Comparison between MODIS aerosol product C004 and C005 and evaluation of their applicability in the north of China

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Abstract: MODIS aerosol product Collection 005 (C005) is an upgrade of C004, and is introduced in detail in this paper. Through fitting with AERONET ground observation aerosol optical thickness (AOT), MODIS aerosol C004 and C005 products of TERRA and AQUA are compared and evaluated to analyze their applicability in the north of China at Beijing and Yulin sites. We match AERONET ground-based data with MODIS aerosol product by band interpolation and temporal-spatial matching, then compare and evaluate them by linear fitting. We conceive a scale of temporal-spatial matching in the north of China considering the local aerosol movement velocity of given sites. The results show that: (1) C005 product algorithm does not improve the accuracy of AOT at Beijing site, and the accuracy drops when AOT<0.8; both C004 and C005 products do not have a significant application at Beijing site, but the C004 performs better than C005 products. (2) At Yulin site, TERRA-MODIS C004 product meets the demand, and the accuracy of AQUA-MODIS C004 product decreases. Compared with the C004 product, the accuracy of the C005 product improves greatly, and correlation coefficients between AOTs of three bands (470nm, 550nm, 660nm) and the AERONET ground observation data are all higher than 0.9. It could be concluded that the method of the surface reflectance determination used in the new algorithm is feasible for dark dense vegetation, but is not suitable for the bright surface.

Key words: MODIS, C005, AERONET, aerosol optical thickness (AOT), validation

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1 INTRODUCTION

Aerosol is a multiphase system composed of gas, solid and liquid particles suspended in air (Sheng et al., 2003). Aerosol originates from both man-made and natural sources. The man-made source aerosol is produced by human activities, such as burning fossil fuels, industrial and agricultural production activities; natural source aerosol is produced by natural phenomena, and can be directly emitted as particles into the atmosphere by forest fires, volcanic eruptions, sea spray, and the wind lifting dust particles in arid regions. Aerosol is one of important components of atmosphere, with characteristics of distributing widely, having short life span, moving rapidly, having complex chemical composition, etc. It plays an important role on climate change of whole world and region, and environment quality. It has become an important domain in the atmospheric science (Houghton et al., 1995; Anderson et al., 2003).

At present, there are two means of detecting aerosol: ground-based observations and satellite remote sensing. The former could provide exact aerosol optical thickness (AOT) for one point of space, but could not observe extensively because of the limitations of observation condition and instrument. The latter overcomes the shortcoming of ground observation. Thus, it could provide global aerosol characteristics. To retrieve aerosol by remote sensing began in 1970s. A series of satellite observation plans had been implemented, such as NOAA/AVHRR (Rao et al., 1989), TOMS (Herman et al., 1997), ATSR-2 (Veerkind et al., 2000), POLDER (Deuze et al., 1993), MODIS (Kaufman et al., 1997a), etc. These plans aimed at obtaining worldwide distribution of aerosol optical characteristic, seasonal and annual variation of aerosol direct and indirect force.

MODIS is the Moderate Resolution Imaging Spectroradiometer aboard Terra (EOS AM) and Aqua (EOS PM) satellites. MODIS acquires data globally in 36 spectral bands ranging in wavelength from 0.4 µm to 14.4µm. MODIS is the first satellite observation plan designed to provide aerosol optical characteristic globally of high spatial-resolution. It has been widely used...

