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Validation of multi-angle imaging spectroradiometer aerosol products in China

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ABSTRACT

Based on AErosol RObotic NETwork and Chinese Sun Hazemeter Network data, the Multi-angle Imaging SpectroRadiometer (MISR) level 2 aerosol optical depth (AOD) products are evaluated in China. The MISR retrievals depict well the temporal aerosol trend in China with correlation coefficients exceeding 0.8 except for stations located in northeast China and at the Lanzhou site. In general, the MISR AOD retrievals agree well with ground-based observations for AOD < 0.5. The retrievals are systematically underestimated for AOD > 0.5 in the east, southwest and northeast regions of China. Concerning surface types, the greatest underestimations occur in farmland and forest ecosystems. The largest and smallest biases are seen in spring and in summer, respectively. The systematic underestimation seems to stem from the use of too high single scattering albedos ~0.96 which is significantly higher than those estimated from ground-based observations. Further improvements to the MISR aerosol algorithm, especially in the aerosol model, are recommended.

1. Introduction

The Multi-angle Imaging SpectroRadiometer (MISR) is a unique sensor that measures upwelling short-wave radiance from the Earth in four spectral bands (446, 558, 672 and 866 nm), and at each of nine view angles (nadir and at 70.5°, 60.0°, 45.6°, 26.1° forward and aftward of the nadir). Validation of MISR data have been widely carried out. Diner et al. (2001) first compared MISR aerosol optical depths (AODs) with surface-based instruments during the SAFARI-2000 dry season campaign. The AOD values obtained from MISR data over desert sites were consistent with ground-based observations, indicating the good quality of MISR retrievals over surfaces with high reflectance (Christopher and Wang, 2004; Martonchik et al., 2004). Notable underestimation of MISR AODs in the Beijing area was observed, especially when aerosol loadings are high (Jiang et al., 2007). These results indicate that the aerosol products from MISR as well as others (e.g. MODIS) over China should be further investigated because of the large spatial and temporal changes in aerosol optical properties over this part of the world (Eck et al., 2005; Li et al., 2007a; Xia et al., 2007a, b; Papayannis et al., 2007).

Ground-based aerosol observation networks have been established in China, such as the AErosol RObotic NETwork (AERONET) and the Chinese Sun Hazemeter Network (CSHNET; Holben et al., 1998; Xin et al., 2007) established under the East Asian Study of Tropospheric Aerosols, an International Regional Experiment (EAST-AIRE) (Li et al., 2007b), and the China Meteorological Administration Sunphotometer Network. The data are widely used to study aerosol properties, radiative forcing, and validation of satellite products (Lee et al., 2007; Li et al., 2007a; Xia et al., 2007a). Overall validation of MODIS aerosol products have been carried out in China, and comparisons indicate that substantial improvement is found in the Collection 5 AOD product relative to the Collection 4 AOD product, with the correlation coefficient of regression with ground measurements increasing from 0.66 to 0.84 and the slope improving

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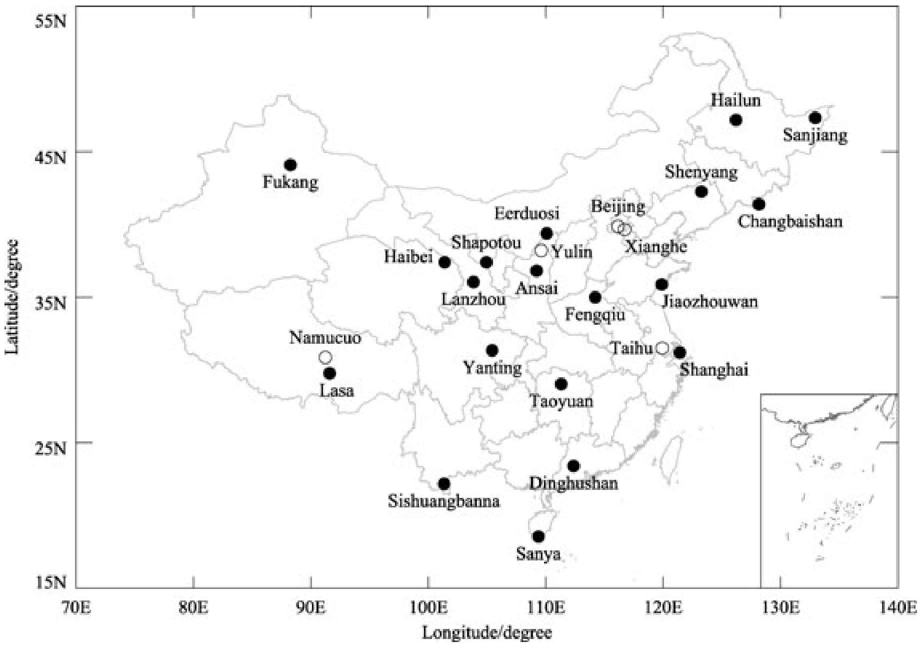

