Aerosol Optical Depth investigated with satellite remote sensing observations in China

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Abstract. In this study, Aerosol Optical Depth (AOD) at 550nm from the MODIS sensor on board the Terra/Aqua satellites were compared with sun photometer (CE-318) measurements from 11 AERONET stations in China. The average correlation coefficient (R) value from the AOD product, using the Aqua-MODIS Deep Blue algorithm, in the Hexi Corridor was 0.67. The MODIS Dark Target algorithm AOD product is superior to Deep Blue algorithm AOD products in SACOL of the Semi-arid regions of the Loess Plateau. These two kinds of algorithm are not applicable to sites in Lanzhou city. The average R value of Dark Target algorithm AOD MODIS products is 0.91 for Terra and 0.88 for Aqua in the eastern part of China. According to the analysis of spatial and temporal characteristics of the two MODIS AOD products in China, high value areas are mainly distributed in the southern part of Xinjiang (0.5~0.8), Sichuan Basin (0.8~0.9), North China (0.6~0.8) and the middle and lower reaches of the Changjiang River (0.8~1.0). The Deep Blue algorithm for Aqua-MODIS is a good supplement for the retrieval of AOD above bright surfaces of deserts in Northwest China.

1. Introduction

As an important factor affecting the climate, aerosol has a major impact on the atmospheric radiation budget, cloud microphysics process, and air quality. Due to uneven aerosol spatial distribution and shortage of global aerosol observational data, the studies on the aerosol radiation forcing effect have large uncertainties[1]. Of all the parameters that describe atmospheric aerosol physical characteristics, AOD is the important one that describes the characteristics of atmospheric aerosol extinction. The definition of AOD is the diminishing of the total solar radiation caused by aerosol absorption and scattering along the radiation transmission path at unit cross section. Related to the total atmospheric column, the total aerosol concentration in the vertical direction is of great importance in projections of aerosol content and in studies on aerosol climatic effects[2-4].

Atmospheric aerosol is a focus of global change monitoring and research. The current aerosol optical depth detection relies mainly on ground-based observations and satellite remote sensing. With high local precision, the data from ground-based observations can be used to test satellite remote sensing data. Satellite remote sensing can provide broadly based aerosol distribution data, and carry out wide-range, high-spatial resolution, and multi-channel remote sensing monitoring. With the application of MODIS on Terra and Aqua satellites, there has been further work on global aerosol remote sensing and monitoring[5-7]. Sundar et al.[8] used satellite remote sensing and ground-based observations to analyze Sahara dust aerosol. Cachorro et al.[9] used AERONET and MODIS data over several years to conduct a comparative study on the change characteristics of the atmospheric aerosol in the southwestern part of Spain. Xie et al.[10] used CARSNET data to compare and verify the applicability of MODIS aerosol products in China. Yu et al.[11] used AERONET aerosol observation data over several years for analysis and concluded that aerosol optical properties in Beijing show significant seasonal variations, such as frequent dust in winter and serious pollution in spring.

This study used AERONET sun photometer data at 11 stations in China to compare and validate MODIS AOD Level 2 product data, to analyze the merits and demerits of AOD products from two satellites using different algorithms and applicable areas in China. Using Terra/Aqua MODIS AOD data to further analyze AOD spatial distribution characteristics, we provide a reference for a comprehensive understanding of aerosol distribution in China.

2. Data and Observation sites

2.1. MODIS data

MODIS is the main sensor in Terra (EOS-AM) and Aqua (EOS-PM) sun-synchronous polar orbit satellites. The MODIS detector covers the Earth once a day, providing 36-channel detection data spanning 0.41-14.4μm, with a scan width of 2330 km. With the continuous improvement of the algorithm, the version of the MODIS aerosol products has been updated to level C5[12]. Levy et al.[13, 14] have made significant modifications to the aerosol inversion algorithm on the basis of level C4[15] data mainly in surface albedo, aerosol model, and aerosol lookup table. It has been verified that level C5 AOD is closer to the ground-based observations[16, 17]. Hsu et al.[18] pointed out that for areas with a bright surface such as an arid area, desert, and the Gobi, the blue waveband (i.e <0.5μm) has a smaller surface albedo. It is therefore appropriate to use the blue waveband channel to calculate the surface albedo and retrieve the aerosol optical depth. This is known as the Deep Blue algorithm.

