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Evaluating the assumptions of surface reflectance and aerosol type selection within the MODIS aerosol retrieval over land: the problem of dust type selection

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Abstract

Aerosol Optical Depth (AOD) and Ångström exponent (AE) values derived with the MODIS retrieval algorithm over land (Collection 5) were compared with ground based sun photometer measurements in Europe, Asia, Africa, North America and South America. In Finland (Jokioinen and Sodankylä) measurements were done with Precision Filter Radiometer (PFR), while in Estonia (Toravere), Italy (Ispra, Rome Tor Vergata), India (Kanpur), China (Xianghe), GSFC (USA), Mexico (Mexico City), Zambia (Mongu) and Brazil (Alta Floresta) Cimel (AERONET, level 2) measurements were used. Comparison results for AOD were generally good, although there seems to be room for improvement in the MODIS aerosol model selection, particularly how dust is taken into account. At all studied sites, the MODIS algorithm often selects the dust aerosol model even when dust does not seem to be present and the air masses are not coming from arid regions. This happens especially when AOD values are relatively small (<0.3). The selection of the dust model reduces the correlation between ground based and MODIS AOD measurements in dust-free situations. Moreover, the current aerosol model selection scheme produces unphysical AE values. Our study suggests that the aerosol model combining is sensitive to the ratio of 660 nm and 2130 nm surface reflectances (slope(660/2130)). Furthermore, the value of the slope in the algorithm is mainly dependent on the Normalized Difference Vegetation Index (NDVI). The current relationship of these two parameters in the algorithm is not supported by the surface albedo climatology derived from MODIS measurements. The use of a more physical relationship improves the AE retrieval at the studied sites. However, at some sites the AOD correspondence deteriorates when the new relationship is used.

1 Introduction

Aerosols play an important role in the Earth's atmosphere. They affect, for example, climate, radiation budget and cloud processes. The direct effect of aerosols on climate involves both scattering and absorption of radiation, while the indirect effect of aerosols is related to their ability to modify the optical properties and lifetimes of clouds. Even though aerosols are ubiquitous, algorithms made to retrieve information from satellites are underdetermined and therefore require assumptions on aerosol properties and on the effect of the underlying surface, especially over land where the surface reflectance often dominates the reflectance measured at the top of the atmosphere. Due to the stronger signal from the surface, the error in the derived aerosol optical depth (AOD) is typically 10 times larger than the error in the predicted surface reflectance (Kaufman et al., 1997). Consequently, the development of the satellite retrieval algorithms is an ongoing task and improved versions of the algorithms are published every few years. One of the most widely used satellite instruments in aerosol remote sensing is the Moderate Resolution Imaging Spectroradiometer (MODIS). In the beginning of the year 2007 the current Collection 5 (hereafter C5) data set became available (Levy et al., 2007a). Levy et al. have provided a detailed documentation of the algorithm and the changes from previous versions.

The major improvements in C5 over land, as compared to Collection 4 (C4), are in the surface reflectance assumptions, aerosol models and their optical properties. The algorithm makes a simultaneous inversion for three channels (0.47, 0.66 and 2.13 µm), introducing information about coarse aerosols from the 2.13 µm channel to the retrieval. The inversion provides three independent parameters, AOD (or τ) at 0.55 µm, the non-dust or fine model weighting (FMW), and the surface reflectance at 2.13 µm. FMW is the fractional contribution of fine aerosol to the total AOD. Another new feature is the inclusion of small negative AOD values (>-0.05) which balance the statistics of AOD at near zero AOD conditions. Validation with data from the Aerosol Robotic Network (AERONET, Holben et al., 1998) shows that retrieval of AOD has improved compared to C4 (Levy et al., 2007a; Mi et al., 2007; Papadimas et al., 2008; Jethva et al., 2007).

C5 uses five aerosol models, which are described in detail by Levy et al. (2007b). The models are: continental, dust, non-absorbing, neutral and absorbing. They have been modified from the results presented by Dubovik et al. (2002). The fine mode dominated models are prescribed by geography and season and the inversion combines designated fine mode dominated and dust models to match the observed spectral reflectance. When the surface is too bright for standard retrieval, the inversion uses the continental aerosol model. The distribution of the fine mode dominated models was determined from cluster analysis described by Levy et al. (2007b). All nondust models contain both fine and coarse modes. The FMW is not a weight between fine and coarse modes, but a weight between nondust and dust models. In addition, the Ångström exponent (AE) is no longer an independent parameter. It's value depends on the combination of the fine dominated and dust models. (Levy et al., 2007a)

MODIS C5 measurements have been extensively compared with AERONET measurements globally (Levy et al., 2010, 2007a; Jethva et al., 2010, 2007; Mi et al., 2007; Kaskaoutis et al., 2007; Papadimas et al., 2008; Misra et al., 2008; Drury et al., 2008; Remer et al., 2008; Mishchenko et al., 2010). Several studies, for example Jethva et al. (2010) and Oo et al. (2008) have concluded that the surface assumptions and aerosol models in the MODIS retrieval are not representative for all locations. In addition, Mishchenko et al. (2007); Liu and Mishchenko (2008) and Mishchenko et al. (2009) have made global comparisons of MODIS and MISR AE and they concluded that there is a large disagreement between the instruments.

In many cases the MODIS retrieval chooses dust model, when there is much evidence that there is little or no dust actually present (climatology, backtrajectory analysis, etc). The question is why does the MODIS algorithm choose dust model? Previous studies have suggested, and Levy et al. (2010) have stated, that the MODIS observations do not contain enough information to robustly separate dust from non-dust. Uncertainties in the surface reflectance, as well as aerosol absorption are too large. However, from the collocations with sunphotometer data, there are indications that there are systematic reasons for discrepancies in some sites. In some sites the mis-identification occurs because the surface reflectance assumptions are consistently wrong, whereas at other sites, the error is dominated by the initial assumption of aerosol model type. In this paper, we study some of the sites where MODIS is consistently picking the wrong aerosol model, which in turn leads to errors in total AOD and especially in AE. We determine the dominant cause of aerosol type mis-identification, and provide evidence that the retrieval can be tuned in a physically meaningful way at these sites.

