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Validation of a modified AVHRR aerosol optical depth retrieval algorithm over Central Europe

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Abstract

The Advanced Very High Resolution Radiometer (AVHRR) carried on board the National Oceanic and Atmospheric Administration (NOAA) and the Meteorological Operational Satellite (MetOp) polar orbiting satellites is the only instrument offering more than 25 years of satellite data to analyse aerosols on a daily basis. The present study assessed a modified AVHRR aerosol optical depth τ_a retrieval over land. The initial approach has used a relationship between Sun photometer measurements from the Aerosol Robotic Network (AERONET) and the satellite data to post-process the retrieved τ_a . Herein a stand-alone procedure, which is more suitable for the pre-AERONET era, is presented. In addition, the estimation of surface reflectance, threshold values, and the aerosol model are adapted. The method's cross-platform applicability was tested by validating τ_a from NOAA-17 and NOAA-18 AVHRR at 15 AERONET sites in Central Europe (40.5° N–50° N, 0° E–17° E) from August 2005 to December 2007. Furthermore, the accuracy of the AVHRR retrieval was related to products from two newer instruments, the Medium Resolution Imaging Spectrometer (MERIS) on board the Environmental Satellite (ENVISAT) and the Moderate Resolution Imaging Spectroradiometer (MODIS) on board Aqua/Terra. Considering the linear correlation coefficient R , the AVHRR results were similar to those of MERIS with even lower root mean square error RMSE. Not surprisingly, MODIS, with its high spectral coverage gave the highest R and lowest RMSE. Regarding monthly averaged τ_a , the results were ambiguous. Focusing on small-scale structures, R was reduced for all sensors, whereas the RMSE solely for MERIS substantially increased. Regarding larger areas like Central Europe, the error statistics were similar to the individual match-ups. This was mainly explained with sampling issues. With the successful validation of AVHRR we are now able to concentrate on our large data archive dating back to 1985. This is a unique opportunity for both climate and air pollution studies over land surfaces.

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1 Introduction

Aerosols do not only affect the climate (IPPC, 2007), but also have a major influence on visibility (Horvath, 1995) and as air pollutants can become hazardous for human health (Samet et al., 2000). Spaceborne techniques have helped to increase our knowledge of the spatial and temporal distribution of aerosols and to learn more about their physical and chemical properties over the past years. Nowadays, various satellite sensors are used to retrieve different aerosol characteristics (e.g. Kokhanovsky et al., 2007; Yu et al., 2006).

Remote sensing of aerosol properties with the Advanced Very High Resolution Radiometer (AVHRR) has a long tradition (Knapp and Stove, 2002), even though aerosol detection was not the initial aim of this instrument. Nonetheless, the AVHRR, carried on board the National Oceanic and Atmospheric Administration (NOAA) and the Meteorological Operational Satellite (MetOp) polar orbiting satellites, is the only instrument offering the opportunity to analyse more than 25 years of satellite data in moderate spatial resolution on a daily basis. Most studies of aerosol properties from AVHRR focused on ocean surfaces (Mishchenko et al., 1999; Geogdzhayev et al., 2002; Ignatov et al., 2004; Mishchenko and Geogdzhayev, 2007), where the spectral properties are generally well known and the surface reflectance is low. The first AVHRR retrieval over land (Soufflet et al., 1997) used the dark dense vegetation (DDV) method suggest by Kaufman and Sendra (1997) to derive the aerosol optical depth τ_a over boreal forest. The disadvantage of this method is the low occurrence of DDV; e.g. in Europe less than 1% of the pixels (Borde et al., 2003) contain DDV. The retrieval over brighter and heterogeneous land surfaces is more complicated and prone to introduce larger errors due to reduced aerosol signal and temporally unstable surface reflectance. Knapp and Stove (2002) derived τ_a from the reduced resolution ($110 \times 110 \text{ km}^2$) Pathfinder-Atmosphere (PATMOS) dataset using also bright surface targets. Hauser et al. (2005a) applied a similar technique to derive τ_a at full resolution ($1.1 \times 1.1 \text{ km}^2$) for Central Europe using NOAA-16 AVHRR and they further qualitatively compared monthly and seasonal

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means from this product with MODIS collection 004 data (Hauser et al., 2005b). A full resolution τ_a climatology from AVHRR covering land surfaces is still missing.

This study is a step toward such a climatology for Europe. In the AVHRR algorithm from Hauser et al. (2005a) a relationship between the satellite data and ground-based

5 Sun photometer measurements from the Aerosol Robotic Network (AERONET) was established to post-process the data resulting in a better retrieval quality. Applied to NOAA-17 and NOAA-18 AVHRR this post-correction did not lead to the same improvement. Therefore, we wanted to assess a stand-alone algorithm which is not dependent on the AERONET data for a correction. Such a procedure is more suitable for the
10 pre-AERONET era, and can thus be applied to our AVHRR dataset dating back to 1985. Moreover, certain retrieval steps from the original algorithm have been adapted, e.g. assumption of the aerosol model and estimation of the surface reflectance. The cross-platform applicability of the method is tested using two satellites with overlapping time period, namely NOAA-17 and NOAA-18 AVHRR, and the retrieved τ_a is validated
15 with Sun photometer measurements of AERONET. Furthermore, the performance of the AVHRR aerosol retrieval is related to products from the newer generation Medium Resolution Imaging Spectrometer (MERIS) on board the Environmental Satellite (ENVISAT) and the widely used Moderate Resolution Imaging Spectroradiometer (MODIS) on board Aqua and Terra. Section 2 summarises the data used in this study, Sect. 3 describes the AVHRR τ_a retrieval and the differences between the original and the proposed method in more detail. In Sect. 4 we shortly describe the method of the data
20 validation. A comprehensive validation of individual overpasses and monthly aggregated data is shown in Sect. 5. Conclusions are drawn in Sect. 6.

2 Data

25 The aerosol optical depth products from three different satellite sensors (AVHRR, MERIS, and MODIS) flown on board five satellites (NOAA-17, NOAA-18, ENVISAT, Aqua, and Terra), which cover mid-morning and afternoon orbits, are validated for the

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geographical area of Central Europe (40.5° N to 50° N, 0° E to 17° E) between August 2005 and December 2007. This time frame was selected because comprehensive data from all satellites were available for this period.

2.1 AERONET

5 A total of 15 Sun photometer measurement sites from the AERONET (Holben et al., 1998) providing level 2.0 data (cloud screened and quality assured) are used for the validation in the investigated area (cf. Table 1). They represent a wide range of aerosol compositions (e.g. urban, rural) and topographic situations (e.g. flat or complex terrain).
10 Additionally, aerosol micro-physical properties are derived from the level 1.5 inversion products (Dubovik and King, 2000).

2.2 MERIS

The MERIS (morning orbit with equator crossing time EXT~10:00 a.m.) standard level 2 aerosol product (Santer et al., 1999) from the European Space Agency (ESA) is based on the detection of DDV (Kaufman and Sendra, 1997) selected with the atmospheric resistant vegetation index, as the reflectance properties of dark targets are known well enough to retrieve the aerosol signal accurately. The main disadvantage
15 of this technique is the rare occurrence of DDV pixels over Central Europe (less than 1%; Borde et al., 2003). Thus, the method has been extended to brighter surface types (Santer et al., 2007). We use τ_a at 443 nm and the Ångström wavelength exponent (α)
20 at $1 \times 1 \text{ km}^2$ resolution to calculate τ_a at 550 nm.

