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Validation of MODIS aerosol observations over the Netherlands with GLOBE student measurements

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[1] We have established a network of secondary schools in the Netherlands with students routinely measuring aerosol optical thickness (AOT) at two wavelengths with hand-held Sun photometers. Students have performed more than 400 measurements between January 2002 and October 2005 over more than 12 locations within the Netherlands as a contribution to Global Learning and Observations to Benefit the Environment (GLOBE). We have developed an improved AOT retrieval algorithm that accounts for the effective wavelength of the broad-band GLOBE detectors and for the spatiotemporal variation of ozone. Results from a theoretical error analysis indicate that GLOBE measurements achieve a precision better than 0.02 AOT for both channels. Comparisons with professional instruments generally give high correlations and low scatter and bias. From these tests, we conclude that student data are scientifically valid and may be used to validate MODIS AOT retrievals over the Netherlands. We find that over land, MODIS AOT is biased by +0.03 (470 nm) and −0.01 AOT (660 nm). Over coastal areas, MODIS overestimates AOT by 0.10 (470 nm) and 0.08 AOT (660 nm). Seasonally averaged MODIS observations over northwestern Europe show relatively highest AOT values over the region of Flanders and the Netherlands, with a seasonal cycle peaking in spring/summer. Our study shows the potential of secondary school-based networks in addition to existing, professional networks that have much less spatial coverage.

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1. Introduction

[2] Over the last decade, various satellite instruments have been measuring the atmosphere's aerosol optical thickness (AOT) (e.g., AVHRR [*Stowe et al.*, 1997], TOMS [*Torres et al.*, 2002], ATSR-2 [*Veefkind et al.*, 1999], POLDER [*Deuzé et al.*, 2001], MODIS [*King et al.*, 1999], MISR [*Kahn et al.*, 2005]). Aerosols are important components of the atmosphere that influence the Earth's energy balance and hydrological cycle [*Intergovernmental Panel on Climate Change*, 2001]. They also affect public health and reduce visibility. Satellite observations of aerosol concentrations are thought to contribute to reducing the large uncertainty in current estimates of aerosol-caused radiative forcing. Because of instrumental degradation, calibration drift, and fundamental difficulties in retrieval algorithms (for instance with respect to infirm a priori knowledge of surface reflectance and aerosol type), it is important to regularly validate satellite retrievals of aerosol optical thickness. Validation efforts however are mostly limited to locations equipped with professional ground-based instrumentation such as from the Aerosol Robotic Network (AERONET [*Holben et al.*, 1998]) and the Global Atmospheric Watch (GAW [*World Meteorological Organization Global Atmosphere Watch*, 2004]). For instance, only one instrumented location (i.e., Cabauw) is currently available for validation of AOT in the densely populated region contending with air pollution problems of the Netherlands. The establishment of a network of schools in the Netherlands, with students making observations during satellite overpasses has the potential to significantly increase the number of instrumented locations available for validation. In this work we take advantage of the temporal coverage and high spatial resolution of MODIS to intercompare student and MODIS AOT measurements at various locations and times between 2002 and 2005. A study by *Chu et al.* [2002] demonstrated that MODIS aerosol retrievals over land are validated relative to AERONET measurements within the expected MODIS retrieval errors. Over coastal areas however, MODIS land retrievals overestimate AOT by up to 0.2 and also suffer from larger random errors than over inland regions. Similar findings have been reported in a study by *Remer et al.* [2005] and *Chu et al.* [2003]. The latter also claimed to demonstrate MODIS' capability for monitoring air pollution on a regional and local scale. However, their claim is based on the validation of MODIS observations over the Los Angeles and Beijing regions, both having only one AERONET Sun photometer, and on validation of MODIS observations over northern Italy with two AERONET Sun photometers that are hundreds of

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kilometers apart. Concerning the local-scale validation of MODIS AOT, the Chesapeake Lighthouse Aircraft Measurements for Satellites (CLAMS) experiment [*Levy et al.*, 2005] was better equipped. During the summer of 2001, MODIS land and ocean AOT was validated along coastal Virginia with a series of correlative data sources including 5 AERONET Sun photometers. It turned out that MODIS generally performed below expectation, likely because of an inappropriate urban/industrial aerosol model, and improper surface reflectance assumptions over coastal Virginia. In our study, we focus on validation of MODIS land AOT over a small country, the Netherlands (200×300 km^2), with various student observations taken only 50–100 km apart. Our study resembles the CLAMS campaign to some extent, as the Netherlands and coastal Virginia share some retrieval conditions, including numerous surface waters and heavy aerosol loadings. Our work however also extends the study by *Levy et al.* [2005] as our comparison covers not just summertime conditions but all seasons that have been sampled between January 2002 and October 2005.

[3] The accuracy and consistency of the reference data, i.e., the student observations, needs to be specified prior to using these data for validation of satellite data. Apart from the objective of intercomparing MODIS AOT retrievals with ground-based data, a second objective of this paper therefore is to address the issue of student measurement quality. In a study on the use of observations made with handheld LED-based Sun photometers, *Brooks and Mims* [2001] showed that these Sun photometers are in principle well adapted to establish a network providing AOT data for scientific use. One step in convincing potential users of the data quality from such a network, is to provide error estimates for individual observations. We elaborate on the work by *Brooks and Mims* [2001] and present error estimates based on theoretical considerations along with error estimates based on an intercomparison of student and professional observations.

[4] A short introduction on the background of the student measurement program is given in section 2. This is followed by section 3 that consists of a GLOBE algorithm description, two worked out algorithm improvements, and a discussion of the calibration of the GLOBE instruments. Section 4 presents the findings of a theoretical error analysis. Practical error estimates are obtained from comparisons between handheld Sun photometer and professional results and these are presented in section 5. In section 6, we analyze MODIS AOT over the Netherlands to illustrate the need for a careful examination of the quality of MODIS data. Subsequently we use GLOBE student observations over the Netherlands to validate MODIS AOT retrievals over the time period 2002–2005. A summary, conclusions and recommendations for future work are given in section 7.

2. GLOBE Aerosol Monitoring Project

[5] All over the world, primary and secondary school students are currently taking measurements as part of the GLOBE (Global Learning and Observations to Benefit the Environment) program. This program is a science and education effort to increase environmental awareness of people throughout the world and to actively involve students in science. An essential part of the program is that students perform measurements that are of research-quality and report their observations to archives designed for the study of the Earth. A third goal is to generate public outreach for Earth Observation satellite missions, in this work for instance EOS (Terra-MODIS, Aura-OMI) and ENVISAT (SCIAMACHY). An example of a successful GLOBE project that involves the counting of airplane contrails has recently been reported by *Chambers* [2005]. For further reading on GLOBE, see *Butler and MacGregor* [2003].

[6] One of the environmental parameters measured in the framework of the GLOBE program is AOT. A robust and inexpensive Sun photometer that uses light emitting diode (LED) detectors [*Mims*, 1992; *Brooks and Mims*, 2001] instead of optical interference filters and photodiodes, was designed with the specific purpose of setting up a network of GLOBE Sun photometers for AOT measurements [*Mims*, 1992; *Brooks and Mims*, 2001]. Such a (global) network of schools has been established [*Mims*, 1999]. Approximately 1700 quality-checked student observations have been reported to the GLOBE archive between 2001 and 2005 and are publicly available via http://www.globe.gov. To our knowledge, these measurements have not yet been published in any peer-reviewed scientific journal.

[7] In this work we report on aerosol measurements from a national network that has been set up by KNMI (Royal Netherlands Meteorological Institute) and SME Advies (Environmental Consultants). This network of schools constitutes the Dutch contribution to the GLOBE effort in the Netherlands and materialized in 2002. More than 20 GLOBE Sun photometers have been assembled from parts provided by D. Brooks from Drexel University (D. Brooks, private communication, 2006) and calibrated at KNMI. SME Advies and KNMI trained teachers and students, on the basis of the GLOBE Aerosol protocol, how to take measurements and equipped them with hand-held Sun photometers. At the moment the school network consists of 12 schools that have actually taken measurements (the total number of measurements up to October 2005 is 408 and is publicly available through http://www.knmi.nl/globe). Table 1 gives an overview of the participating schools, their location, the serial number of the Sun photometer and the number of measurements they have been taking. Students between 15 and 18 years of age have been taking the bulk of the measurements. The locations of the schools that performed measurements that are used for the validation of MODIS retrievals are shown in Figure 7a, which is discussed in detail in section 6.1.

