" test ($\varepsilon > 0.25$), "Angstrom out of bounds" test and "sufficient number" test. The first five tests are applied to all quality flag results (QF = 0 to 3) to reduce the effects of bright surface, cloud pollution, inland water and abnormal data, which can effectively improve the data quality of AOD retrievals. However, the last test whether there is a sufficient number of non-screened pixels is the distinct rule for different data products (QF = 1, 2 and 3). If more than 50, 30, 20 and 12 pixels remain out of possible 120 pixels, then QF = 3, 2, 1 and 0 are assigned to the pixels, respectively. Moreover, retrieved AOD values less than 0.2 are also regard as QF = 3. Fewer pixels can suggest increasing marginal conditions in the retrieval box (Hubanks et al., 2012; Levy et al., 2010). Thus, after quality control, the numbers of collections decrease accordingly and the retrievals are expected to be more accurate. However, this study shows that the collections are reduced for QF = 3, but the overall data quality does not improve over both dark target and bright areas, indicating that the marginal conditions show certain but overall small effects on data quality and it can filter out a lot of normal retrievals. Moreover, because MYD04 DT algorithm is not applicable in bright surfaces, the suitable pixels in a retrieval box will greatly reduce after strict surface reflectance control, resulting in obvious decreasing retrieval results. Therefore, this approach is of little help for bright surfaces. This might be a possible reason that MYD04 DT products have poor spatial continuity and serious missing values (Wei and Sun, 2017; Tao et al., 2015). In contrast, due to improved estimation of surface reflectance, the DB algorithm allows aerosol retrieval over both dark target and bright surfaces, and needs no any pixel control in a retrieval box over bright areas. Therefore, the "sufficient number" test mainly reduces the effects of marginal conditions and increases the overall data quality with slightly reduced number of effective retrievals. Not surprisingly, the DB algorithm can produce more continuous and accurate AOD spatial distributions than DT algorithm over bright areas (Wei and Sun, 2017; Tao et al., 2015). Detailed product quality and retrieval processing of QF over land can be found in [Hsu et al., 2013].

For VIIRS AOD products, QA is first applied at IP AOD product based on several condition tests similar to MODIS AOD products and provide four quality flags including "Not Produced", "Excluded", "Degraded" and "Good". For these pixels with 1) Solar zenith angle > 80°; 2) Missing channel reflectance or ancillary model data (i.e. Precipitation, air temperature, ozone); 3) Cloud, snow/ice, fire, inland or coastal; 4) Bright surface over land with $NDVI_{SWIR} < 0.05$ and M11 > 0.3, they are not performed AOD retrieval as "Not Produced" quality. The "Excluded" quality means a pixel misses reflectance or brightness temperature over land or a retrieval is out of spec range [0, 2]. If an IP pixel satisfies the following requirements 1) solar zenith angle = [65°, 80°); 2) Not cloud, shadow, cirrus, or volcanic ash 3) $NDVI_{SWIR} \leq 0.2$ and 4) Residual > 0.05 when AOD > 0.5 over land, it is a "Degraded" quality. Other IP retrievals ranging from 0 to 2 are designated as "Good" quality. However, VIIRS EDR AOD is averaged based on the 8*8 IP AOD retrievals falling inside or outside of a threshold. It first discards the lowest 20% and highest 40% IP retrievals to avoid possible cloud contamination and shadows. If a retrieval is composed of less than 16 IP "Degraded" or "Good" quality pixels, then it is recorded as "Low" quality and if a retrieval is less than 16 IP "High" quality pixels and no fewer than 16 IP "Degraded" or "Good" quality pixels, then it is recorded as "Medium" quality. An EDR AOD recorded as "High" quality is averaged from greater than 16 available "Good" quality IP AODs (Jackson et al., 2013; Liu et al., 2013). More detailed information on VIIRS AOD product can be found from the Users Guide (http://www.star.nesdis.noaa.gov/smcd/emb/viirs_aerosol/documents.php). However, different from MODIS DT algorithm, "insufficient number" test along with all IP QF tests are applied to EDR AOD Quality assurance process. Thus, after quality controls, the number of retrievals can greatly reduce and the overall data quality is expected to be more accurate at most conditions, which is similar to the results reported in this study. However, due to limitations of DT algorithm itself and its surface reflectance control in the pixel selection over bright surfaces, QA shows little even opposite effects on its accuracy over such areas.

4. Conclusions

Aqua–MODIS (MYD04) Collection 6 (C6) AOD products at 10 km spatial resolution and VIIRS Environmental Data Record (EDR) AOD products at 6 km spatial resolution for different Quality Flags (QF) are obtained and validated against AEORNET AOD measurements from 22 sites in China from 2013 to 2016. Results show that the VIIRS Dark Target (DT) algorithm retrieves about 2.3 and 1.4 times more AOD retrievals than that of MODIS DT and Deep Blue (DB) algorithms over China. Both the VIIRS and MODIS DT AOD retrievals exhibit poor agreements with AERONET AOD with only 39.78% and 49.05% of the AOD collocations falling within the Expected Error (EE), respectively. This indicates that these AOD product do not meet the requirements of the EE, i.e., the percentage of retrievals is less than the 68% as reported by Levy et al. (2013). However, the DB AOD retrievals well agreed with AERONET AOD measurements ($R = 0.935$) at most of the sites and 64.89% of the retrievals fall within the EE with low MAE ~ 0.125 and RMSE ~ 0.217 errors, but significantly underestimate the AOD over the Pearl River Delta region. After quality controls, the overall quality of the retrievals increased for the DB product, but not for the DT product, especially over urban areas mainly due to the quality assurance process and the limitations of the algorithm. It is no doubt that the VIIRS EDR and MODIS DT algorithms work better over vegetated areas, but they have much poorer performances over urban areas than the MODIS DB algorithm. Moreover, VIIRS and MODIS DT algorithms perform overall better in the winter than other three seasons but with the fewest retrievals, yet DB algorithm performs slightly worse in summer with lower data quality than other three seasons mainly due to the disturbance of vegetation change in growing seasons. In general, for quantitative aerosol research and applications in China, it is recommended to use the high-quality ($QF \geq 2$) AOD retrievals for the DB product, in contrast, QF is not an useful and right diagnostic approach for VIIRS EDR and MYD04 DT AOD products, especially for the typical urban areas.

This study first comprehensively validates and analyzes the performance of current two typical operational VIIRS and MODIS aerosol products. Then we reveal the limitations and applicability of different aerosol retrieval algorithms over different land types and regions. This study provides a preliminary basis for a series of subsequent work in the future including 1) Improve the VIIRS aerosol retrieval algorithm and produce a more accurate VIIRS AOD product. 2) Develop an appropriate data fusion method to produce a more accurate merged MODIS AOD product with MODIS DT and DB AOD products, based on their respective algorithmic advantages, carefully considering the effects of surface types, seasonal variations and other factors. 3) Analyze the long-term trends of aerosol or air pollution based on produced or merged high-quality aerosol products in China.

Author contributions

J. Wei designed, conducted the research and wrote the manuscript. L. Sun, B. Huang, M., Bilal, Z. Zhang and L. Wang helped review the manuscript.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2017.11.048.

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