2.3 MODIS

For MODIS, Terra (MOD04L2, morning orbit with EXT~10:30 a.m.) and Aqua (MYD04L2, afternoon orbit with EXT~01:30 p.m.) collection 005 data from the second generation algorithm (Levy et al., 2007a) are used. Compared to prior MODIS

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products, the surface reflectance parametrization (ratios between visible and 2.12 μm channels, VISvs2.12) has been improved, now considering variations by surface type (based on the short-wave infrared normalised difference vegetation index) and angular variability in the VISvs2.12 reflectance relationship. Additionally, the assumed aerosol properties have been updated according to Levy et al. (2007b) and new look-up tables have been computed considering polarisation. Finally, three channels are simultaneously inverted and the 2.12 μm channel is no longer assumed to be totally transparent for aerosols.

2.4 AVHRR

We use daily full resolution ($1.1 \times 1.1 \text{ km}^2$) NOAA-17 mid-morning (EXT~10:25 a.m.) and NOAA-18 afternoon (EXT~01:45 p.m.) overpasses. Calibration, geocoding, orthorectification, cloud and cloud shadow detection are part of the pre-processing of the data and are described in more detail in Hauser et al. (2005a). Meteorological fields of total column ozone, vertically integrated water vapour, and sea level pressure from the European Centre for Medium-Range Weather Forecasts (ECMWF) between 09:00 and 15:00 UTC are interpolated to the time of the satellite overpass and are utilised for the atmospheric correction of water vapour, ozone influence, and Rayleigh optical depth.

In order to estimate τ_a from AVHRR over land surfaces, a modified version of the single-channel ($\sim 630 \text{ nm}$), multi-temporal approach of Hauser et al. (2005a) is applied.

The general principle and modifications are described in the following section.

3 AVHRR aerosol optical depth retrieval

3.1 General principle

For the retrieval of τ_a , the radiation reflected from the earth's surface has to be separated from the satellite signal. The determination of surface reflectance ρ_{SFC} , whose

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accuracy is a critical parameter in the derivation of τ_a , is done by using a multi-temporal technique which employs a time series of 45 consecutive days. Within this period a particular pixel is observed under various satellite zenith angles Θ_v . This is based on the assumption that the radiometric properties of the underlying land surface are almost stable and observations with low aerosol concentrations (background conditions) exist. If the top-of-atmosphere reflectance ρ_{TOA} is considered as a function of Θ_v , ρ_{SFC} can be estimated as the resulting minimum reflectance. A continuous bidirectional reflectance function is obtained by connecting the minimum values using the concept of convex hull (cf. Fig. 1). Then, ρ_{TOA} and ρ_{SFC} together with a pre-defined aerosol model are implemented into the Simplified Method for Atmospheric Correction (SMAC) radiative transfer code (Rahman and Dedieu, 1994), updated to 6S (Vermote et al., 1997), to calculate τ_a .

To enhance the quality of the retrieved τ_a , a spatial filtering procedure within a moving window of 15×15 pixels is applied to each pixel, which ensures that small-scale structures of the τ_a variability are retained. In order to take into account undetected clouds or cloud shadow, only values within the 10 to 40 percentile of the filter window are used to calculate the mean τ_a , which is comparable to the method of the MODIS algorithm in pre-selecting particular pixels for processing (Kaufman et al., 1997; Levy et al., 2007a).

3.2 Differences to the original approach

The original NOAA AVHRR aerosol retrieval from Hauser et al. (2005a) uses a post-processing procedure based on a relationship between Sun photometer (AERONET) measurements and the satellite data (NOAA-16 AVHRR) to enhance the quality of the aerosol product. Employed on NOAA-17 and NOAA-18 AVHRR, the post-correction with the original approach did not lead to the same increase of the retrieval accuracy as for NOAA-16. For this reason and having in mind the derivation of a long-term τ_a climatology dating back to 1985, we were seeking for a stand-alone algorithm which is also more suitable for the pre-AERONET era. In the modified approach we adapted

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several steps of the original processing. In the next paragraphs we will shortly examine the changes introduced with the stand-alone procedure.

First, the accuracy of the retrieval turned out to depend on the land cover type. Accordingly, the estimation of ρ_{SFC} with the convex hull has been improved which substantially reduced the root mean square error in these regions. Furthermore, the aerosol properties were adapted using information from the AERONET inversion products. More details about these changes are explained in Sect. 5.1.

Compared to Hauser et al. (2005a) we reduced the size of the filter window from 25×25 to 15×15 pixels, with the aim not to smooth too much of the small-scale aerosol structures. Despite the reduction of 64% in the filter area, this procedure would still mix values from low and high altitudes in mountainous regions. Matthias et al. (2004) demonstrated with measurements from the European Aerosol Research Lidar Network (EARLINET) that a 500 m height difference corresponds to $\Delta\tau_a \sim 0.05\text{--}0.15$ in the lower planetary boundary layer for several locations in Central Europe. Therefore, we apply a 1 km digital elevation model (HYDRO1k, US Geological Survey) and restrict the pixels of the filter window to be within ± 250 m of the central pixel. Finally, owing to quality reasons we apply two criteria: 1) We restrict the retrieval to pixels with $\rho_{\text{SFC}} \leq 0.07$ and 2) the regional standard deviation of τ_a within the 15×15 region must not exceed 0.1. Even though the brightest surface types are excluded, we do not get considerably less observations than in the original approach. Only areas mainly dominated by bright surfaces are excluded in the processing.

In order to demonstrate the performance of the proposed method compared to the original one, we applied the modified algorithm to the same data set as in Hauser et al. (2005a). Therefore, NOAA-16 AVHRR data were evaluated for the same set of AERONET sites and the same time period (from May 2001 to December 2002) as in the above mentioned publication. Table 2 shows the results from two exemplary AERONET sites, Avignon and Ispra, and the summary of all sites (cf. Hauser et al., 2005a). The surrounding of Avignon is typically dominated by cropland which results in larger uncertainties in the ρ_{SFC} estimation with the original approach, as will be explained later

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on. Ispra, on the other hand, is situated in an area covered by mostly dark surface types like forests and lake water. Focusing on the linear correlation coefficient R one can see that the proposed method clearly outperforms the original approach for Avignon and for the summary of all sites. At Ispra the values of R resemble each other. The same holds true for the standard deviation σ and the linear regression equation $y=A+Bx$.

Although areas widely covered by bright land cover types are excluded in the τ_a retrieval, the better performance over large areas together with the independent design (stand-alone) are obvious advantages of the improved method.

4 Validation methodology

For the comparison of satellite-retrieved and Sun photometer-measured τ_a , former validation studies (e.g. Chu et al., 2002) have recommended to take both spatial and temporal variability of the aerosol distribution into account. The first requirement is achieved by building average τ_a over an area of $50 \times 50 \text{ km}^2$. The box size corresponds to a maximum number of 25 (2500) MODIS (AVHRR, MERIS) τ_a values per box, where at least 20% of the pixels had to be valid to calculate the average. The temporal variability was treated as in the above-mentioned study using at least two out of five possible AERONET measurements within ± 30 min of the satellite overpass to calculate the time average. At the AERONET sites τ_a at 550 nm is computed using a second-order polynomial fit in a lognormal space.