Fig. 1. Geographical locations of the Chinese Sun Hazemeter Network (CSHNET) and AERONET sites. The solid and hollow circles represent the sites of CSHNET and AERONET, respectively.

from 0.74 to 0.98 for all data points (Li et al., 2007a; Wang et al., 2007). Similar validation of MISR data is still limited. This study aims to evaluate the MISR aerosol products over China.

2. Data and methodology

The ground-based aerosol data used in the analysis include CSHNET data from August 2004 to April 2006, and AERONET level 2 data from Beijing, Xianghe, Taihu and Yulin stations (See Fig. 1). Note that AERONET level 2 data has an accuracy of 0.01–0.02 (Eck et al., 1999). The CSHNET was established in August 2004 and includes 25 stations distributed across China representing some typical ecosystems. The network also includes four urban sites, two instrument calibration centres, and one data collection/processing centre. The sun hazemeters were manufactured by the United States Department of Agriculture Forestry Service and has been used to estimate AOD (Hao et al., 2005; Xin et al., 2007). Langley plot and transfer calibration methods were used for calibrating the sun hazemeters, and the mean difference between CSHNET and AERONET is about 0.04 (Xin et al., 2007). The sun hazemeters are used and daily continuous measurements of aerosol optical depths at three wavelengths (405, 500 and 650 nm) have been made since August 2004.

The MISR level 2 aerosol data were obtained from the Atmospheric Sciences Data Center at the NASA Langley Research Center (http://eosweb.larc.nasa.gov). The MISR spatial sampling ranges from 275 m to 1.1 km. Radiometrically calibrated, geo-located radiances at 1.1-km resolution are used to derive empirical orthogonal functions representing the angular shape of the surface signal within a 17.6×17.6 km^2 area. This procedure requires surface spatial contrasts but does not invoke assumptions about the absolute surface reflectance or its spectral characteristics (Martonchik et al., 2002). Due to the narrow swath width of the sensor compared to MODIS, global coverage can be obtained only every 7–9 d. The MISR level 2 AOD products on Terra have a spatial resolution of 17.6×17.6 km^2, and include the AOD at 0.558 μm with an expected accuracy of 0.05 or 20% for aggregated data set, including a preponderance of low-AOD cases, especially over ocean (Kahn et al., 2005). Discrepancies tend to be larger over bright surfaces, such as deserts and urban areas, than dark ones (see table 5 of Kahn et al., 2005).

To ensure temporal and spatial consistencies, ground-based data are averaged within 1 h of the satellite overpass time, and the associated satellite data are averaged within 30×30 km^2 regions centered on the ground station. Because of the remarkable changes in local aerosols that can occur within 2 h under unstable air conditions, the following constraints are employed to diminish the errors in the validation of MISR aerosol products: (1) two ground-based observations around ± 1 h are needed, and the standard deviation must be smaller than 0.05. Note that there is little physical meaning if the numbers of samples are less than 3, so when there are just two observations, the difference of the two observations is less than 0.2. (2) At least two samples of satellite data are required. (3) All sunphotometer data are interpolated to 558 nm to compare with MISR AOD at 558 nm.

