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Improved retrieval of aerosol optical thickness from MODIS measurements through derived surface reflectance over Nanjing, China

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ABSTRACT

Determination of surface reflectance in the red and blue channels is a critical step in retrieving aerosol optical thickness (AOT) from Moderate Resolution Imaging Spectroradiometer (MODIS) measurements. The MODIS Collection 005 (C005) aerosol algorithm uses a ratio method to determine the surface reflectance in the red (0.66 μm) and blue (0.47 μm) channels from the surface reflectance in the 2.1 μm channel using global surface reflectance relationships. In this study, we attempted to improve the retrieval of AOT from MODIS measurements using a new surface parameterization derived using ground-based sunphotometer data and 6S radiative transfer code. The estimated surface reflectance in the red, blue and near-IR channel were used to derive ratio between them for use in the new retrieval from MODIS data. Our results demonstrate that the ratio of surface reflectance in the red and blue channels to the surface reflectance in the 2.1 μm channel varies seasonally in the Xianlin district of Nanjing City, China. These ratios are different from those assumed by the MODIS aerosol algorithm for the retrieval of AOT over land. The use of the appropriate ratio for the study area in a given season significantly improves the accuracy with the absolute error decreased from 0.15 to 0.08 and the relative error reduced from 31% to 17% in retrieving AOT from MODIS data.

1. Introduction

Originating from natural processes and human activities, aerosols refer to suspended particles in the atmosphere. They play an important role in redistributing global solar radiation and hence affecting global climate change. They are also one of the most uncertain factors in climate modelling (Hansen and Lacis, 1990; Charlson et al., 1992; Hansen and Sato, 2001; Anderson et al., 2003). Aerosols themselves are a kind of pollutants in the atmosphere that pose a severe threat to human health. Thus, it is very important to accurately monitor their concentration levels. One important indicator of aerosols in the atmosphere is called aerosol optical thickness (AOT), a widely used parameter indicative of the total column atmospheric aerosol optical property.

AOT retrieval from ground-based measurements is valuable to test and improve satellite retrievals. At present the Aerosol Robotic Network (AERONET) has already established more than 500 stations spread over the globe, out of which about 300 stations are routinely observe the optical and size properties of aerosols. In addition to this, numerous field campaigns, both over land and ocean provide high quality aerosol data for satellite validation and analysis. However, these are columnar point measurements and may be only valid to a small region surrounding the site, whereas satellite-based remote sensing is the only viable means to observe aerosols over globe routinely. Of the satellite images and data in use, Moderate Resolution Imaging Spectroradiometer (MODIS) data have found wide applications in studying aerosols owing to their ease of acquisition and

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broad areal coverage (Running et al., 1994; Remer et al., 2005; Chan et al., 2006). In particular, NASA has released global AOT products derived from MODIS measurements (Remer et al., 2005). The retrieval algorithm to derive aerosol products involves a number of state parameters, such as aerosol model, surface pressure, sun/satellite viewing geometry, surface reflectance and so on. Of these parameters, the surface reflectance in the red (0.66 μm) and blue (0.47 μm) channels are determined using the apparent reflectance in the 2.1 μm channel. Afterwards, MODIS AOT over land is derived using apparent reflectance, estimated surface reflectance and look-up-table (Levy et al., 2007). In the literature it has been reported that the surface reflectance of dark surface targets in the red and blue channels has a ratio of 0.5 and 0.25, respectively, to the apparent reflectance in the 2.1 μm channel (Kaufman et al., 1997a,b; Levy et al., 2007). So far the publicly available AOT products have shown some consistency with ground-based measured results using a sun photometer (Chu et al., 2002; Ichoku et al., 2002; Mao et al., 2002; Remer et al., 2005; Boersma and de Vroom, 2006; Jethva et al., 2007; Misra et al., 2008; He et al., 2010; Jethva et al., 2010; Melin et al., 2010). Nevertheless, there is a discrepancy between the two. Occasionally, the discrepancy is rather large, for instance, as high as 50% in some European areas (Schaap et al., 2008).