5 Results and discussion

5.1 Validation of AVHRR

Figures 2 and 3 give a first impression on the validation results between AERONET and both NOAA spacecraft. They display scatter-density plots and the linear regression equation for the summary of all AERONET sites listed in Table 1 and five additional

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locations as examples for different land cover types and aerosol conditions. According to ESA's GlobCover product (Bicheron et al., 2008) Avignon is mainly dominated by cropland; Fontainebleau is a mixture of cropland and forest in a region with more absorbing aerosols; Ispra is surrounded by forest, lake water, and is influenced by the highly polluted Po Valley; Laegeren is a hilly region with mixed land cover and mostly non-absorbing aerosols; Villefranche is situated on a peninsula at the Mediterranean adjacent to a coastal region with highly variable topography and varying aerosol conditions.

Detailed statistical results are presented in Table 3. A total of 1529 match-ups N for NOAA-17 and 1475 for NOAA-18 have been found during the investigated period. The correlation coefficient R , which expresses the overall ability to retrieve the aerosol signal, equals $R=0.68$ for NOAA-17 and $R=0.71$ for NOAA-18. The root mean square error RMSE (~ 0.1) and the standard deviation σ (~ 0.07) represent the magnitude of random errors which are proportional to radiometric noise, variations in ρ_{SFC} , and sub-pixel cloud contamination.

When using the original approach of Hauser et al. (2005a) to estimate ρ_{SFC} , we found a dependency between the correlation coefficient and the mean surface reflectance $\overline{\rho_{\text{SFC}}}$, with $R=-0.71$. This also holds true for the RMSE. With the help of GlobCover, areas mainly containing cropland ($\sim 39\%$ of the land surface pixels in the investigated area) were identified to result in the largest errors with the original convex hull scheme used to detect the minimum reflectance. Therefore, we adapted the scheme by dividing Θ_v into four bins ($<-30^\circ/-30^\circ-0^\circ/0^\circ-30^\circ/30^\circ<$) and searching the convex hull in each bin. The differences between the old and new scheme, indicated in Fig. 1, are especially obvious in the backward scattering region. Kaufman and Tanré (1996) showed that an error in ρ_{SFC} of 0.01 translates into $\Delta\tau\sim 0.1$. As explained in Hauser et al. (2005a), the convex hull scheme is particular sensitive to negative variations in ρ_{SFC} . Hence, we additionally applied a boxcar average to reduce the influence of very dark observations. With this procedure the correlation was slightly improved and the RMSE could substantially be reduced in regions mainly dominated by cropland, e.g.

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at Avignon from 0.15 (0.12) to 0.09 (0.08) for NOAA-17 (NOAA-18). After applying this change to the ρ_{SFC} estimation, the dependency between R and $\overline{\rho_{\text{SFC}}}$ almost vanished ($R = -0.16$). But still, the darkest surfaces (Ispra, Venice, Villefranche; cf. Table 3) exhibit the best correlations.

5 For most of the sites, the differences between NOAA-17 and NOAA-18 are small and could be due to undetected subpixel clouds or uncertainties in calibration (Li et al., 2009). Interestingly enough, at the offshore platform of Venice the performance of NOAA-17 is clearly worse than that of NOAA-18. On the same time Villefranche, a location on a peninsula containing both water and land, shows good correlations for
10 both satellites. A possible explanation could be the influence of different illumination conditions when viewing the shallow coastal waters around Venice which may also be supported by the different values of $\overline{\rho_{\text{SFC}}}$ in Table 3. A comparison of the monthly averages between the two satellites does not reveal obvious differences (as will be demonstrated in Sect. 5.3.2) and the mean relative difference of $\sim 2\%$ is similar to the
15 one between Terra and Aqua ($\sim 2\%$ for the investigated period).

Considering the linear regression equation $y = A + Bx$ between AVHRR and AERONET, both satellites have a similar offset A , whereas the slope B is steeper for NOAA-18. A nonzero offset indicates a biased retrieval at low τ_a which may be associated with sensor calibration errors or erroneous ρ_{SFC} estimation (Zhang et al., 2001).
20 A slight overestimation at low τ_a can be found for most of the sites. Deviations of B from unity are associated with incorrect assumptions of the aerosol micro-physical properties (Zhang et al., 2001). Choosing a more (less) absorbing aerosol model decreases (increases) the slope. In Table 1 we display the average and standard deviation of the single scattering albedo ω_0 at each AERONET site for the evaluated period. From
25 the above mentioned considerations it follows that with $B = 0.80$ ($B = 0.87$) for NOAA-17 (NOAA-18) the chosen aerosol model is too absorbent. The continental model (original approach) in 6S uses $\omega_0 = 0.89$. Ten AERONET sites in Table 1 exhibit a less absorbing aerosol type than the continental model of 6S, whereas at three sites a more absorbing type is predominant. The exceptionally low value in Davos is expected to be an

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error caused by usually low τ_a at this high altitude resulting in substantial errors in the retrieval of ω_0 (Dubovik et al., 2000). Calculating the average for all AERONET sites, with the exclusion of Davos, reveals $\overline{\omega_0}=0.91$. Zhang et al. (2001) have shown that a $\Delta\omega_0=0.03$ at $\tau_a=0.5$ corresponds to an error of 10% in the retrieval with increasing error for larger τ_a . The standard deviation of ω_0 at some sites shows substantial variations causing temporarily large deviations from the assumed properties of the continental model which will lead to additional errors.

Thus, we derived a new set of aerosol models and tested the effect on the AVHRR data. Similar to Levy et al. (2007b) the aerosol properties were split into the four seasons. For each of these, the average refractive index and size distribution was calculated from the AERONET inversion products. Owing to quality reasons, the level 2.0 dataset is very strict and for most of the AERONET sites used in this study not enough points were available to calculate the seasonal means. Therefore, we changed the level 2.0 threshold (Dubovik et al., 2000) of τ_a (440 nm) from 0.4 to 0.2 and subsequently calculated the averages from the level 1.5 data. In doing so, the slope of both satellites can be improved, for NOAA-17 from 0.80 to 0.92 and for NOAA-18 from 0.87 to 0.94. All the other parameters (R , RMSE, A) remain similar to the original aerosol model. This means that especially high aerosol concentrations are detected more accurately with the new set of aerosol models.

Aside from the aerosol model, a second effect may cause slopes of less than unity. The accuracy of the calculations with the utilised radiative transfer code SMAC decreases for $\tau_a>0.8$ (Rahman and Dedieu, 1994); therefore, the retrieval is limited to $\tau_a\leq 0.8$ and higher aerosol loads than this upper limit are not present in the comparison between AERONET and AVHRR. However, less than 1% of the AERONET observations were larger than 0.8 during the investigated period and the impact on the statistics is assumed to be almost negligible.

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5.2 Comparison between AVHRR, MERIS, and MODIS

This section compares the performance of the AVHRR τ_a retrieval with two other medium resolution sensors, MERIS and MODIS. Instead of relating the results from AVHRR to other validation studies, we want to perform an accurate comparison using the same set of AERONET sites for all satellites during the same time period with the approach explained in Sect. 4. The results are summarised in Table 3 and Fig. 4.

Looking at the scatter-density plot with the summary of all AERONET sites (Figs. 2–4) it is obvious that MODIS shows the best performance, with slightly higher R found for Aqua than for Terra. This is not surprising keeping in mind that, in contrast to AVHRR, MODIS has a much better spectral coverage. However, the correlations of AVHRR and MERIS resemble each other, although Fig. 3 demonstrates that τ_a from the latter is biased high. Considering σ and RMSE, AVHRR reveals lower values than MERIS. The results from MERIS are consistent with Vidot et al. (2008), who found similar errors and explain a part of the high RMSE with the presence of thin clouds, which the current MERIS algorithm is not able to flag. Moreover, they conclude that the underestimation of α results in an additional error. Apparently, MODIS exhibits the lowest error rates (RMSE=0.06), comparable to other MODIS validation studies (Chu et al., 2002; Levy et al., 2007a; Remer et al., 2008). Analogous to AVHRR, Aqua and Terra perform differently at Venice, with a higher RMSE of the morning crossing platform Terra.

