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Atmospheric Measurement Techniques Discussions

Effect of spectrally varying albedo of vegetation surfaces on shortwave radiation fluxes and direct aerosol forcing

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Abstract

This study develops an algorithm for the representation of large spectral variations of albedo over vegetation surfaces based on Moderate Resolution Imaging Spectrometer (MODIS) observations at 7 discrete channels centered at 0.47, 0.55, 0.67, 0.86, 1.24, 1.63, and 2.11 µm. The MODIS 7-channel observations miss several major features of vegetation albedo including the vegetation red edge near 0.7 µm and vegetation absorption features at 1.48 and 1.92 µm. We characterize these features by investigating aerosol forcing in different spectral ranges. We show that the correction at 0.7 µm is the most sensitive and important due to the presence of the red edge and strong solar radiation; the other two corrections are less sensitive due to the weaker solar radiation and strong atmospheric water absorption. Four traditional approaches for estimating the reflectance spectrum and the MODIS enhanced vegetation albedo (MEVA) are tested against various vegetation types: dry grass, green grass, conifer, and deciduous from the John Hopkins University (JHU) spectral library; aspens from the US Geological Survey (USGS) digital spectral library; and Amazon vegetation types. Compared to traditional approaches, MEVA improves the accuracy of the outgoing flux at the top of the atmosphere by over 60 W m^{-2} and aerosol forcing by over 10 W m^{-2}. Specifically, for Amazon vegetation types, MEVA can improve the accuracy of daily averaged aerosol forcing at equator at equinox by 3.7 W m^{-2} (about 70 % of the aerosol forcing calculated with high spectral resolution surface reflectance). These improvements indicate that MEVA can contribute to vegetation covered regional climate studies, and help to improve understanding of climate processes and climate change.

1 Introduction

Vegetation covered land surface and the climate are linked together through complex ecological, hydrological, and biogeochemical processes (Dickinson, 1983, 1995; Dirmeyer and Shukla, 1994; Lyapustin, 1999; Betts, 2000; Lucht et al., 2002). Among

AMTD
5, 4041–4076, 2012

these processes, the surface directly reflects the solar radiation and affects the Earth's energy balance, and hence the climate (Cess, 1978; Lofgren, 1995). The knowledge of the surface albedo properties affects earth-atmosphere system related calculations and retrievals such as the direct aerosol forcing calculation (Yu et al., 2006; McComiskey et al., 2008) and cloud properties retrieval (Popp et al., 2011). Specifically, spectral surface albedo is affected by leaf structure, water content, pigment, chlorophyl, etc. (Collins, 1978; Kim et al., 1994; Asner et al., 2000; Ceccato et al., 2001). The Fig. 1 of the black sky albedo calculated from Moderate Resolution Imaging Spectroradiometer (MODIS) data shows that vegetation albedo has large spatial and spectral variations. Adequate representation of these variations is important for estimating radiative flux and aerosol radiative forcing.

Much work has been done to capture vegetation surface reflectance and albedo. Directly, surface albedo can be obtained from field measurements (Gilgen et al., 1995; Sellers et al., 1992; Hall and Sellers, 1995). Leaf samples have also been collected and their reflectance has been determined by spectrophotometers (Hosgood et al., 1994; Clark et al., 2007). Additionally, remote sensing techniques have been widely used to determine surface albedo, for instance the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Staenz et al., 1996), and many satellite operations including, but not limited to: Global Ozone Monitoring Experiment (GOME) (Kolemeijer et al., 2003), MEdium Resolution Imaging Spectrometer (MERIS) (Muller, 2006), Polarization and Directionality of the Earth's Reflectances (POLDER) (Leroy et al., 1997), Multiangle Imaging Spectroradiometer (MISR) (Diner, 2008), Advanced Very High Resolution Radiometer (AVHRR) (Saunders, 1990), Visible Infrared Imager Radiometer Suite (VIIRS) (Miller, 2002), and Moderate Resolution Imaging Spectroradiometer (MODIS) (Liang et al., 1999; Lucht et al., 2000; Schaaf et al., 2002; Moody et al., 2005).

Specifically, the MODIS sensor on board the NASA polar satellites TERRA (1999–present) and AQUA (2000–present) measures the reflected solar radiation at the top of the atmosphere (TOA) which can be used to retrieve surface properties (Vermote et al., 1997). The MODIS land science team has used the MODIS measurements to

AMTD
5, 4041–4076, 2012

develop a series of surface albedo data products, including MCD43C among others. In detail, MCD43C provides three spectrally dependent parameters f_{iso}, f_{vol}, f_{geo} for calculating black sky albedo and white sky albedo when combined with a BRDF model. These parameters are available at MODIS bands 1 to 7 (nominally centered at 0.47, 0.55, 0.67, 0.86, 1.24, 1.63, and 2.11 µm), and in the spectral ranges of visible (0.3 to 0.7 µm), near infrared (0.7 to 5 µm), and total broadband (0.3 to 5 µm).

Satellite remote sensing techniques have the advantages of having larger spatial and longer temporal coverage than in situ measurements. However, they can only measure albedo at certain narrow bands and have the drawback of inadequately characterizing spectral variations. For flux and aerosol forcing calculations, broadband albedo is generally used and narrow band albedo is usually ignored (Myhre et al., 2005; Zhou et al., 2005; Patadi et al., 2009). The limited spectral reflectance information and the simplified broad band albedos can be error prone in radiative forcing calculations (Wang et al., 2011).

This work presents a new algorithm – the MODIS enhanced vegetation albedo (MEVA) – to provide an integrated vegetation reflectance spectrum, with the advantage of global and temporal coverage over the lifetime of MODIS. Given reflectance at MODIS bands 1–7, this project demonstrates that the vegetation reflectance spectrum determined by the MEVA algorithm improves the accuracy of the TOA flux and aerosol forcing calculations.

2 Methodology

2.1 Traditional approaches

Several methods have been traditionally used to integrate the surface albedo over the whole solar spectrum based on the MODIS bands 1–7. These methods are illustrated in Fig. 3 based on the reflectance spectrum of *miconia guianensis* adapted from Arai et al. (2010): (a) the narrowband reflectance is converted to reflectance in total shortwave broadband (from 0.3 to 2.5 µm) (Liang et al., 1999); (b) narrowband reflectance at MODIS bands 1–7 is converted to reflectance in broadband "visible" (from 0.3 to 0.7 µm) and "near infrared" (from 0.7 to 2.5 µm) according to Liang et al. (1999); (c) the wavelength between two adjacent MODIS channels are averaged (which leads to 0.51, 0.61, 0.77, 1.10, 1.44, and 1.87 µm) and seven reflectance values from MODIS are assigned to the following bands: from 0.3 to 0.51 µm, from 0.51 to 0.61 µm, and so on (denoted "average band MODIS" in following discussions); (d) The reflectance at MODIS bands 1–7 is linearly interpolated. The conversions in approach (a) and (b) are performed through the method described in Liang et al. (1999). Using the reflectance spectrum of vegetation *miconia guianensis* adopted from Arai et al. (2010) as an example, Fig. 3 illustrates the above four approaches.

This research will show that all of these traditional techniques produce significant errors in estimating TOA radiative fluxes and aerosol forcing. The new methodology proposed here based on MODIS bands 1–7 (MEVA – MODIS enhanced vegetation albedo) will minimize these errors. TOA fluxes and aerosol forcing will be calculated for all these methods (traditional and proposed) and will be compared with the results calculated from the high resolution spectral libraries.

2.2 MODIS enhanced vegetation albedo (MEVA)

We now describe a new empirical method which will show how the seven MODIS narrowband albedos can be extended in a continuous reflectance spectrum to minimize errors in the calculation of fluxes at the TOA and lead to more accurate aerosol radiative forcing and flux calculations.

As shown by the solid blue line in Fig. 3d, it is possible to linearly connect reflectance at MODIS bands 1–7 in order to interpolate the reflectance data. However, in this method, there are three distinct features missing from the actual spectrum, which can be seen in the shadowed areas in Fig. 4b.