2 Data and methodology

In this study, AOD available from MODIS is compared with AOD measured with ground-based Precision Filter Radiometers (PFR) located in Finland. In addition, MODIS measurements are compared with Aerosol Robotic Network (AERONET) Cimel sun photometer measurements. The sites are listed in Table 1. PFR measurements in Sodankylä and Jokioinen were made between 2004 and 2008, and 2006 and 2008, respectively. For both sites, data from days with residual snow on the ground were removed from the analysis because snow would render the MODIS retrieval difficult. Cimel measurements at the AERONET sites were done between 2000 and 2008.

2.1 MODIS

MODIS instruments are aboard the Terra and Aqua satellites. Terra MODIS and Aqua MODIS cover the Earth's surface every 1 to 2 days. These instruments have 36 spectral bands and they measure near-nadir radiance over a 2300-km wide swath. The resolution of the measurements varies between 0.25 to 1 km (Anderson et al., 2005). MODIS C5 data from both satellites are used in the comparisons with the ground-based measurements. The expected error over land in the MODIS AOD (or τ) is $\pm 0.05 \pm 0.15\tau$ (Levy et al., 2010). We used only AOD data with best quality (Quality flag=3).

2.2 PFR

The PFR (Wehrli, 2000; Kim et al., 2008) is a passive instrument which measures direct solar irradiance in four narrow spectral bands (368, 412, 500, and 862 nm). The bandwidth of the instrument is 5 nm and the full field of view angle is 2.5 degrees. Derived products from the measurements are AOD for the four wavelengths and AE. The time resolution of the products is 1 min. The uncertainty of the PFR instrument is between 0.01 and 0.02 (Carlund et al., 2003). For the comparison with MODIS, the PFR measurement at 500 nm was interpolated to 550 nm using the Ångström power law, $\tau_{550}=\tau_{500}(550/500)^{-\alpha}$, where τ_{550} is the AOD at 550 nm, τ_{500} is the AOD at 500 nm and α is the AE based on the linear fit taken over all four PFR wavelengths. Cloud screening of the PFR measurements is based on the methods presented by Smirnov et al. (2000).

2.3 AERONET

AERONET (Holben et al., 1998) uses Cimel sun photometers which measure AOD at 340, 380, 440, 500, 675, 870 and 1020 nm. Measurements are provided every 15 min during daytime. AERONET also provides the angular distribution of sky radiances at four wavelengths (440, 670, 870 and 1020 nm), and aerosol properties such as aerosol size distribution, complex refractive index, and single scattering albedo (SSA), once every hour in clear sky conditions. The spectral AOD from AERONET are accurate to within ± 0.01 for wavelengths larger than 400 nm and ± 0.02 for shorter wavelengths (Holben et al., 1998; Eck et al., 1999). Holben et al. (1998) have described AERONET measurements in more detail. For the comparison with MODIS, the AERONET measurement at 500 nm was interpolated to 550 nm by using the Ångström power law. We used cloud screened and quality assured level 2.0 data and level 2.0 inversion products in the analysis.

2.4 Comparison methods

The ground-based measurements were used in the analysis only if the measurements were made within an one hour window centered at the MODIS overpass. The averaging of the satellite and surface measurements was based on the method described by Ichoku et al. (2002). If MODIS had more than 5 aerosol retrievals inside a grid of 5×5 pixels (50×50 km), centered at an AERONET/PFR station, these retrievals were averaged and compared to ground-based measurements. In addition, ground-based measurements were used in the analysis only if there were more than 6 PFR or 3 AERONET measurements within the one hour window. This was done to ensure that one instrument did not measure in the beginning of the time window and the other one in the end.

To compare how well the AERONET and PFR AOD compare, we exploited the concurrent Cimel and PFR sunphotometer measurements carried out at Sodankylä during the SAUNA (Sodankylä Total Column Ozone Intercomparison) campaign between 20 March and 14 April 2006. That period of the year offers large solar zenith angles (SZA) and high total ozone values. The aim of the campaign was to assess the comparative performance of the ground-based instruments and algorithms which measure total columnar ozone at large SZAs and high total column ozone values. The campaign showed that the ground based instruments agree extremely well at all wavelengths. At visual and UV wavelengths (368, 412 and 500 nm) the R^2 values were 0.99. For the longer wavelength band (862 nm) the correlation is almost as good, with R^2=0.97. The comparison was done from 1790 coexistent measurements with less than 3 min time difference.

2.4.1 Aerosol model combination

Comprehensive global comparison between AERONET and MODIS have been presented by Levy et al. (2010), thus we concentrated only on the combination of the aerosol models in the MODIS retrieval algorithm. The algorithm combines the designated fine mode dominated model with the dust model to match the observed spectral reflectance at the top of the atmosphere (TOA). The calculated spectral total reflectance is the weighted sum of the spectral reflectance from a combination of the fine dominated and dust aerosol models. The algorithm selects the best aerosol model combination based on the difference between the calculated TOA reflectance at 660 nm and the observed one. The dust model has always larger TOA reflectance values at 660 nm than the fine dominated model. Thus, when the observed TOA reflectance is larger than the one calculated using the dust model, the result has the smallest error with the dust model. As a result, the retrieval can select the dust model for all locations even though other observations (AERONET AE, HYSPLIT trajectories, color composed satellite images) do not indicate the presence of dust. Our aim was to find reasons for these flawed aerosol type selections. In the comparison studies, we have separated the fine dominated models from dust based on their AE values. Measurements with AE over 1 refer to fine dominated models and AE smaller than 1 refers to the dust model (Eck et al., 1999; Schuster et al., 2006). The dust model has an AE of approximately 0.6 while the AEs in the fine dominated models are around 1.6.