Analysing A and B of the linear regression equation ($y=A+Bx$), at the majority of locations and in the summary of all sites every satellite shows $A>0$ and $B<1$ (cf. Table 3) meaning that at low aerosol concentrations τ_a is overestimated and at high concentrations underestimated. This effect is most pronounced for MERIS. Compared to the work of Vidot et al. (2008), who found a very low offset ($A\sim-0.02-0.03$) in Europe by using three AERONET sites (Ispra, Lille, Minsk), we obtain $A=0.1$ for MERIS using 15 European AERONET sites. A part of the discrepancy can be explained with biased α values (Kokhanovsky et al., 2007; Vidot et al., 2008) used for the calculation of τ_a at 550 nm and similar to the RMSE, with the occurrence of some extreme outliers. Vidot

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et al. (2008) apply a smaller region of $12 \times 12 \text{ km}^2$ around each AERONET site. We also investigated the influence of the box size around each AERONET site using averaging areas between $10 \times 10 \text{ km}^2$ and $50 \times 50 \text{ km}^2$, but the effect on the statistical results turned out to be minor and cannot explain the discrepancies between our results and the one found by Vidot et al. (2008). Aqua and Terra show the lowest offset (0.01) which may also be caused, at least partly, by allowing small negative values of τ_a (Levy et al., 2007a).

As described in the previous section, underestimation of τ_a at high aerosol burden can be caused by insufficient light absorption in the aerosol models. Up to now, the AVHRR retrieval has been based on the same aerosol properties ($\omega_0=0.89$) for whole Europe for the entire year. As shown before, a new set of aerosol models helps to improve the slope of the AVHRR aerosol product and predicts high aerosol loads more accurately. Regarding the MODIS retrieval, a nonabsorbing model ($\omega_0 \sim 0.95$) with dynamic size parameters depending on the optical depth is used for the investigated area (Levy et al., 2007b), which results in a slope close to unity. Considerable deviations are only found for the mountain site Davos, which may, to a certain extent, be explained with the small sample number. Aqua also shows at Venise larger than average deviations from unity. The MERIS retrieval applies 12 different aerosol models without absorption and one would expect the slope to be greater than unity. Nonetheless, $B=0.71$ is not in agreement with the above mentioned considerations. Possible explanations could be a relatively high overestimation of low aerosol concentrations and as mentioned before, errors introduced with a biased α .

5.3 Comparing monthly means

5.3.1 Spatial distribution

First, in order to show spatial differences between the aerosol products, we qualitatively compare MODIS as a reference with AVHRR (MERIS). Figure 5 is an example of the monthly mean τ_a during April 2007. This month was chosen since stable weather

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conditions due to high surface pressure yielded to a high observation frequency and also led to a high aerosol burden in the Po River Valley. To calculate the average at a particular pixel at least 10% of the days had to provide valid values.

5 The overall pattern between MODIS and AVHRR looks comparable with respect to the geographical pattern, but the magnitude of τ_a especially in the Po River Valley is clearly underestimated by the latter. This is in accordance with the results of the regression analysis (cf. Table 4) in which the slope of NOAA's AVHRR is clearly below unity meaning that high aerosol loads are underestimated. In the vicinity of the Rhone River delta ($\sim 43.5^\circ$ N, 4.5° E) AVHRR also displays lower τ_a than MODIS. Focusing
10 on the Alpine region (stretch from 44° N/ 7° E to 47.5° N/ 15° E), AVHRR shows more details compared to MODIS, with clearly emerging valleys which could mean that the former aerosol product seems more appealing for climate or air pollution studies in such regions. Not only does MERIS capture the high concentrations in the Po River Valley well, but is also capable of detecting τ_a in the Alpine valleys. Nonetheless,
15 MERIS exhibits a substantial overestimation of τ_a in most regions compared to MODIS. Furthermore, the MERIS image contains more areas with data gaps (gray) which may be due to the lower repeat cycle of ENVISAT.

5.3.2 AERONET versus satellites

Finally, this comparison demonstrates the capability of the polar orbiting platforms to
20 represent the monthly average conditions at ground level which is of interest for climate studies. Therefore, at each location shown in Table 1 the monthly average $\overline{\tau_a}$ was calculated for AERONET using all available Sun photometer measurements and for the satellites using all retrieved τ_a during a particular month. The spatial averaging of the satellite data is done as described in Sect. 4. For both AERONET and satellite at
25 least 10% of days with data have to be available to calculate $\overline{\tau_a}$. Results are shown in Table 4 and Fig. 6.

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In contrast to the linear regression of the individual collocations, all satellites show increasing offsets and decreasing slopes. Myhre et al. (2005) found a similar behavior for aerosol retrievals over oceans and argued that sampling issues are the main reason. This is supported by Anderson et al. (2003) who investigated mesoscale variations of tropospheric aerosols and found that the concentration of the airborne particles is barely homogeneous over time scales of more than 12 h. This is supported by the fact that the largest offset is found for MERIS, whose smaller swath width results in a lower repeat cycle compared to the other two sensors. At high aerosol loads, τ_a is most clearly underestimated by AVHRR, probably caused by the cutoff at $\tau_a > 0.8$. As explained before, the cutoff is due to limitations of the radiative transfer code SMAC (Rahman and Dedieu, 1994). A more detailed inspection of the data revealed that some outliers can either be explained with low frequency of AERONET or satellite observations for certain months. After filtering the data with a criterion of at least 20% of days with valid measurements per month, the statistics were slightly improved.

Apparently, a reduction of R can be found for all sensors with regard to the individual overpasses. The RMSE, however, is similar to the individual match-ups, solely the MERIS RMSE significantly increased. As explained above, high temporal variability in τ_a and sampling issues are the major cause for this behaviour. Table 4 supports this finding since the strongest decrease of R and increase of RMSE is found for MERIS. With a repeat cycle of approximately three days, the capability of reproducing the “true” $\overline{\tau_a}$ with MERIS is limited.

In Fig. 7 we compare the aggregated monthly averages of all sites together for each of the 29 months between August 2005 and December 2007. Most of the time the reference curve of AERONET is at the lower end of the monthly values meaning that the satellite sensors usually overestimate them. Nonetheless, the yearly cycle is altogether represented well by all of them. As before, most of the differences may be explained with sampling issues which explains that they are largest for MERIS. Considering MODIS and AVHRR, R (RMSE) of the aggregated monthly averages is significantly higher (lower) than for the averages of the single sites shown in Table 4 with R

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of 0.89, 0.88, 0.74 and 0.71 for Terra, Aqua, NOAA-17 and NOAA-18, respectively; the RMSE can be found in the range of 0.041 (Terra) to 0.051 (NOAA-18). Only for MERIS the statistics did not improve a lot with $R=0.46$ and $RMSE=0.21$.

5.3.3 Intersatellite comparison

5 Since we are strongly interested in the compilation of an AVHRR long-term climatology, the robustness of the proposed method is an important issue. Hence, we shortly examine the intersatellite differences and compare the consistency of the AVHRR retrieval with the one of MODIS. The scatter plots in Fig. 8 and Table 5 reveal that the cross-satellite performance of NOAA's AVHRR is similar to MODIS with almost the
10 same R and somewhat lower RMSE. Moving from small-scale (individual averages, Fig. 8a) to large-scale (aggregated averages, Fig. 8b) areas, for both instruments the statistics significantly improve with NOAA's linear regression equation almost at the 1:1 intersection line. From this we can conclude that despite local differences the overall performance is good. These are important findings with regard to the compilation of an
15 AVHRR τ_a climatology and they demonstrate that the proposed method works platform independently.

