Assessment of Aerosol Modes Used in the MODIS Ocean Aerosol Retrieval

JIACHENG WANG
College of Physics and Electronic Information, Fuyang University, Fuyang, China

QIANG ZHAO, SHENGCHENG CUI, AND CHENGJIE ZHU
Key Laboratory of General Optical Calibration and Characterization Techniques, and Remote Sensing Laboratory, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, HeFei, China

(Manuscript received 12 February 2012, in final form 9 July 2012)

ABSTRACT
Coastal and island Aerosol Robotic Network (AERONET) sites are used to determine characteristic aerosol modes over marine environments. They are compared with the assumed modes used in the operational Moderate Resolution Imaging Spectroradiometer (MODIS) ocean aerosol algorithm, and the results show that 1) the standard deviation values of three fine aerosol modes (0.6) and one dustlike aerosol mode (0.8) are much higher than the corresponding statistical AERONET modal values (0.45 and 0.6, respectively). The values of three sea salt aerosol modes (0.6) are somewhat lower than the corresponding statistical AERONET modal value (0.675). 2) The number median radius of the current fine and dustlike aerosol modes cannot span the dynamic range of corresponding aerosol distribution properly. 3) AERONET products show that the standard deviation and the number median radius exhibit an obvious negative correlation, especially for sea salt and dustlike aerosol modes. According to this, a refinement of the current aerosol modes is made. These revised modes are used in a version of the MODIS retrieval over ocean. Compared with the current aerosol modes: 1) more retrieved aerosol optical depths (AODs) from the revised aerosol modes lie within the expected error bars and 2) the linear regression lines of the retrievals from the revised aerosol modes and AERONET are closer to the 1:1 line.

1. Introduction
With some assumptions, the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol algorithm can derive three primary products: the spectral aerosol optical depth, the effective radius of the aerosol, and the fraction of the total optical depth contributed by the fine mode aerosol (Tanré et al. 1997). Some evaluation works on the MODIS aerosol retrieval over ocean have been done. For example, Remer et al. (2005, 2006) reported that two-thirds of the retrieved aerosol optical depth at 0.55 μm lie within the expected error bars; the correlation of MODIS-retrieved aerosol effective radius and Aerosol Robotic Network (AERONET) retrievals is less than 0.5. Kleidman et al. (2005) reported that although the correlation is high (R = 0.8), relative to the results of AERONET inversions, MODIS tends to slightly overestimate fine fraction for low values and underestimate fine fraction for high values. Some improved measures have been taken, such as changing the refractive indices of coarse modes (Remer et al. 2006). Although the changes to the coarse mode refractive indices make an improvement to the retrieval of aerosol size parameters over ocean, not all issues have been solved. The nonsphericity effect described by Levy et al. (2003) also has been taken into account, but its effects on the retrievals did not yield the desired results (Remer et al. 2006).

Some factors influence MODIS ocean aerosol retrievals. For example, the MODIS ocean algorithm is based on the weighted average of the radiances of two aerosol modes, which is not generally valid in scattering atmospheres, especially for larger aerosol optical depths (AODs), or absorption aerosol appearance. In addition, the same weighting parameter is used for all wavelengths; this is unreasonable (Zhang et al. 2007; Tanré et al. 1997). Aside from these factors, remote sensing of
tropospheric aerosols over sea is mainly impacted by uncertainties in the assumed aerosol properties, including size distribution, single-scattering albedo, and phase function (King et al. 1999). So, aerosol modes play a key role in aerosol retrieval over ocean, and retrieval error will increase if aerosol modes cannot represent ambient aerosols properly. The early aerosol modes proposed by Kaufman and Tanré (1998) are derived mainly from ground-based sampling of the aerosol characteristics, and they may not fully represent the size distribution of the ambient aerosol integrated along the vertical column (Kaufman and Tanré 1998). The current aerosol modes are shown in Table 1 (Remer et al. 2005). Four fine modes (F1–F4) represent water soluble aerosols, three coarse modes (C1–C3) represent sea salt aerosols, and two coarse modes (C5 and C6) represent dustlike aerosols. These aerosol modes are described by three parameters, that is, the refractive index, the median radius \( r_{\text{m}} \), and its standard deviation \( \sigma \). The refractive indices are based mostly on laboratory analysis. The median radius and the standard deviation are based on the Nakajima (1996) inversions of early AERONET instruments, which can retrieve the columnar aerosol features with accuracy and efficiency in several environmental situations, provided the input parameters are correctly given, but the observations are relatively small. AERONET has been used for nearly two decades and is implemented to measure the climatology and variability of the size distribution and scattering phase function of the ambient undisturbed aerosol for the entire vertical column (Holben et al. 1998; Dubovik and Smirnov 2000; Dubovik et al. 2002; Li et al. 2006, 2007, 2008, 2009). With the accumulation of such a large amount of AERONET observations, it is now feasible to assess aerosol modes used in the MODIS ocean aerosol retrieval. In this study, aerosol modes are assessed and refined based on the AERONET data. Tests of the revised aerosol modes show that the retrieved three main parameters (aerosol optical depth at 0.55 \( \mu \text{m} \), fine mode fraction, and effective radius) are improved.