3. Determining AOT With GLOBE Sun Photometers

3.1. Measurement Principle

[8] Students from secondary schools joining the GLOBE aerosol monitoring project perform their AOT measurements with handheld GLOBE Sun photometers, instruments that measure the intensity of a direct beam of sunlight. The retrieval is based on Lambert-Beer's law; that is, the students manually align the instrument with the Sun in situations when the Solar disk is not obscured by clouds. The extinction of light in the atmosphere can be determined once the extraterrestrial signal is known. In the official

Table 1. Overview of Dutch Schools Participating in the GLOBE Aerosol Monitoring Project[a]

School	Site	Sun Photometer	Latitude	Longitude	Number of Observations
Anna van Rijn	Nieuwegein	RGK-217	52.02°N	5.08°E	12
Bernard Nieuwentijt	Amsterdam	RGK-201	52.38°N	4.93°E	57
Bernard Nieuwentijt	Marken[a]	RGK-201	52.45°N	5.11°E	33
Brokleden	Breukelen	RGK-218	52.11°N	4.60°E	2
Farel	Amersfoort	RGK-525	52.17°N	5.42°E	6
Fivel	Delfzijl	RGK-213	53.19°N	6.53°E	9
KNMI	De Bilt	RG2-047	52.10°N	5.17°E	150
Mozaiek	Arnhem	RGK-202	51.98°N	5.92°E	7
Het Nieuwe Lyceum	Bilthoven	RGK-216	52.08°N	5.10°E	1
De Populier	The Hague	RGK-206	52.05°N	4.16°E	61
Rembrandt	Veenendaal	RGK-217	52.03°N	5.55°E	12
Stevensbeek	St. Anthonius	RGK-523	51.68°N	5.91°E	10
Zwin	Oostburg	RGK-214	51.32°N	3.486°E	47

[a] Bernard Nieuwentijt student Sven Commandeur performed measurements during summer holidays in 2003 from his parents' house in Marken.

GLOBE protocol (http://www.globe.gov), the Lambert-Beer law is reformulated to obtain the principal retrieval equation. This equation accounts for solar zenith angle, the distance of the Earth to the Sun, and corrects for Rayleigh optical thickness, but not for ozone. Not taking into account ozone absorption leads to misunderstanding ozone optical thickness for AOT.

[9] A specific algorithm has been developed for the Dutch contribution to the GLOBE Aerosol Monitoring Project, independent from the official GLOBE AOT algorithm maintained by David Brooks (that can be found at http://www.globe.gov). This is motivated by the need to (1) take into account ozone absorption and (2) correct for the fact that the effective wavelength calculated for the broad-band LED detectors is influenced by the AOT itself. One additional advantage of the development of an independent retrieval algorithm for GLOBE AOT measurements in the Netherlands is that it allows a detailed error analysis, discussed in section 4.

3.2. Correction for Ozone

[10] The retrieval algorithm that we developed is a straightforward update of the official GLOBE protocol. We now account for the absorption of visible light by ozone (the ozone optical thickness τ_{O3} depends on N_{O3}, the overhead ozone column) and the retrieval equation thus reads:

$$\tau_a = \frac{1}{M(t)} \ln\left(\frac{V_0 - V_d}{r(t)^2 (V - V_d)}\right) - \tau_R(p) - \tau_{O_3}(N_{O_3}) \qquad (1)$$

with M the air mass factor that is computed from the reported time t of the measurement ($M = 1$ for overhead Sun), V_0 the extraterrestrial solar signal that the instrument would observe outside of the Earth's atmosphere (i.e., $M = 0$) normalized to an Earth-Sun distance of 1 AU. The calibration constant V_0 is obtained from a separate calibration procedure at KNMI, described in section 3.4. V_d the "dark" signal of the instrument when its field of view is obstructed, r the Earth-Sun distance in AU, V the actually measured solar signal at the Earth's surface, and $\tau_R(p)$ the estimated Rayleigh optical thickness. The Rayleigh optical thickness is calculated from the surface pressure p relative to a reference pressure. Most schools are equipped with barometers as they often also contribute to a separate GLOBE project in which they take weather measurements. Since overhead ozone columns are not measured by students, we obtain these columns from assimilated SCIAMACHY ozone fields [*Eskes et al.*, 2003] (publicly available through http://www.temis.nl) to compute τ_{O3}. *De Vroom* [2004] found that not taking into account ozone absorption leads to systematically overestimating AOT up to 0.02 at 508 nm and 0.04 at 625 nm. Normally, students take a measurement triplet that consists of three consecutive measurements of V and V_d within a period of 1–2 min.

3.3. Correction for Effective Wavelength

[11] The simple and inexpensive (cost 50 US dollar for material and assembly) GLOBE instrument uses two LEDs as detectors, and has been described extensively by *Brooks and Mims* [2001]. An important characteristic of the LED-based detectors is their broad spectral sensitivity. Figure 1 shows the response curves of the two LED detectors that are part of the GLOBE Sun photometer. The spectral responses have been measured with an Optometrics monochromator using a 25 W tungsten/halogen light source and a high-gain transimpedance amplifier. The output voltage varies among samples of the same LEDs, translating into different output voltage for different Sun photometers, but the normalized spectral response is very consistent for LEDs from the same batch (D. Brooks, private communication, 2006). The "green" LED in Figure 1 shows maximum sensitivity at approximately 520 nm and the "red" LED at approximately 625 nm. The wide sensitivity curves complicate straightforward retrieval of AOT as the Lambert-Beer law is valid for monochromatic light. Nevertheless an "effective" wavelength can be defined on the basis of the following premises: (1) The GLOBE Sun photometer measures the window-averaged atmospheric transmission T_a that can be expressed by an exponential function (as demonstrated by *Brooks and Mims* [2001]), and (2) the effective wavelength is defined as the monochromatic wavelength for which it holds that its (monochromatic) transmission $T_{\lambda_{eff}}$ equals the window-averaged transmission T_a. T_a is defined in equation (2):

$$T_a = \frac{\int R(\lambda) I_0(\lambda) T(\lambda) d\lambda}{\int R(\lambda) I_0(\lambda) d\lambda} \qquad (2)$$

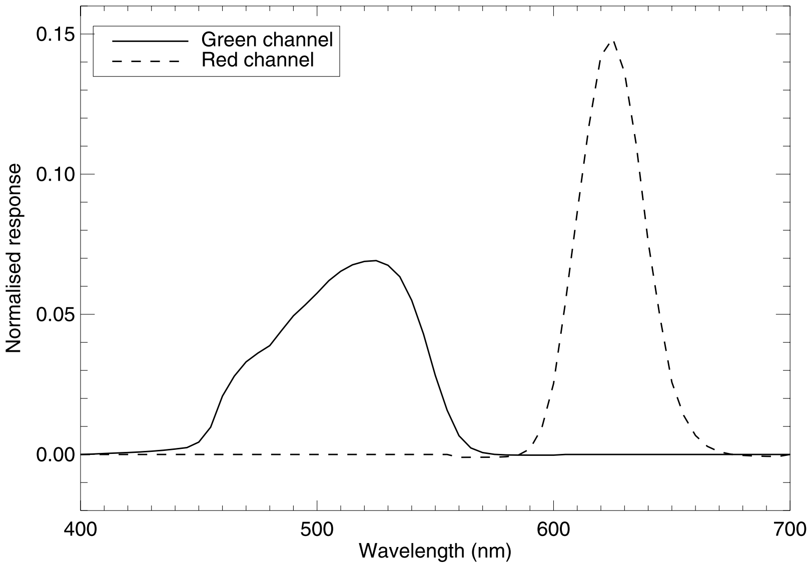

Figure 1. Normalized response of the LED detectors in the GLOBE Sun photometer as a function of wavelength.

with $R(\lambda)$ the spectral response curves shown in Figure 1, $I_0(\lambda)$ the Solar irradiance at the top of the atmosphere, and $T(\lambda)$ the spectral transmission of the atmosphere. $T(\lambda)$ is a function of wavelength as scattering and absorption processes are strongly wavelength-dependent. $T_{\lambda_{eff}}$ is by definition (Lambert-Beer):

$$T_{\lambda_{eff}} = e^{-M\left(\tau_R\left(\lambda_{eff}\right)+\tau_{O_3}\left(\lambda_{eff}\right)+\tau_a\left(\lambda_{eff}\right)\right)} \tag{3}$$

with M the air mass factor, and $\tau_R(\lambda_{eff})$ the Rayleigh, $\tau_{O3}(\lambda_{eff})$ the ozone, and $\tau_a(\lambda_{eff})$ the aerosol optical thickness. Equation (3) uses the simplification that M is independent of the vertical profile of the constituent. Results from *Thomason et al.* [1983] show that errors arising from different air mass factors for species with different vertical distributions are significant only at large solar zenith angles. All measurements in this paper have been taken for solar zenith angles smaller than 70°, so these errors are neglected.