The study used the MODIS Level 2 aerosol product dataset (C5) released by NASA from the Terra and Aqua satellites, with a spatial resolution of 10km×10km. The object area was 70°E - 135°E and 15°N - 55°N. Specific MODIS AOD product data are shown in Table 1. As for the northwest desert with its bright surface which lacks measurements, aerosol product data using the Deep Blue algorithm from the Aqua-MODIS satellite were used.

Table 1. MODIS aerosol optical depth product data

Satellite	Time (a)	Arithmetic	Products	Wave (nm)
Terra	2001-2010	Dark Target	Optical_Depth_Land_And_Ocean	550
Aqua	2003-2010	Dark Target	Optical_Depth_Land_And_Ocean	550
Aqua	2003-2010	Deep Blue	Deep_Blue_Aerosol_Optical_Depth_550_Land	550

2.2. Sunphotometer data

AERONET is a ground-based global observation network established by NASA and its partners using the sun photometer (CE-318) produced by the French CIMEL Company.

The AERONET released inversion products of AOD that have undergone rigorous calibration, cloud mask processing and sensitivity standard decision control[19]. The precision of the retrieved AOD is 0.01-0.02[20]. The retrieved AOD has been taken by scientists as the true ground-based observation value of aerosol characteristics, and therefore can be used to test the retrieved satellite AOD values. Table 2 indicates AERONET stations in China to be validated. We selected those

AERONET data that have completed Level 2.0 aerosol products for cloud testing and quality inspection, and we inverted 440nm and 675nm AOD into 550nm AOD according to formula (1) to allow comparison with MODIS-AOD product data.

- $$\tau_{\lambda} = \beta\lambda^{-\alpha} \quad (1)$$

in which, τ_{λ} is AOD at wavelength as λ, β is the turbidity coefficient (Generally 0-0.5, $\beta \leq 0.1$ represents clean weather, $\beta \geq 0.1$ represents relatively cloudy weather[21]), and α is the Ångström exponent.

Table 2. Geographic information in each AERONET site

Areas	Site Name	Lon (°E)	Lat (°N)	Altitude (m)	Observing period
Hexi corridor	Zhangye	100.276	39.079	1461	Apr, 2008-Jun, 2008
	Minqin	102.959	38.607	1373	May, 2010-Jun, 2010
	Jingtai	104.100	37.333	1604	Feb, 2008-May, 2008
Semi-arid of Loess Plateau	SACOL	104.137	35.946	1965	Aug, 2006-Oct, 2008
	Lanzhou_City	103.853	36.048	1516	Oct, 2009-Mar, 2010
North of China	Beijing	116.381	39.977	92	Apr, 2002-Oct, 2010
	Xinglong	117.578	40.396	970	Feb, 2006-Jul, 2010
	Xianghe	116.962	39.754	36	Sep, 2004-Aug, 2010
The middle and lower reaches of Changjiang River	Taihu	120.215	31.421	20	Aug, 2006-Oct, 2008
	Hefei	117.162	31.905	36	Dec, 2007-Nov, 2008
	Shouxian	116.782	32.558	22	May, 2008-Dec, 2008