The first missing feature is associated with the vegetation red edge around 0.7 µm, which is the division between the low reflectance in the visible and high reflectance

AMTD
5, 4041–4076, 2012

in the near infrared. The red edge in the vegetation surface reflectance spectra have been used to study chlorophyl, water content, pigment content properties, and more (Horler et al., 1983; Guyot et al., 1992; Gitelson et al., 1996; Sims and Gamon, 2002; Stimson et al., 2005). As shown in Fig. 4a, solar radiation is strong around 0.7 µm, which intensifies the errors in flux and aerosol forcing calculations associated with the missing feature of the red edge. The other two important missing features in the interpolated spectrum are around 1.44 and 1.92 µm due to radiation absorption by water. These two missing features are expected to lead to smaller errors, due to the weaker solar radiation and the strong atmospheric water vapor absorption in these two spectral ranges as shown in Fig. 4a. These error sensitivities are discussed in more detail in the following section through flux and aerosol forcing calculation in different spectral ranges as shown in Table 3.

The MODIS enhanced vegetation albedo (MEVA) algorithm is proposed here to minimize the errors in flux and aerosol forcing calculations associated with these missing features. Based on these missing features, MEVA include 7 auxiliary channels (0.69, 0.72, a variable channel at the top of the red edge, 1.44, 1.84, 1.92, and 3 µm). Four of these auxiliary channels are shown in Fig. 5: the reflectance at 0.69 µm is obtained by linearly extrapolating the reflectance at 0.55 and 0.67 µm; the reflectance at 0.72 µm is the average between 0.69 µm and 0.86 µm; the reflectance at 1.44 µm is 40 % of the reflectance at 1.24 µm; the reflectance at 1.92 µm is 20 % of the reflectance value at 1.63 µm. The remaining three auxiliary channels are a variable channel at the top of the red edge, and at 1.84 and 3 µm as shown in Fig. 6. The variable channel at the top of the red edge is defined as the crossing point between the linearly extrapolated line connecting 0.69 to 0.72 µm and the linearly extrapolated line connecting 1.24 and 0.86 µm; the reflectance at 1.84 µm is determined by linearly interpolating the reflectance at 1.63 and 2.11 µm; the reflectance at 3 µm is set to zero. Finally, the reflectance between 0.3 and 0.4 µm were set constant to the reflectance at 0.47 µm. The auxiliary channels and the values of ratios were determined here by the general behavior of vegetation spectra. The final result is a reflectance spectrum based on

AMTD
5, 4041–4076, 2012

the MODIS bands 1–7 that better resembles the most important features of a typical vegetation spectral reflectance. With *miconia guianensis* (named "vegetation 5" in the discussion) as an example, the MEVA spectrum is displayed as the solid blue line in Fig. 6.

3 Evaluation of the methodology

In order to evaluate the relative merits of the MEVA methodology versus traditional approaches to interpolate the MODIS bands 1–7, several vegetation spectra were used in the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) program (Ricchiazzi et al., 1998) to calculate examples of the outgoing flux at TOA and the direct aerosol forcing. Here the direct radiative forcing is defined as the difference of total outgoing flux at TOA under clear sky with and without aerosols. A positive direct aerosol forcing value indicates that aerosols warm the earth-atmosphere system, and a negative value shows that aerosols cool the earth-atmosphere system. During the simulation, the surface is assumed to be Lambertian, albedo is equal to reflectance, aerosol optical depth (AOD) (at 0.55 µm) = 0.32, single scattering albedo (SSA) (at 0.55 µm) = 0.89, and solar zenith angle (SZA) = 30°. The vegetation reflectance spectra used in this study (denoted "true" in following discussions) were taken from the JHU spectral library, the USGS Digital Spectral Library (Clark et al., 2007), and the spectral signatures of leaves from Amazonian trees presented by Arai et al. (2010).

3.1 Dry grass, green grass, conifer, and deciduous surfaces

In this section, the sampled vegetation types are dry grass, green grass, conifer, and deciduous; their reflectance spectra are provided by the JHU spectral library. Given reflectance at MODIS bands 1–7, the reflectance spectra are reconstructed through the methods discussed in the last section. Figure 7 shows the reflectance spectrum provided by the spectral library ("true") and MEVA. Though the dry grass case shows large

AMTD
5, 4041–4076, 2012

difference between MEVA and the "true" spectrum, it was kept in all our calculations as an example of the "worst case" scenario.

For each vegetation type, the outgoing flux at TOA and aerosol forcing (from 0.3 to 2.5 µm) was calculated with the reflectance spectrum obtained from the high resolution spectral libraries ("true"), traditional approaches (the linear MODIS, the averaged band MODIS, the Liang visible and near infrared, the Liang shortwave), and the MEVA method. The results are summarized in Table 1 and Table 2. As shown in Table 1, MEVA produces the outgoing flux that is closest to the "true" in all cases, with the difference varying from 0.58 to 1.31 $W m^{-2}$, while the maximum deviation associated with other methods reaches 23 $W m^{-2}$. With the exception of dry grass, Table 2 shows that MEVA yields the aerosol forcing that is closest to the "true" with regard to aerosol forcing magnitude (varying from 0.43 to 0.63 $W m^{-2}$) and percentage (below 10 %). The exception of dry grass is explained in the following sensitivity discussion.

The sensitivity of aerosol forcing in different spectral ranges are investigated and shown in Table 3 for a deciduous vegetation surface. For the aerosol forcing in the spectral range of 0.55 to 1.24 µm, MEVA provides a difference of 0.35 $W m^{-2}$ from the "true", as compared to differences between −1.41 to −2.67 $W m^{-2}$ from traditional approaches. This demonstrates that MEVA surpasses traditional approaches in calculating aerosol forcing. It can also be observed from Table 3 that the spectral range from 0.55 to 1.24 µm presents the largest difference between each method and calculations with the "true" spectrum (except for the case of Liang shortwave). These results indicate the importance of the correction for the missing feature of the vegetation red edge around 0.7 µm, which is consistent with the discussion in Sect. 2.2. In the same fashion, corrections through MEVA for the other missing features around 1.48 and 1.92 µm lead to the closest aerosol forcing to "true", with differences of −0.03 and 0.01 $W m^{-2}$, compared to the values from 0.01 to 0.08 $W m^{-2}$ estimated through traditional approaches.

According to Table 3, the values of differences for the correction of the water absorption missing features (shown in the spectral range of 1.24 to 1.63 and 1.84 to 2.1 µm) are smaller than the values of the difference obtained for the correction of the red edge missing feature (shown in the spectral range of 0.55 to 1.24 µm). This result indicates that corrections for the water absorption missing features are relatively less sensitive than that for the missing red edge feature. This conclusion is well explained by the relatively weaker solar radiation and stronger atmospheric water absorption around 1.48 µm and 1.92 µm than those around 0.7 µm as shown in Fig. 4a. Very similar results were derived in the analysis of green grass, conifer, aspens, and Amazon vegetation. The spectral analysis for dry grass indicates that the aerosol forcing difference of 1.84 $W m^{-2}$ between MEVA and "true" (as in Table 2) is predominantly caused by the difference in the spectral range of 0.3 to 0.55 µm, where the difference is 1.86 $W m^{-2}$ (compared to 0.17, −0.14, −0.01, −0.01, and −0.01 in the other five spectral ranges: 0.55 to 1.24, 1.24 to 1.63, 1.63 to 1.84, 1.84 to 2.1 and 2.1 to 2.5 µm). This might be related with the distinct spectral feature of dry grass in the range of the 0.3 to 0.55 µm where the reflectance peak at 0.55 µm is absent compared with other vegetation types (as shown in Fig. 7). This spectral behavior might be caused by the low chlorophyl and water moisture content of dry grass (Hoffer, 1978). In general, the results in Table 3 justify the corrections by MEVA for the three missing features shown in Fig. 4.

3.2 Aspen surfaces

In this section, the above procedures are applied to the reflectance spectrum for aspen surfaces provided by the USGS digital spectral library (Clark et al., 2007). "Aspen 1" (green leaf), "aspen 2" (green leaf), "aspen 3" (yellow-green leaf), and "aspen 4" (yellow leaf) were sampled in Boulder, Colorado, USA, and their reflectances were measured by a laboratory spectrometer; "aspen 5" was sampled in Yellowstone National Park, Wyoming, USA, and its reflectance spectrum was retrieved from AVIRIS data; "aspen 6" was collected in Denver, Colorado, USA, and its reflectance spectrum is the average of the three measured spectra. Figure 8 shows the reflectance spectra from "true" and MEVA for these six different aspen surfaces.