[12] Obtaining the effective wavelength from $T_a = T_{\lambda_{eff}}$ is slightly different from the method described by *Brooks and Mims* [2001]. Their definition (their equation (9)) is in fact a weighted sum of the spectral response to the Solar irradiance and wavelength. They derive 508 nm and 625 nm as effective wavelengths for the "green" and "red" channels. However, from equations (2) and (3) it becomes clear that an effective wavelength is a function of also the spectral transmission and hence of M, τ_{R_λ}, $\tau_{O_{3_\lambda}}$, and τ_{a_λ}. This is illustrated in Figures 2a and 2b. Figure 2a shows the sensitivity of the effective wavelength of the retrieved AOT for various values of M and AOT. The "green" channel is much more sensitive to changes in AOT and M than the "red" channel consistent with the asymmetry in the "green" response curve weighted toward lower wavelengths relative to the fairly symmetric "red" channel. Furthermore, the "green" LED has a considerably broader bandwidth than the "red" LED. As a consequence of the asymmetry of the "green" response curve, the effective wavelength for this channel is somewhat sensitive to aerosol type. This is illustrated by Figure 2b that shows the sensitivity of the effective wavelength for various values of Ångström coefficients. However, within a range of Ångström coefficients typically observed over the Netherlands (1.0–2.0) [*Stammes and Henzing*, 2000], λ_{eff} varies less than 1 nm, and hence we neglect this dependency in the remainder of this work. We also found the sensitivity of the effective wavelength for changes in ozone and surface pressure to be negligible.

[13] Because it is impractical to report different effective wavelengths for every individual AOT retrieval, we choose to correct our AOT retrievals for the difference between effective wavelength (and hence AOT) and reference wavelengths (λ_{ref}), 508 and 625 nm as defined by *Brooks and Mims* [2001]. Effective wavelengths are stored in look-up tables (LUTs) as a function of M and $\tau_{a,in}$, the initially retrieved AOT. The correction then proceeds by first extracting λ_{eff} from the LUT, i.e., Figure 2a, for the actual M and τ_a of the measurement, and subsequently applying Ångström's relation for a correction:

$$\tau_a = \tau_{a,in}\left(\frac{\lambda_{ref}}{\lambda_{eff}}\right)^{-\alpha} \tag{4}$$

with τ_a the final reported AOT at the reference wavelengths, $\tau_{a,in}$ the initially retrieved AOT, and α set at 1.5, close to the average value for α derived from professional measurements [*Stammes and Henzing*, 2000].

[14] Figure 3 quantifies the impact of the correction proposed above for all GLOBE AOT observations over the Netherlands with observed AOTs up to 0.8 ("green") and 0.7 ("red"). The corrected AOT is always higher than the initial AOT; that is, the effective wavelengths are always smaller than the reference wavelengths. This is consistent with the LUT presented in Figure 2a, showing that only for very uncommon air mass factor and AOT values ($M > 5$ and AOT > 0.3), the effective wavelength exceeds 508 nm for the green channel. The absolute value of the correc-

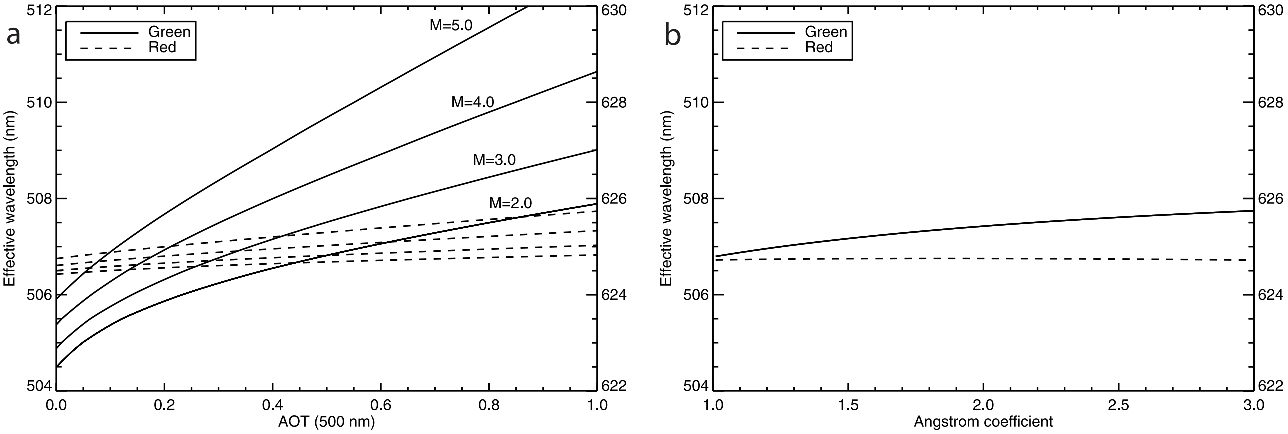

Figure 2. (a) Effective wavelength of AOT retrieval as a function of initial AOT. The solid (dashed) line shows the sensitivity curves for the "green" ("red") channel for various values of M. The Ångström parameter was assumed to be 2.0, total ozone column 300 DU and the surface pressure 1013 hPa. (b) Effective wavelength of AOT retrieval as a function of aerosol type (Ångström coefficient). The initial AOT at 500 nm was assumed to be 0.5, M = 2.0, total ozone column 300 DU and the surface pressure 1013 hPa.

tion is small, <0.002 AOT for 508 nm and <0.0005 AOT for 625 nm. This is equivalent to relative corrections <1% for 508 nm and <0.5% for 625 nm. As expected from the sensitivity curve in Figure 2a, the absolute correction increases with increasing AOT. We conclude that the effective wavelength correction proposed for AOT values typically retrieved over the Netherlands is small compared to estimated total uncertainties in AOT from AERONET of ±0.01 [*Holben et al.*, 1998]. Nevertheless the correction procedure proposed here corrects for a small but known systematic error of at most 1% of the retrieved AOT and has been applied in the GLOBE AOT retrieval algorithm at KNMI.

3.4. Calibration

[15] An accurate and precise determination of the calibration constant V_0 is a principal requirement for accurate and precise retrievals of AOT. In this section we report on a number of Langley analyses performed at KNMI with the RG2-047 instrument, which is subsequently used as a reference for relative calibration of the other instruments that have been disseminated among the schools.

[16] On three different days in 2003 and 2004 with clear-sky conditions, a suite of measurements of V was performed over a wide range of values of air mass factors M. Figure 4 shows the logarithm of the measured voltage (corrected for dark voltage) at KNMI as a function of air mass factor M on 7 April 2003. This day had extreme clear-sky conditions (by

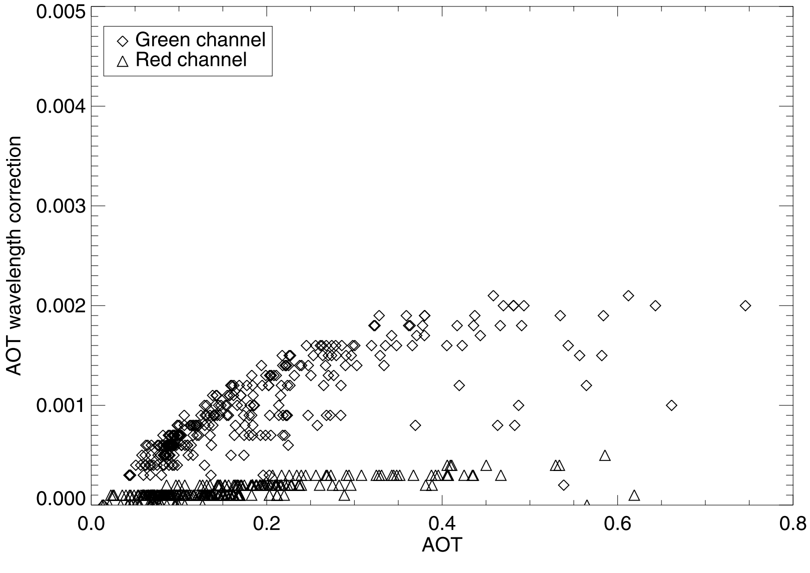

Figure 3. AOT effective wavelength corrections as a function of retrieved AOT for all GLOBE retrievals over the Netherlands.