6 Conclusions

We assessed the performance of a modified version of an AVHRR aerosol optical depth retrieval algorithm for land surfaces. In contrast to the original approach, it is a stand-alone procedure which is more suitable for the pre-AERONET era. The scheme to
20 derive ρ_{SFC} has been adjusted which turned out to substantially reduce the RMSE over areas mainly dominated by cropland (~39% of land surface pixels). What is more, the aerosol model used for the AVHRR retrieval proved to be too absorbent in the investigated area. With the help of a new set of aerosol models, the retrieval at high
25 aerosol concentrations could be slightly improved. With the aim to compile a long-term

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τ_a climatology for Europe making use of our AVHRR archive dating back to 1985, the method should be robust and cross-platform applicable. Therefore, two AVHRR sensors with overlapping time period flown on board NOAA-17 and NOAA-18 were used in this study. The results were validated against τ_a from AERONET Sun photometer measurements and were compared with two other medium resolution satellite sensors, MERIS and MODIS. Related to the newer generation sensors, AVHRR reveals good results and also the cross-platform differences are only minor which is an important step towards a climatology. Although low aerosol concentrations are slightly overestimated and high aerosol loads underestimated. This effect is pronounced in the MERIS data and less obvious for MODIS.

Finally, the linear regression analysis of monthly average $\overline{\tau_a}$ between each AERONET site and the various satellites results in lower correlations with higher intercepts and lower slopes than for the individual match-ups. Simultaneously, when aggregating all AERONET sites to monthly means and comparing these with the satellites, the overall capability of them to reproduce the true atmospheric conditions is mostly good. This means that variations at small-scale are harder to capture than those of regional or even larger scale. An explanation for this may mainly be sampling issues which is also supported by the fact that AVHRR and MODIS, having a higher repeat cycle than MERIS, show the smallest increase in the error statistics. This is of importance when selecting satellite data for long-term studies.

Owing to sampling issues difference between time-aggregated ground-based and satellite measurements will always occur. Therefore, considering climate studies, not only should we focus on the absolute values of a comparison, but also investigate whether the trend of the aerosol concentration can be captured right. Hence, based on the robust method introduced and validated in this study and making use of the large AVHRR data archive at our institute, the next step will be the extension of the proposed method to prior AVHRR sensors to perform a trend analysis and, finally, the compilation of an aerosol long-term climatology covering Central Europe.

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Table 1. AERONET sites in Central Europe (40.5° N–50° N, 0° E–17° E) included in the validation. Beside the abbreviation used for the analysis later on, the geographical coordinates and the altitude of each site, information about the aerosol model in terms of the average and standard deviation of the single scattering albedo ω_0 for the period between August 2005 and December 2007 is included as well (cf. Sect. 5.1).

AERONET site	Abbr.	Lat. [° N]	Lon. [° E]	Alt. [m]	$\overline{\omega_0} \pm \sigma$
ALL					0.91±0.11
Avignon	AVI	43.933	4.878	32	0.91±0.09
Carpentras	CAR	44.083	5.058	100	0.89±0.10
Davos	DAV	46.813	9.844	1596	0.82±0.15
Fontainebleau	FON	48.407	2.680	85	0.88±0.12
Ispra	ISP	45.803	8.627	235	0.87±0.09
Karlsruhe	KAR	49.093	8.428	140	0.91±0.08
Laegeren	LAE	47.480	8.351	735	0.94±0.05
Modena	MOD	44.632	10.945	56	0.91±0.07
Munich University	MUN	48.148	11.573	533	0.93±0.10
Palaiseau	PAL	48.700	2.208	156	0.92±0.08
Paris	PAR	48.867	2.333	50	0.91±0.07
Toulon	TLN	43.136	6.009	50	0.90±0.09
Toulouse	TOU	43.575	1.374	150	—
Venise	VEN	45.314	12.508	10	0.94±0.06
Villefranche	VIL	43.688	7.329	130	0.90±0.11

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Table 2. Comparison of the original (Hauser et al., 2005a) and the proposed method to derive τ_a from AVHRR over land surfaces. The differences of the various methods are explained in Sect. 3. R denotes the linear correlation coefficient, σ is the standard deviation, A and B are the coefficients of the linear regression equation $y=A+Bx$.

Site	R	σ	A	B
Hauser et al. (2005a) no post-processing				
AVI	0.50	0.15	0.19	1.00
ISP	0.83	0.10	0.10	0.89
ALL	0.57	0.16	0.13	0.92
Hauser et al. (2005a) with post-processing				
AVI	0.67	0.08	0.08	0.97
ISP	0.87	0.08	0.06	0.68
ALL	0.70	0.11	0.04	0.69
proposed method (stand-alone)				
AVI	0.75	0.04	0.00	0.83
ISP	0.84	0.09	−0.01	0.71
ALL	0.77	0.07	0.00	0.73

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Table 3. Statistical results for the comparison between AERONET and the various satellites. For NOAA-17 and NOAA-18 AVHRR the estimated mean surface reflectance $\overline{\rho_{\text{SFC}}}$ is included as well. Abbreviations are the AERONET sites and are explained in Table 1.