The outgoing flux at TOA and aerosol forcing were calculated using these reflectance spectra as surface albedo, and the results are shown in Tables 4 and 5. With the exception of aspen 4, MEVA leads to the minimum difference to "true" for both flux and aerosol forcing compared to traditional approaches. The aerosol forcing difference between MEVA and "true" is 0.61 W m^{-2} for aspen 4, which is greater than the difference of −0.36 W m^{-2} from the average band MODIS method. This might be related with the leaf color being "yellow", which implies strong reflectance in the range of 0.57 to 0.59 µm which can be seen in Fig. 8. Similar to the spectral behavior of dry grass, the spectral behavior of aspen 4 might be caused by its low chlorophyl and water moisture content (Hoffer, 1978). This indicates that MEVA works best for green vegetation types, but still produces reasonable results for yellow leaves. Overall, MEVA consistently improves the accuracy of the calculated outgoing flux at TOA and aerosol forcing.

3.3 Amazon vegetation

Results for Amazonian vegetation are specifically investigated in this section. The Amazon forest plays a unique role in climate change (Shukla et al., 1990; Nobre et al., 1991). However, Amazon vegetation reflectance data is scarce (Roberts et al., 1990; Arai et al., 2010). The reflectance spectrum for six Amazon vegetation types from Arai et al. (2010) were shown in Fig. 9 overlaid with their MEVA. The spectra from Arai et al. did not show the reflectance value in the range of 1.35 to 1.45 µm and 1.85 to 1.95 µm, which were linearly connected in this study to represent "true".

In a more detailed analysis, the outgoing flux at TOA and aerosol forcing were calculated with three different typical biomass burning aerosol models shown in Fig. 10: SSA (at 0.55 µm) = 0.95, 0.89, and 0.83, with AOD (at 0.55 µm) = 0.32. The SSA curves are simulated from Mie code (Wiscombe, 1980) with 1.4589 as the real part of the refractive index and three cases of imaginary refractive index equal to 0.0073, 0.0173, and 0.0273. The size distribution was calculated through the Amazonian forest aerosol model by Dubovik et al. (2002).

Similar to the earlier results for green grass, canopy, deciduous, and aspens, the results for Amazon vegetation also indicate that the MEVA algorithm leads to the best approximation to the "true" surface albedo spectra, regarding the accuracy of the outgoing

AMTD
5, 4041–4076, 2012

flux at TOA and the aerosol direct forcing. Furthermore, Fig. 11 shows that MEVA yields an aerosol forcing efficiency (in $W m^{-2}$/AOD) closest to that provided by "true" surface albedo spectra.

Moreover, the differences of the aerosol forcing efficiency associated with different methods to estimate reflectance spectrum are averaged over the studied six Amazonian vegetation types. The results in Fig. 12 indicate that the aerosol forcing efficiency calculated through MEVA, about $1 W m^{-2}$/AOD, is the closest to that from "true" than traditional approaches. The same conclusion is drawn from the studies with AODs equal to 0.64 and 1.28 (at 0.55 µm).

In order to investigate the daily average aerosol forcing at equator at equinox, the aerosol forcing was calculated with SZA varying from 0 to 90°. Figure 13 indicates that MEVA yields aerosol forcing closest to that from "true" for all vegetation types and under all SZAs (especially when SZA is smaller than 60°) than traditional approaches. The daily averaged aerosol forcing at equator at equinox was determined by the 24 h average aerosol forcing. Table 6 shows that MEVA produces a daily average aerosol forcing at equator at equinox closest to that from "true" compared to traditional approaches for all vegetation types. We also average the daily average aerosol forcing at equator at equinox over the studied six vegetation types. The results, shown in the last column of Table 6, indicate that MEVA is the best approximation to the "true" case using the high resolution surface reflectance spectrum. The magnitude of the average aerosol forcing difference between MEVA and "true" is about $0.05 W m^{-2}$, much smaller than −0.95, −1.09, −0.73, and $3.80 W m^{-2}$ calculated using traditional approaches. The magnitude of the ratio of this difference to that from "true" is also the minimum at −0.9 % compared to 18.0 %, 20.6 %, 13.8 %, and −71.8 % estimated through traditional approaches. A similar investigation was done with different aerosol models: SSA (at 0.55 µm) = 0.95 and 0.83; AOD (at 0.55 µm) = 0.64 and 1.28. Consistently, the results show that MEVA yields average aerosol forcing closest to that from "true" compared with traditional approaches.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD

5, 4041–4076, 2012

Effect of spectrally varying albedo of vegetation surfaces

L. Zhu et al.

4 Conclusions

In this research, a new approach called MEVA was developed to estimate the continuous vegetation reflectance spectrum using the reflectance measurements acquired from MODIS seven bands, namely 0.47, 0.55, 0.67, 0.86, 1.24, 1.63, and 2.11 µm. The approach enhances the MODIS vegetation albedo product by characterizing large spectral variation features at 0.7, 1.44, and 1.92 µm that are missing in the MODIS observations. Several sources of vegetation spectral reflectance were used to evaluate the MEVA approach: the JHU spectral library (for dry grass, green grass, conifer, and deciduous surfaces), the USGS digital spectral library (for aspen surface), and measurements of six Amazon vegetation types. The correction to the missing red edge feature at 0.7 µm is the most significant due to the strong solar radiation input in this spectral range; the other two corrections are less important, due to the weaker solar radiation and strong atmospheric water absorption.

Flux and aerosol forcing calculation results indicate that MEVA has significant advantages over traditional approaches in accurately calculating radiative fluxes and aerosol radiative forcing. In the studied cases with AOD (at 0.55 µm) = 0.32, MEVA improved the accuracy of the outgoing flux at TOA by 60 W m^{-2} (nearly 20 % of the flux value derived from "true"), aerosol forcing by 10 W m^{-2} (about 70 % of the forcing value derived from "true"), daily averaged aerosol forcing at equator at equinox by 3.7 W m^{-2} (about 70 % of the forcing value derived from "true"). A similar conclusion was drawn from parallel studies applying AOD (at 0.55 µm) = 0.64 and 1.28. For aerosol forcing, MEVA led to errors less than 1 W m^{-2} with the exception of dry grass which produced an error of 1.84 W m^{-2}. This greater error might be associated with lower chrolophyl and water content of dry grass compared with the other discussed vegetation types. The combination of MEVA results with our retrievals of SSA for biomass burning aerosols (Zhu et al., 2011) will improve the estimate of radiative forcing and their impacts on climate by providing more accurate flux and aerosol forcing calculations.

AMTD
5, 4041–4076, 2012

Our exercise in this study shows that MEVA can be employed to improve the accuracy of flux and aerosol forcing calculations for vegetated surfaces. Particularly, with the publically available global surface albedo data at MODIS seven channels, MEVA can be integrated into radiative transfer calculations and contribute to regional climate studies over vegetated areas.

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AMTD
5, 4041–4076, 2012

Table 1. The calculated outgoing flux (in W m^{-2}; from 0.3 to 2.5 µm) at TOA over dry grass, green grass, conifer, and deciduous surfaces. Other parameters used include AOD (at 0.55 µm) of 0.32, SSA (at 0.55 µm) of 0.89, and SZA of 30°. Bold numbers represent the difference in flux associated with different approaches to estimate the surface reflectance spectrum.