Table 1. Comparisons of MISR aerosol optical depth (AOD) at 558 nm with ground-based measurements (SFC) made at all CSHNET and AERONET stations (labelled by asterisk)

Region	Province	Site	N	MISR AOD	SFC AOD	RME (%)	R	RMSE	Slope	Offset	Value within 0.05 or 20%	α
Northwest	Xinjiang	Fukang	45	0.21	0.20	3.5	0.95	0.04	1.00	0.00	82.2	0.97
	Neimeng	Eerduosi	36	0.20	0.19	15.7	0.71	0.08	0.90	0.04	66.7	0.65
	NingXia	Shapotou	19	0.30	0.34	−9.2	0.64	0.08	0.56	0.11	52.6	0.63
	Gansu	Lanzhou	8	0.26	0.46	−42.5	0.64	0.23	0.50	0.03	25.0	1.00
	Shanxi	Yulin*	21	0.28	0.29	6.6	0.90	0.08	0.79	0.06	66.7	0.84
	Shanxi	Ansai	9	0.16	0.21	−24.0	0.61	0.08	0.51	0.05	44.4	1.33
Qinghai-Tibet Plateau	Qinghai	Haibei	16	0.10	0.09	42.0	0.82	0.03	0.83	0.03	93.8	1.13
	Xizang	Lasa	11	0.10	0.10	−5.0	0.84	0.03	1.19	−0.02	90.9	0.30
Northeast	Heilongjiang	Hailun	22	0.22	0.15	51.5	0.57	0.15	1.47	0.00	27.3	1.78
	Heilongjiang	Sanjiang	20	0.13	0.15	−4.2	0.59	0.06	0.54	0.05	65.0	1.25
	Jilin	Changbaishan	19	0.09	0.09	11.9	0.72	0.03	0.57	0.04	89.5	2.05
	Liaoning	Shengyang	29	0.22	0.36	−29.6	0.55	0.22	0.30	0.11	17.2	1.08
Northern China	Beijing forest	Beijing	25	0.14	0.20	−31.7	0.98	0.08	0.78	−0.01	60.0	0.77
	Beijing City	Beijing*	60	0.25	0.29	−1.5	0.95	0.11	0.66	0.06	78.3	1.08
	Hebei	Xianghe*	49	0.23	0.24	15.9	0.93	0.09	0.71	0.06	65.3	1.09
	Henan	Fengqiu	14	0.31	0.39	−22.8	0.95	0.10	0.92	−0.05	50.0	1.15
Eastern China	Shandong	JiaozhouB	22	0.42	0.57	−26.9	0.96	0.19	0.70	0.02	22.7	1.13
	Jiangsu	Taihu*	12	0.44	0.50	−10.9	0.90	0.11	0.69	0.09	58.3	1.28
	Shanghai	Shanghai	10	0.36	0.41	−14.8	0.90	0.10	1.07	−0.08	50.0	1.06
Middle China	Hunan	Taoyuan	13	0.46	0.57	−15.0	0.80	0.18	0.61	0.12	38.5	1.10
Southwest	Sichuan	Yanting	4	0.49	0.62	−16.7	0.97	0.19	0.76	0.02	50.0	1.24
	Yunnan	Xishuangbanna	13	0.20	0.33	−36.5	0.93	0.15	0.53	0.03	15.4	1.67

Notes: N is the number of samples; RME is the relative mean error [(MISR-SFC)/SFC]; R is the correlation coefficient; RMSE is the root mean square error; slope and offset are the slope and y-intercept of the linear regression, respectively; α is the Ångström exponent (CSHNET: 405, 500 and 650 nm, AERONET: 440–675 nm).