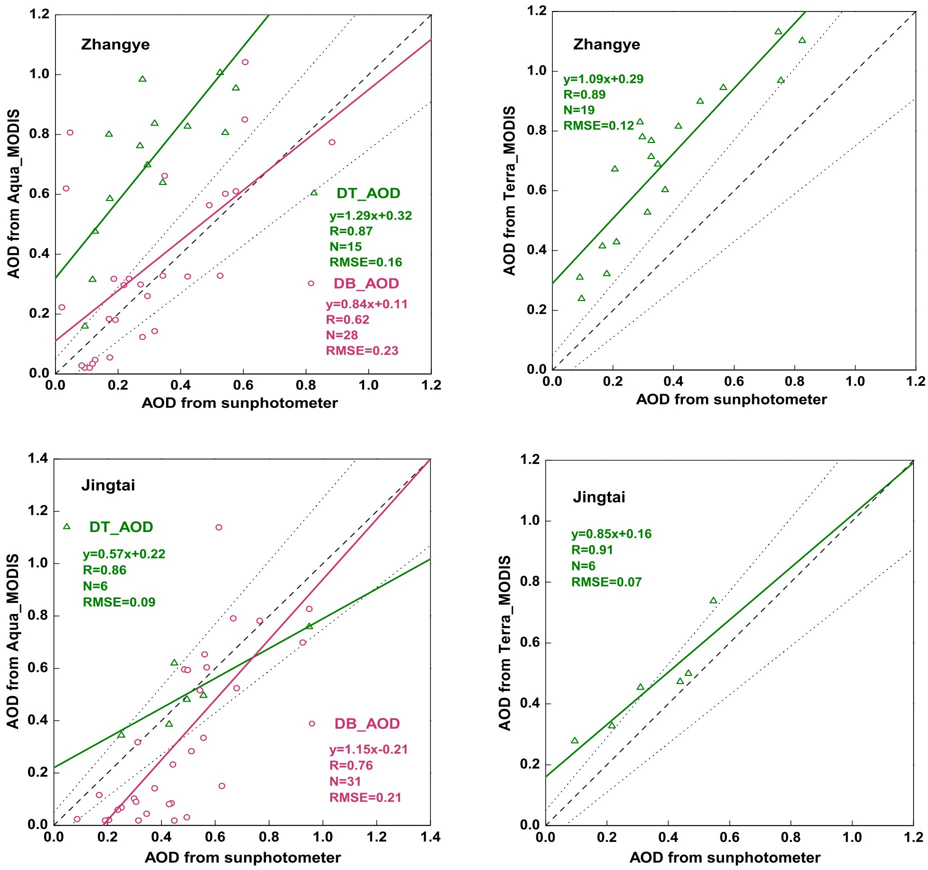
3. Results and discussion

The matching rule for Terra/Aqua satellite data and sunphotometer data comparison: (1) Take the sun photometer station as the center, invert the AOD average of MODIS within the range of 50 km × 50 km; (2) Invert the AOD average of sun photometer observations at the satellite transit time ± 30 min.

3.1. Comparison of the MODIS and sunphotometer data

3.1.1. Hexi corridor region sites

The Hexi Corridor is characterized by insufficient vegetation and high reflectivity of the underlying surface. The study simultaneously validated MODIS Dark Target algorithm and the Deep Blue algorithm. Figure 1 shows the comparison between sun photometers of various stations in the Hexi Corridor and Terra/Aqua MODIS Level 2 AOD products. The results show that the Aqua-MODIS Deep Blue algorithm retrieval of AOD products has more samples than the Dark Target retrieves, and the value of the correlation coefficient R is 0.6 or more, which better represents the change in atmospheric aerosol characteristics for the bright surface condition. The Jingtai Observation Station has the highest correlation coefficient of 0.76, followed by the Minqin Observation Station which had a correlation coefficient of 0.64. At the same time, there is a certain systematic deviation of inversion results. The AOD products retrieved with the MODIS Dark Target algorithm have insufficient samples and there are more AOD products than in the ground-based observations. The Minqin Observation Station is characterized by desert surface and lack of Terra-MODIS satellite data. The Zhangye Observation Station has a high correlation coefficient (0.87/Aqua and 0.89/Terra). However, the overestimated systematic deviation made the sample points beyond the range of error lines.



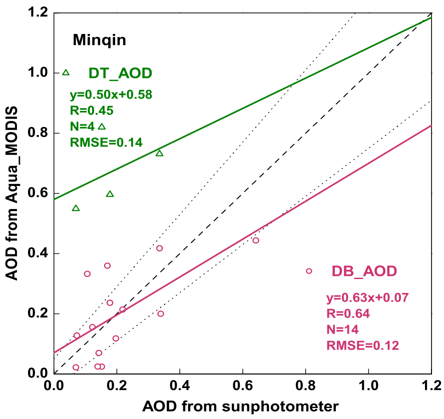


Figure 1. Scatterplots of AOD from MODIS versus sun photometer at sites in the Hexi corridor. Solid lines represent the fitting curve and the dotted lines are retrieval errors of $\Delta\tau = \pm 0.05 \pm 0.15\tau$. DT_AOD is the Dark Target algorithm sample. DB_AOD is the Deep Blue algorithm sample. N is data number and RMSE is standard deviation.