2.4.2 MODIS standalone algorithm

In the more detailed analysis of the performance of the MODIS retrieval algorithm we used a standalone version of it. The standalone version includes all the physics and mathematics of the operational aerosol retrieval. However, it does not include cloud screening, pixel selection, or any of the other MODIS processing overhead (making HDF files, etc.). As an input, the standalone version requires top of the atmosphere reflectance at multiple channels, geometry, location, and month. Outputs are aerosol properties: AOD, AE and FMW. The use of the standalone version enabled us to study how changes in different parameters affected the retrieved parameters, mainly AOD and AE. In C5, the relationship between the visible surface reflectance (0.47 µm and 0.66 µm) and the 2.13 µm reflectance measured at the top of the atmosphere is no longer fixed. The new relationships depend on vegetation and scattering angle.

2.4.3 Evaluation of the surface assumptions

To evaluate the quality of the assumed surface properties in the algorithm we used a MODIS based surface albedo climatology created by Moody et al. (2005). The global climatology contains spatially complete white-sky albedo (bihemispherical reflectance) data from the years 2000–2004. Moody et al. have also made a five-year aggregate of high quality MOD43B3 data which was filled using a interpolation technique (accuracy of 3–8%; Moody et al., 2008) in order to provide a five-year climatology that can be used as an average year. In addition, the data set contains surface albedo statistics (average and standard deviation) by ecosystems at various resolutions of each 16-day time period's snow-free filled albedo maps for the separate years and the five-year climatology. The available resolutions for the statistics are (degrees of latitude×degrees of longitude): 0.5×0.5, 1×1, 2×2, 2.5×2.5, 3×3, 4×4, 5×5, 10×10, 10×20, 10×30, 10×45, 10×60, 10×120, 10×180, 60×120, 60×180, 90×180, and 90×360. For our comparisons we selected the albedo statistics for the five-year climatology with the 60×120 resolution. This data provided us averaged albedo values at three wavelengths (0.66, 1.24 and 2.13 µm) categorized by ecotypes at 9 different areas, each 60×120 (latitude×longitude) degrees. Combined, these 9 areas cover the whole globe. The albedo values have a 16-day time resolution, thus giving the yearly cycle with 23 values. Hence, for each ecotype in each of the 9 areas we get 23 surface albedo values representing the yearly cycle. The overall accuracy of the MODIS surface albedo data is within 0.05 (Liu et al., 2009).

Surface albedo is the ratio of the radiant flux reflected from a unit surface area into the whole hemisphere to the incident radiant flux of hemispherical angular extent (Schaepman-Strub et al., 2006), thus it is not angle dependent. The reflectance in the MODIS retrieval, however, depends on the solar and viewing geometry. To minimize the discrepancies resulting from the comparison of slightly different quantities we decided to compare ratios instead of absolute values. The selected ratios were the slope(660/2130) (ratio of 660 nm and 2130 nm surface reflectance) and Normalized

Difference Vegetation Index (NDVI or $\mathrm{NDVI}_{\mathrm{SWIR}}$ in this case). These parameters were selected because the slope(660/2130) is the most important parameter governing the wavelength dependence of the surface reflectance in the MODIS retrieval and it depends on NDVI as follows (Levy et al., 2007a):

$$\mathrm{slope}\left(\frac{660}{2130}\right) = \begin{cases} 0.48;\ \mathrm{NDVI} < 0.25 \\ 0.48 + 0.2(\mathrm{NDVI} - 0.25);\ 0.25 < \mathrm{NDVI} < 0.75 \\ 0.58;\ \mathrm{NDVI} > 0.75 \end{cases}$$

The slope(660/2130) also depends on the scattering angle, however, it does not have as large effect as the NDVI. In addition to the slope(660/2130), the retrieval algorithm uses a ratio of 470 nm and 660 nm surface reflectance (slope(470/660)). However, this second slope does not have as strong effect on the aerosol model combination.

3 Results

Table 2 summarizes the differences between MODIS and AERONET/PFR AOD measurements at the sites studied. All parameters are presented for all measurements, for the measurements with MODIS AE over 1, and for the measurements with MODIS AE under 1. At Alta Floresta, GSFC, Ispra, Mexico City, Mongu, and Toravere the correlation coefficient squared (R^2) is lowest for the measurements with AE under 1. At Jokioinen, Rome, Sodankylä, and Xianghe the values of R^2 for the measurements with AE under 1 are slightly lower or in the same range as in the other classes. At Kanpur the R^2 values are equal for the over and under classes. The averaged difference between the instruments (mean(gb-M)) and the Root-Mean-Square of the difference (RMS diff) are very similar for all the categories. In addition, Table 2 shows the percentage of the measurements within the expected MODIS accuracy. At all sites the percentages are larger or in the same range as the results presented by Remer et al. (2008) and Jethva et al. (2007). Both reported that more than 70% of the measurements at 550 nm over land were within expected accuracy.

Figure 1 shows examples of comparisons of the AODs from MODIS and ground-based instruments at 550 nm wavelength. At sites where coarse aerosols are not common AE from MODIS has values under 1 when AODs are typically smaller than 0.5. The R^2 values for these measurements are lower than for the measurements with AE over 1. For these sites (e.g. Mongu, Toravere, GSFC) the AE from AERONET was rarely under 1. For the sites where AERONET indicated the presence of coarse aerosols (Kanpur, Rome and Xianghe) the MODIS AE is under 1 also for larger AOD values and the correlation coefficients for fine dominated and dust aerosols are equal.