Table 2. Monthly means of aerosol optical depth (AOD) for Beijing from MISR and from AERONET for the same time interval from July 2004 to June 2006

	1	2	3	4	5	6	7	8	9	10	11	12
MISR AOD	0.19	0.17	0.36	0.32	0.48	0.63	0.41	0.39	0.42	0.34	0.16	0.16
AERONET AOD	0.61	0.49	0.55	1.02	0.88	0.89	0.65	0.67	0.64	0.58	0.51	0.36

3. Results

Statistical results regarding coincident and colocated MISR AODs and surface measurements made at all CSHNET and AERONET stations are listed in Table 1. AODs retrieved from MISR and AODS derived from ground-based data are well correlated in most regions of China, with correlation coefficients exceeding 0.9 in the northern, southwestern, and eastern parts of China. The regression slopes are generally less than 1, especially for data from the east and southwest parts of China, indicating that MISR retrievals are lower than ground-based observations. Fifty-five percent of MISR AOD values fall within the expected accuracy of 0.05 or 20% of ground-based observations, similar to the finding of Kahn et al. (2005). Note that the slope and intercept of the regression relation from Fukang in northwest China are 1.00 and 0.00, respectively, with 82% of data within the MISR AOD estimated error. The monthly means computed from MISR often result in significant underestimation compared to AOD from AERONET (See Table 2). Besides of the physical limitation of MISR 7–9 d revisit period resulting that the monthly means of MISR could not depict well the real AOD values of one's region, another important reason is MISR does not retrieve AOD values in regions where high aerosol concentrations occur frequently.

The surface types are classified as follows in order to investigate the applicability of MISR aerosol products over different surface types: urban (Beijing and Shanghai), forest (Beijing Forest, Xishuangbanna and Changbaishan), farmland (Ansai, Lasa, Fengqiu, Shenyang, Taoyuan and Yanting) and desert (Fukang, Shapotou, Eerduosi and Yulin).

Figure 2 shows AOD comparisons for the four different surface types. A systematic underestimation of MISR AOD is seen at urban sites when the ground-based AOD values are larger than 0.5; a similar underestimation is also seen at the forest and farmland sites when AODs are greater than 0.3. There is no systematic variation in MISR AOD values at desert sites which is consistent with the conclusions of Christopher and Wang (2004). Figure 3 illustrates the variations of AOD for the four different surface types from 2004 to 2006. Overall, the temporal variation of MISR AODs and ground-based measurements of AOD agree well although some differences exist. MISR AODs are considerably lower than AODs derived from ground measurements at

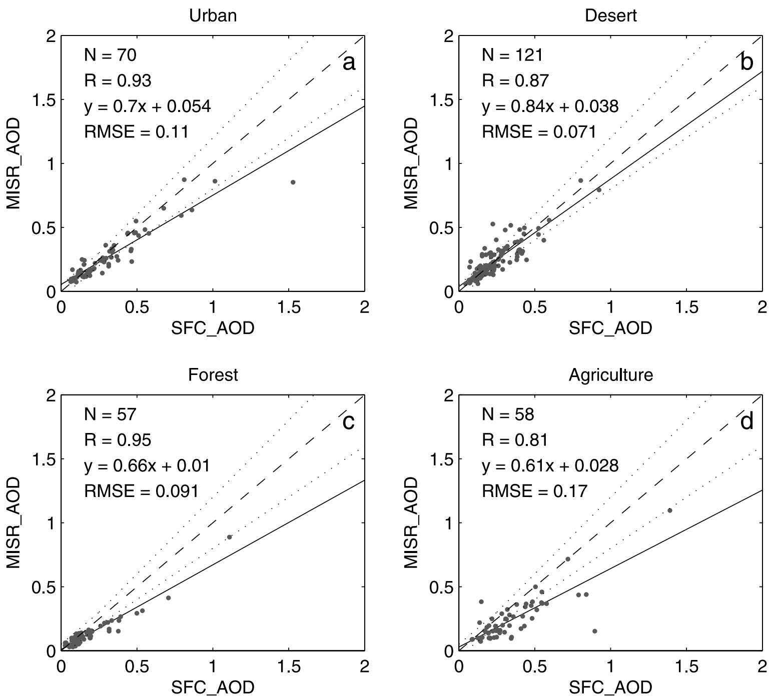

Fig. 2. MISR aerosol optical depth (AOD) at 558 nm as a function of ground-based measurements for different surface types. AODs with α greater than 0.75 are shown as dots; AODs with α less than 0.75 are shown as plus signs (Liu et al., 2004). Note that α is the Ångström exponent measured by sunphotometer (CSHNET: 405, 500 and 650 nm, AERONET: 440–675 nm).