Flux (in W m^{-2})	Dry grass	Green grass	Conifer	Deciduous
True	362.17	237.18	234.99	251.21
MEVA	361.59	238.49	235.84	252.49
Linear MODIS	357.37	223.53	218.61	235.17
Averaged band MODIS	360.04	223.05	218.84	234.98
Liang visible and near infrared	352.63	221.03	218.42	235.96
Liang shortwave	363.12	213.79	212.33	229.96
Differences of flux (in W m^{-2})				
MEVA – True	**−0.58**	**1.31**	**0.85**	**1.28**
Linear MODIS – True	**−4.8**	**−13.65**	**−16.38**	**−16.04**
Average band MODIS – True	**−2.13**	**−14.13**	**−16.15**	**−16.23**
Liang visible and near infrared – True	**−9.54**	**−16.15**	**−16.57**	**−15.25**
Liang shortwave – True	**0.95**	**−23.39**	**−22.66**	**−21.25**

AMTD
5, 4041–4076, 2012

Table 2. The calculated aerosol forcing (in $W m^{-2}$; from 0.3 to 2.5 µm) over dry grass, green grass, conifer, and deciduous surfaces. Other parameters used include AOD (at 0.55 µm) of 0.32, SSA (at 0.55 µm) of 0.89, and SZA of 30°. Bold numbers represent the difference in aerosol forcing associated with different approaches to estimate surface reflectance spectrum. The numbers in parentheses indicate the ratio of the absolute difference to the aerosol forcing calculated with "true".

Aerosol forcing (in $W m^{-2}$)	Dry grass	Green grass	Conifer	Deciduous
True	14.28	−8.25	−7.86	−6.28
MEVA	16.12	−7.62	−7.43	−5.7
Linear MODIS	13.43	−10.39	−10.54	−8.84
Averaged band MODIS	15.2	−10.38	−10.33	−8.7
Liang visible and near infrared	17.72	−9.88	−10.07	−8.06
Liang shortwave	27.03	−0.46	−0.74	2.66
Differences of aerosol forcing (in $W m^{-2}$)				
MEVA – True	**1.84 (13 %)**	**0.63 (8 %)**	**0.43 (5 %)**	**0.58 (9 %)**
Linear MODIS – True	**−0.85 (6 %)**	**−2.14 (26 %)**	**−2.68 (34 %)**	**−2.56 (41 %)**
Average band MODIS – True	**0.92 (6 %)**	**−2.13 (26 %)**	**−2.47 (31 %)**	**−2.42 (39 %)**
Liang visible and near infrared – True	**3.44 (24 %)**	**−1.63 (20 %)**	**−2.21 (28 %)**	**−1.78 (28 %)**
Liang shortwave – True	**12.75 (89 %)**	**7.79 (94 %)**	**7.12 (91 %)**	**8.94 (142 %)**

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AMTD
5, 4041–4076, 2012

Effect of spectrally varying albedo of vegetation surfaces

L. Zhu et al.

Table 3. The calculated aerosol forcing (in W m^{-2}) in different spectral ranges over deciduous surface. Other parameters used include: AOD (at 0.55 µm) = 0.32; SSA (at 0.55 µm) = 0.89; and SZA = 30°. Bold numbers represent the differences in aerosol forcing between applying specific approaches and “true” in specified spectral ranges.

Aerosol forcing (in W m^{-2})	0.3–0.55 µm	0.55–1.24 µm	1.24–1.63 µm	1.63–1.84 µm	1.84–2.1 µm	2.1–2.5 µm
True	−10.25	3.37	0.47	0.11	0	0.02
MEVA	−9.99	3.72	0.44	0.11	0.01	0.02
Linear MODIS	−11.13	1.61	0.55	0.1	0.01	0.01
Averaged band MODIS	−10.07	0.7	0.53	0.11	0.01	0.02
Liang visible and near infrared	−10.31	1.41	0.55	0.17	0.04	0.08
Liang shortwave	0.4	1.96	0.17	0.07	0.01	0.03
Difference of aerosol forcing (in W m^{-2})						
MEVA – True	**0.26**	**0.35**	**−0.03**	**0**	**0.01**	**0**
Linear MODIS – True	**−0.88**	**−1.76**	**0.08**	**−0.01**	**0.01**	**−0.01**
Average band MODIS – True	**0.18**	**−2.67**	**0.06**	**0**	**0.01**	**0**
Liang visible and near infrared – True	**−0.0**	**−1.96**	**0.08**	**0.06**	**0.04**	**0.06**
Liang shortwave – True	**10.65**	**−1.41**	**−0.3**	**−0.04**	**0.01**	**0.01**

AMTD
5, 4041–4076, 2012

Table 4. The calculated integration of the outgoing flux (in $W\,m^{-2}$; from 0.3 to 2.5 µm) at TOA over aspen surface. Other parameters used in the calculation include AOD (at 0.55 µm) of 0.32; SSA (at 0.55 µm) of 0.89; and SZA of 30°. Bold numbers represent the difference of the flux associated with applying different approaches to estimate the reflectance spectrum.

Flux (in $W\,m^{-2}$)	Aspen 1	Aspen 2	Aspen 3	Aspen 4	Aspen 5	Aspen 6
True	235.81	296.29	291.82	302.30	172.65	218.16
MEVA	234.74	292.37	284.38	300.04	174.18	219.67
Linear MODIS	219.98	277.69	273.17	296.36	164.42	204.73
Averaged band MODIS	220.86	282.53	273.93	298.44	163.87	204.91
Liang visible and near infrared	218.08	278.32	263.25	277.86	162.01	202.83
Liang shortwave	208.10	252.65	219.64	253.95	165.69	198.23
Differences of flux (in $W\,m^{-2}$)						
MEVA – True	**−1.07**	**−3.92**	**−7.44**	**−2.26**	**1.53**	**1.51**
Linear MODIS – True	**−15.83**	**−18.60**	**−18.65**	**−5.94**	**−8.23**	**−13.43**
Average band MODIS – True	**−14.95**	**−13.76**	**−17.89**	**−3.86**	**−8.78**	**−13.25**
Liang visible and near infrared – True	**−17.73**	**−17.97**	**−28.57**	**−24.44**	**−10.64**	**−15.33**
Liang shortwave – True	**−27.71**	**−43.64**	**−72.18**	**−48.35**	**−6.96**	**−19.93**

AMTD
5, 4041–4076, 2012

Table 5. The calculated aerosol forcing (in $W m^{-2}$; from 0.3 to 2.5 µm) over aspen surfaces. Other parameters used in the calculation include AOD (at 0.55 µm) of 0.32; SSA (at 0.55 µm) of 0.89; and SZA of 30°. Bold numbers represent the differences of aerosol forcing associated with applying different approaches and "true"; the numbers in parentheses represent the ratio of the absolute difference in aerosol forcing to the results calculated with "true".

Aerosol forcing (in $W m^{-2}$)	Aspen 1	Aspen 2	Aspen 3	Aspen 4	Aspen 5	Aspen 6
True	−7.28	5.79	3.04	6.32	−15.65	−10.37
MEVA	−6.90	6.11	2.58	6.93	−15.09	−9.73
Linear MODIS	−9.88	1.93	0.23	5.31	−16.95	−12.47
Averaged band MODIS	−9.43	4.21	0.44	5.96	−16.99	−12.37
Liang visible and near infrared	−9.18	4.30	1.01	7.89	−17.05	−12.17
Liang shortwave	−1.57	6.98	0.67	7.23	−9.95	−3.49
Differences of aerosol forcing (in $W m^{-2}$)						
MEVA – True	**0.38 (5 %)**	**0.32 (6 %)**	**−0.46 (15 %)**	**0.61 (10 %)**	**0.56 (4 %)**	**0.64 (6 %)**
Linear MODIS – True	**−2.60 (36 %)**	**−3.86 (67 %)**	**−2.81 (92 %)**	**−1.01 (16 %)**	**−1.30 (8 %)**	**−2.10 (20 %)**
Average band MODIS – True	**−2.15 (30 %)**	**−1.58 (27 %)**	**−2.60 (86 %)**	**−0.36 (6 %)**	**−1.34 (9 %)**	**−2.00 (19 %)**
Liang visible and near infrared – True	**−1.90 (26 %)**	**−1.49 (26 %)**	**−2.03 (67 %)**	**1.57 (25 %)**	**−1.40 (9 %)**	**−1.80 (17 %)**
Liang shortwave – True	**5.71 (78 %)**	**1.19 (21 %)**	**−2.37 (78 %)**	**0.91 (14 %)**	**5.70 (36 %)**	**6.88 (66 %)**

AMTD
5, 4041–4076, 2012

Effect of spectrally varying albedo of vegetation surfaces

L. Zhu et al.

Table 6. The calculated daily average aerosol forcing at equator at equinox (in W m^{-2}; from 0.3 to 2.35 µm) with different approaches to the surface reflectance spectrum. The last column presents the average aerosol forcing over the six vegetation types. Bold numbers indicate the differences in daily averaged aerosol forcing associated with different approaches; the numbers in parentheses represent the ratio of these differences to the results calculated with "true." Other parameters used in the simulation include SSA (at 0.55 µm) of 0.89 and AOD (at 0.55 µm) of 0.32.