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to compute climate model, analyze dynamic change of environmental pollution, and monitor air quality in the global scope (Ichoku et al., 2004). During the past ten years, MODIS aerosol product algorithm had experienced modifications for many times. In 2006, collection 005 was introduced as the latest version of aerosol product to replace the Collection 004 (Levy et al., 2007). In recent years, a growing number of researchers began to study aerosol characteristic of China using MODIS aerosol product, and it is the basic research to evaluate MODIS aerosol product using ground observation. Mao et al. (2002) validated MODIS aerosol product of Beijing area using ground observation of Peking University. He found the nearest pixel from the ground site, which is within 15km away, then compared the pixel value with the arithmetical average of ground sun photometer observation in an hour. Due to the limitations of ground-based observations, timing differences between the two occur. So, the validation process requires temporal and spatial matching. Li et al. (2003) evaluated and confirmed TERRA-MODIS aerosol product of Beijing and Hong Kong areas using ground observations of two sites, and then studied aerosol optical characteristic and seasonal variation characteristic of the eastern China area using MODIS aerosol product. Xia (2006) contrasted AERONET AOT and MODIS aerosol product over land, and concluded that MODIS aerosol product overestimated AOT in most parts of the world. Wang et al. (2007) evaluated the applicability of MODIS aerosol product in different ecology types and geography regions of China using Chinese Sun Hazemeter Network (CSHNET). Mi et al. (2007) evaluated MODIS aerosol product in China using ground observations of Xianghe and Tai Lake sites. Li et al. (2003) Xia (2006), Wang et al. (2007), Mi et al. (2007) as mentioned above, all adopted the validation method provided by NASA to evaluate the MODIS aerosol product globally over land. The method is to match the version 2 AERONET AOT data within ±30 min of MODIS overpass times with MODIS retrieved AOT over a 50km×50km area centered on the AERONET sites. This method is designed for the global scale, and as such is not suitable for the local regions. This article will give full consideration to the velocity of aerosol in China, evaluate and discuss the applicability of old and new versions of MODIS aerosol products in the north China with AERONET ground observation data.

2 ALGORITHM OF MODIS AEROSOL PRODUCT C005 OVER LAND

So far, TERRA-MODIS aerosol product has been upgraded for 4 times: Collection 002, 003, 004, 005 (C002, C003, C004, C005 for short). C002 is the first version of the operational product, and is mainly applied in validation and analysis, and has not been widely used. C003 and C004 products have been released and are widely used. AUQU-MODIS aerosol product has been updated for 3 times: Collection 003, 004, 005, and the algorithm is similar to that of the same version of TERRA, but some minor complements (Levy et al., 2007). MODIS aerosol product C005 was released in the latter half year of 2006, and made a great improvement to the algorithm of C004 (Levy et al., 2007; Ichoku, 2005). This article will introduce the important improvements of MODIS aerosol products algorithm from the following three aspects.

2.1 Change of inversion idea

The C004 algorithm assumes that aerosol is transparent in the 2.12μm channel, and surface reflectances in the visible channels are constant ratios to the observed reflectance (equal to surface reflectance) in 2.12μm. The C005 algorithm does not hold on this assumption, for many studies show that the 2.12μm channel contains information of coarse mode aerosol as well as the surface reflectance (Levy et al., 2007).

The C004 algorithm adopts the assumption proposed by Kaufman et al. (1997b) that over vegetated and dark soiled surfaces, the surface reflectances in some visible channels correlate with the surface reflectance in the SWIR. That is, surface reflectances in 0.47μm (channel 3) and 0.66μm (channel 1) are assumed to be one-quarter and one-half of the surface reflectance in SWIR 2.12μm (channel 7) respectively (Kaufman et al., 1997b). Later, many researches found that the VIS/SWIR surface ratios vary as a function of scattering geometry, and do not meet the relationship proposed by Kaufman et al. (1997b) under certain geometries (Remer et al., 2001; Gatebe et al., 2001). Therefore, these relationships between visible bands and SWIR band are completely broken. The C005 algorithm adopts a new assumption: over dark surfaces, the RED/SWIR surface ratio varies as a function of scattering angle and vegetation index, and the RED/BLUE surface ratio is assumed to be fixed. As follows (Levy et al., 2007):

$$\rho_{0.66}^s = f(\rho_{2.12}^s) = \rho_{2.12}^s \times \text{slope}_{0.66/2.12} + y_{\text{int}}$$

$$\rho_{0.47}^s = f(\rho_{0.66}^s) = \rho_{0.66}^s \times \text{slope}_{0.47/0.66} + y_{\text{int}}$$

where:

- slope$_{0.66/2.12} = \text{NDVI}_{\text{SWIR}} + 0.002\theta - 0.27$
- y$_{\text{int}} = -0.00025\theta + 0.033$
- slope$_{0.47/0.66} = 0.49$
- y$_{\text{int}} = 0.005$
- slope$_{0.66/2.12} = 0.48$, NDVI$_{\text{SWIR}} < 0.25$
- slope$_{0.66/2.12} = 0.58$, NDVI$_{\text{SWIR}} > 0.75$
- $0.25 \leq$ NDVI$_{\text{SWIR}} \leq 0.75$

$$\rho_{0.66}^m, \rho_{0.47}^m, \rho_{2.12}^m$$ represent the surface reflectance in 0.66μm, 0.47μm, 2.12μm, respectively; $\rho_{2.12}^m$ represent the measured surface reflectance in 1.24μm, 2.12μm respectively; $\theta$ is the scattering angle.