3.1 SSA and surface reflectance studies

We used single scattering albedo (SSA) data from AERONET level 2.0 inversion products to study whether absorption could explain the differences between MODIS and AERONET AOD values. To avoid measurement uncertainties associated with low AOD values, only measurements with AOD over 0.3 (both MODIS and AERONET) were considered. Figure 2 shows two examples of comparisons of SSA spectra for MODIS a-priori aerosol models with SSA values from the AERONET inversion categorized by MODIS AE. At Toravere, the a-priori SSA spectra in the MODIS algorithm are in agreement with the AERONET data for both size classes. The classification of the coarse aerosols coincides with a strong dust plume advected from the Sahara, thus for these cases MODIS selects the aerosol models correctly. On the other hand, the measured SSA spectra in Mexico City are lower than those for the a-priori model, at each wavelength. Similar behavior was also detected at Ispra and Mongu. On the basis of AERONET AE, none of these sites were influenced by coarse particles. This can also be seen from the spectral behavior of the SSA. For small particles the SSA decreases as wavelength increases while for larger particles the SSA increases, as can be seen in the Toravere figure. In Mexico City, however, both types have similar wavelength dependence, indicating fine dominated aerosols which absorb more than assumed in the model. The only difference between the types is that on average the dust measurements are associated with slightly smaller SSA values. This raises the question whether absorption capacity of the fine dominated aerosols could affect the combination of the aerosol models in the MODIS aerosol retrieval?

In the next step, we investigated the surface reflectance values from the C5 data for single pixels and divided the data into two classes based on MODIS AE as before. Then we calculated the monthly mean surface reflectances at 660 nm from all measurements and normalized the surface reflectance values with these mean values to remove seasonal variations. Figure 3 presents the normalized surface reflectances for measurements with MODIS AE over 1, and under 1, as a function of AERONET AE. The surface reflectance data was binned into 0.1 wide AE classes. This example from Mongu is also representative for other sites which had a sufficient number of measurements from both classes (Alta Floresta, Kanpur, Xianghe). At these sites, measurements with AE over 1 had larger normalized surface reflectance values than the measurements with AE under 1. This was also seen in the 2.13 µm surface reflectance data. Surface reflectance should not depend on the AE, as the AERONET AE data shows. However, in the MODIS retrieval, larger particles (dust model) are associated with lower surface reflectance values.

3.2 Analysis with the standalone algorithm

We carried out a number of sensitivity studies with the standalone version of the MODIS aerosol retrieval algorithm. We modified the surface reflectance parameters (slope(660/2130) and slope(470/660)) to check how they affect the aerosol model combination (i.e. FMW), AE, and overall AOD. The FMW parameter was most sensitive to the changes in the slope(660/2130) values. Figure 4 shows an typical example from Mongu how the modification of the slope(660/2130) affects the aerosol model combination. The black line is the measured top of the atmosphere (TOA) reflectance spectrum while the green line is the result for FMW=0.5 from the original retrieval. The red and blue lines are results (FMW=0.5) from retrievals where the slope(660/2130) has been multiplied by 0.9 and 1.1, respectively. The errorbars at 660 nm show how much the combining of the fine dominated and dust aerosol models affects the results. The upper bar indicates pure dust model while the lower bar is for pure fine dominated model. In this case, the original retrieval resulted in the best fit with pure dust model because the measured TOA reflectance at 660 nm was larger than the calculated one. When the slope(660/2130) was 10% larger than the original, the calculated TOA reflectance at 660 nm became larger and closer to the measured value, thus changing the selected aerosol type from dust to fine dominated. On the other hand, if the slope(660/2130) was 10% smaller than the original, the calculated TOA reflectance at 660 nm moved further away from the measured value without affecting the aerosol type selection.

As illustrated in the Fig. 4, the combination of aerosol models (and therefore AE) is sensitive to the value of the slope(660/2130),therefore it is extremely important that the slope value represents the surface under investigation. The MODIS AOD retrieval calculates the slope(660/2130) as a function of NDVI and scattering angle. To study the quality of the slope-NDVI relationship in the algorithm, we compared it with MODIS surface albedo climatology. Figure 5 presents the dependence of the slope(660/2130) on NDVI based on global MODIS surface albedo data. The different ecotypes are separated by colors and symbols. In the surface albedo climatology, the globe was divided into 9 areas (60×120 degrees each) and averaged surface albedo values for all the ecotypes in these areas were calculated. Each ecotype from each of the 9 areas has 23 points representing the yearly cycle of the vegetation. The solid black line in each of these figures shows how the relationship of the parameters is taken into account in the MODIS aerosol retrieval. Figure 5 shows that the relationship between NDVI and slope(660/2130) has a large variation between different ecotypes. However, for all the ecotypes the slope(660/2130) decreases as NDVI increases which is the opposite to the trend in the retrieval. In addition, the retrieval assumes smaller slope(660/2130) values than the surface albedo data shows.