The value of the ratio of surface reflectance in the red and blue channels to the surface reflectance in the 2.1 μm channel governs the surface reflectance in the red and blue channels that is instrumental in AOT retrieval. Any uncertainty in determining surface reflectance will lead to inaccuracy (Kaufman et al., 1997b; Jethva et al., 2009). Kaufman et al. (1997b) reported that every variation in surface reflectance by 0.01 would introduce an error of 0.1 to the retrieved AOT. After studying the relationship between surface reflectance in the red and blue channels with the surface reflectance in the 2.1 μm channel based on a hand-held spectrometer from a light aircraft, Remer et al. (2001) reported that their ratio varies seasonally. The value of ratio of surface reflectance also depends on the type of surface, NDVI and scattering angle (Levy et al., 2007).

The purpose of this study is to determine how much the accuracy of retrieving AOT from MODIS data can be improved using a new surface parameterization that uses ground-based columnar AOT data for the atmospheric correction from the sun photometer over the period of October 2007–November 2009 and MODIS data of the same period in the Xianlin district, Nanjing City, China. The ground-based columnar AOT data were applied to the 6S atmospheric correction model (Vermote et al., 1997) in order to determine the surface reflectance in the red, blue and 2.1 μm channels, from which the most appropriate ratio of surface reflectance of the red and blue channels to the surface reflectance of the 2.1 μm channel for this geographic region in different seasons was determined. Afterwards, the 6S radiative transfer model was used to construct a look-up table to be used in retrieving AOT from MODIS data.

2. Method

2.1. Measurements using sun photometer

The CE-318 sun photometer used in this study was manufactured by the French CIMEL company. It was mounted on the top of a tall building at the Xianlin campus of Nanjing Normal University (32.12°N, 118.91°E). This area is located 15 km to the northeast of central Nanjing. Encompassing the measurement spot are hills of dense forests in all sides. This site represents the backbone of the ecological protection network east of Nanjing City. Its landscape is characterized by a hilly terrain with a mixed juxtaposition of hills, valleys, plains, and peaks at an average elevation of 25–50 m a.s.l. over an extended range. The study site lies in an area that has been designated for developing high education institutions and high-tech companies. As such, many universities are clustering around, with little thoroughfare traffic.

The sun photometer has eight channels, of which the 1.02 μm, 0.87 μm and 0.44 μm channels are applicable for AOT retrieval (Gai et al., 2006). The instrument was calibrated using the Langley method before use. The AOT measurements have an accuracy of ±0.01–0.02. AOT has a following relationship with wavelength λ

$$\mathrm{AOT}(\lambda) = \beta\lambda^{-\alpha}, \tag{1}$$

where β refers to the atmospheric turbidity coefficient, and α stands for wavelength exponent. Both parameters are derivable by regressing AOT measured in multiple channels such as the 1.02 μm, 0.87 μm and 0.44 μm channels. From eq. (1) it is possible to determine AOT at 0.55 μm and other MODIS wavelengths, such as red (0.66 μm) and blue (0.47 μm). The data used in this study were measured under clear skies over the period of October 2007–November 2009, totalling 119. In addition, cloud masking was undertaken in accordance with the method recommended by Smirnov et al. (2000).

2.2. AOT retrieval from MODIS data

The MODIS data used in this study were obtained in the same period as the ground-based measured sun photometer data. All the collected MODIS Level 1B reflectance data have a spatial resolution of 1 km. Before AOT was retrieved from MODIS observations, multispectral MODIS cloud detection algorithm was used to get cloud-free pixels (Ackerman et al., 1998). The MODIS-retrieved AOT values within a window of 5 by 5 pixels centred at the sunphotometer, corresponding to 5 by 5 km^2 on the ground, were averaged. This value was then compared with the sunphotometer-derived AOT averaged within ±30 min of satellite pass (Ichoku et al., 2002). The entire procedure of AOT retrieval from MODIS data is illustrated in Fig. 1.