3.1.2. Semi-arid region of Loess Plateau sites

Figure 2 shows the comparison between sun photometers of two stations in the semi-arid areas of the Loess Plateau and the MODIS AOD. These two stations represent the suburbs (SACOL) and city (Lanzhou). Different underlying surfaces and aerosol types cause different results when comparing with MODIS AOD products. At SACOL, the comparison correlation coefficient is 0.75 for the Deep Blue algorithm AOD products. An AOD of less than 0.4 indicates that the MODIS AOD has underestimated the deviation from the Sun photometers AOD. The Terra MODIS Dark Target algorithm AOD comparison correlation coefficient is 0.69, better than the Aqua MODIS coefficient of 0.62, and most of the points fall within the error range line, indicating that the underlying surface is basically native vegetation. The Dark Target algorithm AOD products are applicable to SACOL which is not much affected by human activities. In the Lanzhou Observation Station, the results of the comparison between the two-algorithm AOD products are not satisfactory. The MODIS inversion product is about 0.3 less than the results of ground-based observations. This is possible because Lanzhou is an industrial city, significantly impacted by anthropogenic aerosol. The MODIS inversion AOD aerosol model selection showed a large error, indicating smaller MODIS inversion results in the case of serious aerosol pollution.

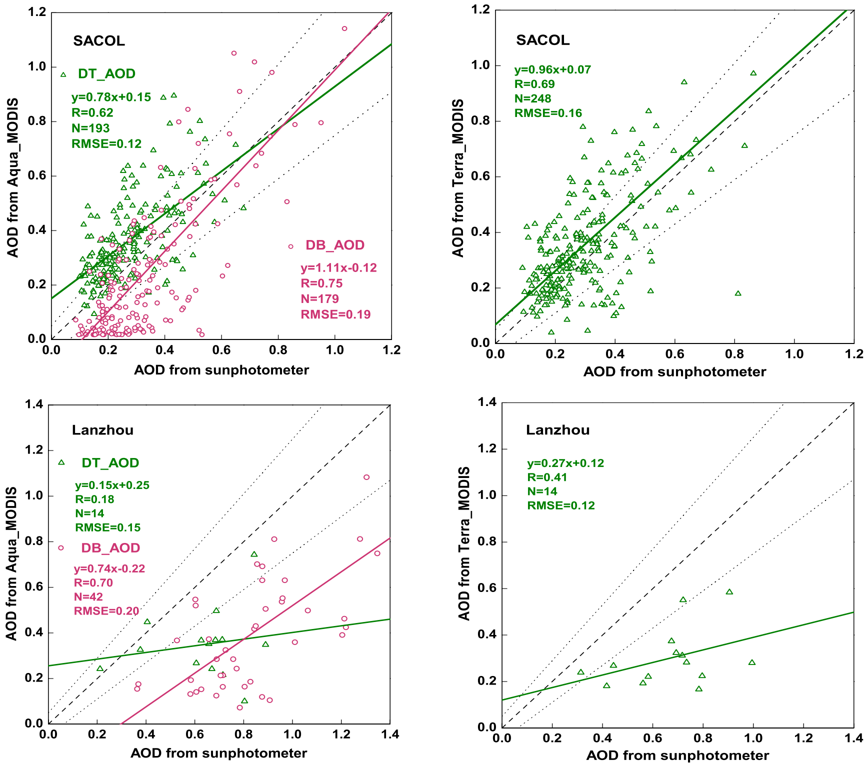


Figure 2. Scatterplots of AOD from MODIS versus sun photometers at sites in Semi-arid region of Loess Plateau. Solid lines represent fitting curve and the dotted lines are retrieval errors of $\Delta\tau = \pm 0.05 \pm 0.15\tau$. DT_AOD is Dark Target algorithm sample. DB_AOD is Deep Blue algorithm sample. N is data number and RMSE is standard deviation.