2. Aerosol mode

There are two commonly used forms of the lognormal function for expressing aerosol size distribution. One form is volume particle size distribution, given by

\[
\frac{dV}{d\ln r} = V_0 \frac{r}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(\ln r - \ln r_{\text{eff}})^2}{2\sigma^2} \right],
\]

(1)

where \( V_0 \) denotes the column volume of the particles per cross section of atmospheric column, \( r_{\text{m}} \) is the volume median radius, and \( \sigma \) is the standard deviation of the natural logarithm of the radius for the volume distribution. Another form is the number particle size distribution, defined as

\[
\frac{dN}{d\ln r} = N_0 \frac{r}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(\ln r - \ln r_{\text{eff}})^2}{2\sigma^2} \right],
\]

(2)

where \( N_0 \) denotes the number of the particles per cross section of atmospheric column; \( r_{\text{m}} \) is the median radius of the number size distribution; and \( \sigma \) stays the same for

<p>| TABLE 1. Parameters of the current and revised aerosol modes. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Aerosol mode</th>
<th>( \lambda = 0.47–0.86 \mu m )</th>
<th>( \lambda = 1.24 \mu m )</th>
<th>( \lambda = 1.64 \mu m )</th>
<th>( \lambda = 2.12 \mu m )</th>
<th>Current modes</th>
<th>Revised modes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1 1.45 – 0.0035i</td>
<td>1.45 – 0.0035i</td>
<td>1.43 – 0.01i</td>
<td>1.40 – 0.005i</td>
<td>0.07</td>
<td>0.4</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>F2 1.45 – 0.0035i</td>
<td>1.45 – 0.0035i</td>
<td>1.43 – 0.01i</td>
<td>1.40 – 0.005i</td>
<td>0.06</td>
<td>0.6</td>
<td>0.15</td>
<td>0.08</td>
</tr>
<tr>
<td>F3 1.40 – 0.002i</td>
<td>1.40 – 0.002i</td>
<td>1.39 – 0.005i</td>
<td>1.36 – 0.003i</td>
<td>0.08</td>
<td>0.6</td>
<td>0.20</td>
<td>0.1</td>
</tr>
<tr>
<td>F4 1.40 – 0.002i</td>
<td>1.40 – 0.002i</td>
<td>1.39 – 0.005i</td>
<td>1.36 – 0.003i</td>
<td>0.10</td>
<td>0.6</td>
<td>0.25</td>
<td>0.12</td>
</tr>
<tr>
<td>C1 1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>0.4</td>
<td>0.6</td>
<td>0.98</td>
<td>0.4</td>
</tr>
<tr>
<td>C2 1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>0.6</td>
<td>0.6</td>
<td>1.48</td>
<td>0.6</td>
</tr>
<tr>
<td>C3 1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>0.8</td>
<td>0.6</td>
<td>1.98</td>
<td>0.8</td>
</tr>
<tr>
<td>C4 1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>1.35 – 0.001i</td>
<td>1.0</td>
<td>0.6</td>
<td>0.65</td>
<td>2.50</td>
</tr>
<tr>
<td>C5 1.53 – 0.003i (0.47 ( \mu m ))</td>
<td>1.46 – 0.000i</td>
<td>1.46 – 0.000i</td>
<td>1.46 – 0.000i</td>
<td>0.6</td>
<td>0.6</td>
<td>1.48</td>
<td>0.6</td>
</tr>
<tr>
<td>C6 1.53 – 0.003i (0.47 ( \mu m ))</td>
<td>1.46 – 0.000i</td>
<td>1.46 – 0.000i</td>
<td>1.46 – 0.000i</td>
<td>0.5</td>
<td>0.8</td>
<td>2.50</td>
<td>0.8</td>
</tr>
</tbody>
</table>
both volume and number size distributions. The parameter \( r_n \) is related to \( r_v \) by