Daily average aerosol forcing (in W m^{-2})	Veg 1	Veg 2	Veg 3	Veg 4	Veg 5	Veg 6	Average over the six vegetation
True	−2.65	−8.68	−5.42	−4.80	−4.94	−5.25	−5.29
MEVA	−2.56	−8.68	−5.51	−4.73	−4.94	−5.04	−5.24
Linear MODIS	−3.91	−9.35	−6.54	−5.94	−6.09	−5.60	−6.24
Averaged band MODIS	−4.03	−9.50	−6.63	−6.14	−6.34	−5.63	−6.38
Liang visible and near infrared	−3.61	−9.57	−6.37	−5.91	−5.78	−4.85	−6.02
Liang shortwave	2.21	−7.32	−2.66	−1.14	0.02	−0.07	−1.49
Difference of daily average aerosol forcing (in W m^{-2})							
MEVA – True	**0.09**	**0.00**	**−0.09**	**0.07**	**0.00**	**0.21**	**0.05 (−0.9 %)**
Linear MODIS – True	**−1.26**	**−0.67**	**−1.12**	**−1.14**	**−1.15**	**−0.36**	**−0.95 (18.0 %)**
Average band MODIS – True	**−1.38**	**−0.81**	**−1.21**	**−1.34**	**−1.40**	**−0.38**	**−1.09 (20.6 %)**
Liang visible and near infrared – True	**−0.96**	**−0.89**	**−0.95**	**−1.11**	**−0.84**	**0.39**	**−0.73 (13.8 %)**
Liang shortwave – True	**4.86**	**1.37**	**2.76**	**3.66**	**4.96**	**5.17**	**3.80 (−71.8 %)**

AMTD
5, 4041–4076, 2012

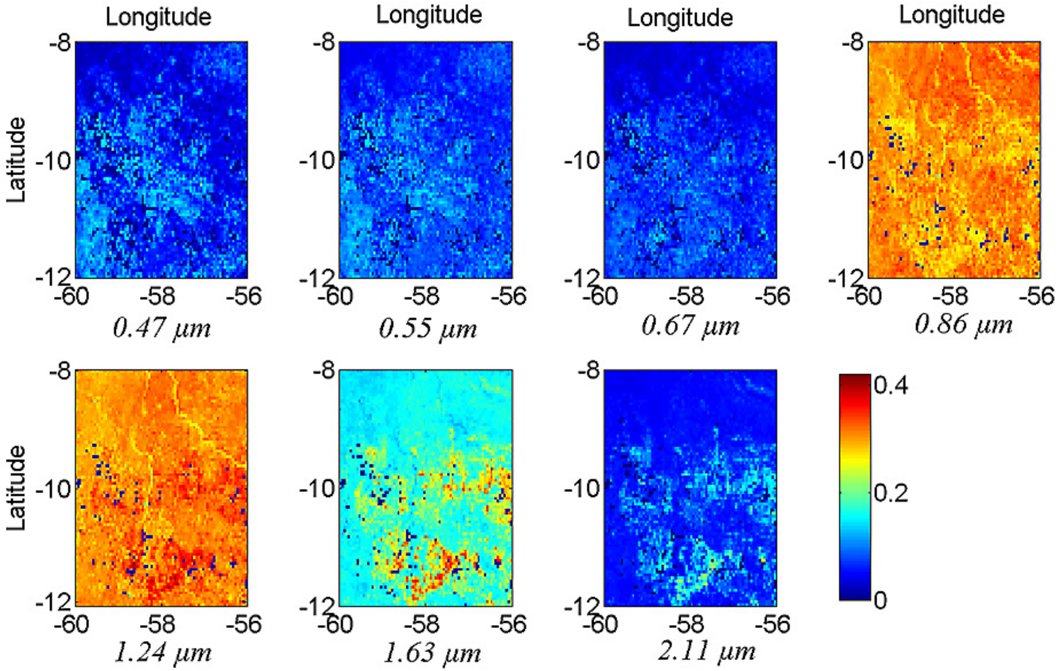

Fig. 1. Black sky albedo maps at MODIS bands 1–7 calculated from the MODIS file MCD43C1.A2006241.005.2008109074010.hdf with SZA equaling 32°.

AMTD
5, 4041–4076, 2012

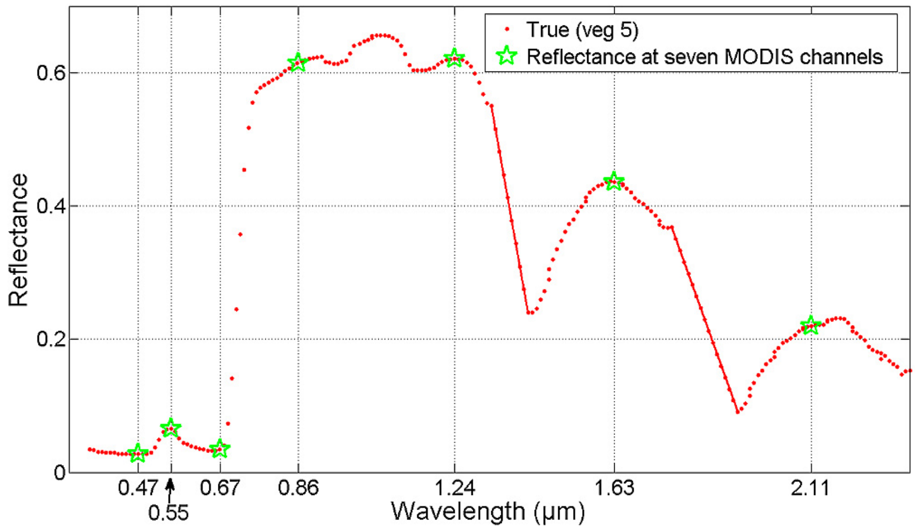

Fig. 2. The x-axis represents the wavelength from 0.3 to 2.35 µm labeled by seven MODIS channels; the dotted red curve is the spectral reflectance for vegetation 5 (*miconia guianensis*) adapted from Arai et al. (2010); the green stars represent the corresponding reflectance at MODIS bands 1–7. In this figure, the spectral reflectance results between 1.35 to 1.45 µm and 1.85 to 1.95 µm were linearly interpolated based on Arai et al. (2010) data. These solid red lines are shown as dots in Figs. 3, 5, 6, and 9.

AMTD
5, 4041–4076, 2012

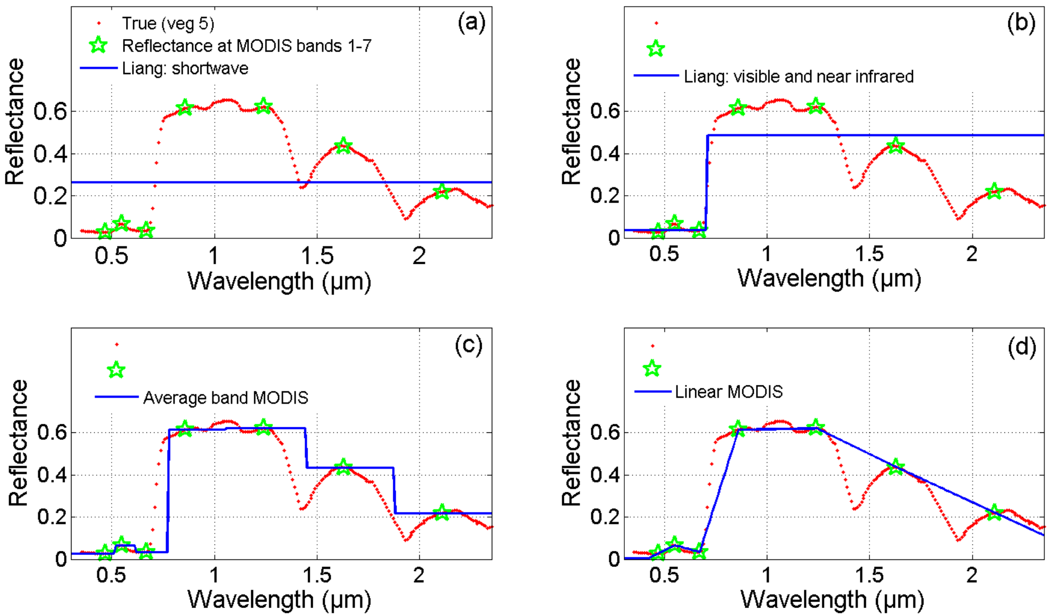

Fig. 3. Traditional approaches to estimate the continuous reflectance spectra based on MODIS bands 1–7: Liang short wave, Liang visible and near infrared, average band MODIS, and linear MODIS. In each subplot, the x-axis represents the wavelength from 0.3 to 2.35 μm; the dotted red curve is the spectral reflectance for *miconia guianensis* as shown in Fig. 2; the green stars represent the corresponding reflectance at MODIS bands 1–7; the solid blue lines represent each traditional approach.