To test how the AE and AOD results are affected if we assume the slope-NDVI relationship to behave more like the albedo data suggest, we, as a first try, applied an inverse relationship that better fits the data (shown in Fig. 5 with dashed lines). As an attempt to evaluate the AE quality we used AERONET data and decided that the instruments agree on the particle size if both AEs were either larger than 1.4 or smaller than 0.9. In other cases the instruments were thought to disagree. The measurements with AEs between 0.9 and 1.4 were left out of the analysis to avoid the difficult comparison of mixed aerosols. In this study, we compared single measurements, whose time difference was less than 10 min. The number of the usable measurement (n_{all}, Table 3) changes for the different cases due to the "AE buffer zone" (from 0.9 to 1.4) and the exclusion of retrievals with AOD less than 0.3 or negative surface reflectance at 2.13 µm. The comparison results are presented in Table 3, which includes two main sections: Original and Inverse. Original refers to the retrievals done with the original C5 slope-NDVI relationship, while the Inverse section is for the retrievals done with the inverse relationship. Both of these sections have subsections: Abs and nonabs, which refer to retrievals where the aerosol model was forced to be either absorbing or non-absorbing. Table 3 shows that at all studied sites (Alta Floresta, Kanpur, Mexico City, Mongu, Rome, Xianghe) the modification of the slope-NDVI relationship improved the AE agreement (marked with light blue). For example, in Alta Floresta the original AE agreement (ORIGINAL: *agree*) was 0.849 and with the inversed relationship the AE agreement (INVERSE: *agree*) increased to 0.915. When the inverse relationhip was combined with the nonabsorbing model, the AE agreement increased to 0.934. Unfortunately, the AOD correspondence did not improve as clearly (best values marked with red and green). The squared correlation coefficients between MODIS and AERONET AOD (R^2) only improved at half of the sites (Alta Floresta, Mexico City, Xianghe). However, the averaged AOD difference (mean(gb-M)) decreased at all sites, except in Mongu. In Mongu and Xianghe the AOD correspondence can be improved by using the absorbing and nonabsorbing models, respectively. However, this does not improve the AE agreement. In Alta Floresta and Mexico City, AOD and AE correspondence can be improved at the same time by using the inversion of the slope and nonabsorbing and absorbing models, respectively. In Kanpur and Rome the two AOD correspondence parameters give mixed results. By using the inversion slope and absorbing model in Kanpur we get the best values for AE agreement and mean difference, but

R^2 indicates the best AOD correspondence with original slope-NDVI relationship and nonabsorbing model.The absorptivity the fine dominated aerosol model does not affect the AE agreement, however, it has a significant effect on the AOD correspondence at some sites, like Alta Floresta and Xianghe. The results in Mexico City are poor in all the cases because it is an urban site with a bright surface. The slope(660/2130) should be as much as 1.6 times larger than the original to introduce significant improvements into the AE and AOD agreements.

4 Discussion

The MODIS retrieval algorithm over land often selects the dust aerosol model for locations where dust is unlikely to be found. In addition, there seems to be very little mixing between the fine dominated and dust models. The selection of the dust model reduced the correlation between MODIS and ground based measurements at the sites where other observations (AERONET AE, HYSPLIT trajectories, color composed satellite images) did not show any indication of dust.

Our findings are in agreement with the recent studies presented by Levy et al. (2010) and Jethva et al. (2010). In contrast to their studies, we also analyzed single MODIS measurements and therefore were able to study the combining of the fine dominated and dust models in more detail. When employing the spatio-technique of Ichoku et al. (2002), it is harder to see what happens in the combining of the aerosol models due to the averaging of at least 5 measurements. Single measurements, on the other hand, show clearly that the combination of the models usually results as either pure fine dominated aerosols or pure dust. Because AE depends only on the combination of the models, the AE retrieval fails if the combining fails. Our results suggest that the combining is extremely sensitive to the assumed value of the slope(660/2130) while the absorption capacity of the fine dominated aerosol models does not affect it substantially. However, the selection of the fine dominated model affected AOD retrievals significantly.

5 Conclusions

We compared Collection 5 MODIS data to PFR and Cimel (AERONET) measurements at eleven locations in Europe, Asia, Africa North America and South America. In Northern Europe, the AOD values were quite low (<0.3), especially in Northern Finland. AOD values from MODIS and PFR/AERONET in Kanpur, Rome, and Sodankylä agree reasonably well (R^2 between 0.78 and 0.80) while AERONET and MODIS measurements in Alta Floresta, GSFC, Ispra, Jokioinen, Mongu, Toravere, and Xianghe agree very well (R^2 over 0.87). In Mexico City the R^2 value was only 0.64. At all studied sites the MODIS algorithm selected often the dust aerosol model even though other observations (AERONET AE, HYSPLIT trajectories, color composed satellite images) did not show any indication of dust. This happened especially when AOD values were small. According to Levy et al. (2010) MODIS does not provide quantitative information about aerosol size (AE) over land. However, it is an important parameter if one tries to estimate the anthropogenic component of aerosols. Our study suggests that the surface reflectance assumptions, especially the slope(660/2130) in the MODIS algorithm is the major reason for the unphysical AE values and the flawed aerosol model combining in the algorithm. Comparison of the surface parameters showed that the slope(660/2130)-NDVI relationship used in the MODIS retrieval algorithm is not supported by the MODIS albedo climatology:

1. the albedo data show that the slope-NDVI relationships depend strongly on ecotypes. The possibility to take this into account in the future Collections should be studied further.
2. the slope(660/2130) values based on the climatology were larger than the ones in the algorithm
3. the albedo data also shows that the slope(660/2130) decreases as the NDVI increases for all the ecotypes which is the opposite to the relationship in the algorithm

4. changing the slope-NDVI relationship in the algorithm to agree better with the albedo data increased the correspondence of MODIS and AERONET AE at the studied sites. AOD correlation did not improve as clearly, but the mean difference decreased at all sites, except in Mongu

5. the absorption capacity of the fine dominated aerosol model does not have a significant effect on the AE agreement between MODIS and AERONET, however, it affects the AOD correspondence.

Although, the modification of the slope(660/2130) improved the AE retrieval at all studied sites and AOD retrieval at some sites, the effect on global scale is not yet known. This will be studied further in the future.

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Table 1. Sunphotometer sites used in the study. PFR sites were in Finland and AERONET data was used elsewhere.