\[
r_n = r_v \exp(-3a^2).
\]  

(3)

An actual size distribution can be expressed by a sum of lognormal functions, each representing a different physical or chemical process and can be described by one of the three modes, that is, nuclei mode, accumulation (or fine) mode, and coarse mode (Whitby 1978). The use of the lognormal functions for tropospheric aerosol size distribution was also suggested by Shettle and Fenn (1979), d’Almeida (1987), Kaufman et al. (1994), and Kaufman and Holben (1996). However, the nuclei mode is often not considered since it corresponds to particles that are too small to be detected from the scattered light. Therefore, bimodal lognormal distribution, defined by Eq. (4), is used to express the actual aerosol size distribution:

\[
dN/d\ln r = \sum_{i=1}^{2} N_{0,i} \exp \left[ -\frac{\ln r - \ln r_{n,i}}{2\sigma_i^2} \right].
\]  

(4)

3. AERONET data

Using the statistically optimized method, AERONET can provide aerosol optical properties of the total atmospheric column derived from the direct and diffuse radiation measured by sun photometers. The properties include retrieved properties (such as size distribution, complex refractive index, and partition of spherical/nonspherical particles) and calculated properties (such as phase function, single-scattering albedo, spectral and broadband fluxes, etc.). The inversion code finds the minimum \( dV/d\ln r \) within the size interval from 0.439 to 0.992 \( \mu \text{m} \). The radius correspond to the minimum is used as a separation point between fine and coarse modes. Based on this, optical depth, median radius, and standard deviation etc., can be derived for fine and coarse aerosols (http://aeronet.gsfc.nasa.gov; Dubovik et al. 2006).

There are several AERONET inversion products that can be used to assess aerosol modes, such as refractive index, median radius, and standard deviation of fine and coarse aerosols. But two reasons make it impossible to assess refractive indexes of aerosol modes. First, an accurate refractive index can be retrieved only for high aerosol loading [i.e., \( \tau_a(440) \geq 0.5 \)] (Dubovik and Smirnov 2000), but such high values rarely occur in marine environments. Second, the retrieval is implemented under the assumption that the complex refractive index is the same for both fine and coarse aerosols. The product, therefore, does not offer refractive indexes for fine and coarse aerosols. Because of the above-mentioned reasons, the refractive indexes from AERONET are not suitable for evaluation of MODIS ocean aerosol modes. However, Dubovik et al. (2000) has proven that the AERONET inversions of the particle volume size distribution, such as concentration, median, and effective radii, etc., are shown to be adequate in all situations. Therefore, the size distribution parameters (such as median radius and its standard deviation) of fine and coarse aerosols from AERONET are suitable for assessing the current MODIS ocean aerosol modes. AERONET products are fitted from \( dV/d\ln r \) distributions. We must convert \( r_v \) to \( r_n \) using Eq. (3), because \( r_n \) is used to describe the current MODIS aerosol modes.