Satellite	AVI	CAR	DAV	FON	ISP	KAR	LAE	MOD	MUN	PAL	PAR	TLN	TOU	VEN	VIL	All
Linear Correlation Coefficient (<i>R</i>)																
N17-AVHRR	0.55	0.59	0.25	0.49	0.79	0.85	0.72	0.69	0.77	0.70	0.78	0.71	0.64	0.60	0.83	0.68
N18-AVHRR	0.74	0.65	0.42	0.60	0.78	0.81	0.73	0.67	0.62	0.72	0.51	0.74	0.65	0.78	0.79	0.71
MERIS	0.77	0.62	0.44	0.70	0.85	0.91	0.71	0.67	0.84	0.53	0.87	0.27	0.75	–	0.58	0.73
A-MODIS	0.94	0.91	0.75	0.84	0.96	0.83	0.94	0.93	0.88	0.92	0.84	0.88	0.76	0.91	0.86	0.89
T-MODIS	0.83	0.91	0.77	0.95	0.93	0.96	0.92	0.91	0.90	0.91	0.83	0.95	0.88	0.86	0.90	0.87
Root Mean Square Error (RMSE)																
N17-AVHRR	0.09	0.11	0.10	0.10	0.11	0.06	0.11	0.12	0.10	0.09	0.05	0.09	0.12	0.11	0.08	0.10
N18-AVHRR	0.08	0.11	0.06	0.08	0.10	0.07	0.10	0.12	0.10	0.09	0.10	0.07	0.13	0.10	0.08	0.10
MERIS	0.10	0.09	0.21	0.09	0.12	0.06	0.16	0.09	0.10	0.13	0.06	0.12	0.10	–	0.12	0.12
A-MODIS	0.06	0.05	0.07	0.04	0.06	0.06	0.03	0.06	0.03	0.05	0.04	0.04	0.07	0.06	0.07	0.06
T-MODIS	0.04	0.05	0.04	0.04	0.09	0.06	0.05	0.07	0.05	0.07	0.05	0.04	0.06	0.10	0.05	0.06
Standard Deviation (σ)																
N17-AVHRR	0.06	0.07	0.07	0.07	0.07	0.04	0.07	0.08	0.06	0.06	0.03	0.06	0.08	0.08	0.06	0.07
N18-AVHRR	0.05	0.07	0.04	0.05	0.07	0.04	0.06	0.08	0.06	0.06	0.05	0.05	0.08	0.07	0.06	0.06
MERIS	0.07	0.06	0.10	0.06	0.08	0.04	0.10	0.09	0.07	0.10	0.04	0.07	0.08	–	0.09	0.08
A-MODIS	0.04	0.03	0.04	0.03	0.04	0.03	0.03	0.03	0.02	0.04	0.02	0.04	0.07	0.04	0.05	0.04
T-MODIS	0.05	0.04	0.04	0.03	0.05	0.03	0.03	0.05	0.04	0.04	0.04	0.03	0.04	0.07	0.04	0.05
Intercept of Regression Line (<i>A</i>)																
N17-AVHRR	0.06	0.07	0.09	0.02	0.04	–0.03	0.03	0.04	0.03	0.02	–0.03	0.04	0.05	0.01	–0.00	0.04
N18-AVHRR	0.04	0.07	0.06	–0.01	0.04	–0.04	0.05	0.03	0.05	0.00	–0.01	0.03	0.03	0.03	0.00	0.04
MERIS	0.05	0.13	0.17	0.08	0.10	0.00	0.09	0.25	0.07	0.06	–0.05	0.20	0.06	–	0.13	0.10
A-MODIS	0.01	0.01	0.01	–0.03	–0.00	–0.05	–0.01	0.04	–0.01	0.02	0.03	0.01	0.04	0.01	0.01	0.01
T-MODIS	0.00	0.02	–0.00	–0.03	–0.03	–0.04	–0.01	0.03	0.04	0.02	–0.01	–0.01	0.02	0.04	–0.01	0.01
Slope of Regression Line (<i>B</i>)																
N17-AVHRR	0.73	0.82	–0.15	0.59	0.74	0.89	1.04	0.54	1.03	0.88	1.08	1.02	0.99	0.89	1.13	0.80
N18-AVHRR	0.98	0.90	0.40	0.82	0.78	0.95	1.02	0.58	0.85	0.84	0.62	0.91	1.37	0.98	0.93	0.87
MERIS	1.02	0.50	0.76	0.72	0.71	1.19	1.00	0.50	0.88	0.69	1.49	0.27	0.81	–	0.67	0.71
A-MODIS	1.10	1.00	1.31	1.00	0.98	1.02	1.06	0.92	1.09	0.97	0.94	0.87	0.91	0.75	1.00	0.92
T-MODIS	1.00	0.95	1.27	1.02	0.83	0.87	0.93	0.94	0.81	0.98	1.13	0.95	0.99	1.04	1.10	0.92
Number of coincident measurements (<i>N</i>)																
N17-AVHRR	100	203	72	97	295	17	106	33	67	67	24	198	66	106	78	1529
N18-AVHRR	88	194	62	84	281	23	100	33	65	58	23	154	61	168	81	1475
MERIS	16	51	28	39	105	8	56	19	42	41	11	36	20	–	42	514
A-MODIS	56	113	14	35	78	14	50	18	43	24	11	74	54	108	94	786
T-MODIS	71	142	34	56	88	10	64	26	54	33	17	108	72	129	100	1004
Estimated mean surface reflectance $\overline{\rho_{\text{SFC}}}$ (averaged for 50×50 km ² region)																
N17-AVHRR	0.067	0.067	0.054	0.049	0.039	0.049	0.050	0.066	0.065	0.067	0.069	0.049	0.069	0.019	0.038	–
N18-AVHRR	0.063	0.064	0.057	0.041	0.038	0.051	0.049	0.066	0.065	0.062	0.067	0.046	0.064	0.016	0.038	–

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Table 4. Comparison of monthly average $\overline{\tau_a}$ between AERONET and the various satellites. The parameters are the same as in Table 3.

Satellite	R	RMSE	σ	N	A	B
ENVISAT MERIS	0.41	0.25	0.12	122	0.23	0.78
Aqua MODIS	0.63	0.07	0.04	113	0.07	0.69
Terra MODIS	0.66	0.07	0.04	141	0.04	0.88
NOAA-17 AVHRR	0.60	0.07	0.04	169	0.10	0.65
NOAA-18 AVHRR	0.56	0.08	0.05	166	0.10	0.60

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Table 5. Intersatellite comparison of monthly average $\overline{\tau_a}$ between NOAA-17 and NOAA-18, Terra and Aqua, respectively. The individual monthly averages are the monthly averages of each site in Table 1 separately (max. 435 possible values). For the aggregated values, all sites are averaged for a particular month (max. 29 possible values). The parameters are the same as in Table 3.

Satellite	<i>R</i>	RMSE	σ	<i>N</i>	<i>A</i>	<i>B</i>
Individual monthly averages						
NOAA-17 vs. NOAA-18	0.80	0.034	0.030	333	0.03	0.83
Terra vs. Aqua	0.82	0.054	0.034	224	0.03	0.84
Aggregated monthly averages						
NOAA-17 vs. NOAA-18	0.91	0.020	0.013	29	−0.00	1.01
Terra vs. Aqua	0.92	0.026	0.016	29	0.01	0.91

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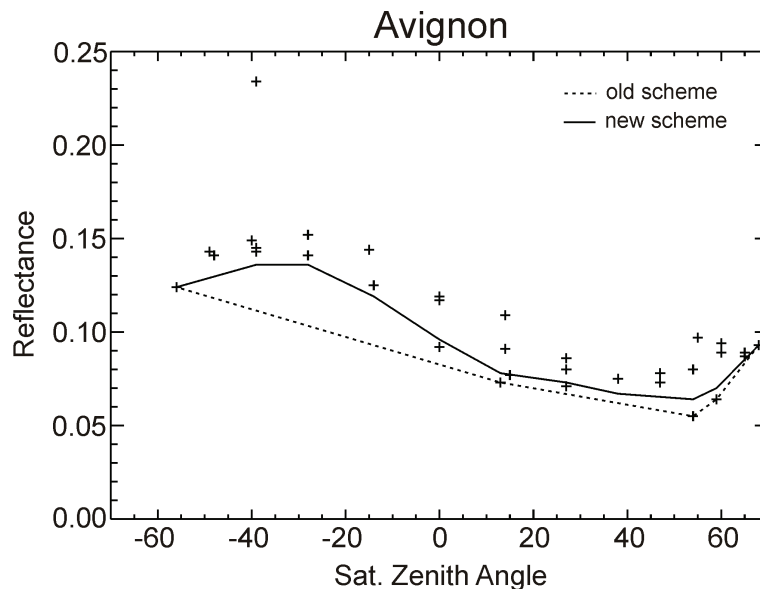


Fig. 1. Example for the estimation of ρ_{SFC} at the AERONET site of Avignon. Crosses indicate cloud and cloud shadow free reflectance observations under varying satellite zenith angle during a 45-days period in Summer 2005. The dotted line indicates the old convex hull scheme of Hauser et al. (2005a), the solid line is the result of the new scheme for the landuse type cropland (cf. Sect. 5.1). Positive satellite zenith angles refer to forward scattering.