The atmospheric radiative transfer model used in the retrieval is the 6S model (Vermote et al., 1997). It is a time-consuming

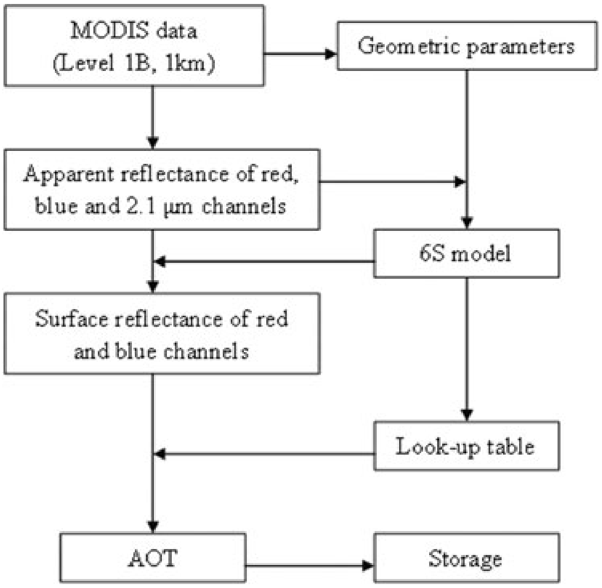

Fig. 1. The flowchart illustrating AOT retrieval from MODIS data.

process to derive AOT from this model directly. In order to save time, AOT retrieval is derived from a pre-calculated look-up table. A complete table lists a wide range of AOT values corresponding to many given values of solar and satellite geometric parameters, atmospheric model, aerosol type, target altitude, sensor height, surface reflectance, apparent reflectance and so on. Thus, it is possible to find AOT quickly from the table if the values of the aforementioned parameters are known.

In this study the atmospheric model was mid-latitude summer (April to September) and mid-latitude winter (October to following March), respectively. Aerosol type was set to continental for winter and spring, and to urban for summer and autumn (Huang, 2009). In the 6S model these two aerosol types have an SSA value of 0.893 and 0.651, respectively, at 0.55 μm. The altitude of target (sunphotometer) was 0.03 km above sea level and satellite was assumed to be located in space about 1000 km from the surface. Solar and satellite geometric parameters, and apparent reflectance were read from the MODIS images. Surface reflectance of the red and blue channels is determined from the apparent reflectance of the 2.1 μm channel with the assistance of their ratio to the surface reflectance of the 2.1 μm channel. Given that all the parameters are known, their corresponding AOT is also known from the look-up table.

Two separate look-up tables were constructed for the MODIS red and blue channels with the assistance of the 6S model on a daily basis. For a given day the solar and satellite geometric parameters (the mean value within a window of 5 by 5 pixels centred at the sunphotometer), the atmospheric model, aerosol type, target altitude and sensor height all have a fixed value. Surface reflectance corresponding to AOT (at an increment of 0.003) and apparent reflectance at an interval of 0.001 was calculated, based on which the look-up tables for the red and blue channels among AOT, apparent reflectance and surface reflectance were constructed. With the assistance of these tables, AOT at 0.55 μm was determined from any given apparent reflectance and surface reflectance. In constructing the look-up tables for the red and blue channels, the input AOT value to the 6S model was that at 0.55 μm. Thus, the two AOT values obtained from the look-up tables for the red and blue channels are virtually two AOTs at 0.55 μm. In reality, these two values are rarely identical to each other. Thus, both values were subsequently averaged to derive the AOT for this particular day.

2.3. Determination of the ratio of the surface reflectance of the red and blue channels to the surface reflectance of the 2.1 μm channel