Site	Country	Lat., Lon.
PFR:		
Sodankylä	Finland	67.37° N, 26.63° E
Jokioinen	Finland	60.81° N, 23.50° E
AERONET:		
Toravere	Estonia	58.26° N, 26.46° E
Rome Tor Vergata	Italy	41.84° N, 12.65° E
Ispra	Italy	45.80° N, 8.63° E
Kanpur	India	26.51° N, 80.23° E
Xianghe	China	39.75° N, 116.96° E
Mongu	Zambia	15.25° S, 23.15° E
GSFC	USA	38.99° N, 76.84° W
Mexico City	Mexico	19.33° N, 99.18° W
Alta Floresta	Brazil	9.87° S, 56.10° W

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

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

Table 2. Statistics of the concurrent AERONET/PFR and MODIS measurements. Subscript "all" refers to all coexistent measurements, "over" refers to measurements with MODIS AE over 1, and "under" refers to measurements with MODIS AE under 1. n is the number of measurements, R^2 is the correlation coefficient squared, mean(gb-M) is the average difference between the ground-based and satellite measurements, RMS diff is the Root-Mean-Square Difference, and Pixels is the percentage of pixels within the expected accuracy of MODIS.

	Alta Floresta	GSFC	Ispra	Jokioinen	Kanpur	Mexico City	Mongu	Rome	Sodankylä	Toravere	Xianghe
n_{all}	244	895	652	126	340	172	1085	785	127	252	462
n_{over}	193	541	640	79	26	56	862	233	105	212	76
n_{under}	51	354	12	47	314	116	223	552	22	40	386
R^2_{all}	0.97	0.93	0.90	0.90	0.80	0.64	0.87	0.78	0.80	0.95	0.94
R^2_{over}	0.97	0.96	0.90	0.90	0.82	0.68	0.89	0.77	0.81	0.96	0.96
R^2_{under}	0.64	0.67	0.72	0.89	0.82	0.62	0.56	0.77	0.80	0.90	0.93
mean(gb-M)$_{\text{all}}$	−0.02	−0.02	0.02	0.01	−0.06	0.01	0.01	−0.02	0.02	0.02	−0.02
mean(gb-M)$_{\text{over}}$	−0.03	−0.02	0.02	0.01	0.07	0.03	0.02	−0.00	0.02	0.02	0.02
mean(gb-M)$_{\text{under}}$	0.05	−0.03	−0.00	0.01	−0.07	0.01	−0.01	−0.02	0.02	0.00	−0.03
RMS diff$_{\text{all}}$	0.20	0.05	0.06	0.03	0.14	0.10	0.08	0.05	0.03	0.05	0.12
RMS diff$_{\text{over}}$	0.22	0.04	0.06	0.03	0.13	0.08	0.08	0.04	0.03	0.05	0.15
RMS diff$_{\text{under}}$	0.07	0.06	0.04	0.03	0.14	0.10	0.07	0.06	0.03	0.04	0.11
[%] Pixels	67	92	86	97	79	71	85	88	92	87	80

Table 3. Comparison of the AE and AOD agreement parameters from the original retrieval (ORIGINAL), and the retrieval with the inverse NDVI-slope relationship (INVERSE) at 6 sites. In addition, retrievals where aerosol models were forced to be either absorbing (ABS) or nonabsorbing (NONABS) are presented for both classes. *n* is the number of measurements while subscripts all, diff, and same refer to all usable measurements, to measurements in which MODIS and AERONET AEs disagree, and to measurements in which the instruments agree on the AE. Agree refers to AE agreement while mean(gb-M) is the averaged AOD difference between the instruments. R^2 is the AOD correlation coefficient squared. The best values for the parameters are color coded.

	Alta Floresta	Kanpur	Mexico City	Mongu	Rome	Xianghe
ORIGINAL:						
n_{all}	119	332	221	224	148	49
n_{diff}	18	24	205	43	101	8
n_{same}	101	308	16	181	47	41
agree	**0.849**	**0.928**	**0.072**	**0.808**	**0.318**	**0.837**
mean(gb-M)	−0.054	−0.199	−0.273	0.050	−0.117	−0.032
R^2	0.739	0.764	0.289	0.632	0.468	0.887
ORIGINAL, ABS:						
n_{all}	147	334	222	239	149	56
n_{diff}	17	23	206	47	104	10
n_{same}	130	311	16	192	45	46
agree	**0.884**	**0.931**	**0.072**	**0.803**	**0.302**	**0.821**
mean(gb-M)	−0.329	−0.189	−0.259	0.044	−0.117	−0.084
R^2	0.754	0.763	0.336	0.635	0.447	0.809
ORIGINAL, NONABS:						
n_{all}	138	332	222	247	148	53
n_{diff}	16	21	208	48	103	10
n_{same}	122	311	14	199	45	43
agree	**0.884**	**0.937**	**0.063**	**0.806**	**0.304**	**0.811**
mean(gb-M)	−0.040	−0.207	−0.274	0.055	−0.119	−0.019
R^2	0.840	0.767	0.314	0.623	0.464	0.931
INVERSE:						
n_{all}	130	294	200	176	96	39
n_{diff}	11	15	174	27	48	5
n_{same}	119	279	26	149	48	34
agree	**0.915**	**0.949**	**0.130**	**0.847**	**0.500**	**0.872**
mean(gb-M)	−0.027	−0.107	−0.204	0.098	−0.064	0.053
R^2	0.758	0.761	0.286	0.523	0.441	0.827
INVERSE, ABS:						
n_{all}	153	295	202	175	93	50
n_{diff}	11	15	173	26	50	7
n_{same}	142	280	29	149	43	43
agree	**0.928**	**0.949**	**0.144**	**0.851**	**0.462**	**0.860**
mean(gb-M)	−0.345	−0.095	−0.201	0.100	−0.066	−0.030
R^2	0.714	0.757	0.357	0.531	0.421	0.761
INVERSE, NONABS:						
n_{all}	152	293	195	167	96	43
n_{diff}	10	17	170	26	48	7
n_{same}	142	276	25	141	48	36
agree	**0.934**	**0.942**	**0.128**	**0.844**	**0.500**	**0.837**
mean(gb-M)	−0.012	−0.110	−0.200	0.112	−0.064	0.048
R^2	0.841	0.762	0.313	0.487	0.441	0.915