4. Dataset

The AERONET level 1.5 data that go through the rigorous cloud screening process are collected for this study. More than 80 sites are selected, including 17 marine sites, 9 African and the Middle Eastern coastal sites, and 63 other coastal sites. The locations of these sites are shown in Fig. 1; the stars denote main sites that contain more than 80% of the observations. Fine aerosol data of all sites are used to assess fine aerosol modes. For the reason that coarse aerosols include not only sea salt aerosols but also dustlike aerosols, especially in the coastal environment; therefore, the coarse aerosol data must go through the following screening steps before they are used to assess sea salt and dustlike aerosol modes.

First, all the AERONET retrievals will be screened by the minimum-quality parameters suggested by Dubovik et al. (2000), including a solar zenith angle greater than 45°, a radiance retrieval error less than 4%, and \( \tau_a(440) \geq 0.05 \). In this way, the reliable data will be selected.
Second, the selected AERONET sites are classified into two groups, that is, African and Middle Eastern coastal sites (referred to as Africa sites), and the rest of the sites (referred to as non-Africa sites). This is the coarse screening process because coarse aerosols are dominated by dustlike and sea salt aerosols in Africa and non-Africa sites, respectively. Figures 2a,b show the correlation of \( r_n \) and \( \sigma \) of coarse aerosols in Africa and non-Africa sites. The two figures have similar shapes, that is, each of them has two clusters. In Africa sites, coarse aerosols are dominated by dustlike aerosols; therefore, the main cluster represents dustlike aerosols (black dots, i.e., the left branch, Fig. 2a), and the other cluster represents sea salt aerosols (gray dots, i.e., the right branch, Fig. 2a). Similarly, the main cluster in non-Africa sites represents sea salt aerosols (gray dots, i.e., the right branch, Fig. 2b), and the other cluster represents dustlike aerosols (black dots, i.e., the left branch, Fig. 2b). The joint histograms (Figs. 3a,c) show the results of the coarse screening process. As expected, the occurrence frequency of sea salt aerosols is much lower than dustlike aerosols in Africa sites and a higher occurrence than dustlike aerosols in non-Africa sites. These data can be used to validate dustlike and sea salt aerosol modes after further screening in the next step.

Third, coarse aerosol data must be screened by the requirements of \( \tau_{a}(440) \leq 0.35 \) for Africa sites and \( \text{sphericity} \geq 80\% \) for non-Africa sites (sphericity is a retrieved parameter of AERONET; higher sphericity means particles are closer to sphericity) (Dubovik et al. 2006). The criterion of \( \tau_{a}(440) \leq 0.35 \) is based on some studies. For example, Smirnov et al. (2002) ascribe \( \tau_{a}(500) > 0.35 \) [the corresponding \( \tau_{a}(440) \) is slightly larger than 0.35] to dust-dominated cases. In addition, Schuster et al. (2012) have pointed out that in “pure” dust cases, the average \( \tau_{a}(532) \) is 0.324. Analyses of Africa sites data show that \( \tau_{a}(532) \) and \( \tau_{a}(440) \) exhibit high correlation (correlation coefficient is about 0.96), and their relationship can be expressed as

\[
\tau_{a}(440) = 0.977 \times \tau_{a}(532) + 0.036. \tag{5}
\]

According to this, the \( \tau_{a}(440) \) value is 0.352 when \( \tau_{a}(532) = 0.324 \). Based on these studies, the criterion of \( \tau_{a}(440) \leq 0.35 \) is applied for screening coarse aerosol data in Africa sites. As shown in Fig. 3b, the right branch that represents sea salt aerosols is removed. This further proves that the criterion of \( \tau_{a}(440) \leq 0.35 \) is valid, and the selected data can be used to assess dustlike aerosol modes. Because sea salt aerosols are hygroscopic and have high sphericity, sphericity can serve as a sensitive parameter for screening coarse aerosol data in non-Africa sites. Statistical analyses of dustlike aerosols used in this study show that the sphericity of most dustlike aerosols is smaller than 80\%, and only 0.78\% of dustlike aerosols have sphericity higher than 80\%. Therefore, the criterion of sphericity greater than 80\% is applied for screening coarse aerosol data in non-Africa sites. As shown in Fig. 3d, the left branch that represents dustlike aerosols is removed. This also further proves that the criterion of sphericity greater than 80\% is valid, and that the selected data can be used to assess sea salt aerosol modes.