3.1.3. North China and the middle and lower reaches of the Changjiang River areas sites

Figure 3 shows the comparison between sun photometers of various stations and Terra/Aqua-MODIS AOD for sites in North and South China. The results show that the average correlation coefficient (R) between the Terra-MODIS AOD and ground-based observation stations is 0.91, and the average standard deviation (RMSE) is 0.14, better than the results of the Aqua-MODIS AOD (average R is 0.88, and average RMSE is 0.15), indicating that the Terra-MODIS AOD product data in Northeast China are closer to the ground-based observations. At the same time, Aqua as the afternoon satellite, also has good results, which can complement the changes of the aerosol optical depth.

Comparison of the correlation coefficients for different Observation Stations shows that values that span 0.87-0.95 lead to better results. In terms of error percentage, there is some systematic deviation. Taihu, Beijing and Hefei sites had significantly overestimated the deviation and the Xinglong site comparison results were ideal, indicating that the Dark Target algorithm is feasible under conditions of dense vegetation, fewer human activities, e.g. the Xinglong site. For cities with insufficient vegetation and complex underlying surfaces, such as Beijing and Hefei, the difference in comparison results is significant. It is mainly due to the inconsistency between the assumptions of the MODIS inversion algorithm's surface albedo estimation error and the aerosol model and the actual result.

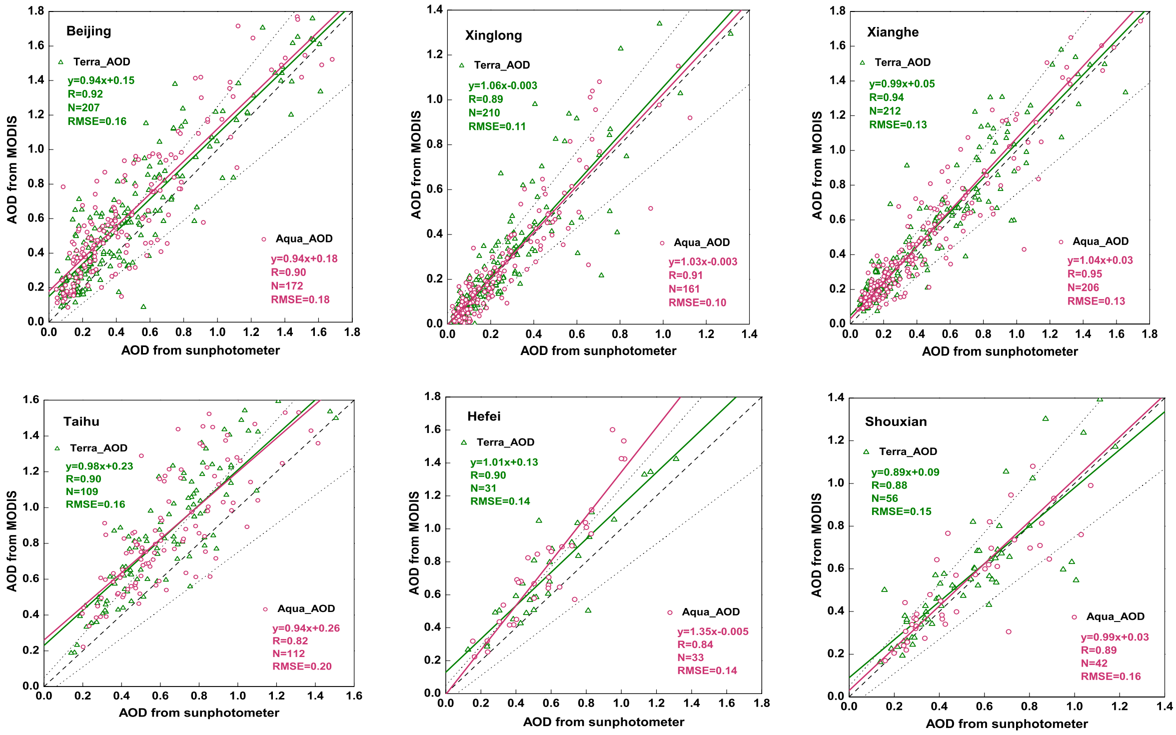
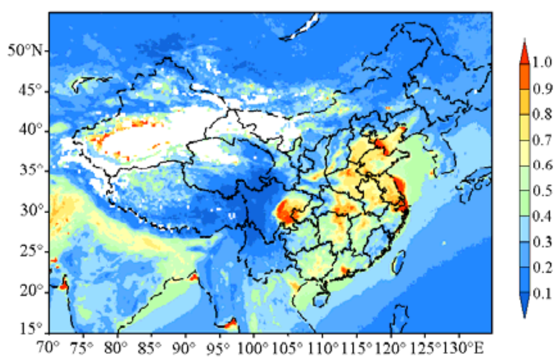