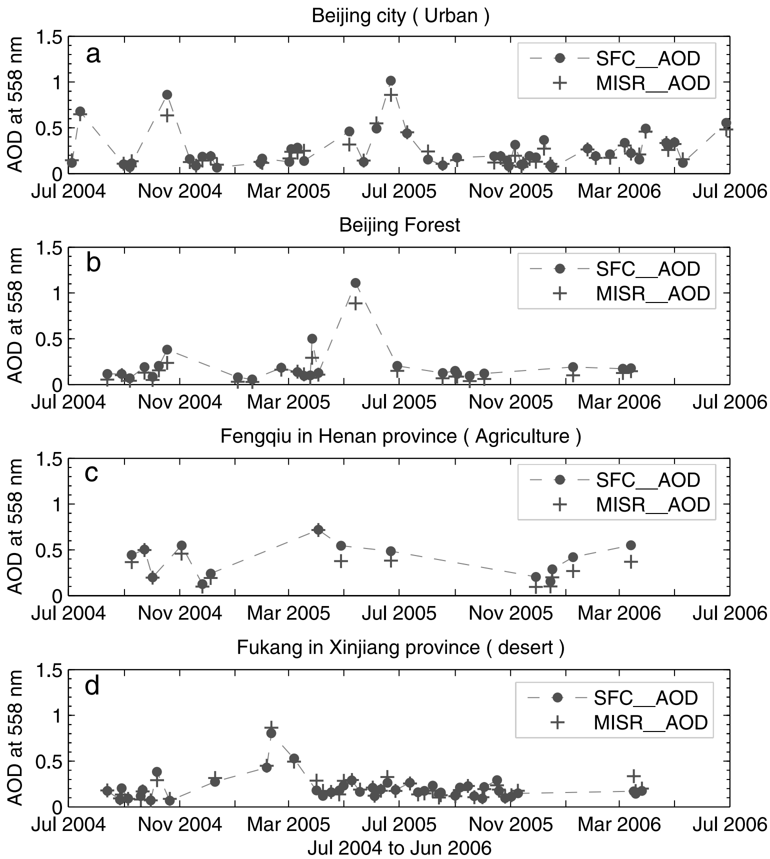

Fig. 3. Time series of aerosol optical depth (AOD) at 558 nm retrieved by MISR and ground-based observations from July 2004 to June 2006.

Beijing, Beijing Forest and Fengqiu. The best agreement between MISR-retrieved AODS and ground measurements is seen at the desert site. Figure 4 shows MISR AODs as a function of AODs derived from ground measurements for the four seasons. Overall, MISR retrievals are still well correlated with observations. Correlation coefficients are all greater than 0.80, again demonstrating the good quality of MISR aerosol products for depicting the temporal variation of aerosols. Based upon statistics obtained for the four seasons, the accuracy of MISR AODs during the summer is the best; the RMSE, slope, and offset are 0.08, 0.84 and 0.028, respectively. Systematically underestimated MISR AODs are seen when AODs are greater than 0.5 during the autumn. The greatest differences between MISR and ground-based AODs occur in the winter when 50% of the data fall within the MISR expected error.