2.2 Change of radiative transfer code

The C004 MODIS lookup table (LUT) is calculated using
the non-polarized (scalar) SPD radiative transfer (RT) code (Dave et al., 1970). Fraser et al. in 1992 and Levy et al. in 2004 found that under some observation conditions, the neglect of the polarization scattering information would lead to significant errors in top of atmosphere reflectance. The algorithm chooses RT3 (Evans & Stephens, 1991), a vector RT code, to calculate the C005 MODIS lookup table (LUT). RT3 runs in scalar and vector modes, in order to keep joined with the former version. It is combined with MIEV (Wiscombe, 1981) for spherical fine aerosol and T-matrix (Dubovik et al., 2002a) for the non-spherical coarse aerosol to calculate the scattering properties of models (Levy et al., 2007).

2.3 Change of aerosol model

The C005 algorithm defines the aerosol models according to the geographical distribution. Five kinds of aerosol models: continental, dust, non-absorbing, neutral absorbing, and highly absorbing, are defined by slightly modifying the result of Dubovik et al.’s research (2002b). They are quite different from those in previous versions which were defined according to the research done by Remer et al. in 1998. Continental aerosol model is used only over bright surface; non-absorbing, neutral absorbing, and highly absorbing aerosol models are all fine models, which change with seasons and geographical locations; C005 algorithm defines a combination aerosol model by choosing dust model and one of those fine models (Levy et al., 2007).

The C005 algorithm redefines aerosol optical characteristic according to AERONET, especially for single scattering albedo (SSA): SSA~0.95 for the non-absorbing model, SSA~0.90 for the neutral absorbing model, and SSA~0.85 for the highly absorbing model (Levy et al., 2007). In China, except for the eastern coast, most areas are defined as neutral absorbing model. Over the past few years, so sparse the sites of AERONET in China there are that aerosol optical characteristics were not sufficiently studied. With the ground-based observations of aerosols in China being increasing in recent years, AERONET sites in China have increased significantly, while many provincial and municipal institutions have begun to observe on their own. Institute of Atmospheric Physics, Chinese Academy of Sciences, establishes the Chinese Sun Hazemeter Network, which currently has 19 ecology observation sites of Chinese Ecosystem Research Network, 4 urban observation sites, 2 calibration centers and 1 data center. Institute of Remote Sensing Application, Chinese Academy of Sciences, set a CE318 sun photometer on the roof of the institute building, to monitor the atmosphere condition around the Olympic venues during the Olympic Games in 2008. Hebei, Shanxi and many other provinces have begun to use CE318 sun photometer to observe aerosol. It is believed that in the next few years, there will be a more detailed and accurate description of aerosol characteristics of China.

Some other modifications are also done in the C005 algorithm, such as the choice of dark target, cloud mask, snow mask, the definition of the center wavelength, elevation correction, etc. These would not be expatiated in this paper, please refer to relevant literatures if interested (Levy et al., 2007).

3 DESIGN THE VALIDATION SCHEME FOR MODIS AEROSOL PRODUCT IN CHINA

3.1 Preparation of data

TERRA/AQUA-MODIS aerosol C004 and C005 products from August 28 to October 8 in 2002 covering the north of China are adopted in this paper, AERONET aerosol data of Beijing and Yulin sites of the same time in northern China are also chosen. MODIS C004 and C005 products of TERRA and AQUA are validated by these two AERONET sites.

AERosol RObotic NETwork (AERONET) program provides globally distributed observations of spectral aerosol optical characteristic in representative regions, for global aerosol transmission and radiative research, validation of radiative transfer model and satellite retrievals. The AERONET program is a federation of ground-based remote sensing aerosol networks with vast observation sites all over the world. The whole network uses multi-band sun photometer of CIMEL Company, France. The network imposes standardization of instruments, calibration, processing and distribution. The observation data possesses fine accuracy, and thus, are now widely applied to verify the accuracy of spectral aerosol optical characteristic achieved by other methods. AOT data 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) (Holben et al., 1998). Level 2.0 AERONET AOT data is adopted to validate MODIS aerosol product in this paper.

3.2 Methods of data matching

MODIS aerosol products and AERONET aerosol observations have different center wavelengths and temporal and spatial resolutions. Thus, band interpolation and spatial-temporal matching processing should be done to AOT in order to make it feasible to compare these two kinds of AOT data reasonably (Chen et al., 2005).