According to the forward atmospheric radiative transfer equation, the apparent reflectance measured at the top-of-atmosphere is a function of aerosols (AOT and SSA that is captured by aerosol type in the 6S model) and surface reflectance. If the surface reflectance is known, AOT can be calculated from the equation on the basis of the apparent reflectance and SSA. The determination of surface reflectance of the red and blue channels relies primarily on the pre-determined relationship between surface reflectance of the red and blue channels and the surface reflectance of the 2.1 μm channel that is less subject to the influence of AOT. The study area is almost never subject to the influence of dust from northern China with aerosols chiefly being of the continental and urban types (Huang, 2009). There is a definite ratio between the two sets of parameters. In this study the ratio value of 0.5 and 0.25 of surface reflectance in the red and blue channels with the surface reflectance in the 2.1 μm channel as determined by Kaufman et al., (1997a, b) is defined as R1 that holds for MODIS, and expresses assumptions in the MODIS retrieval. On the other hand, this ratio is also a function of seasonality (Remer et al., 2001). Therefore, it is necessary to determine accurately the seasonal ratio of red and blue channel surface reflectance to the 2.1 μm channel surface reflectance.

In general, surface reflectance at a given wavelength can also be inferred from the 6S radiative transfer model if the values of AOT and top-of-atmosphere reflectance, recorded on the same day, are known. For instance, in this study the surface reflectance in the red, blue and 2.1 μm channels was derived from the 6S model after the apparent reflectance of the three MODIS channels and the ground-based columnar AOT data measured using the sun photometer were plugged into the model. This derived surface reflectance in the red and blue channels on a given date was then divided by the same-day surface reflectance in the 2.1 μm channel. The results were averaged by season to calculate the seasonal ratio. This ratio is termed R2 and is applicable for Nanjing City. Afterwards, the AOT in a given season was retrieved from the surface reflectance of the red and blue channels determined by the same seasonal ratio.

Furthermore, the surface reflectance of the red, blue and 2.1 μm channels in a season was filtered with one standard deviation. Any value above one standard deviation of surface reflectance was thus eliminated. The ratio of the red and blue channels to the 2.1 μm channel in each season is hence updated accordingly. This filtered ratio is termed R3 that holds true only for the location of Nanjing.

3. Results

3.1. *Seasonal ratio of the surface reflectance of the red and blue channels to the surface reflectance of the 2.1 μm channel*

The three kinds of seasonal ratios of surface reflectance of the red and blue channels to the surface reflectance of the 2.1 μm channel are listed in Tables 1 and 2, respectively. Apparently, the numbers in the tables show that these ratios exhibit distinctive seasonality. The surface reflectance of the red channel has the smallest ratio to the surface reflectance of the 2.1 μm channel in winter (<0.4), but is as high as 0.7 in spring. The largest ratio occurs in summer (>0.72), but it drops to 0.5 in autumn. The ratio in four seasons averages 0.58. For the blue channel, surface reflectance also has the smallest ratio with the surface reflectance of the 2.1 μm channel at 0.11 in winter, but is slightly larger at 0.21 in spring. The maximum is 0.28 in summer (lower at 0.18 in autumn). The ratio has a mean of 0.2. Compared with the red channel, apparently, the blue channel has a smaller range of ratio variation. This indicates that the ratio of both channels varies with seasons for Nanjing. In retrieving AOT from satellite data, the indiscriminate adoption of 0.5 for the red channel and 0.25 for the blue channel for all seasons undoubtedly introduces a large uncertainty to the retrieved results for the location of Nanjing.

Table 1. Seasonal ratio of the surface reflectance of the red (0.66 μm) channel to the surface reflectance of the 2.1 μm channel (R1 is the ratio suggested by Kaufman et al. (1997a, b); R2 and R3 are applicable to the study area. R3 was obtained by filtering the surface reflectance of the red, blue and 2.1 μm channels in a season with one standard deviation)

Ratios	Spring	Summer	Fall	Winter	Mean
R1	0.5	0.5	0.5	0.5	0.5
R2	0.704	0.741	0.485	0.394	0.581
R3	0.708	0.729	0.492	0.397	0.582

Table 2. Seasonal ratio of the surface reflectance of the blue (0.47 μm) channel to the surface reflectance of the 2.1 μm channel (R1 is the ratio suggested by Kaufman et al. (1997a, b); R2 and R3 are applicable to the study area. R3 was obtained by filtering the surface reflectance of the red, blue and 2.1 μm channels in a season with one standard deviation)