4. Discussion

Even though 55% of the data points in China fall within the MISR expected error similar to that found by Kahn et al. (2005) for global aggregated values, it ranges from 17 to 94% for individual stations. When AODs are greater than 0.5, most MISR aerosol retrievals in china are underestimated, which is consistent with results from India (DiGirolamo et al., 2004). Similarly, Ichoku et al. (2003) showed this issue of the sensitivity of AOD retrieval to the assumed SSA at high AOD from MODIS data. This led Levy et al. (2007) to use SSA derived from AERONET in refined regional maps for MODIS C005 retrievals. The MISR AOD underestimation seems to be greatest when observing forest or urban pollution aerosols, and is smaller or non-existent for desert dust situations over China. The observed SSA for desert dust in field measurements is close to that used for the desert dust optical model in the MISR Standard retrieval algorithm climatology (Kalashnikova and Kahn, 2006). However, as noted in this paper and in previous MISR publications, there is a lack of spherical, absorbing particles in the current algorithm climatology that would be optical analogs for biomass burning or urban pollution aerosols in China. Sensitivity to retrieving particle SSA in the MISR data is unfortunately limited and SSA generally varies considerably with time and location. Our finding suggests that it is essential to improve the MISR aerosol algorithm for application to data over China in order to address the systematic underestimation of AOD throughout most of that country. The current MISR aerosol algorithm approach uses the same set of component aerosol particles and mixtures for the entire, global data set. Although regionally specific aerosol particle assumptions could be introduced (as MODIS does over land), this could also introduce other biases in the resulting

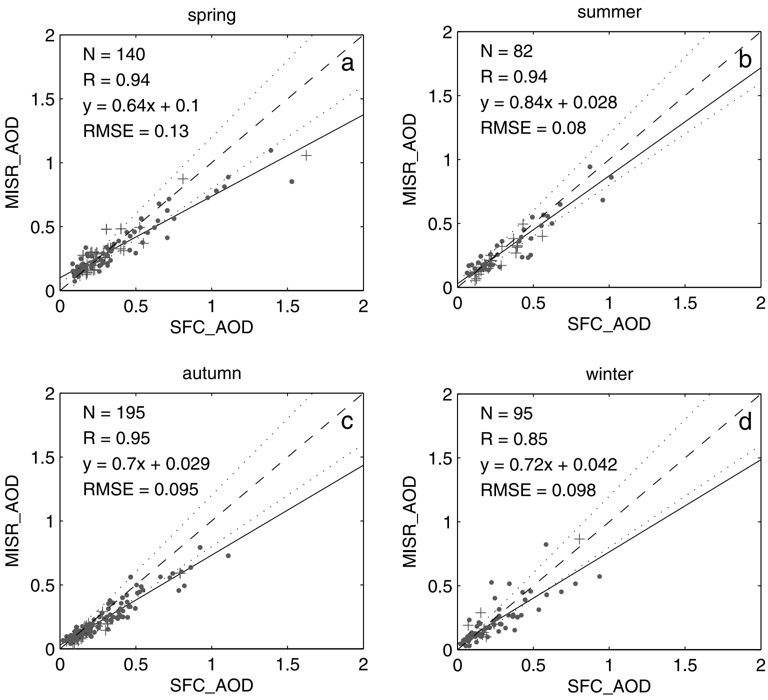

Fig. 4. Same as Fig. 2 but for different seasons.

MISR aerosol products, especially important for large-scale and long-term trend studies.

One approach would be to allow more absorbing particles only at locations and times where smoke or urban pollution are expected from model simulations (Chen et al., 2008). Alternatively, one may use a climatology of the SSA as derived by Lee et al. (2007) derived from a combination of satellite reflectance measurements and ground-based transmittance measurements made across China. A comparison of MISR-retrieved and ground-based estimated SSA was made and results are presented in Fig. 5. Note that the wavelengths of SSA retrievals from MISR and ground-based observations are at 558 and 550 nm, respectively. The aerosol models from OPAC 3.1 (Hess et al., 1998) are for the sensitivity analysis of the SSA retrieval from CSHNET sites (Lee et al., 2007). After radiative transfer calculations, the radiances were computed at TOA as measured by MODIS and at surface as measured by the CSHNET, from which SSA are estimated following their retrieval scheme as illustrated in their diagram 2. Such tests were repeated for different aerosol and atmospheric conditions. The differences between the retrieval and model true values are regarded as retrieval uncertainties. The uncertainties in SSA retrievals are 0.02–0.03 for AOD = 1.0 and 0.03–0.05 for AOD = 0.5 at 0.47 μm. The SSA values at 550 nm retrieved from CSHNET sites range between 0.81 and 0.96. MISR SSAs are systematically larger, all greater than 0.96. It is noted that at Yulin site in northwest China the very large