Figure 3. Scatterplots of AOD from Terra/Aqua MODIS versus sun photometers at sites in North and South of China. Solid lines represent the fitting curve and the dotted lines are retrieval errors of $\Delta\tau = \pm 0.05 \pm 0.15\tau$. N is data number and RMSE is standard deviation.

3.2. Distribution of AOD in China area

Figure 4 shows the average distribution of the AOD of Terra-MODIS Dark Target algorithm aerosol products, with the blank space representing areas with the higher bright surface albedo that fail to provide data, such as the desert and Gobi. Figure 5 shows the average distribution of AOD in combination with the data from the Aqua-MODIS Dark Target algorithm and Deep Blue algorithm, filling in the gap of the distribution of AOD in the northwest desert with the bright surface. Northwest China gives an AOD between 0.2 and 0.3, except for the Taklimakan Desert (0.5) and Qaidam Basin (0.8). The Qinghai-Tibet Plateau, Inner Mongolia, and Yunnan-Guizhou Plateau also indicate a low AOD value. High AOD value areas are mainly distributed in the Sichuan Basin (0.8~0.9), North China (0.6~0.8), and the middle and lower reaches of the Changjiang River region (0.8~1.0). AOD distribution in China has obvious regional characteristics. The high AOD in the Northwest is related to sand and dust and other natural aerosol releases, but that in the Southeast is related to urban development and a larger population.



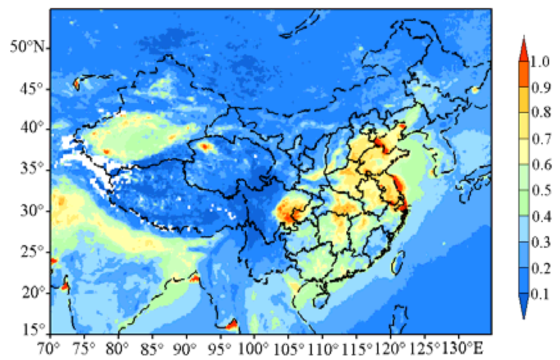


Figure 4. Spatial distribution of Terra MODIS AOD in 2000-2010 over China

Figure 5. Spatial distribution of Aqua MODIS AOD in 2003-2010 over China

4. Summary and conclusion

This paper used AERONET sun photometer data to compare and verify Terra/Aqua MODIS AOD products in China. Aqua-MODIS Deep Blue algorithm AOD products in the Hexi Corridor gave an average comparison R value of 0.67 and had a large number of samples. The MODIS Dark Target algorithm AOD products were superior to the Deep Blue algorithm AOD products in SACOL of the Semi-arid region of the Loess Plateau. But the two algorithms were not applicable to sites in Lanzhou city. The average R value of Terra/Aqua MODIS Dark Target algorithm AOD product comparison in the eastern part of China was 0.91 and 0.88 respectively, applicable to most parts of North China and the middle and lower reaches of the Changjiang River. A high value for the AOD is seen mainly in the Sichuan Basin (0.8 to 0.9), North China (0.6 to 0.8) and the middle and lower reaches of the Yangtze River (0.8 to 1.0). Aqua-MODIS Deep Blue algorithm AOD products obtained the proper characteristics of AOD distribution in the northwest desert with a bright surface.

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