After these screening steps, the resulting dataset is composed of 33 142 fine aerosol inversions, 29 156 sea salt aerosol inversions, and 2411 dustlike aerosol inversions. These data will be used to assess the four fine modes (F1–F4), three sea salt aerosol modes (C1–C3), and two dustlike modes (C5 and C6) (Table 1).

5. Assessment

MODIS ocean-aerosol modes are relatively simple, four fine and five coarse modes are used to describe the
ambient fine and coarse aerosols, respectively; therefore, they should be able to represent the ambient fine and coarse aerosol distribution for wide regions in all seasons. The best method to assess such aerosol modes is the statistical analysis of the AERONET data collected from wide areas in all seasons.

The assessment focuses on the size distribution parameters of aerosol modes, that is, the number median radius, standard deviation, and effective radius.

a. Assessment of fine aerosol modes

The frequency distributions of the number median radii of fine aerosols at coastal, marine, and total sites are shown in Figs. 4a–c, respectively. They exhibit the following characteristics: First, the distribution of marine sites is narrow and peaks around 0.08 μm, while the distribution of coastal sites is relatively broader and peaks around 0.1 μm. This may be caused due to the different fine aerosol sources between coastal and marine environments. Second, the frequency distribution of the number median radii of all sites (Fig. 4c) presents a good symmetry, and nearly 90% of retrievals are contained within the number median radius range (0.06 ≤ \( r_n \) ≤ 0.12 μm). Therefore, in order to represent fine aerosols in both coastal and marine environments properly, the modal values of 0.08 and 0.1 μm should be assigned to the number median radii of fine aerosol modes. The number median radii (with values of 0.06, 0.07, 0.08, and 0.1 μm) of the current four fine modes can, to some extent, represent the number median radius distribution of fine aerosols; but as shown in Fig. 4c, the highest value of 0.1 μm is somewhat small and they cannot span the dynamic range properly. Thus, the number median radius values of the four fine aerosol modes can be changed to 0.06, 0.08, 0.1, and 0.12 μm, respectively.

The frequency distributions of \( \sigma \) of fine aerosols at coastal, marine, and total sites are shown in Figs. 5a–c, respectively. The maximums of \( \sigma \) frequency distributions at marine and coastal sites appear at around 0.45 and 0.425, respectively; and nearly 90% points lie within the range (0.35 ≤ \( \sigma \) ≤ 0.55). However, the standard deviations of current MODIS ocean fine aerosol modes are 0.6, except for the first fine aerosol mode with a value of 0.4. In both marine and coastal environments, the
standard deviation of 0.6 represents very few situations and should be changed.

Figure 6a shows the correlation of $r_n$ and $\sigma$ of fine aerosols at all sites. They display a nearly exponential decay relationship. The correlation coefficient is about 0.69. According to the relationship, $\sigma$ of the four fine aerosol modes should be 0.546, 0.479, 0.441, and 0.418, respectively.

Figure 7a shows the frequency of effective radius occurrences of fine aerosols at all selected sites. If the size distribution parameters of current fine aerosol modes are revised as above, the corresponding mode effective radii are 0.126, 0.142, 0.162, and 0.186 $\mu$m, respectively. These mode effective radii can properly span the dynamic range in Fig. 7a. The effective radii of the current fine modes F1 and F4 are 0.098 and 0.25 $\mu$m, respectively, and their occurrence frequencies are very low.

b. Assessment of sea salt aerosol modes

Figures 8a–c show the frequency distributions of number median radii of sea salt aerosols at coastal, marine, and total sites, respectively. In marine environments, the median radius distribution is narrow, and the modal value of the number median radius is around 0.6 $\mu$m. As shown in Fig. 8b, the median radius range ($0.25 \leq r_n \leq 0.95 \mu$m) contains about 90% of the retrievals. Thus, the median radii (with values of 0.4, 0.6, and 0.8 $\mu$m) of the current three sea salt modes can properly represent the median radius distribution of sea salt aerosols in marine environments. In coastal environments, however, larger sea salt aerosols ($r_n > 0.8 \mu$m) cannot be ignored (Fig. 8a); a new sea salt aerosol mode (C4) with a number median radius of 1.0 $\mu$m is added. In addition, the refractive indices of the current sea salt modes are assigned to the new mode due to the lack of reliable refractive indices from AERONET in marine environments.