AMTD
5, 4041–4076, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂| |▸
◂ ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

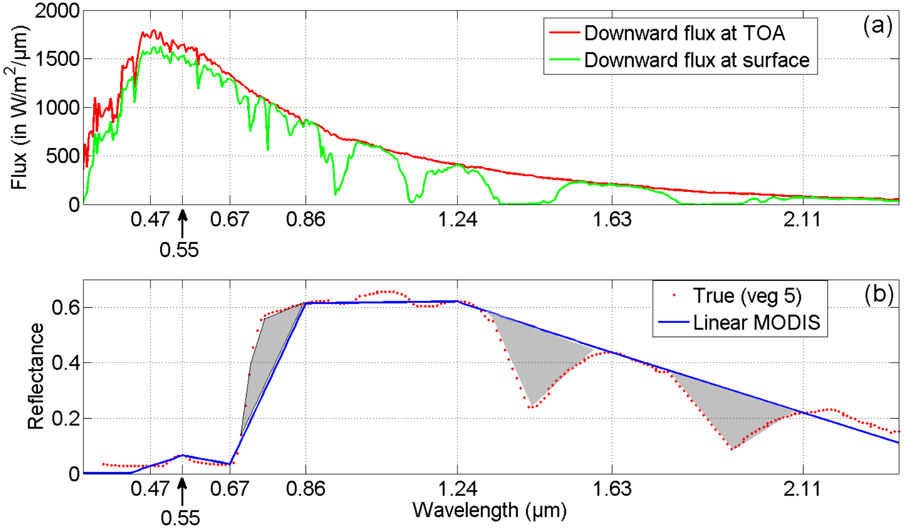

Fig. 4. (a) Downward fluxes at the TOA and surface. The x-axis is the wavelength (from 0.3 to 2.5 µm) labeled with MODIS bands 1–7; the red curve represents the incoming solar radiation at the top of the atmosphere (TOA); the green curve represents the downward radiation reaching the surface. The simulation was done with the following inputs: no boundary layer aerosols, SZA = 30°, tropical atmospheric profile, and surface albedo being as the red curve in Figs. 2 and 4. **(b)** The three missing features by linearly connecting the reflectance at MODIS bands 1–7. The x-axis is the wavelength from 0.3 to 2.5 µm labeled with MODIS bands 1–7; the dotted red curve represents the reflectance as shown in Fig. 2; the solid blue line represents the linearly connected reflectance at MODIS bands 1–7; the shaded areas represent three distinct missing features: missing vegetation red edge feature at around 0.7 µm, and the missing water absorption features at around 1.44 and 1.92 µm.

AMTD
5, 4041–4076, 2012

Effect of spectrally varying albedo of vegetation surfaces

L. Zhu et al.

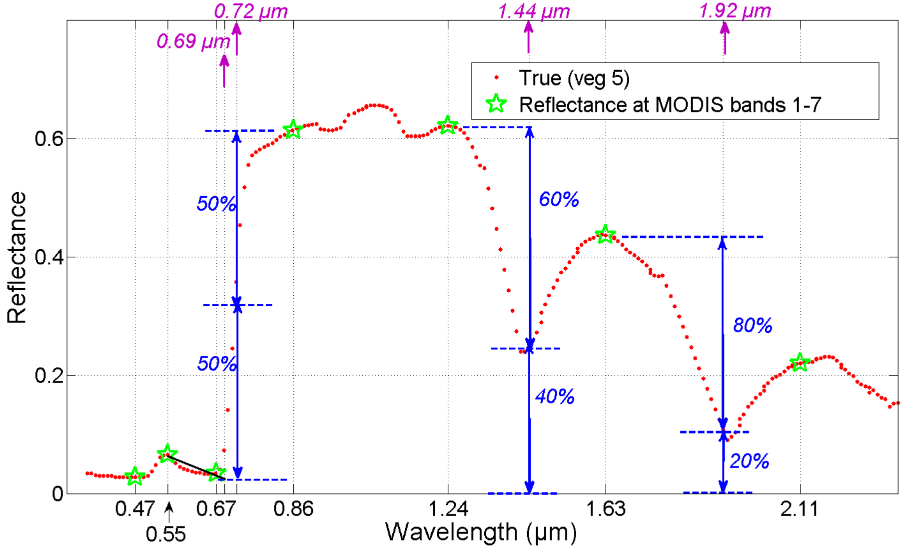

Fig. 5. This figure illustrates four auxiliary channels and the ratios used to determine the MODIS enhanced surface albedo (MEVA), where the x-axis represents wavelength (from 0.3 to 2.35 µm) labeled with MODIS bands 1–7 on the bottom and four auxiliary channels (0.69, 0.72, 1.44, and 1.92 µm) at the top. Dotted red curve ("True") represents the reflectance spectrum as shown in Fig. 2; the green stars present the corresponding reflectance at MODIS bands 1–7. The reflectance at the four auxiliary channels are determined as: at 0.69 µm, the reflectance is obtained by linearly extrapolating the reflectance at 0.55 and 0.67 µm; at 0.72 µm, the reflectance is the average of the reflectance at 0.69 and 0.86 µm; at 1.44 µm, the reflectance is 40 % of the reflectance at 1.24 µm; at 1.92 µm, the reflectance is 20 % of the reflectance at 1.63 µm.

AMTD
5, 4041–4076, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

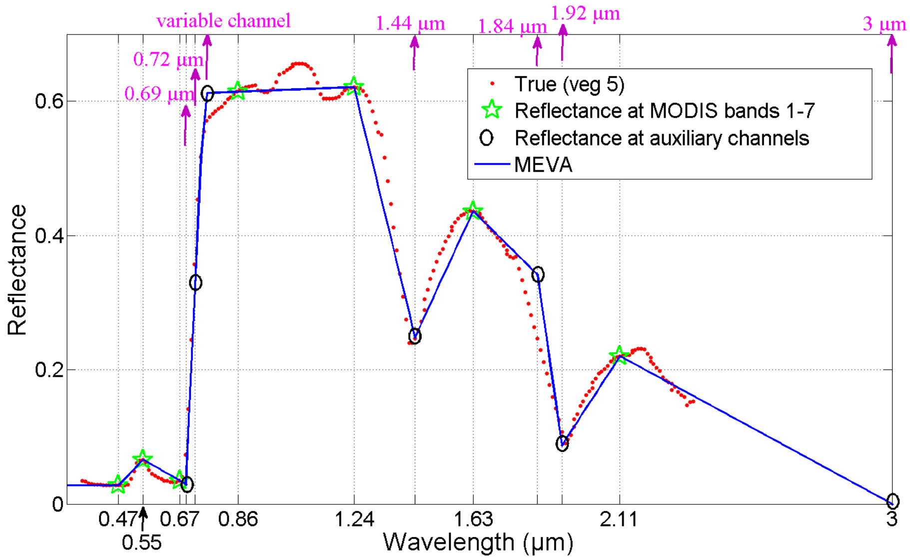

Fig. 6. Processes used to develop MEVA. The x-axis is wavelength (from 0.3 to 3 µm) labeled with MODIS bands 1–7 on the bottom and the auxiliary channels (0.69, 0.72, the variable channel ending the red edge, 1.44, 1.84, 1.92, and 3 µm) at the top. Four of these auxiliary channels were shown in Fig. 5. For the other three auxiliary channels, the variable channel ending the red edge is the crossing point between the linearly extrapolated line from 0.69 to 0.72 µm and the linearly extrapolated line from 1.24 to 0.86 µm; the auxiliary channel at 1.84 and 3 µm are determined by averaging the experimental results of several types of vegetation. The dotted red curve ("True") represents reflectance spectra as shown in Fig. 2; the green stars present the corresponding reflectance at MODIS bands 1–7; the ovals represent the determined reflectance at auxiliary channels; the solid blue line represents MEVA. The detailed procedures for MEVA are explained in Sect. 2.2.