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

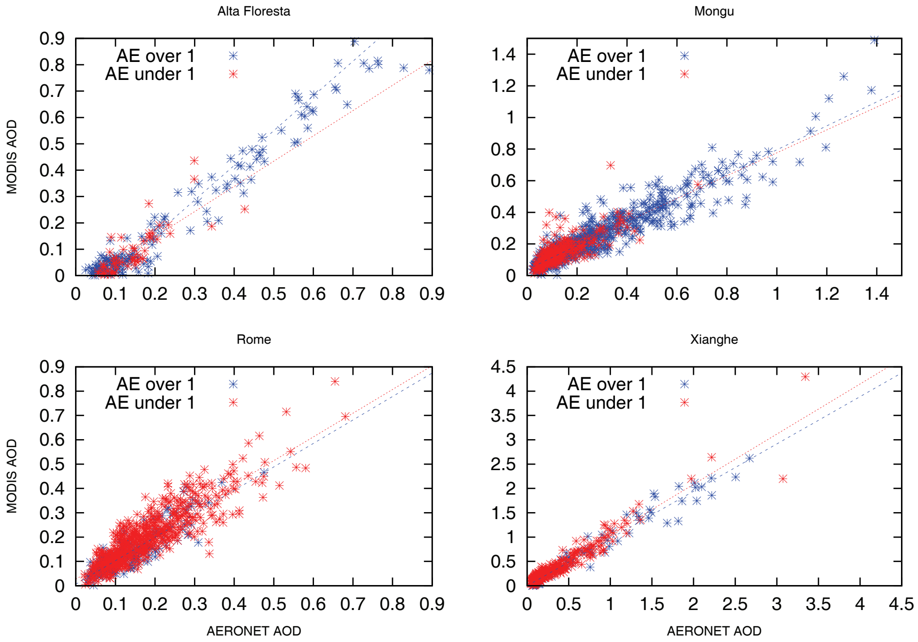

Fig. 1. Correlation of AERONET and MODIS measurements in Alta Floresta, Mongu, Rome and Xianghe. Blue points indicate measurements with MODIS AE over 1, and red points measurements with MODIS AE smaller than 1. Statistics for the comparisons are shown in Table 1.

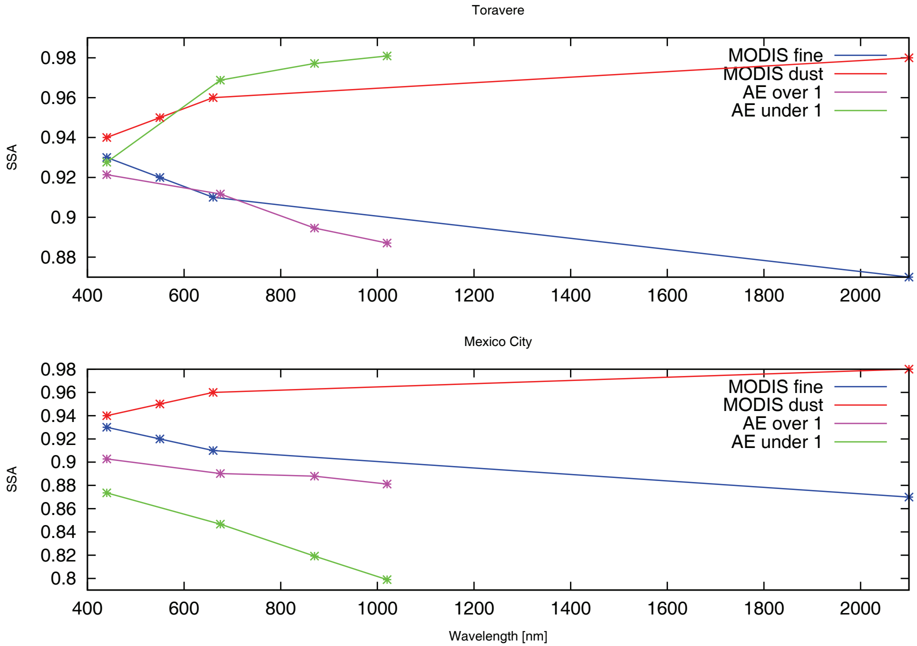

Fig. 2. MODIS aerosol model SSAs compared with AERONET SSA products at two sites: Toravere and Mexico City. SSA spectra for dust and fine dominated aerosol models are shown in red and blue, respectively. The magenta line represents the averaged SSA spectrum from AERONET measurements for observations whose MODIS AE is over 1 (fine dominated). The green color is an average for observations whose MODIS AE is smaller than 1 (dust). Only measurements with AOD values larger than 0.3 (MODIS and AERONET) are considered.