3.2.1 Band interpolation

AERONET sun photometers usually derive AOT in 340, 380, 440, 500, 670, 870, and 1020 nm wavelengths from direct solar radiation measurements, while MODIS aerosol algorithm routinely retrieves AOT in 470 and 660nm wavelengths (and interpolates in 550 nm) over land surfaces. AERONET and MODIS wavelengths do not match exactly. Therefore, interpolation of AERONET AOT is needed to be done to enable the comparison, AERONET AOT in 470, 550, and 660nm are interpolated from AERONET AOT in 440 and 870 nm based on the assumption of uniform spectral dependence between these two wavelengths. The data in 500nm is not taken into interpolation for the sake of the universality of the algorithm. Not all the AERONET sites are able to get the data in this band.
AERONET offers observation in 670nm, which is close to the band of 660nm of MODIS. In order to ensure the observation in 670nm is independent of the accidental calibration error as those in the other two bands do, the data in 660nm for AERONET is calculated by interpolation of those two bands in this paper (Fraser et al., 1992; Remer et al., 2005).

In the band with no influence of water vapor, the size distribution of aerosol particles fits Junge-distribution, and the relation of AOT and wavelength fits the Angstrom function (Angstrom, 1964):

\[ \tau_\lambda = \beta \lambda^{-\alpha} \]

where, \( \tau_\lambda \) represents AOT in the band of \( \lambda \); \( \beta \) represents Angstrom turbidity, which is related with aerosol particle quantity, particle size distribution, and refraction coefficient; \( \alpha \) represents Angstrom wavelength, which is related to the average radius of aerosol particles, ranging in \([0,4]\). The larger the aerosol particle is, the smaller the value is.

Assuming there are no influence of water vapor in the bands of \( \lambda_1 \) and \( \lambda_2 \) then:

\[ \tau_{\lambda_1} = \beta \lambda_1^{-\alpha} \]
\[ \tau_{\lambda_2} = \beta \lambda_2^{-\alpha} \]

Therefore:

\[ \alpha_{870/440} = -\frac{\ln(\tau_{\lambda_1}(870)/\tau_{\lambda_2}(440))}{\ln(870/440)} \]

Then, the AOT in the bands of 470, 550nm and 660nm could be calculated by the following equation respectively:

\[ \tau_{\lambda}(\lambda) = \frac{\tau_{\lambda_1}(870)(\lambda / 870)^{-\alpha_{870/440}}}{\lambda} \]

The error of interpolation is between 0% and 10%, and depends on the types of aerosol models. The error is larger when the fine mode is in the dominant place and the AOT is large; while the error is smaller if the aerosol model is mixed or coarse mode (Eck et al., 1999).

3.2.2 Temporal and spatial matching processing of MODIS aerosol product and AERONET observation

AERONET AOT is acquired at 15-minute intervals on average on some instrumented locations, while MODIS could provide aerosol spatial distribution of a fixed time with a pixel size of 10km×10km. The MODIS aerosol product of TERRA and AQUA are chosen. The satellite passing time is around 10:30 AM locally for TERRA and 1:30 PM for AQUA. The aerosol observations of MODIS and AERONET are different in temporal and spatial scales. If simply comparing the AOT of AERONET at the time of MODIS passing and that of a single pixel of MODIS covering the site, which is actually a comparison of the AOT at one point and the average AOT in the region of 10km×10km, no persuasive conclusion could be achieved. Therefore, another stable and reliable matching processing is required. At present, NASA and many researchers adopt a matching method for MODIS aerosol product proposed by Ichoku et al. (2002). They thought that the level 2.0 AERONET AOT within ±30 min of MODIS overpass times were matched with MODIS retrieved AOT over a 50km×50 km area centered on the AERONET sites. The equivalence described by Ichoku et al. (2002) is based on the assumption that, air masses transporting aerosol travel a distance of approximately 50 km per hour on average by estimates of Saharan dust transport. It is not the case in the local scale.