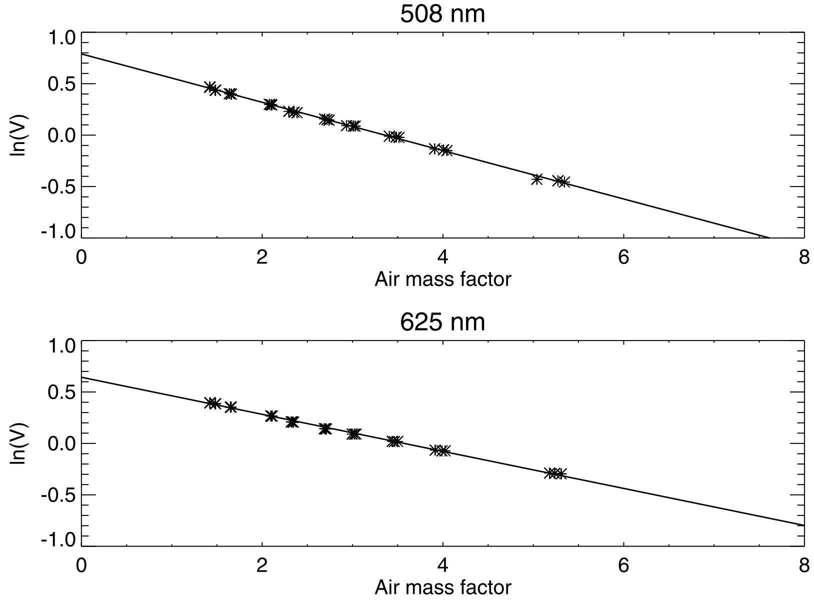

Figure 4. Langley plot for 7 April 2003 at KNMI, De Bilt, the Netherlands for (top) 508 nm and (bottom) 625 nm. The *x* axis features the air mass factor, and the *y* axis features the logarithm of the measured voltage.

Dutch standards) with a reported visibility of 40 km and an AOT of 0.05 at 508 nm. Sky conditions hardly changed during the day, supported by very high correlation coefficients between ln V and M ($R^2 > 0.998$ ($n = 25$)) for both channels. From a linear least squares regression we find an intercept of 2.209 (±0.011)V for 508 nm and 1.907 (±0.009)V for 625 nm. Table 2 summarizes the results of the Langley analyses done for the three different days. All estimates have been normalized to $r = 1$AU. As individual estimates are different within their estimated uncertainties, the average V_0 is taken as the best estimate of the calibration constant and the spread of the values as a first-order estimate of the uncertainty. For the RG2-047 this uncertainty amounts to 21 mV (1.0%) at 508 nm and 35 mV (1.9%) at 625 nm.

[17] All Sun photometers listed in Table 1 have been calibrated relative to the RG2-047 instrument. For every instrument, a series of measurements simultaneous with the RG2-047 has been carried out. The simultaneous measurements were done for a range of atmospheric conditions so as to cover a large voltage range of the instrument. The calibration constant for instrument i is determined from $V_{0,i} = V_{0,RG2\text{-}047} \cdot \rho_i$ with ρ_i the average ratio of all pairs of simultaneously measured signals V_i and $V_{RG2\text{-}047}$. The standard deviation on ρ_i is taken as an estimate of the precision of ρ_i so that the final error in $V_{0,i}$ is computed from the combined uncertainties in $V_{0,RG2\text{-}047}$ and ρ_i. Thus the errors in $V_{0,i}$ have a lower limit of 1.0% for 508 nm and 1.9% for 625 nm (see Table 2). In Table 3 a summary is given of the calibration constants and their precisions based on a calibration relative to the reference instrument RG2-047. Table 3 shows that the calibration constants range from 1.5 to 2.4 V for the green LED and from 0.7 to 1.9 V for the red LED. Typical uncertainties in the calibration constants are 2–5% for both channels. The precision of the calibration constants can be improved if more simultaneous measurements are carried out.

4. Error Analysis

4.1. Theoretical Error

[18] The error in the computation of the AOT is determined by the errors in the forward function parameters V_0, V (from read out errors, misalignment), M (from errors in t), τ_R (from errors in p), and τ_{O_3} (from errors in ozone column N_{O_3}). The error variance of the AOT reads:

$$\sigma^2_{\tau_a} = \langle \epsilon^2_{\tau_a} \rangle = \sum\nolimits_{i=1}^{5} \left(\frac{\partial \tau_a}{\partial x_i} \right)^2 \sigma^2_{x_i} \qquad (5)$$

with $x_1 = V_0$, $x_2 = V$, and so forth. The total error depends on details in the retrieval; that is, sensitivities $\frac{\partial \tau_a}{\partial x_i}$ often depend on the value of x_i itself, and therefore the contribution of errors in x_i to the total error should be evaluated around the

Table 2. Overview of Langley Analyses for RG2-047

Date	V_0 508 nm	Error 508 nm	V_0 625 nm	Error 625 nm	r^2	Visibility
7 April 2003	2.209 V	0.011 V	1.907V	0.009 V	>0.998	40 km
8 April 2003	2.167 V	0.019 V	1.849 V	0.011 V	>0.998	30 km
9 September 2004	2.181 V	0.013 V	1.845 V	0.014 V	>0.996	25 km
Average	2.186 V	0.035 V	1.867V	0.021 V		

Table 3. Overview of Calibration Constants and Estimated Precisions for Sun Photometers in the Dutch GLOBE Aerosol Monitoring Project

School	Sun Photometer	V_0 508 nm	Precision	V_0 625 nm	Precision
Anna van Rijn	RGK-217	1.885 V	0.031 V	1.310 V	0.057 V
Bernard Nieuwentijt	RGK-201	1.964 V	0.064 V	1.447 V	0.047V
Brokleden	RGK-218	1.795 V	0.028 V	1.389 V	0.049 V
Farel	RGK-525	2.424 V	0.021 V	1.687 V	0.038V
Fivel	RGK-213	2.361 V	0.028 V	0.746 V	0.073 V
KNMI	RG2-047	2.186 V	0.035 V	1.867 V	0.021V
Mozaiek	RGK-202	1.543 V	0.071 V	1.378 V	0.042 V
Het Nieuwe Lyceum	RGK-216	1.596 V	0.026 V	1.438 V	0.045V
De Populier	RGK-206	2.202 V	0.032 V	1.391 V	0.045V
Rembrandt	RGK-217	1.885 V	0.031 V	1.310V	0.057 V
Stevensbeek	RGK-523	1.767 V	0.029 V	1.685 V	0.057 V
Zwin	RGK-214	1.938 V	0.035 V	1.379 V	0.042 V

actual values of x_i. From the definition of τ_a (equation (1)), we find:

$$\begin{aligned}
\frac{\partial\tau_a}{\partial V_0} &= \frac{1}{M(t)(V_0 - V_d)};\\
\frac{\partial\tau_a}{\partial V} &= \frac{-1}{M(t)(V - V_d)};\\
\frac{\partial\tau_a}{\partial t} &= \frac{\partial\tau_a}{\partial M(t)}\frac{\partial M(t)}{\partial t}\\
&= \frac{-1}{M(t)^2}\ln\left(\frac{r(V_0 - V_d)}{V - V_d}\right)\frac{\partial M(t)}{\partial t};\\
\frac{\partial\tau_a}{\partial p} &= \frac{-\tau_R}{p_0};\\
\frac{\partial\tau_a}{\partial N} &= \frac{-\tau_{O_3}}{N_{0_3}}.
\end{aligned} \tag{6}$$

From the first two sensitivities we conclude that retrieval of AOT is most sensitive to errors in calibration constant V_0 and in measured signal V for measurements performed with small air mass factor value, i.e., in the middle of the day. Instruments with small V_0 (V) are more prone to retrieval errors from errors in V_0 (V). Note also the change in signs between the first and second sensitivity equation that can be employed to investigate the nature of systematic errors in AOT retrievals. For $\frac{\partial\tau_a}{\partial t}$, $\frac{\partial M(t)}{\partial t}$ is computed numerically and the sensitivity curve indicates that AOT retrieval is more sensitive to errors in t in summer than in winter, and is most sensitive around sunrise and sunset, when the air mass factor is changing rapidly with time (not shown, for details we refer to *de Vroom* [2004]). The last two sensitivities show that the green channel (508 nm) is more (less) sensitive to pressure (ozone) errors than the red channel (625 nm). This is because the window-averaged Rayleigh optical thickness is larger for the green channel than for the red channel. In contrast, the window-averaged ozone optical thickness is smaller for the green channel than for the red channel.

[19] Errors in r (from errors in t) are discarded because typical errors in reporting measurement time in the order of 1 min do not affect r. All error sources are considered mutually uncorrelated since they arise from independent retrieval steps. The following list gives an overview of the source of the forward function parameters (i.e., the retrieval input) and typical errors:

[20] 1. The reference voltage V_0 is the result of calibration measurements performed at KNMI. The calibration procedure (described in section 3.4) involves a Langley analysis for a reference instrument and subsequent relative calibrations for all other instruments. Every instrument has its own calibration uncertainty, typically in the 1% to 5% range.

[21] 2. The measured voltage $V - V_d$ is reported by students and we conservatively estimate the read-out error σ_V to be 20 mV, typically 1–3%.

[22] 3. The air mass factor M is determined from the time of the measurement that is assumed to be reported precise up to 1 min. The expression we use is from *Young* [1994], and takes into account the curvature of and internal refraction in the Earth's atmosphere.