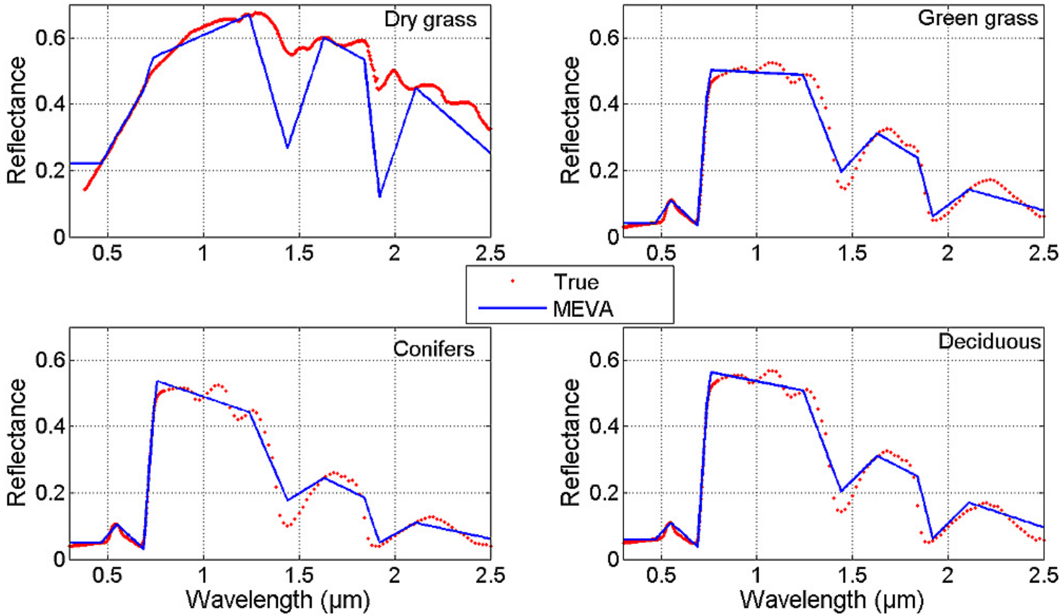

Fig. 7. The procedures for MEVA were applied to the reflectance spectra from the JHU spectral library for dry grass, green grass, conifer, and deciduous. The x-axis represents the wavelength from 0.3 to 2.5 μm; the y-axis represents the reflectance; the dotted red curves represent the reflectance spectra from the JHU spectral library; the solid blue lines represent the MEVA results.

AMTD
5, 4041–4076, 2012

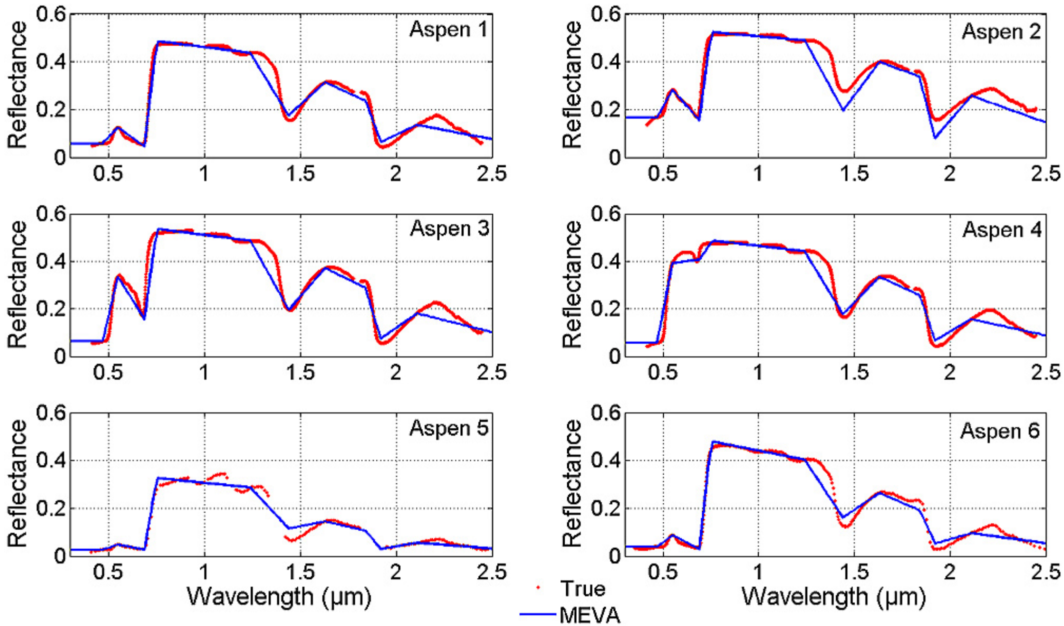

Fig. 8. In each subplot, the x-axis represents wavelength from 0.3 to 2.5 μm; the y-axis represents reflectance. The dotted red curves represent reflectance spectra for aspens from the USGS digital spectral library; the solid blue lines represent the MEVA results.

AMTD
5, 4041–4076, 2012

Effect of spectrally varying albedo of vegetation surfaces

L. Zhu et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

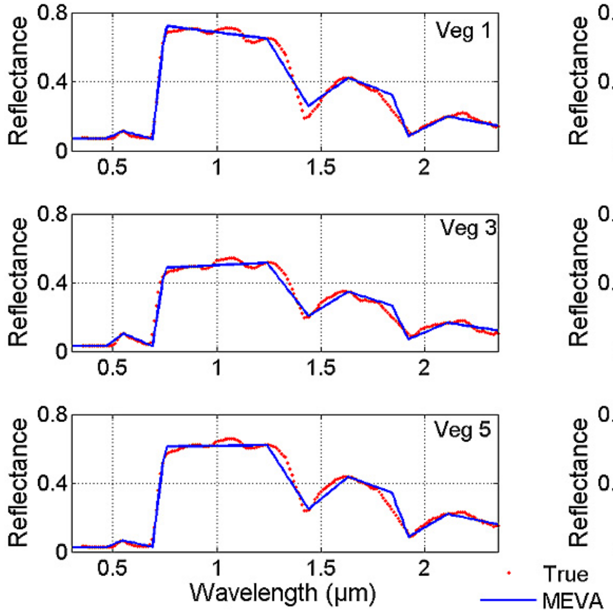

Fig. 9. In each subplot, the x-axis represents wavelength from 0.3 to 2.5 μm; the y-axis represents reflectance. The solid blue lines represent the MEVA results; the dotted red curves represent the "true" reflectance spectra (adopted from Arai et al., 2010) for the following six Amazonia vegetation types: veg 1: *manilkara Hubert*; veg 2: *couratari guianensis*; veg 3: *lecythis lurida*; veg 4: *genipa Americana*; veg 5: *miconia guianensis*; and veg 6: *litter*.