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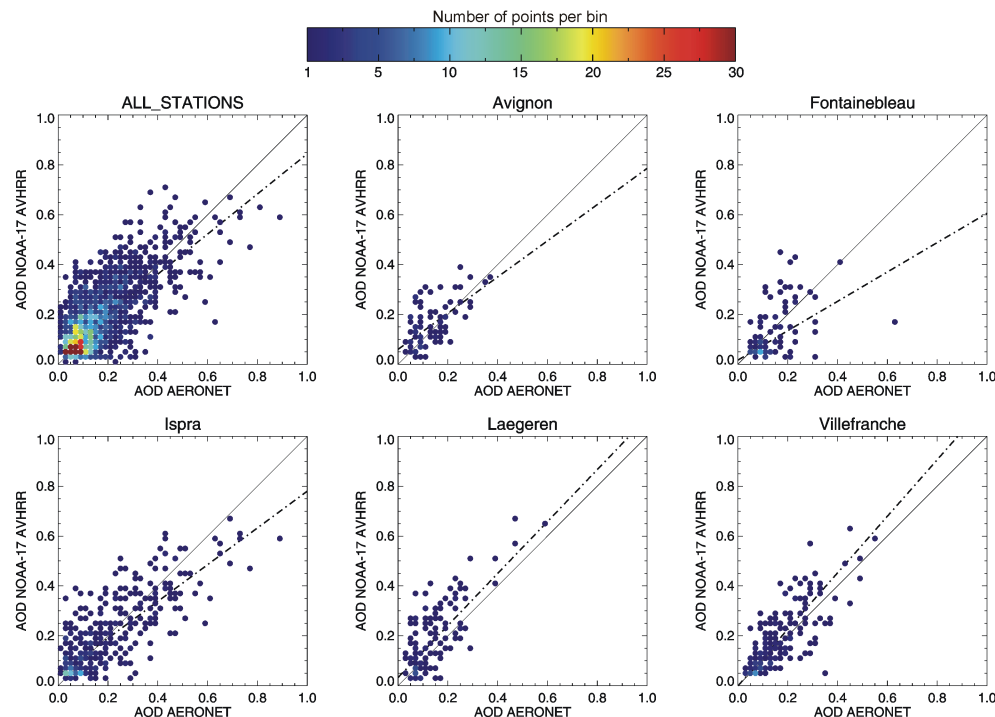
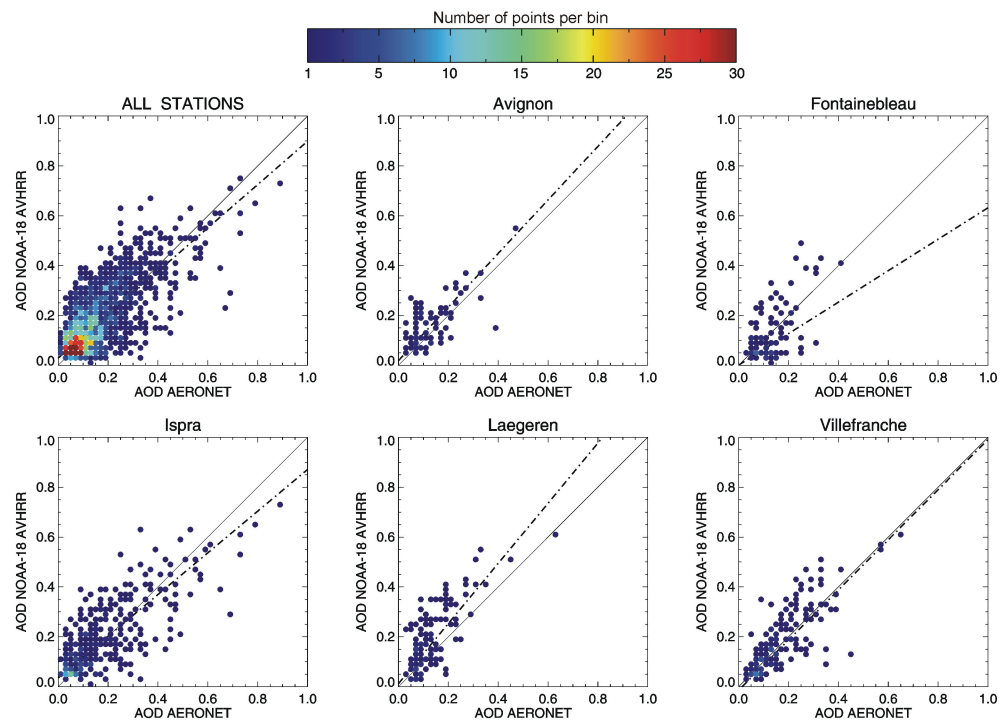


Fig. 2. Scatter-density plots for NOAA-17 AVHRR using the summary of all AERONET sites and five exemplary locations. For the density plot the point to point comparisons were binned into boxes of 0.02×0.02 and were assigned to the center of the box, while the statistics are based on the point to point comparison. In addition the 1:1 intersection line (solid) and the linear regression lines (dash-dotted) are shown. Detailed statistical results are displayed in Table 3.

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**Fig. 3.** Same as Fig. 2 for NOAA-18 AVHRR.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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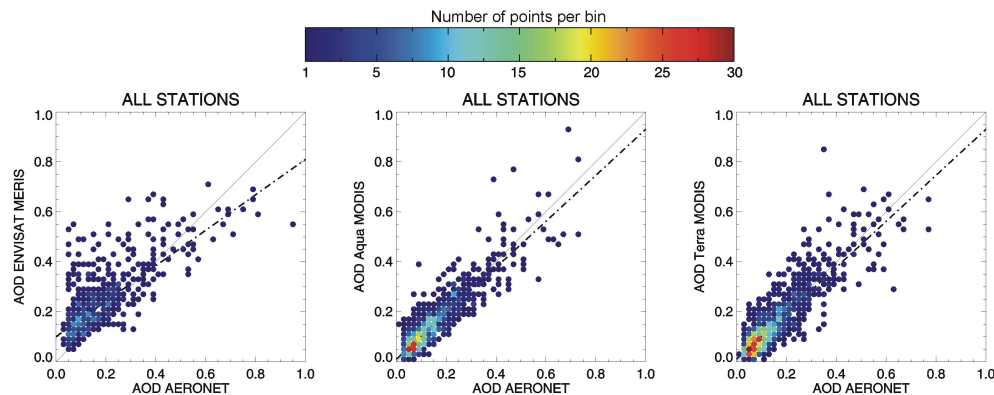


Fig. 4. Same as Fig. 2 for ENVISAT MERIS, Aqua MODIS, and Terra MODIS showing the summary of all AERONET sites.