[23] 4. The Rayleigh optical thickness τ_R is determined from the surface pressure p measured at the student measurement site. The uncertainty in the pressure σ_p is estimated at 5 hPa, a conservative estimate of the precision of simple barometers used by schools. This translates into $\sigma_{\tau R} < 0.001$ for both channels.

[24] 5. The ozone optical thickness τ_{O_3} is taken from assimilated SCIAMACHY ozone fields. Accounting for small errors in these fields (<5 DU according to *Eskes et al.* [2005]) and time differences between GLOBE and SCIAMACHY, we estimate the $\sigma_{\tau O_3}$ to be < 0.001 for both channels.

[25] Substituting the sensitivities from equation (5) and the estimates σ_{xi} listed above in equation (5) for all observations taken at KNMI, the single most important contribution to the total error budget comes from errors in V_0 (0.01 AOT for both channels). Contributions from errors in V and t are much smaller (<0.002 AOT for both channels) than the contribution by V_0 errors. The errors in p and N have a negligible contribution to the error in τ_a. From a quantitative error propagation for the complete set of KNMI retrievals we estimate that the precision in τ_a is always smaller than 0.02 in both channels.

[26] Next to establishing the measurement error from a theoretical error analysis, which is done above, the error is also estimated from taking the standard deviation of the AOT measurement triplet. In this manner, the measurement error is established in two independent ways. The final quoted error in the remainder of this work is the higher of the theoretical error and the triplet standard deviation.

4.2. Systematic Errors

[27] Three types of systematic errors may bias AOTs measured by students, errors (1) in V_0, (2) in V, and (3) due to instrument heating. First of all, the calibration constant V_0 may be inaccurate and this will immediately

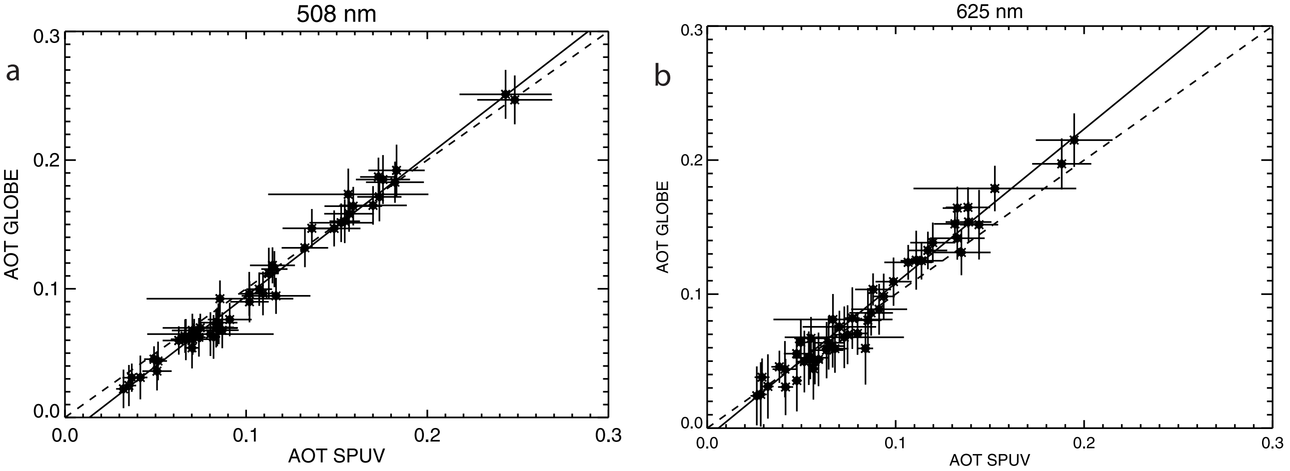

Figure 5. (a) Scatter plot of GLOBE and SPUV observed AOT values in De Bilt between September 2002 and March 2003. The solid line is the result from a regression analysis taking into account errors of the data (shown as error bars). The dashed line is the $y = x$ line. (b) Same as Figure 5a but now for 625 nm.

translate into systematic errors in the retrieved AOTs. The uncertainty in V_0 (that we know) and its propagation into the total error has been discussed in the previous section. Here we discuss the inaccuracy of V_0 that we do not know. Note that every school instrument has its own unique inaccuracy, and V_0 maybe either too high or too low, giving rise to systematically too high AOT at one location and too low AOT at another. A second systematic error may be the misalignment of the GLOBE Sun photometer with the Sun. Especially measurements by unexperienced students may suffer from misalignment which always results in too low voltages V and hence always in an overestimation in AOT. The third possible systematic error is due to possible heating of the LED detectors. This type of error may occur when LEDs are exposed to Sunlight for a long time, and, as a consequence, warm up, affecting the sensitivity of the instrument. Instrument heating may also be an issue when comparing summer and winter measurements, as the LEDs are exposed to outside temperatures during operation. In our training of students and teachers we emphasize that the Sun photometer should be kept at room temperature as much as possible. In winter, when outside temperatures are significantly below room temperature in the Netherlands, students are taught to keep the Sun photometers covered by their jackets until right before the measurement. Doing so, we believe that the effect of ambient temperature differences may be damped. At the moment, it is difficult to establish the magnitude of any instrument heating effect, as the temperature of the LED within the GLOBE Sun photometer is very hard to measure.

5. Comparison With Professional Aerosol Measurements

5.1. Comparison at KNMI (De Bilt) With SPUV Measurements

[28] As mentioned in section 3.4, the Langley procedure to independently calibrate the RG2-047, and a suite of simultaneous observations by the RG2-047 and Sun Photometer UV (SPUV, YES, Inc. [*Stammes and Henzing*, 2000]) taken between September 2002 and March 2003, allows for a detailed comparison of two independent data sets. As the SPUV takes measurements in a continuous fashion, and the RG2-047 observations were taken right next to the SPUV (distance ≈2 m) on the roof of KNMI, the instruments sample the very same air mass and errors due to representativity differences are neglected. The GLOBE measurements were taken by “professionals.”

[29] Between September 2002 and March 2003, a total of 49 coincident measurements has been accomplished. Figure 5 shows the agreement between the AOT observations from the professional SPUV instrument and from the GLOBE Sun photometer for both 508 nm and 625 nm. The SPUV data, recorded at 501 nm and 675 nm, has been interpolated to the GLOBE wavelengths using Ångström’s relationship, with the Ångström coefficient determined from the SPUV 501 and 675 nm channels.

[30] For both channels, we find high correlation coefficients (R^2 > 0.98), small biases, and root-mean-squared differences smaller than 0.012 AOT. The upper part of Table 4 gives an overview of the comparison results. From a regression analysis, taking into account errors in both data sets, we find small intercepts and slopes that deviate slightly from 1. Note that the highest observed value during the intercomparison period is less than 0.25 AOT, so that the comparison results indicate that the GLOBE Sun photometer is able to detect small variations in AOT. Moreover, the small bias and RMS provide evidence that observations taken with the GLOBE Sun photometer are far from inferior to observations taken by fully automated instruments.

5.2. Comparison at De Populier (the Hague) With AERONET Measurements

[31] The previous section discussed the comparison of manual GLOBE observations, taken by professionals, and observations taken by a fully automatic, professional instrument. In this section we discuss a comparison of observations taken by students from secondary school “De Populier” in The Hague, and measurements (level 2.0 data)

Table 4. Comparison Results of Observations Taken by GLOBE Sun Photometers and Professional Instruments

Location	n	R^2	Bias	RMS	Regression
KNMI 508 nm	49	0.992	−0.005	0.009	$y = -0.02 + 1.10x(\pm 0.06)$
KNMI 625 nm	49	0.980	+0.004	0.012	$y = -0.01 + 1.15x(\pm 0.08)$
De Populier 508 nm	22	0.956	+0.035	0.029	$y = 0.05 + 0.93x(\pm 0.06)$
De Populier 625 nm	22	0.927	+0.039	0.033	$y = 0.07 + 0.81x(\pm 0.10)$

from the CIMEL Sun photometer operated at TNO-FEL and part of the AERONET [*Holben et al.*, 1998]. The sites of De Populier and TNO-FEL are approximately 4 km apart.

[32] Figure 6 displays the agreement of CIMEL AERONET and student measurements at “De Populier,” taken within 30 min of one another. As in the previous comparison, the professional retrievals (at 470 nm and 660 nm) have been interpolated to GLOBE Sun photometer wavelengths making use of the Ångström relation. The reported uncertainty of the level 2.0 data for The Hague is based on the reported variability of a measurement triplet [*Smirnov et al.*, 2000] and is on the order of 10% of the observed AOT value. The error bars on the GLOBE data were derived as described in section 4. The results of the quantitative analysis of the differences between school and professional measurements are presented in the lower part of Table 4. Again, we find GLOBE (student) and professional observations to be highly correlated ($R^2 > 0.92$), but the bias and RMS is somewhat larger than for the comparison at KNMI. GLOBE retrievals tend to be higher by approximately 0.04 AOT for both channels. Note that The Hague, a coastal city in an industrial region, influenced by both industrial and sea salt aerosols, shows a wider range of AOTs than the inland location of De Bilt. This may well be due to sampling issues, as the set of observations at The Hague covers all seasons, whereas measurements at KNMI have been compared mainly during winter and early spring.