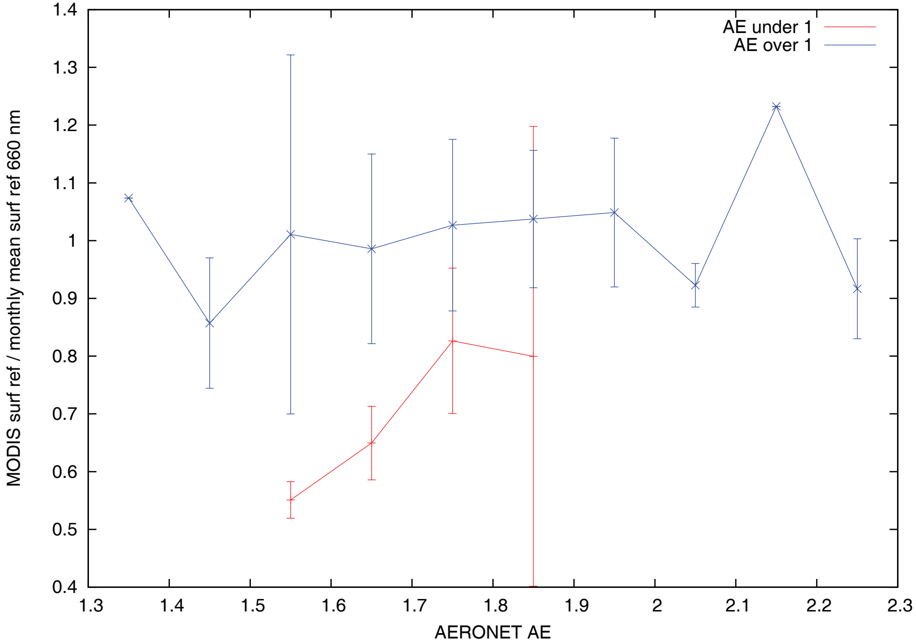

Fig. 3. MODIS surface reflectance at 660 nm, normalized with monthly mean values as a function of AERONET AE. All available measurements from Mongu were used. Measurements with MODIS AE larger (blue) or smaller (red) than 1 are shown separately. Only measurements with AOD values larger than 0.3 (MODIS and AERONET) are considered. In addition, standard deviation of the surface reflectances inside the bins are shown with bars.

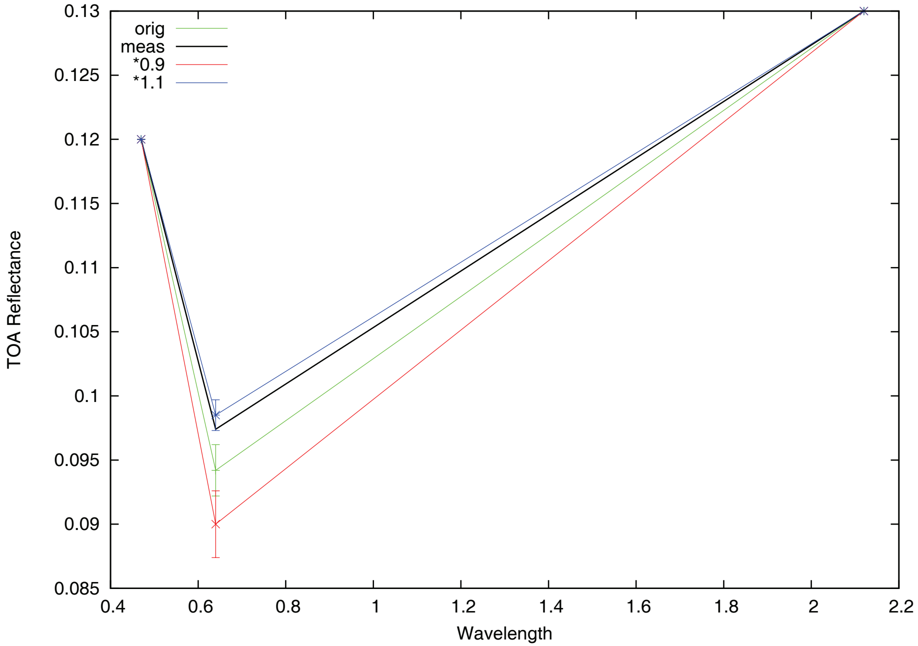

Fig. 4. Example how small changes in the slope(660/2130) affect the retrieved TOA reflectance. The black line is the observed TOA reflectance and the green line is the result from the original retrieval. The red and the blue lines are results from retrievals where the slope(660/2130) has been multiplied by 0.9 and 1.1, respectively. The errorbars show how much the combination of the aerosol models affects the results. The top of the bar indicates pure dust model while the bottom of the bar is for pure fine dominated model.

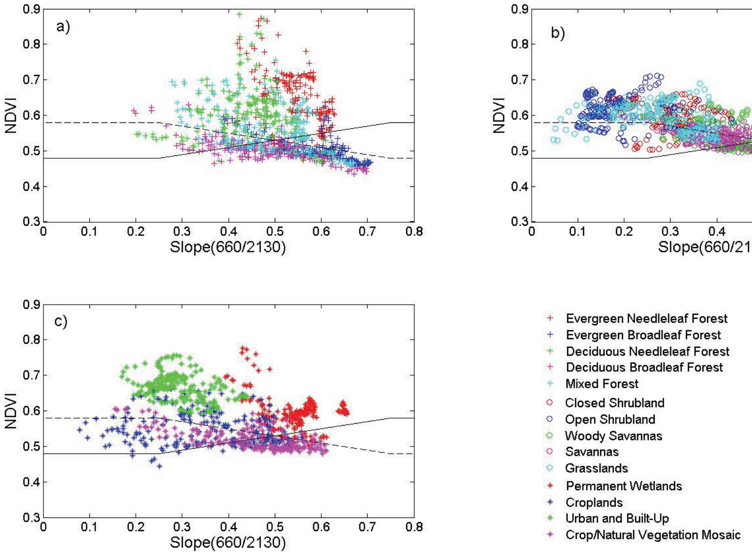

Fig. 5. Dependence of slope(660/2130) on NDVI for different ecotypes based on MODIS surface albedo data. Plot **(a)** presents forest ecotypes (crosses), plot **(b)** savanna ecotypes (circles) and plot **(c)** other ecotypes (stars). The solid black line indicates the relationship of the parameters used in the MODIS retrieval while the dashed line is the inverse version of it.