Ratios	Spring	Summer	Fall	Winter	Mean
R1	0.25	0.25	0.25	0.25	0.25
R2	0.207	0.286	0.188	0.113	0.199
R3	0.203	0.282	0.177	0.113	0.194

It is the spectral reflectance response in different seasons that leads to varying ratios of the red and blue channel surface reflectance to the surface reflectance of the 2.1 μm channel (Fig. 2). As shown in the figure, the surface reflectance is rather low in winter. With the arrival of spring, surface vegetation turns to green and starts to grow quickly, causing reflectance to rise rapidly. It peaks in the summer season, but starts to decline afterwards and approaches to the previous winter's level. Naturally, solar zenith angle and snow also exert a potential influence on the apparent seasonality in surface reflectance. Especially for low sun (i.e. in winter), BRDF effects may play an important role, and snow may also interfere with the apparent seasonality. Analysis of MODIS-derived surface reflectance and BRDF product data reveals that the increase in solar zenith angle caused a reduction in surface reflectance by <0.01 in winter in the study area. Over Nanjing, the influence of snow can be safely ignored as there is hardly any snow accumulation in winter. So, the inability of MODIS to perform over snow/ice surface is not an issue. This seasonal cycle in surface reflectance spectrum results in the observed seasonality of the ratio of the red and blue channels surface reflectance to the surface reflectance of the 2.1 μm channel.

Tables 3 and 4 list the standard deviation of the ratio of the red and blue channels surface reflectance to the surface reflectance of the 2.1 μm channel in different seasons, respectively. They suggest that the ratio (R3) of both the red and blue channel surface reflectance to the surface reflectance of the 2.1 μm channel in different seasons have the smallest standard deviation. This demonstrates that the ratio (R3) has a higher seasonal stability. It is predicted that the AOT retrieval accuracy is much higher if this ratio (R3) is used.

3.2. *Errors in retrieving AOT based on different ratios*

The retrieved AOT results based on different ratios were compared with their ground-based counterparts measured using the sun photometer (Fig. 3). With the ratio changing from R1 to R2 and eventually to R3, the R^2 of the regression model improves from 0.47 (Fig. 3a) to 0.55 (Fig. 3b), and further to 0.59 (Fig. 3c). The errors of retrieving AOT from the MODIS data (Tables 5 and 6) indicate that those associated with R2 are smaller than those with R1. The accuracy of retrieving AOT is hence considerably improved with the mean absolute error reduced from 0.15 to 0.10 and the relative error dropped from 31% to 21%. Moreover, the use of R2 has homogenized the seasonal disparity of

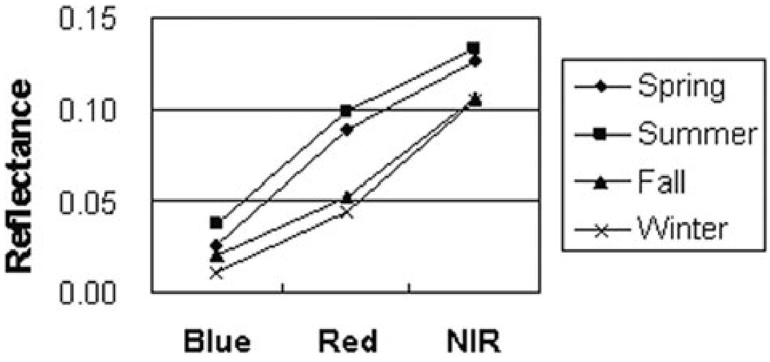

Fig. 2. Seasonal variation of surface reflectance in the study area.