The velocities of aerosol spatial movement in different region are different, and are influenced by many factors, such as wind in horizontal direction and onflow in the vertical direction. In this paper, only the movement in horizontal direction is taken into account. The month average wind velocity of Beijing and Yulin sites from 1971 to 2000, shown in Table 1, is collected from the climate background statistical data supplied by China Meteorological Data Sharing Service System (CMDSSS). Taking Beijing site for example, the wind velocity of these three months differs little. The data of September is chosen, considering most of MODIS aerosol products used in this paper are in this month. The wind velocity is 7.2 km/h. As wind is the carrier of aerosol in the horizontal direction, it is supposed that the velocity of aerosol movement is the same with the wind speed in the horizontal direction. The aerosol moving velocity is regarded as 7.2 km/h for Beijing, and 6.48 km/h for Yulin. The pixel size of MODIS aerosol product is 10km×10km. Therefore, we will match AERONET data within ±30 min of MODIS overpass time with a pixel of MODIS aerosol product covering the AERONET sites.

Table 1  Month average wind velocity of study sites/(m/s)

<table>
<thead>
<tr>
<th>Site</th>
<th>August</th>
<th>September</th>
<th>October</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>1.8</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Yulin</td>
<td>2.2</td>
<td>1.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

3.3 Validation method

After band interpolation of AERONET data and spatial-temporal matching processing of MODIS data, a linear fitting analysis is to be done for these two data:

\[ \tau_{\text{MODIS}} = A \tau_{\text{AERONET}} + B \]

where, \( \tau_{\text{MODIS}} \) is the retrieved AOT of MODIS, \( A \) is the slope, \( \tau_{\text{AERONET}} \) is the observed AOT of AERONET, \( B \) is the intercept.

Under ideal condition, the retrieved AOT of MODIS should be equal to the observed AOT of AERONET, that is: \( A=1, B=0 \), correlation coefficient \( R=1 \). However, due to the error resulted from sun photometer itself, band interpolation, spatial-temporal matching processing, and especially MODIS aerosol retrieval, these two data are not equal. In this paper, the accuracy of AOT of MODIS is evaluated by the linear correlation coefficient \( R \), slope \( A \), intercept \( B \), and percentages of MODIS AOT falling within the specified uncertainty bounds as shown in Table 2 and Table 3.
4 RESULTS AND ANALYSIS

As shown in Fig. 1 and Fig. 2, there are the linear fitting results between TERRA/AQUA MODIS AOT and AERONET ground observation AOT in 470nm, 550nm, 660nm three bands at Beijing and Yulin sites. The X-axel is the observed AOT of AERONET, and the Y-axel is the retrieved AOT of MODIS. The expectation error range of MODIS aerosol product defined by NASA is adopted in this paper, which is: \( \tau = \pm 0.05 \pm 0.15 \tau_{AERONET} \) (Remer et al., 2005). The linear fitting function and correlation coefficient \( \left( R \right) \) are presented in Fig. 1 and Fig. 2.

As shown in the left of Fig. 1, there are the linear fitting results between TERRA-MODIS AOT and AERONET ground observation AOT in 470nm, 550nm, 660nm three bands at Beijing site. Among all the TERRA-MODIS C004 and C005 products at Beijing site used in the paper, there are 26 valid
Moreover, the percentages of sample falling into the NASA expectation error range are lower than those of TERRA. AQUA-MODIS aerosol product of Beijing site is not applicable, and is weaker than that of TERRA in accuracy. It must result from the systemic error of these two satellite systems.

Beijing site (39.977N, 116.381E) is located on a terrace on the roof of the Institute of Atmospheric Physics building. There are resident buildings, commercial buildings, roads, and scattering greenbelt other than vast green land around it. Thus, it is typical urban aerosol. TERRA\AQUA-MODIS aerosol C004 and C005 products are compared and evaluated through linear fitting with the AERONET ground observation AOT at Beijing site. The results show that both C004 and C005 products are lack of applicability, but the C004 performs better than C005; improvements of C005 product algorithm do not improve the accuracy of AOT at Beijing site, and accuracy drops when AOT< 0.8. There are notable difference between C005 aerosol product and the true value, and we think that it is caused by inaccurate reflectance retrieved by the algorithm of MODIS AOT over the bright surface. It still needs to look for the dark dense vegetation in the algorithm of MODIS C005 aerosol product. However, there is no large scale vegetation around the Beijing site. Data selected in this paper is during autumn, which makes it more difficult to find dark pixels. So there is no way to determine the ground reflectance accurately. Otherwise, urban aerosol almost originates from human being activities, whose characteristic is difficult to describe exactly. We think that it is an important factor influencing the accuracy of retrieved AOT. In a word, both of MODIS C004 and C005 products are not applicable over the bright surface.