[33] Information on prevailing aerosol types may be obtained by analyzing the Ångström coefficients derived from GLOBE and AERONET (using the Ångström relation with two wavelengths). Ångström coefficients α, averaged over the comparison period, are shown in Table 5. The consistently higher mean Ångström coefficients found over The Hague indicate that for the set of GLOBE measurements over The Hague, aerosol particles are smaller than for the set of GLOBE measurements over De Bilt. Over The Hague, the mean Ångström coefficients also match more closely than over De Bilt, most likely because of the wider range of observed aerosol values. The determination of Ångström coefficients from small AOT signals with large relative errors is difficult and may explain the discrepancy between the mean Ångström coefficients at De Bilt. For instance, if only data with a (GLOBE 508 nm) AOT > 0.1 at De Bilt is taken, the GLOBE Ångström coefficient increases to 0.87 ± 0.57 ($n = 20$) whereas the SPUV coefficient does not change significantly (1.14 ± 0.32). The yearly mean Ångström coefficient from AERONET over The Hague is 1.21 (J. Kusmierczyk-Michulec, private communication, 2006), very close to the yearly mean value of 1.29 found over De Bilt from SPUV. Hence the differences between the GLOBE Ångström coefficients over The Hague and De Bilt are most likely due to sampling differences.

[34] The agreement of GLOBE and SPUV AOT measurements at KNMI can be interpreted as the maximum attainable agreement for two reasons. First of all, professionals carried out the measurements, and, secondly, the exact same air mass was sampled, excluding representativity errors. In contrast, the agreement of GLOBE and CIMEL measurements over The Hague was expected to be worse, since relatively unexperienced students have done the measurements. Moreover, the comparison suffers from representativity errors as the measurement sites are 4 km apart and a time difference up to 30 min between the measurements was allowed. We do not expect a strong influence due to

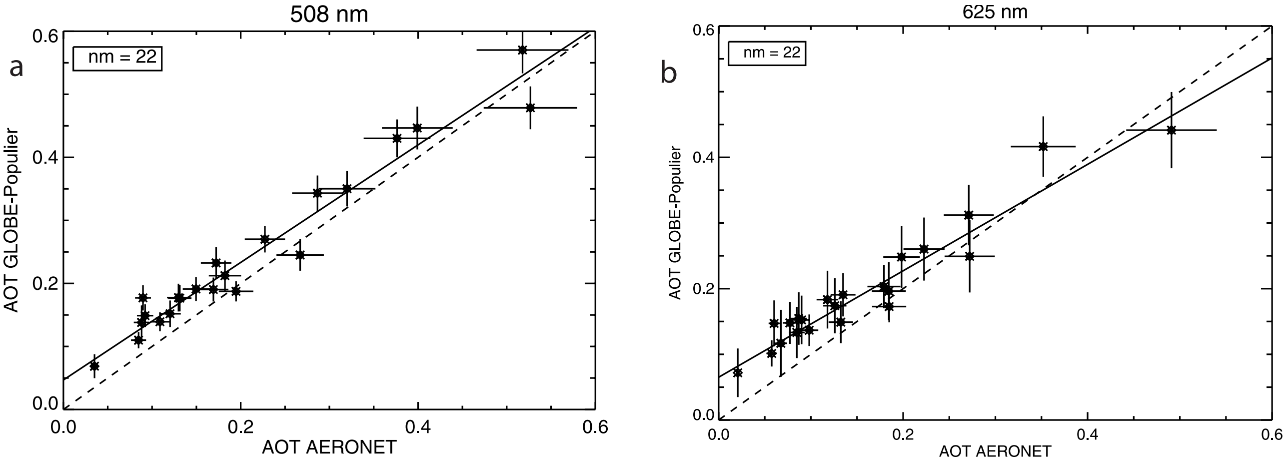

Figure 6. (a) Scatter plot of GLOBE and AERONET CIMEL observed AOT values in The Hague between September 2002 and March 2003. The solid line is the result from a regression analysis taking into account errors of the data (shown as error bars). The dashed line is the $y = x$ line. (b) Same as Figure 6a but now for 625 nm.

Table 5. Ångström Coefficients Averaged Over the September 2002 to March 2003 Period[a]

Instrument	De Bilt (n = 49)	The Hague (n = 22)
GLOBE Sun photometer	0.66 ± 0.73	1.35 ± 0.65
Professional instrument	1.15 ± 0.34	1.46 ± 0.62

[a]Associated standard deviations are given as well. The wavelengths used are 508 nm and 625 nm for the GLOBE Sun photometer, 501 nm and 675 nm for the SPUV, and 440 nm and 660 nm for the AERONET instrument.

wavelength differences between professional and GLOBE instruments, as a number of tests indicated that different choices of Ångström coefficients used in the Ångström relation-based interpolation affected AOTs by no more than 0.01 – 0.02 AOT. The results of this comparison give a first-order estimate of the practically attainable precision and accuracy of student AOT measurements. We estimate that student precision is better than the root-mean-squared difference of 0.03 AOT, as issues of spatiotemporal representativity may have contributed to this number. For "De Populier" in the Hague, we find a bias of 0.04 AOT that may be due to small misalignment errors, calibration errors, or even algorithm differences between the GLOBE Sun photometer algorithm and AERONET retrieval procedures. In summary, from the favorable comparison to independently retrieved, professional data, and the consistency of our results with theoretical error estimates, we use GLOBE student data with confidence for validation of satellite retrievals.

6. Intercomparison of GLOBE Student and MODIS Observations of Aerosol Optical Thickness

6.1. Aerosol Seasonal Variability Over Northwestern Europe

[35] In this section, we obtain a picture of the seasonal and regional variability of MODIS AOTs over the Netherlands. Such an exercise is a typical example of an application of MODIS AOT data, depicts aerosol variability in the context of the GLOBE students' measurements in the region of the Netherlands, and furthermore serves to illustrate the need for a detailed validation of MODIS AOT retrievals. We collected daily MODIS observations over northwestern Europe, between one and three MOD04 granules (a history of algorithm modifications can be found at http://modis-atmos.gsfc.nasa.gov/MOD04_L2/history.html) per day, for the year 2004. There was no MODIS level2 AOT data available for the period of 1 – 18 September 2004. For each granule, AOT data were binned on a 0.15° × 0.15° grid and subsequently averaged on a seasonal basis. Only MODIS AOT pixels with cloud fractions smaller than 0.1 were selected.

[36] Figure 7 shows the total mean seasonal AOTs for winter (December, January, and February: DJF) (Figure 7a), spring (MAM) (Figure 7b), summer (JJA) (Figure 7c), and fall (SON) (Figure 7d) from MODIS at 470 nm. At least 5 MODIS AOT retrievals must have been averaged in a grid cell in order for it to be displayed. However, we have relaxed this constraint to the equivalent of at least 3 MODIS observations in winter and summer, in order to obtain a better spatial coverage for these seasons. For grey areas, the MODIS retrieval has not been performed (i.e., over the open sea and ocean), has been subject to persistent cloud cover, or sampling was too scarce.

[37] Figure 7 shows high AOT values over the relatively densely populated and highly industrialized regions of Flanders and the Netherlands, whereas relatively sparsely populated areas such as the Ardennes (in eastern Belgium) and the Eifel (in the west of Germany) display low AOT values in all seasons. Similarly, *Robles González et al.* [2003] observed high AOT during the August 1997 over strongly industrialized European regions from ATSR-2, and *Barnaba and Gobbi* [2004] found the highly industrialized Po Valley in northern Italy to be affected by high (MODIS) AOT values throughout the year 2001. Furthermore, comparing the four panels in Figure 7 shows a strong cycle in AOT over the Netherlands, with the lowest AOT observed in fall/winter and the highest AOT in spring/summer. This seasonal march cannot be explained from antropogenic emissions, as nitrate contributions to AOT are believed to have a minimum in summer [*Schaap et al.*, 2004], and sulphate concentrations, that contribute most to AOT, show little seasonal variation [*Schaap et al.*, 2004]. The seasonal march may however be related to increased photochemical and convective activity. Relative humidity is generally high in spring and especially in summer, leading to larger particles and higher scattering efficiencies [i.e., *Kiehl and Briegleb*, 1993] in these seasons. Also the more efficient removal of aerosols in fall and winter is likely to play an important role. During fall and winter, precipitation is highest over the Netherlands and is thought to reduce the mean residence time of aerosols in the atmosphere by washing them out.