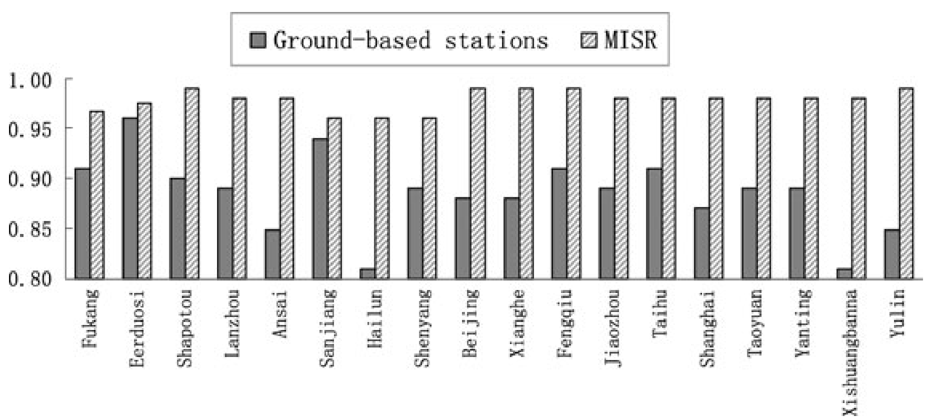

Fig. 5. Comparisons of MISR single scattering albedos at 558 nm with ground-based retrievals at 550 nm from AERONET and Lee et al. (2007). AERONET sites include Beijing, Xianghe, Taihu and Yulin, and its SSA at 550 nm is interpolated from the 440 and 675 nm retrievals.

differences of SSA in MISR (∼1.00) and AERONET (∼0.85) suggest that compensating errors (wrong SSA combined with possibly erroneous surface reflectance) have resulted in the fortuitous result presented in Table 1 (The correlation coefficient are greater than 0.9, and the mean biases are ∼0.01). Thus even some cases where AOD agreement is good may have occurred for reasons other than a physically robust retrieval. AERONET retrievals at 550 nm from Beijing, Xianghe, Taihu and Yulin are 0.88, 0.88, 0.91 and 0.85, respectively, while the corresponding MISR SSA values are greater than 0.97. The higher SSA values used in the MISR aerosol algorithm throughout most of China appear to be the primary cause for the underestimation of AOD, thus further investigation should be warranted (Levy et al., 2007).

5. Conclusions

Using ground measurements made at CSHNET and AERONET stations, MISR aerosol products over China were evaluated with regard to geographic location, surface type, and season. The results are as follows:

MISR aerosol products can properly depict the temporal trend of aerosols over most of China with linear correlation coefficients exceeding 0.9 in the northern, southwestern, and eastern parts of China. At the desert sites (Fukang) in northwest China where any conventional dark-surface algorithm fails, the correlation coefficients are greater than 0.9, and the mean biases are ∼0.01. Both C004 and C005 versions of the MODIS aerosol product tend to overestimate AOD over deserts/semideserts, tend to underestimate AOD over forests, and are more accurate over agricultural and suburban sites. The poorest retrievals occur over urban areas (Li et al., 2007a,b). This demonstrates that the MISR aerosol products are robust over bright surfaces when dust aerosols predominate and can thus complement aerosol retrievals from other satellites.

On the other hand, however, the MISR AOD product over China tends to be underestimated and the underestimation generally increases with increasing aerosol loading. For AOD $<$ 0.5, the majority of AOD retrievals fall within the expected range of uncertainty. The underestimation is more pronounced in the east, southwest and northeast of China than other parts, and also better in summer than in winter. A comparison of the aerosol single scattering albedo used in the MISR algorithm for the region ($>$0.96) is substantially larger than those estimated from ground-based measurements (CSHNET and AERONET). It is thus recommended to revise the single scattering albedo in the MISR retrievals to improve the retrieval accuracy of AOD in this region.

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