As shown in the right of Fig. 1, there are the linear fitting results between AQUA-MODIS AOT and AERONET ground observation AOT in 470nm, 550nm, 660nm three bands at Beijing site. It is used to omit AQUA-MODIS aerosol data in validating MODIS aerosol product. Passing time is around 1:30 pm locally for AQUA, at which AERONET data is rich. Therefore AQUA-MODIS aerosol product could lend strong support to the validation. Among all AQUA-MODIS aerosol C004 and C005 products at Beijing site used in the paper, there are 24 valid values for C004, but only 20 for C005. Limited valid value for C005 results from the stricter cloud screening of C005. After the temporal matching processing with the AERONET data, 14 valid values of C004 and 12 valid values of C005 are able to be applied to fitting. By looking through the fitting formula in the three bands as shown on the right of Fig. 1, it is concluded that the fitting effect of all is poor. All the intercepts are over 0.1, the slopes are far from 1, and the correlation coefficients are low in most bands except that 0.5751 in 470 nm for C005. Moreover, the percentages of sample falling into the

<table>
<thead>
<tr>
<th>Band</th>
<th>470nm</th>
<th>550nm</th>
<th>660nm</th>
</tr>
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<tbody>
<tr>
<td>Product</td>
<td>C004</td>
<td>C005</td>
<td>C004</td>
</tr>
<tr>
<td>TERRA%</td>
<td>46.7</td>
<td>26.7</td>
<td>33.3</td>
</tr>
<tr>
<td>AQUA%</td>
<td>42.9</td>
<td>25.0</td>
<td>42.9</td>
</tr>
</tbody>
</table>
Fig. 2  Linear fitting between TERRA (left), AQUA (right) MODIS AOT and AERONET ground observation AOT in 470nm (upper), 550nm (middle), 660nm (lower) three bands at Yulin site.

Table 3  The probability statistics of TERRA, AQUA MODIS AOT falling into the NASA expectation error range at Yulin site

<table>
<thead>
<tr>
<th>Band</th>
<th>470nm</th>
<th>550nm</th>
<th>660nm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C004</td>
<td>C005</td>
<td>C004</td>
</tr>
<tr>
<td>TERRA%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>52.0</td>
<td>76.5</td>
<td>68.0</td>
<td>64.7</td>
</tr>
<tr>
<td>AQUA%</td>
<td>43.8</td>
<td>91.7</td>
<td>50.0</td>
</tr>
</tbody>
</table>

The data points of MODIS C004 AOT and AERONET AOT matched in time and space. The fitting line of MODIS C004 AOT and AERONET AOT. The data points of MODIS C005 AOT and AERONET AOT matched in time and space. The fitting line of MODIS C005 AOT and AERONET AOT. The NASA expectation error range of MODIS AOT.

High as 68.0%. Both C004 and C005 products are highly reliable in this band. C005 product has higher accuracy than C004. In 660nm (as shown in the lower left of Fig. 2), for C005 product, the fitting results are also good, and percentage of sample...
falling into the NASA expectation error range is 87.5%. So the product is reliable. However for C004 product, the correlation coefficient drops to 0.5242, and percentage of sample falling into the NASA expectation error range is 32.0%. Thus, the accuracy declines sharply comparing to the other two bands. In conclusion, for C004 product, the accuracy in 470nm is the best, that in 500nm is less, and the 600nm is the least. The products in the first two bands are reliable. For C005, the accuracies in these three bands are close to each other, and are all in a high level. Thus, products all share the merit of applicability.

As shown in the right of Fig. 2, there are the linear fitting results between AQUA-MODIS AOT and AERONET ground observation AOT in 470nm, 550nm, 660nm three bands at Yulin site. After temporal matching with AERONET data, there are 16 and only 12 valid values for C004 and C005 products respectively. Considering the slope, intercept and correlation coefficient of the linear fitting equation and the percentages of sample falling into the NASA expectation error range (as shown in Table 3) in these three bands, it could be concluded that: for C005 product, its accuracy remains a level as high as that of TERRA product, but its slope becomes larger; for C004 product, the correlation coefficient decreases tremendously, and percentages of sample falling into the NASA expectation error range also decline. In Yulin area, the AQUA-MODIS C005 product has the merit of applicability.