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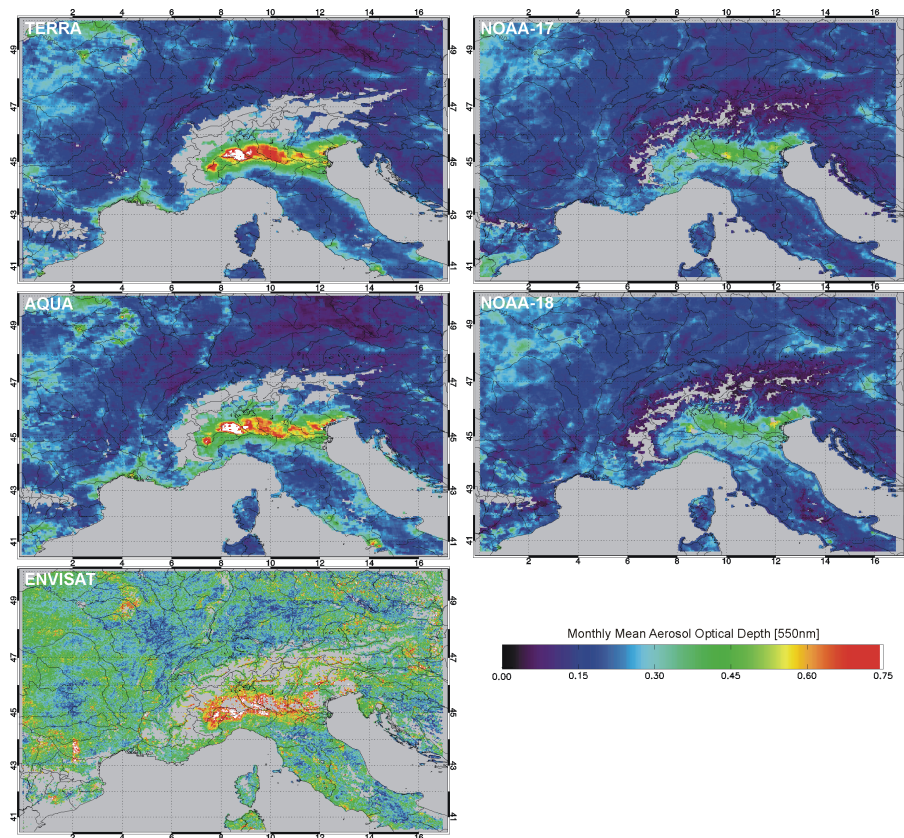


Fig. 5. Example of the monthly mean τ_a over land using Terra MODIS, Aqua MODIS, ENVISAT MERIS, NOAA-17 AVHRR and NOAA-18 AVHRR for the study region (40.5° N–50° N, 0° E–17° E) in April 2007. Gray areas indicate regions with less than 10% of days with valid values for this particular month or sea surfaces.

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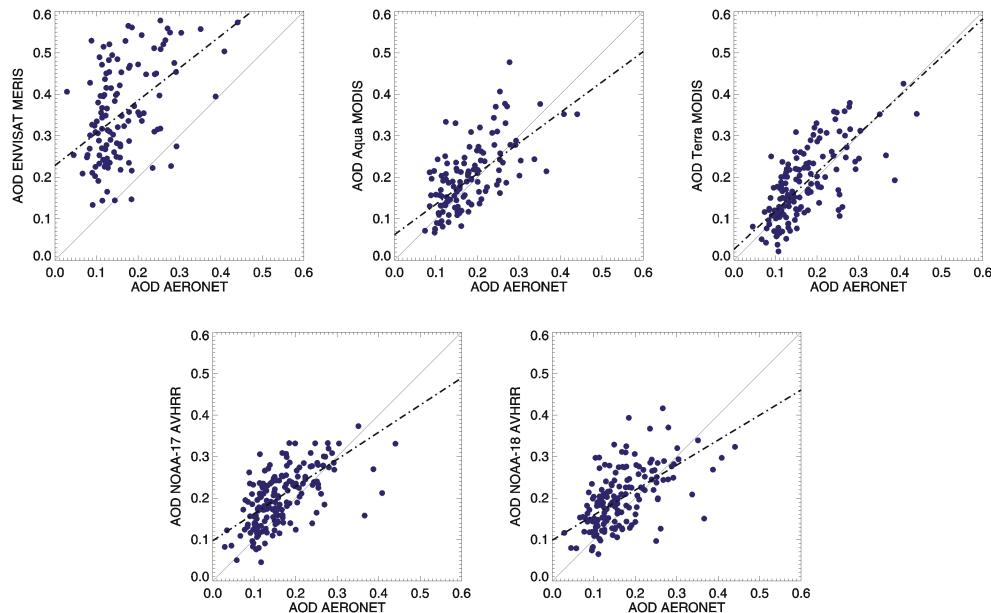


Fig. 6. Scatter plots of monthly average $\overline{\tau_a}$ between AERONET and the various satellites. The 1:1 intersection (solid) and the linear regression line (dash-dotted) are shown as well. Detailed statistical results are shown in Table 4.

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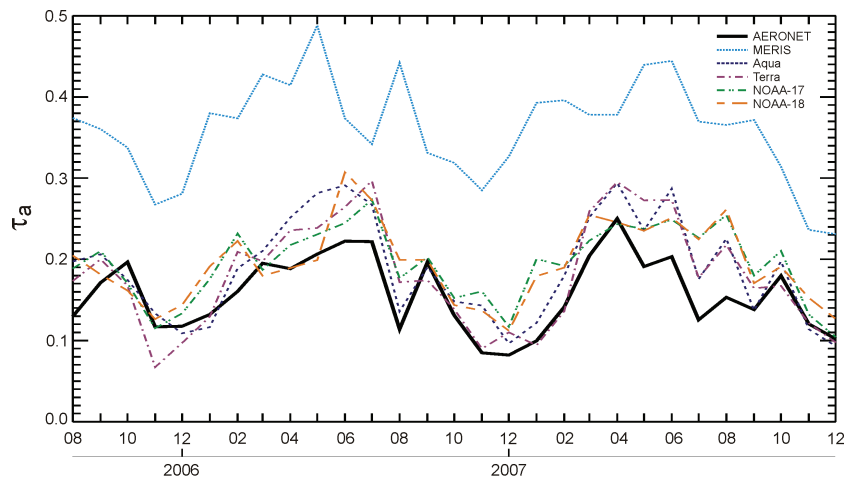


Fig. 7. Combined monthly values from the average of all sites together for each of the 29 months between August 2005 and December 2007 (cf. Sect. 5.3.2).

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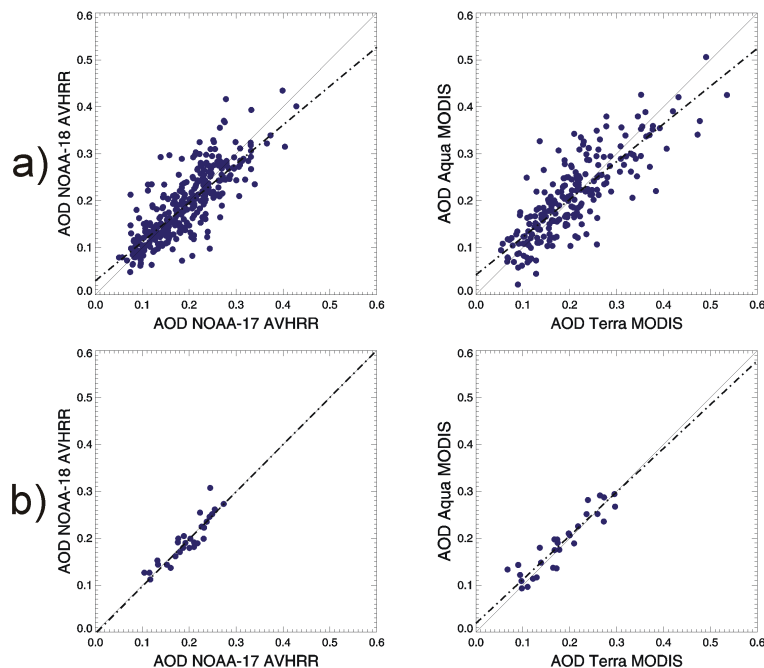


Fig. 8. Scatter plots of the intersatellite comparisons of monthly average $\overline{\tau_a}$ between NOAA-17 and NOAA-18, Terra and Aqua, respectively. The plots in (a) show the individual monthly averages of each site in Table 1 separately. For the aggregated values (b), all sites are averaged for a particular month. Statistical results can be found in Table 5.

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