The frequency distributions of standard deviations of sea salt aerosols at coastal, marine, and total sites are shown in Figs. 9a–c, respectively. The modal values of all distributions appear at around the same $\sigma$ value of 0.675, while the $\sigma$ values of all three sea salt modes is 0.6 and its occurrence frequency is less than 4% and 2% for coastal and marine sites, respectively. Therefore, it cannot represent sea salt aerosols properly and should be revised.

Figure 6b shows that the linear correlation between $r_n$ and $\sigma$ of sea salt aerosols from AERONET data is more than 0.87. According to the relationship, the $\sigma$ values of the four new sea salt aerosol modes will be 0.725, 0.685, 0.645, and 0.605.
Figure 7b shows the frequency of effective radius occurrences of sea salt aerosols at selected sites. If the size distribution parameters of current sea salt aerosol modes are revised as above, then the corresponding mode effective radii are 1.49, 1.94, 2.26, and 2.5 \( \mu m \), respectively. These mode effective radii can properly span the dynamic range in Fig. 7b. The effective radius of the current sea salt mode C1 is 0.98 \( \mu m \) and its occurrence frequencies is nearly zero. The highest effective radius of the current sea salt modes is 2.0 \( \mu m \), but there are more than 30\% of the effective radii that lie outside of 2.0 \( \mu m \). So, adding the new sea salt aerosol mode (C4) with effective radius of 2.5 \( \mu m \) is necessary.

c. Assessment of dustlike aerosol modes

Figure 10a shows the frequency distribution of number median radii of dustlike aerosols. The modal value of median radii is about 0.7 \( \mu m \), and more than 90\% of retrievals lie within the median radius range (0.5 \( \leq r_n \leq 0.9 \mu m \)). The number median radii (with values of 0.5 and 0.6 \( \mu m \)) of the two dustlike modes cannot fully represent the number median radius distribution of dustlike aerosols (Fig. 10a). Maybe the number median radius value of C6 (0.5 \( \mu m \)) should be replaced by 0.8 \( \mu m \).

The standard deviations of the two dust modes are 0.6 and 0.8. As shown in Fig. 10b, the value of 0.8 is too large and its occurrence frequency is nearly equal to zero.

Figure 6c shows the correlation between \( r_n \) and \( \sigma \) of dustlike aerosols. They display an approximate linear relationship. The correlation coefficient is about 0.81. According to the relationship, the \( \sigma \) values of the two dustlike aerosol modes are 0.63 and 0.55.

Figure 7c shows the frequency distribution of effective radius of dustlike aerosols at the selected sites. If the size distribution parameters of current dustlike aerosol modes are revised as above, then the corresponding effective radii are 1.64 and 1.76 \( \mu m \), respectively. The effective radius of the current dustlike coarse mode C6 is 2.5 \( \mu m \), and its occurrence frequencies is nearly zero.
It should be noted that sea salt aerosols have a larger effective radius than dustlike aerosols (Figs. 7b,c). Thus, adding the new sea salt aerosol mode with a large effective radius (2.5 μm) and removing one dustlike aerosol mode with an effective radius of 2.5 μm is necessary.

Based on these results, a suggested revision of the current aerosol modes is proposed and shown in Table 1.