Yulin site (38.283N, 109.717E) is located on a terrace on the roof of the Shaanxi Desert Institute in Yulin at an elevation of 1080 meters. There is strong blast of wind laden with sand in spring and plenty of rain in summer. In summer and fall, the vegetation cover is fine, and the weather condition is good. Through the comparison above, it is known that TERRA-MODIS aerosol product C005 could satisfy the requirement, while the accuracy of AQUA-MODIS aerosol product C004 is lower. For C005 product, both satellites perform well in accuracy, and also share the merit of applicability. The modification for method of determining land surface reflectance in C005 algorithms exerts tremendous influence in the region with fine vegetation cover. In this paper, the retrieved AOT at Yulin site is improved notably.

5 CONCLUSIONS

TERRA/AQUA-MODIS aerosol C004 and C005 products are compared and evaluated through fitting with the AERONET ground observation AOT at Beijing and Yulin sites in this paper. The results show that: (1) improvements of C005 product algorithm do not improve the accuracy of AOT at Beijing site, and the accuracy drops when AOT<0.8. Both C004 and C005 products do not have obvious applicability, but C004 product performs better than C005 product. (2) At Yulin site, TERRA-MODIS C004 product could satisfy the demands, but the accuracy of AQUA-MODIS C004 product drops slightly. The accuracy of C005 product improves greatly, and the correlation coefficients between AOTs of three bands (470mm, 550nm, 660nm) and the AERONET ground observation data are all higher than 0.9. Both C004 and C005 have obvious applicability. It shows that the method of the surface reflectance determination used in the new algorithm is feasible for dark dense vegetation area, but not suitable for the bright surface. In a word, TERRA/AQUA-MODIS aerosol C004 and C005 products all do not have obvious applicability over bright surface in the north of China; TERRA-MODIS C004 product has certain reliability over dark dense vegetation area, while AQUA-MODIS C004 product has lower accuracy than that of TERRA; C005 products of TERRA and AQUA all have high accuracy over dark dense vegetation area in the north of China, and show a good applicability.

There are various surface types in China, and thus there is more work to do in order to improve the accuracy of retrieved AOT. On one hand, it is necessary to accurately determine the reflectance of different types of land surface, such as dark dense vegetation, sparse vegetation, high reflectance surface and inner land lake. At present, though there is reliable model for dark dense vegetation surface, further research needs to be done for other land surface types. On the other hand, the aerosol characteristic could exert significant influence on the accuracy of product, including single scattering albedo, refraction index, size distribution, etc. With the development of ground-based observation, it is possible to describe the aerosol characteristic precisely, and as such to improve the accuracy of satellite remote sensing retrieving aerosol.

Acknowledgements: Thanks Dr. Song Yu in Peking University for his direction and help in aerosol movement. Thanks NASA GSFC for MODIS aerosol product data and AERONET ground-based data needed in this paper.

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Deuze J L, Breon F M, Deschamps P Y, Devaux C, Herman M, Podaire A and Roujean J L. 1993. Analysis of the POLDER (Polarization and Directionality of Earth’s Reflectances) airborne in-
MODIS C004 C005

周春艳, 柳钦火, 唐勇, 王凯, 孙林, 何颖霞

摘要：MODIS C004 C005

1. MODIS AERONET TERRA C004 C005
2. MODIS TERRA C004 AQUA MODIS C004 C005
3. MODIS AQUA C004 MODIS TERRA C004
4. MODIS C004

关键词：MODIS, C005, AERONET

中图分类号：P407 文献标识码：A

1

1. 01042500.01042500 01042500 (Houghton, 1995; Anderson, 2003)
2. 01042500
3. 01042500
4. 01042500
5. 01042500

收稿日期：2018-04-14 修订日期：2018-05-14
基金项目：KZCX2-YW-313 KZCX2-YW-313
通讯作者：KZCX2-YW-313 E-mail: mezhouchnyuan@126.com
2 MODIS C005