[38] In summary, Figure 7 shows that the number of suitable retrievals in some seasons is low (illustrated by the considerable number of grey grid cells in Figures 7a and 7c). As AOT varies strongly from day to day, the representativity of the seasonal means may be seriously compromised. Moreover, errors on MODIS AOT retrievals reported in the literature are as large as $\pm(0.05 + 0.20\tau)$ and systematic errors are known to occur over coastal areas [*Chu et al.*, 2002]. The case of a typical application of MODIS AOT retrievals, i.e., maps of seasonally averaged AOT based on a limited number of retrievals, therefore demonstrates that there is a clear need to examine individual MODIS retrievals in detail. This is done in the next section.

6.2. Comparison Over Land

[39] All collocated and coincident measurements taken by GLOBE Sun photometers and MODIS between 2002 and October 2005 have been collected. We define matching observations as those measurements that have been taken within three hours of another, and that have exact spatial overlap, meaning that a single MODIS pixel of 10 × 10 km^2 must overlay the location of the GLOBE measurement. Doing so, we depart from the approach taken by the MODIS team in their papers [*Ichoku et al.*, 2002; *Chu et al.*, 2002, 2003] on validation. They average MODIS AOT over a 50 × 50 km^2 area (i.e., they average over up to 25 pixels) and compare this average with AERONET surface observations taken within 30 min of the MODIS measurement. As such they actually validate a spatially smoothed aerosol data product instead of the single-pixel product that they provide to the scientific user community, which is the aerosol optical thickness at

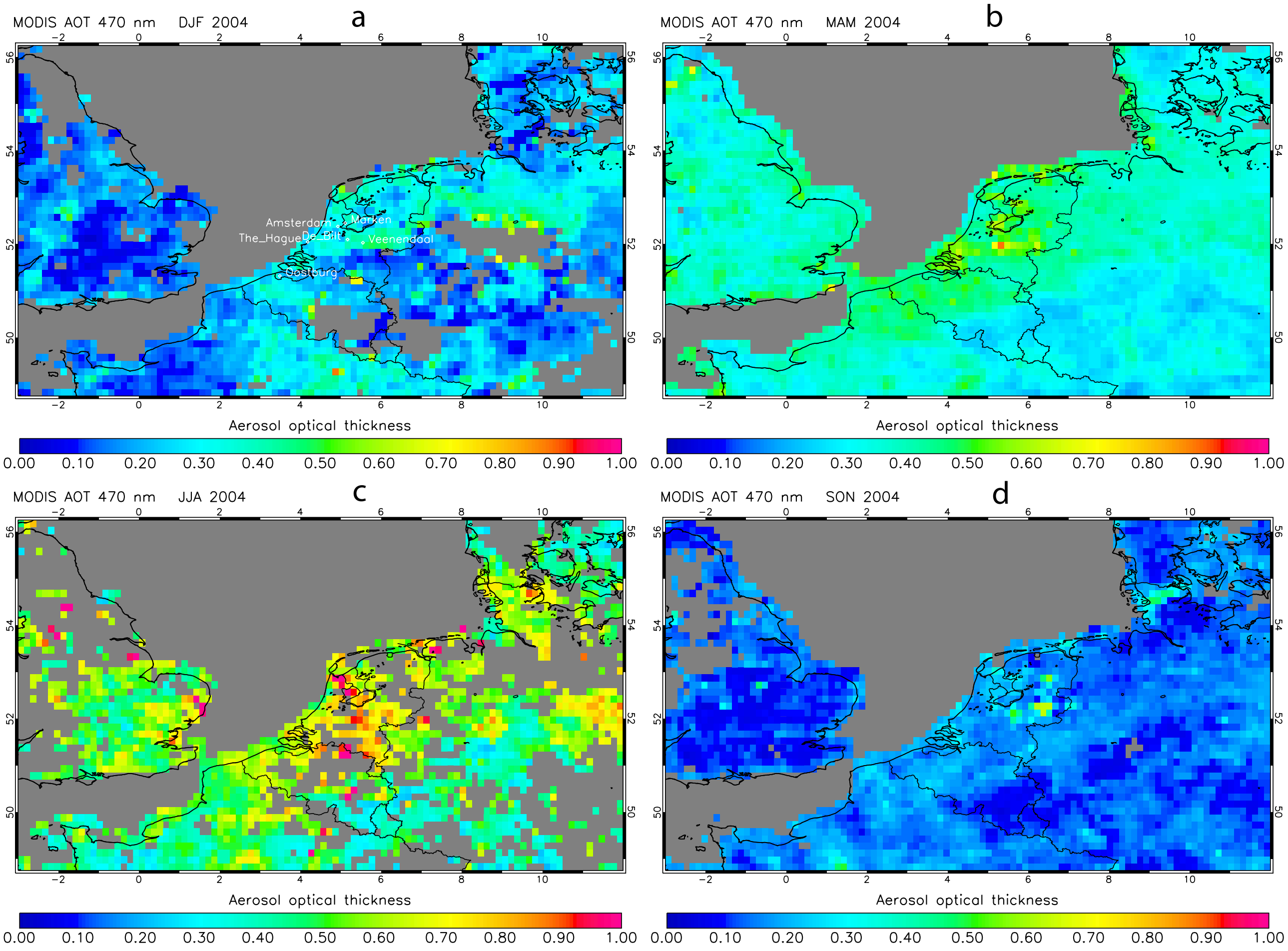

Figure 7. (a) Winter (DJF) 2004 mean seasonal aerosol optical thickness at 470 nm. Grey areas correspond to areas where the MODIS retrieval has not been performed (i.e., over open sea and ocean), has been subject to persistent cloud cover, or with too scarce sampling (see text). GLOBE locations that contributed to the validation of MODIS AOT data are shown in white. (b) Same as Figure 7a but now for spring (MAM) 2004. (c) Same as Figure 7a but now for summer (JJA) 2004. (d) Same as Figure 7a but now for fall (SON) 2004.

10×10 km^2. We have been forced to use a quite crude temporal criterion of 3 hours in order to obtain sufficient matches for a meaningful comparison. Within 3 hours, air masses may incidentally travel over distances that span as many as several tens of MODIS pixels. We expect that, given the range of geographical locations, seasons, and pollution regimes covered, both GLOBE and MODIS capture the dominant patterns of aerosol loadings in space and time. The time differences are expected to affect the comparison, but largely through increased scatter, not bias, as students will measure before and after MODIS measurements, and wind directions and speeds are highly variable. The maximum allowed MODIS cloud fraction is 10%.

[40] Figures 8a and 8b are scatterplots for 61 matching observations taken by GLOBE and MODIS between 2002 and October 2005. In order to compare GLOBE to MODIS AOT data at 470 nm and 660 nm, we extrapolated GLOBE AOT to MODIS wavelengths using Ångström's relation and the Ångström coefficient obtained from the GLOBE data itself. Error bars on the GLOBE data account for contributions to the uncertainty due to extrapolation. Observations from 5 different locations, indicated by different colors, contribute to the comparison of MODIS AOT at 470 nm (Figure 8a and at 660 nm (Figure 8b). Maximum aerosol concentrations are higher over Amsterdam (Bernard Nieuwentijt) and The Hague (De Populier) than over the inland location of De Bilt (KNMI), possibly because of few summertime observations at De Bilt. For Bernard Nieuwentijt measurements taken at the Marken peninsula and all Populier measurements taken at the coastal city of The Hague, we have actually replaced the overlaying MODIS pixels by the adjacent, inland pixels. This avoids comparing a MODIS data ensemble including some (coastal site) observations that have been contaminated by surface reflectance problems, and some that have not. For a discussion of the comparison for "coastal" pixels we refer to section 6.3.