Table 3. Standard deviation of the ratio of the red (0.66 μm) channel surface reflectance to the surface reflectance of the 2.1 μm channel in different seasons (R1 is the ratio suggested by Kaufman et al. (1997a, b); R2 and R3 are applicable to the study area. R3 was obtained by filtering the surface reflectance of the red, blue and 2.1 μm channels in a season with one standard deviation)

Ratios	Spring	Summer	Fall	Winter	Mean
R1	–	–	–	–	–
R2	0.043	0.071	0.110	0.101	0.081
R3	0.040	0.057	0.090	0.081	0.067

Table 4. Standard deviation of the ratio of the blue (0.47 μm) channel surface reflectance to the surface reflectance of the 2.1 μm channel in different seasons (R1 is the ratio suggested by Kaufman et al. (1997a, b); R2 and R3 are applicable to the study area. R3 was obtained by filtering the surface reflectance of the red, blue and 2.1 μm channels in a season with one standard deviation)

Ratios	Spring	Summer	Fall	Winter	Mean
R1	–	–	–	–	–
R2	0.048	0.037	0.058	0.022	0.041
R3	0.045	0.037	0.047	0.022	0.038

the errors. The maximum absolute error stands at 0.13 in winter, but only 0.09 in the summer season. In other words, the retrieval errors do not fluctuate widely with seasons. This situation is drastically different from that associated with R1. The universal application of a fixed ratio to the entire year causes the errors of retrieval to have a relatively wide fluctuation with seasons.

After the surface reflectance data were filtered using one standard deviation, the accuracy of retrieving AOT was further improved. In relative terms, the pace of improvement is the largest for those AOTs retrieved using the R3 ratio. Their mean absolute error of 0.08 and relative error of 17% have both halved the corresponding figure associated with R1. R3 also results in the smallest absolute and relative errors in every season. In comparison with the standard deviation of every ratio in Tables 3 and 4, ratio R3 also has the lowest value after it has been filtered using one standard deviation. The R3-derived AOT is also the most accurate.

4. Conclusions

In this study we attempted to improve the accuracy of retrieving AOT from MODIS measurements with the assistance of ground-based measured sun photometer data collected over the period of October 2007–November 2009 in the Xianlin district of Nanjing City, China. With the use of the 6S radiative transfer model and ground-based spectral AOT measurements, the ratio of surface reflectance of the red and blue channels to the surface reflectance of the 2.1 μm channel appropriate for the study area in different seasons was thus determined. In the study area the ratio of surface reflectance in the red and blue channels to the surface reflectance in the 2.1 μm channel varies seasonally. This ratio is the smallest in winter, it rises in spring and reaches the maximum in summer, but declines in autumn. These ratios are different from that assumed by the MODIS aerosol algorithm for the retrieval of AOT over land. The seasonal behaviour of the ratio is related closely to the annual cycle of the surface reflectance spectrum. The apparent seasonality in surface reflectance values is subject to the possible influence of vegetation, snow and solar zenith angle. The use of the appropriate ratio for the study area in a given season significantly improves the accuracy of the retrieval of AOT from MODIS data. On average, the accuracy is improved with the absolute error nearly halved from 0.15 to 0.08 and the relative errors decreased from 31% to 17%. Besides, the retrieval accuracy does not vary widely across different seasons. This study has demonstrated that the uncertainty involved in the general ratio value of surface reflectance in the red and blue channels to the surface reflectance in the 2.1 μm channel is the cause for the relatively large error observed in the current practice of retrieving AOT from MODIS data. By comparison, the more precisely determined ratio for a given geographic area in a specific season is able to improve this retrieval accuracy level considerably.