2.1 C004, C005

\[ \rho'_{0.66} = f(\rho'_{0.47}) = \rho'_{0.47} \times \text{slope}_{0.66} + \text{yin}_{0.66} \]

\[ \rho'_{0.47} = f(\rho'_{0.66}) = \rho'_{0.66} \times \text{slope}_{0.47} + \text{yin}_{0.47} \]
\( \text{slope}_{0.66:2.12} = \text{slope}_{\text{NDVI SWIR}} + 0.002\Theta - 0.27, \)
\( \text{yint}_{0.66:2.12} = -0.00025\Theta + 0.033, \)
\( \text{slope}_{0.47:0.66} = 0.49, \)
\( \text{yint}_{0.47:0.66} = 0.005. \)
\( \text{slope}_{\text{NDVI SWIR}} = 0.48, \) \( \text{NDVI SWIR} < 0.25, \)
\( \text{slope}_{\text{NDVI SWIR}} = 0.58, \) \( \text{NDVI SWIR} > 0.75, \)
\( \text{slope}_{\text{NDVI SWIR}} = 0.48 + 0.2(\text{NDVI SWIR} - 0.25); \)
\( 0.25 \leq \text{NDVI SWIR} \leq 0.75. \)
\( \text{NDVI SWIR} = (\rho_{0.24}^{1a} - \rho_{0.24}^{2a})(\rho_{0.24}^{3a} + \rho_{0.24}^{4a}). \)
\( \rho_{0.66}, \rho_{0.47}, \rho_{2.12}, \rho_{1.2}, \rho_{0.66}, 0.47, 1.24, 2.12 \mu m, \)
\( \rho_{2.24}, \rho_{2.12}, \rho_{0.66}, 1.24, 2.12 \mu m \)
\( \Theta_1 \Theta_2 \Theta_3. \)

2.2  


2.3  

C005 (Dubovik, 2002b), (Levy, 2007).

AERONET (SSA): SSA-0.95, SSA-0.90, SSA-0.85 (Levy, 2007).

3  

3.1  

AERONET (SSA), NASA.

CNRS.

AERONET (SSA-0.95, SSA-0.90, SSA-0.85, Level 1.0, Level 1.5, Level 2.0).

AERONET (Holben, 1998). Level
2.0 AERONET MODIS MODIS

3.2 AERONET MODIS AERONET

3.2.1 AERONET MODIS AERONET

3.2.2 MODIS AERONET MODIS AERONET

Table 1: Study Station Wind Speed (m/s)

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<td>1.8</td>
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3.3 MODIS

MODIS MODIS MODIS MODIS MODIS MODIS

\[ \tau_{\text{MODIS}} = A\tau_{\text{AERONET}} + B \]
## 表2 北京站点TERRA、AQUA的MODIS气溶胶光学厚度满足NASA期望误差范围的概率统计

<table>
<thead>
<tr>
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<th>470nm</th>
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<th>660nm</th>
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<td>14.2</td>
<td>26.7</td>
<td>33.3</td>
</tr>
<tr>
<td>TERRA%</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
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<td>AQUA%</td>
<td>21.4</td>
<td>16.7</td>
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### 470nm

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<th>C005</th>
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<td>26.7</td>
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<td>MODIS</td>
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### 550nm

<table>
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<td>26.7</td>
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<tr>
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<td>20.0</td>
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### 660nm

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<td>16.7</td>
</tr>
<tr>
<td>MODIS</td>
<td>26.7</td>
<td>20.0</td>
</tr>
</tbody>
</table>

### 关于TERRA-MODIS

- TERRA-MODIS气溶胶光学厚度满足AERONET期望误差范围的概率统计
- AERONET气溶胶光学厚度满足TERRA-MODIS期望误差范围的概率统计

### NASA

- NASA期望误差范围为
  - 14.2\% ±0.05 ±0.15 \% (times)
  - 26.7\% ±0.05 ±0.15 \% (times)
  - 33.3\% ±0.05 ±0.15 \% (times)

### 470nm

<table>
<thead>
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<tbody>
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### 550nm

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### 660nm

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<tr>
<td>MODIS</td>
<td>20.0</td>
<td>20.0</td>
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</table>
表3 榆林站点TERRA、AQUA MODIS的气溶胶光学厚度产品满足NASA期望误差范围的概率统计

<table>
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<td>C005</td>
<td>C004</td>
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<td></td>
<td>52.0</td>
<td>76.5</td>
<td>68.0</td>
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<tr>
<td>AQUA</td>
<td>43.8</td>
<td>91.7</td>
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</table>
AERONET 16 12 470 550 660nm
AQUA C005 2 18 26 470 550 660nm
TERRA-MODIS C004 470 550 660nm

REFERENCES


Angstrom A. 1964. The parameters of atmospheric turbidity. Tellus, 16: 64—75

Chen B Q and Yang Y M. 2005. Validation of MODIS aerosol opti-

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**附中文参考文献**

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