[41] We find that MODIS and GLOBE data compare well over land. On average, GLOBE and MODIS measurements were taken within 65 min of another. The comparison is best

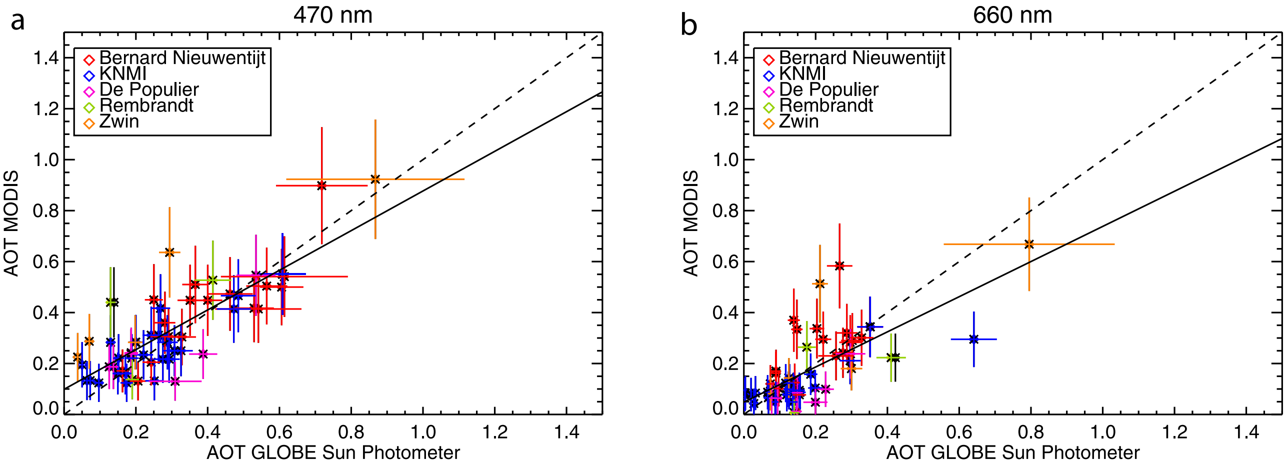

Figure 8. (a) Scatter plot of MODIS and GLOBE observed AOT values at 470 nm at various locations over the Netherlands between September 2002 and October 2005. The solid line is the result from a regression analysis. The dashed line is the $y = x$ line. (b) Same as Figure 8a but now for 660 nm.

at 470 nm ($R^2 = 0.66$) with MODIS overestimating GLOBE AOT by 0.03 AOT (RMS = 0.11). At 660 nm ($R^2 = 0.50$), the mean bias amounts to −0.01 AOT (RMS = 0.11). A linear regression gives $y = 0.10 + 0.78x$ for 470 nm, and $y = 0.05 + 0.69x$ for 660 nm, shown as solid black lines in Figures 8a and 8b. This result is very similar to regressions obtained by *Remer et al.* [2005] for a global validation of MODIS data with as many as 5906 matches. She found $y = 0.09 + 0.83x$ for 470 nm and $y = 0.06 + 0.70x$ for 660 nm.

[42] A test with synthetic data allows us to investigate to what extent the RMS of the differences (0.11) is consistent with the reported uncertainty of MODIS measurements ($0.05 + 0.20\tau$). In this experiment, we assumed that the set of 61 GLOBE observations is without error, and is reproduced by MODIS within the reported errors following:

$$\tau_{M,s} = \tau_G + \nu(0.05 + 0.2\tau_G), \tag{7}$$

with $\tau_{M,s}$ the synthetic MODIS observation, based on the GLOBE observed AOT τ_G, a noise term ν (a normally distributed random number with a mean of 0 and a standard deviation of 1), and the estimated error from literature. To obtain enough statistics, we repeated our experiment 100 times, and find on average (of course) a negligible bias, and an average RMS of 0.12 at 470 nm and 0.09 at 660 nm. This is similar to the RMS of 0.11 that we found in our "real" comparison, suggesting that the reported uncertainty in the MODIS data of $0.05 + 0.2\tau$ is realistic. As most of the scatter is explained by errors in MODIS data, possible errors in GLOBE data (due to time differences and extrapolation issues) are small, and unlikely to have had a strong impact on the comparison results.

6.3. Comparison Over Coastal Areas

[43] In section 6.2 we explained that we used adjacent, inland pixels for our "inland" comparisons in Marken (Bernard Nieuwentijt) and The Hague (De Populier). Here we do use collocated and coincident coastal pixels. For a total of 13 comparisons (average absolute time difference is 1 hour) we find that MODIS overestimates AOT over coastal areas by 0.10 (RMS = 0.17) at 470 nm, and by 0.08 (RMS = 0.14) at 660 nm. These biases are reduced to +0.03 at 470 nm and +0.01 at 660 nm if the adjacent, inland pixels are taken. Although we have only a small sample ($n = 13$), our findings are consistent with results by *Chu et al.* [2002], who found similar MODIS biases over coastal areas in the United States.

7. Summary, Conclusions, and Outlook

[44] In this work we have shown that secondary school students equipped with simple and cheap, hand-held Sun photometers may provide accurate and precise aerosol data at small spatial scales that can be used for validation of satellite-retrieved AOT in addition to existing professional networks.

[45] To arrive at a student's validation of satellite-retrieved AOTs we have established a small network of secondary schools in the Netherlands as part of the international GLOBE program. A new retrieval algorithm has been developed with two improvements over earlier (GLOBE) AOT retrieval algorithms: (1) a correction for ozone optical thickness based on assimilated SCIAMACHY ozone fields and (2) an explicit correction for the dependence of the effective wavelength on the AOT itself.

[46] From an error analysis we estimate that GLOBE AOT precisions are better than 0.02 AOT. This is dominated by the uncertainty in the calibration constant of the GLOBE Sun photometer. We followed an efficient method to calibrate a series of GLOBE photometers, based on a detailed, independent calibration of one reference instrument by means of the Langley-method, and subsequently using this reference for the relative calibration of all other GLOBE instruments. With this method, we achieve a calibration precision of typically 2–4%.

[47] A detailed comparison of exactly coinciding measurements by GLOBE and professional Sun photometer at KNMI shows remarkable agreement with absolute biases smaller than 0.01 AOT and little scatter. This indicates that the GLOBE instrument and algorithm live up to professional standards. A comparison of student and CIMEL AERONET observations over The Hague taken within 4 km and 30 min,

shows that the students' AOTs correlate very well ($R^2 > 0.95$ for both channels) with CIMEL AOTs and exhibit small biases (+0.04 AOT) and scatter (0.03 AOT). These encouraging results show that students are able to measure AOT in a consistent fashion and that their observations are scientifically valid.

[48] As a typical example of the use of MODIS data, we obtained maps of seasonally averaged AOT at 470 nm over the Netherlands. In principle, these maps are compromised as a result of sparse sampling and reported retrieval errors. To examine the validity of such maps, a validation of MODIS AOT retrievals with GLOBE measurements has been carried out.

[49] We used GLOBE Sun photometer measurements over 5 different locations in the Netherlands to validate MODIS AOT. Over land, MODIS shows a mean bias of +0.03 at 470 nm and −0.01 AOT at 660 nm relative to GLOBE. From a small number of matching observations over the coastal GLOBE sites of The Hague and Marken, we find confirmation of an earlier reported overestimation (470 nm: +0.10 AOT, 660 nm: +0.08 AOT) of MODIS AOT over coastal areas. MODIS AOT is therefore likely biased high over the northern and western parts of the Netherlands. A large number of pixels there contains surface waters varying from a few ditches to large lakes.

[50] MODIS data for places and times with persistently low AOT (<0.1) are likely to be overestimated by approximately 0.05–0.10 AOT. Vice versa, MODIS AOT for situations with persistently high AOT is likely too low. A test with synthetic data shows that the RMS differences between MODIS and GLOBE are largely explained by the expected uncertainty in the MODIS observations of $\pm 0.05 + 0.2\tau$.

[51] Interpretation of our validation results needs careful treatment. Every GLOBE instrument has a different bias because of errors in the calibration constants for that particular instrument. These biases have been established for The Hague (bias <0.04) and De Bilt (bias <0.01). For other locations, biases are unknown. These biases are a source of error in the comparison with MODIS and may have influenced the validation results.

[52] A number of improvements is needed in order to mature the GLOBE Aerosol monitoring project in the Netherlands. As calibration errors provide the single, largest contribution to the error budget, the calibration of both reference and school instruments needs to be improved. Furthermore it is recommended that, although there are no clear indications that the GLOBE Sun photometer is suffering from degradation, calibration efforts are regularly repeated.

[53] To increase the usefulness of student data, it is expedient to visit all schools participating in the project on a regular basis. Students should be encouraged to perform measurements on a more frequent basis. Furthermore, school visits should be used to urge students to perform their measurements as near as possible to the overpass time of satellite instruments. This may significantly increase the number of coinciding measurements, and further constrain the quite loose time difference requirement of 3 hours used in this work. Routine has it that involved parties are often short of time, and that incidental visits are not only hard to organize, but also often abandoned. This is regretful, as some schools, after a promising start, fail to continue their measurement record. In summary, school visits are essential to maintaining and prospering a project as described in this study, and should be performed as often as possible.

[54] Validation is a continuing effort, and MODIS retrievals are expected to be improved in the near future concerning their aerosol model and surface albedo assumptions. The GLOBE data set used in this work could be used with little effort to monitor whether these improvements work for retrievals over the Netherlands. We envisage that future studies with GLOBE data will also pay attention to validation of MODIS-retrieved Ångström coefficients. Also, a study of intrapixel variability with two or more schools falling in one pixel would be useful to establish the representativity of 10×10 km^2 averaged AOT for smaller spatial scales. Future applications of the GLOBE student data are expected to focus on validating AOT retrievals from SCIAMACHY and OMI.

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