6. Test of the revised aerosol modes

At this stage, we just test the validity of the proposed modes for the retrieval of aerosol properties. Further assessment of the new modes will be done and reported later.

a. Calculation of lookup tables

New lookup tables (LUTs) are calculated based on the revised aerosol modes. The calculation should account for multiple scattering in the atmosphere by molecules and aerosol particles and for reflection of the light by the ocean surface, that is, the Fresnel reflection on the waves, the Lambertian reflectance coming from underwater scattering elements, and reflection by foam. The polarization effects should also be included (Tanré et al. 1997). The current LUTs used in the MODIS ocean algorithm is calculated with the radiative transfer code developed by Ahmad and Fraser (1982). Because of the lack of accessing of the same code, the Second Simulation of a Satellite Signal in the Solar Spectrum (6S) vector radiative transfer code, which fully accounts for all of the above factors, is used to calculate LUTs for the revised aerosol modes.

Retrievals with the revised aerosol modes are carried out by using the International MODIS/Atmospheric Infrared Sounder (AIRS) Processing Package (IMAPP) aerosol standalone software. The code is based on the algorithm described in Remer et al. (2006). The code requires MODIS level 1B hierarchical data format (HDF) radiance and geolocation files. These HDF data are extracted into flat binary files and used as input into the science product software. Some external dynamic ancillary data are also needed, for example, the Television Infrared Observation Satellite Operational Vertical Sounder (TOVS) global ozone gridded binary (GRIB)
data or Toast global ozone data, etc. (ftp://ftp.ssec.wisc.edu/pub/eosdb/ancillary/00README_ANCILLARY.txt). All required dynamic ancillary datasets are updated daily and are available online (ftp://ftp.ssec.wisc.edu/).

b. Test approach

A test of the revised aerosol modes is carried out by comparing with collocated measurements from AERONET, which go through a rigorous cloud screening process (Smirnov et al. 2000). For the Dubovik inversion, the optical depth and the optical extinction ratios of fine to total aerosol are calculated at 0.44 and 0.67 \( \mu \text{m} \) and are linearly interpolated to the MODIS reference wavelength at 0.55 \( \mu \text{m} \). The methodology of comparing temporally varying AERONET data with spatially varying MODIS data is described in Ichoku et al. (2002). AERONET data within a 1-h window (±30 min) around the MODIS overpass are averaged and compared with the mean of the MODIS data collected in a 50 km × 50 km (5 × 5 aerosol “pixels”) box centered on the AERONET site. Not all of the 25 aerosol pixels contain ocean-aerosol retrievals because of the appearance of clouds, sun glint, case II water, or land. In order for more data to be included in the validation, we require a minimum of one AERONET retrieval within the hour and 4 out of 25 MODIS ocean retrievals within the box.

The AERONET data of Clouds and the Earth’s Radiant Energy System Ocean Validation Experiment (COVE), Martha’s Vineyard Coastal Observatory (MVCO), Hong_Kong_Hok_Isui, Dakar, and Midway Island sites are selected for testing the revised aerosol modes. The level 2.0 data, which are pre- and postfield calibrated, cloud screened, and quality assured, are used in the test. However, AERONET level 1.5 data will be used if the level 2.0 data are unavailable. Different aerosol sources, aerosol loading, and size distribution are the main reasons for selecting these sites. COVE (36.900°N, 75.710°W), MVCO (41.3°N, 70.55°W), and Hong_Kong_Hok_Isui (22.2097°N, 114.258°E) are located in coastal areas for measuring the background and marine aerosols. Aerosols in the three sites include fine, dustlike, and sea salt aerosols. Dakar (14.39°N, 16.9°W) is an Africa coastal site that is influenced by dustlike aerosols. Midway Island (28.21°N, 177.38°W) is a marine site. Different from the other four sites, aerosols here are mainly dominated by sea salt and fine aerosols.

c. Test results

Figure 11a shows the retrieved AOD at 0.55\( \mu \text{m} \) from the current and the revised aerosol modes compared with AERONET data. About 71.1% of retrievals from the revised aerosol modes lie within the expected error bars, more than the current aerosol modes (about 61.3%). The improvements occurred mainly in coastal sites; this is because fine aerosol modes have been better revised and fine aerosols are the main components in coastal environments.