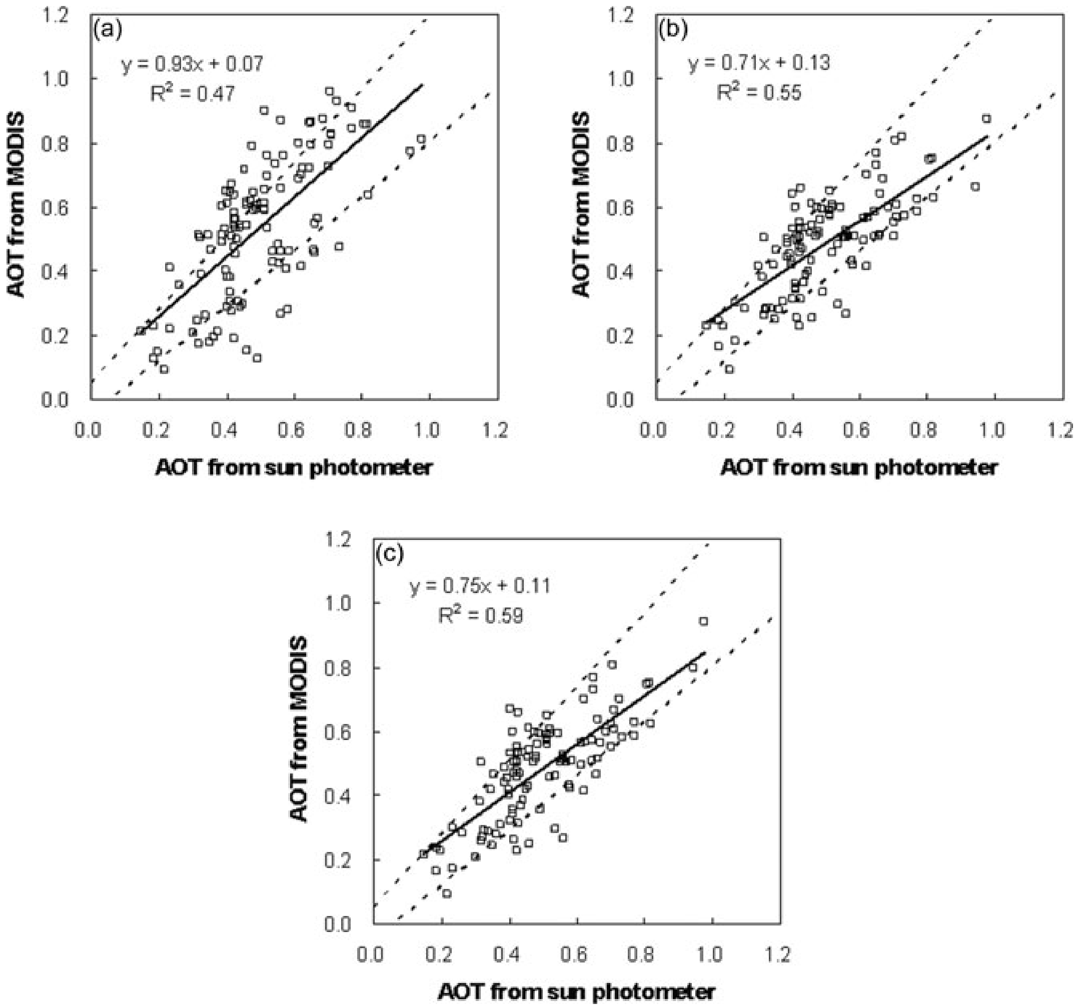

Fig. 3. Comparison of the MODIS retrieved AOT using different ratios with the ground-based sun photometer measured results. The dashed lines are predicted uncertainty of $\Delta\tau = \pm 0.05 \pm 0.15\tau$, where τ is aerosol optical thickness, and solid line is linear regression fit. (a) R1; (b) R2; (c) R3.

Table 5. Absolute errors of retrieving AOT based on different ratios (R1 is the ratio suggested by Kaufman et al. (1997a, b); R2 and R3 are applicable to the study area. R3 was obtained by filtering the surface reflectance of the red, blue and 2.1 μm channels in a season with one standard deviation)

Ratios	Spring	Summer	Fall	Winter	Mean
R1	0.1407	0.1867	0.1025	0.1668	0.1492
R2	0.0988	0.0910	0.0976	0.1261	0.1034
R3	0.0692	0.0813	0.0702	0.1000	0.0802

Table 6. Relative errors (%) of retrieving AOT based on different ratios (R1 is the ratio suggested by Kaufman et al. (1997a, b); R2 and R3 are applicable to the study area. R3 was obtained by filtering the surface reflectance of the red, blue and 2.1 μm channels in a season with one standard deviation)

Ratios	Spring	Summer	Fall	Winter	Mean
R1	28.83	39.19	22.58	34.90	31.38
R2	17.35	19.09	19.33	26.51	20.57
R3	12.01	16.71	16.54	22.40	16.92

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