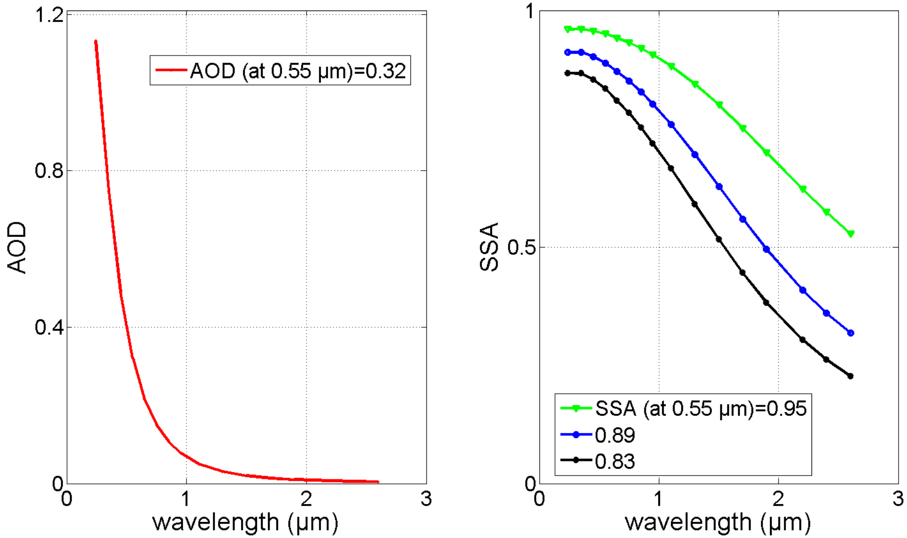

Fig. 10. The plot on the left shows the wavelength dependence of AOD for the aerosol models used in the TOA flux and aerosol forcing calculations; the plots on the right display three different aerosol models used in the flux and aerosol forcing calculations: SSA (at 0.55 μm) = 0.95, 0.89, and 0.83.

AMTD
5, 4041–4076, 2012

AMTD
5, 4041–4076, 2012

Effect of spectrally varying albedo of vegetation surfaces

L. Zhu et al.

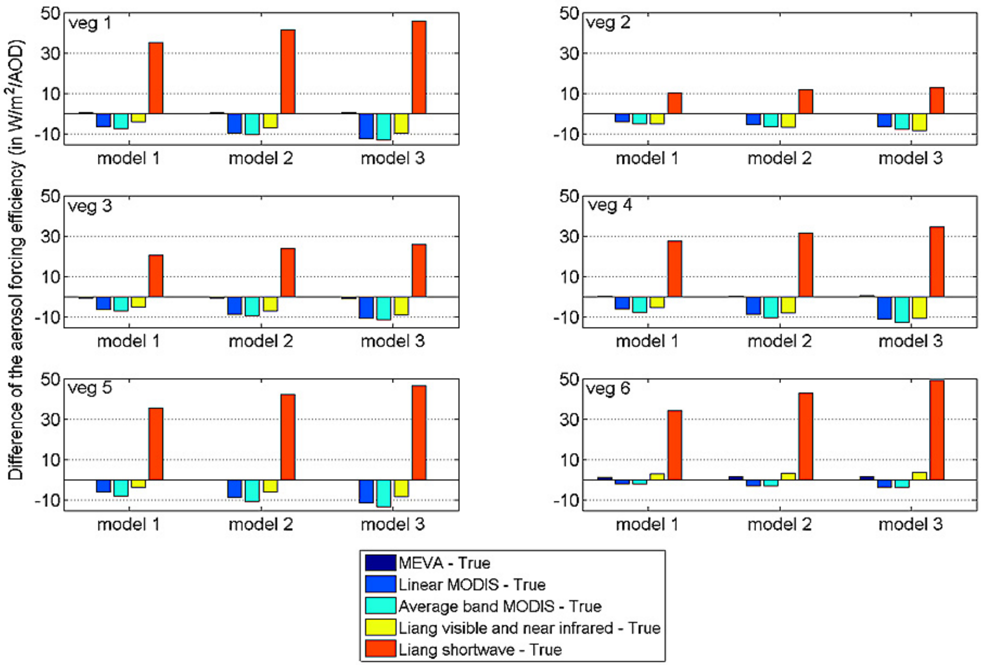

Fig. 11. Difference of the aerosol forcing efficiency (in $W m^{-2}$/AOD) associated with different approaches to estimate reflectance spectra for vegetation types shown in Fig. 9. In each subplot, three groups indicate the results caused by using three different aerosol models shown in Fig. 10: SSA (at 0.55 µm) = 0.95 (noted as "model 1"), 0.89 (noted as "model 2"), and 0.83 (noted as "model 3"). Other parameters used in the calculations include AOD (at 0.55 µm) = 0.32 and SZA = 30°.

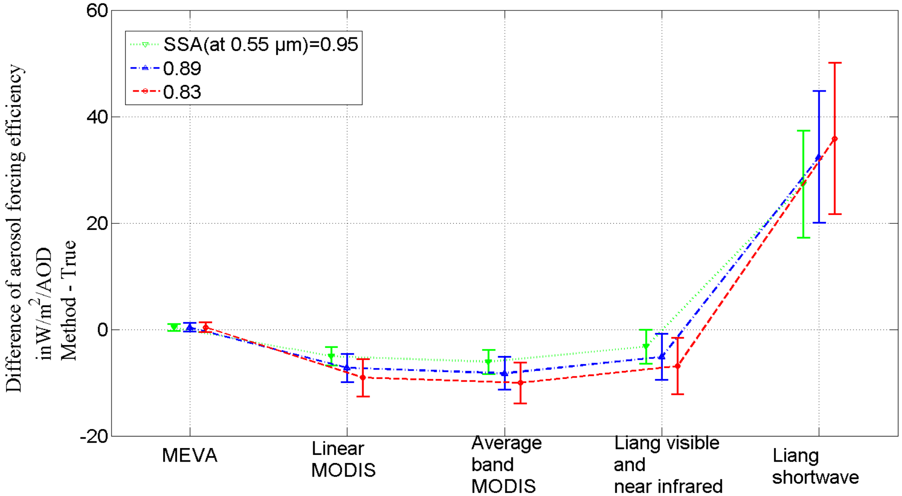

Fig. 12. The difference of aerosol forcing efficiency derived from averaging the results shown in Fig. 11 over the six Amazonian vegetation types. Bars represent the standard deviation of the aerosol forcing efficiency differences among the six vegetation types. The labels on the x-axis denote different methods to estimate vegetation reflectance spectrum used in the aerosol forcing calculation. The curves in green, blue, and red represent the results for different aerosol models: SSA (at 0.55 µm) = 0.95, 0.89, and 0.83. Other parameters used include AOD (at 0.55 µm) of 0.32 and SZA of 30°.

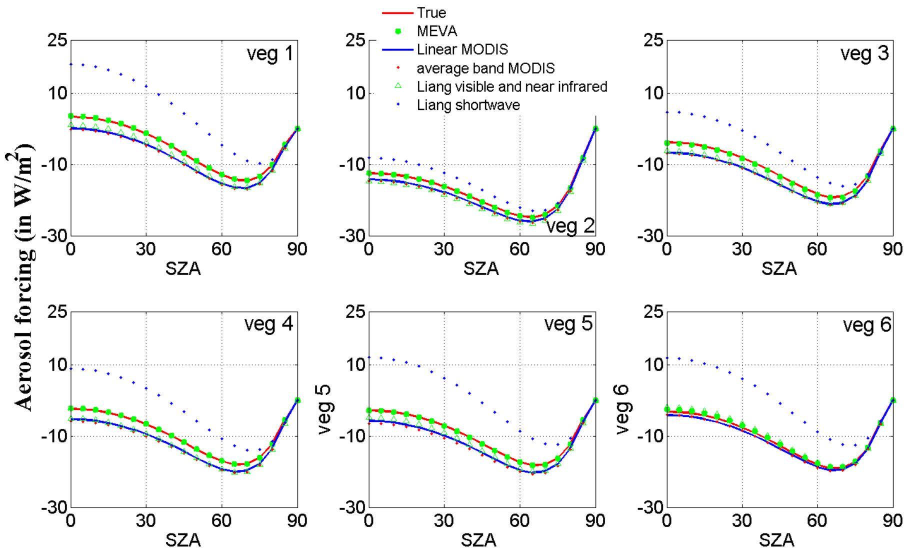

Fig. 13. Aerosol forcing when SZA varies from 0 to 90° for vegetation types shown in Fig. 9. Curves in different symbols are associated with different approaches to estimate vegetation reflectance spectrum used in the aerosol forcing calculation. Other parameters used in the calculations include AOD (at 0.55 µm) of 0.32 and SSA (at 0.55 µm) of 0.89.

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