Figure 11b shows the retrieved fine aerosol fraction (the fraction of the total optical depth contributed by the fine mode aerosol) from the current and the revised aerosol modes compared with AERONET data. The correlation of the retrieved fine aerosol fraction between the revised aerosol modes and AERONET is about 0.88, and the fit line is close to the 1:1 line, while the correlation of the retrieved fine aerosol fraction between the current aerosol modes and AERONET is about 0.84, and the current aerosol modes tends to overestimate the fine aerosol fraction for low values.

Figure 11c shows the retrieved effective radius from the current and the revised aerosol modes compared with AERONET data. The current aerosol modes tend to underestimate the effective radius, especially for high values. The revised aerosol modes have corrected such a case. The reasons may be as follows: First, adding new sea salt aerosol mode C4 (Table 1), whose effective

---

*Fig. 10. The frequency of number median radius and standard deviation occurrences of dustlike aerosols.*
radius is 2.5 μm. Second, the standard deviations of the current sea salt aerosol modes C1–C3 have been changed to large values according to the relationship of $r_m$ and $\sigma$, and this leads to the increase of their effective radii, therefore influencing the retrieved aerosol effective radius.

7. Conclusions and discussion

The aerosol modes used in the MODIS ocean-aerosol retrieval are assessed based on the AERONET data of coastal and marine sites. The principal conclusions drawn from this study can be summarized as follows:

1) The number median radius of the current fine and dustlike aerosol modes cannot span the dynamic range of the corresponding aerosol distribution properly.

2) The standard deviation values of the current three fine aerosol modes (0.6) and one dustlike aerosol mode (0.8) are much higher than the corresponding statistical AERONET modal values (0.45 and 0.6, respectively). The values of three sea salt aerosol modes (0.6) are somewhat lower than the corresponding statistical AERONET modal value (0.675).

3) AERONET products show that the standard deviation and the number median radius exhibit an obvious negative correlation, especially for sea salt and dustlike aerosol modes.

4) The revised aerosol modes are proposed based on the analysis of AERONET data, and they can improve aerosol retrievals of aerosol optical depth, fine aerosol fraction, and effective radius to some degree.

One of the advantages of the revised aerosol modes is the adoption of the dynamic standard deviation according to the relationship between the median radius and the standard deviation. At present, some aerosol modes use invariable standard deviations for fine and coarse modes, such as the new suite aerosol models proposed by Ahmad et al. (2010) for the retrieval of atmospheric and oceanic optical properties from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and MODIS sensors. The new suit of aerosol models are constructed from fine and coarse modes at 8 relative humidity (RH) values and 10 distributions by varying the fine mode fraction from 0 to 1. In their study, they focus on the relationship between aerosol mode parameters and RH. Because the standard deviation and RH do not show any correlation, they use the 1-month average values—i.e., 0.437 and 0.672—for fine and coarse modes, respectively. It should be noted that the standard deviation of fine and coarse modes vary from about 0.4 to 0.6 and from 0.6 to 0.75, respectively. Average approximation will influence the aerosol and water-leaving radiance retrievals. The proposed parameter relationship in this study will help to determine reasonable standard deviations for fine and coarse modes.

The disadvantage is that the refractive index is not assessed and stays the same with the current aerosol modes. AERONET provides a long-term, continuous database of aerosol optical, microphysical, and radiative properties for aerosol research and characterization, and validation of satellite retrievals. But it fails to provide a reasonable refractive index when the aerosol optical depth is low, and the refractive indexes are assumed the same for both fine and coarse aerosols. However, there may be still some work that can be done based on the AERONET database. For the next step, we would try to evaluate the refractive index of dustlike aerosol modes using AERONET data from Africa sites where high AODs often occur and a reliable refractive index can be obtained from AERONET.
Acknowledgments. We are grateful to the various MODIS software development and support teams for the production and distribution of the MODIS data, and to the AERONET teams for collecting, processing, and making available ground-based aerosol observations from around the world. We also thank Lorraine Remer for giving us some constructive suggestions. This work was supported by the Project KJ2012B137 and by the National Natural Science Foundation of China Grants 41005016 and 41174037.

REFERENCES


