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Systematic differences of two similar approaches to the determination of the AOD from Brewer direct sun UV measurements

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The determination of the aerosol optical depth (AOD) in the ultraviolet spectral region has become interesting due to the important role that the particles play in the Earth climate and its relation to the photochemical effects. The aim of this work is to determine the systematic differences of two similar approaches which use the same methodology to retrieve AOD from Brewer direct sun measurements. Those proposed by Sellitto et al. (2006), and by Stanek (http://www.o3soft.eu/o3baod.html). The tests have been performed using one-year Brewer measurements at Lampedusa Station. The Stanek AOD values are smaller than those provided by Sellitto et al., showing absolute differences between them from 0.02 to 0.7. No dependence on wavelength and the increase with AOD was observed. Linear regression between both approaches has very good agreement for all the wavelengths ($R > 0.997$). We have reprocessed the Stanek values using the linear regression coefficients yielding absolute deviations less than 0.04 which falls inside of the error assigned to the AOD.

1. Introduction

The aerosol optical depth retrieval in the ultraviolet (UV) spectral region has been of interest in the last decade. This is especially due to the important role that the atmospheric particles play in the Earth climate modifying the earth-atmosphere energy budget through the absorption and scattering of solar radiation. Furthermore, the aerosol characterization is also interesting in relation with the photochemical effects together with the harmful effects of UV radiation on the biosphere.

The determination of the AOD in the UVB (280- 320 nm) is made difficult by the strong spectral absorption of ozone, which is the dominant absorber in this wavelength range. The approach usually requires very complex and accurate instruments because of the weak signals involved and the large dynamic range of the measured ultraviolet solar radiation. Different methodologies have been developed to obtain AOD in UV range using Brewer spectrophotometers. The most common methodologies are based on in situ calibration using the Langley Plot (LP) techniques (Carvalho and Henriques, 2000; Marenco et al., 2002; Cheymol and De Backer, 2003; Sellitto et al., 2006).

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The aim of this work is to characterize the differences observed in the AOD retrieval using two similar approaches based on the same methodology, proposed by Marenco et al. (2002). The first approach was carried out using the modifications done by Sellitto et al. (2006), which is an open code. The second approach was carried out using the O3Baod software developed by M. Stanek. Only the ".exe" files are available on http://www.o3soft.eu/o3baod.html.

2. Instrumentation and measurements

The Brewer spectrophotometers were originally designed to measure the columnar amount of atmospheric ozone (Kerr et al., 1980) and it is considered as the reference instrument for the world atmospheric ozone measurements network (WMO/GAW). The Brewer spectrophotometer is deployed on a solar azimuth tracker which allows automatic measurements of spectral solar global irradiance in the 286-363 nm spectral range, zenith radiance (ZS) and direct sun (DS) radiance and ozone vertical profiles by the Umkehr method (Kerr et al., 1980). The Brewer MKIII is a double monochromator spectrometer with a 3600 lines mm^{-1} diffraction grating. The DS measurements are carried out only at six operational channels (303.2, 306.3, 310.1, 313.5, 316.8, 320.1 nm) with a field of view of 2° and a spectral resolution of about 0.6 nm full width at half maximum (FWHM). The first wavelength is used for spectral calibrations, while the rest is used for ozone retrieval. The DS observation in the Brewer routine takes about 4 minutes doing five consecutive DS measurements. The value of the measurement is the average value for these five independent measurements, and their standard deviation is considered as the measurement uncertainty. The total ozone algorithm uses the combination of measured solar radiances to eliminate the effects of molecular scattering, scattering and absorption by aerosols, and SO_2 absorption in the ultraviolet spectral region (Kerr et al., 1985).
The AOD retrieval from Sellitto et al. and Stanek have been tested using one-year of Brewer #123 DS measurements carried out at Lampedusa during 2008. Lampedusa is a small island (20 km^2) located in the central Mediterranean (35.52ºN, 12.63ºE, 45 m a.s.l.) where the ENEA Station for Climate Observations is operational.

3. Methodology

The methodology that has been applied in this work is based on that proposed by Marenco et al. (2002) which uses DS measurements to perform Langley plots to determine the total atmospheric optical depth (τ_{tot}) following the Beer´s law (1).

$$\tau_{tot}(\lambda) = -\frac{1}{m}\ln\left(\frac{I(\lambda)}{\rho^{-2}I_0(\lambda)}\right) \qquad (1)$$

where $I(\lambda)$ and $I_0(\lambda)$ are the spectral direct sun radiance measured by the Brewer at ground level and at the top of the atmosphere, respectively. The factor ρ^{-2} accounts for the seasonal correction for changes in the Sun-Earth distance. The airmass factor m is a geometrical coefficient that takes into account the slant path through the atmosphere. The AOD is then obtained subtracting the known contributions of the other atmospheric species that present absorption in the UV spectral region. Only the Rayleigh scattering by molecules and the ozone absorption have been considered in this study.

$$AOD(\lambda) = \tau_{tot}(\lambda) - \tau_{Ray}(\lambda) - \tau_{O3}(\lambda) = -\frac{1}{m}\ln\left(\frac{V_\lambda}{\rho^{-2}V_{0\lambda}}\right) - \frac{p}{p_0}\tau_R(\lambda) - D_{O3}k_{O3}(\lambda)\frac{\ln 10}{1000} \qquad (2)$$

where p is the atmospheric pressure at the measurements site and p_0 is the standard pressure at sea level (1013.25 hPa). The Rayleigh optical depth is $\tau_R(\lambda)$, D_{O3} is the total ozone content (Dobson units), and $k_{O3}(\lambda)$ is the ozone absorption coefficient (in cm^{-1}).
The calibration of the Brewer is obtained using the Langley plot (LP) technique. The LP is the linear regression of the logarithm of the measured radiance ($\ln I(\lambda)$) versus airmass factor (m). The extraterrestrial constant ($\ln I_0(\lambda)$) is determined as the extrapolated radiance at zero airmass, and represents the calibration factor (CF). The LP is performed only under stable atmosphere conditions. The selected data should satisfy the following criteria: a) the LP is obtained from at least ten direct sun measurements at air masses m < 3, for minimizing the diffuse irradiance, the stray light, and to eliminate days with only a few data covering a limited number of airmasses; b) the standard deviation of the total ozone must be < 2.5 DU since the cases of large standard deviation of ozone are associated with cloudy conditions; c) the root mean deviation of the measured radiances from the fitting function is < 0.025, to set a threshold on the goodness of the fit and removes cases with high aerosol variability (Sellitto et al., 2006). The CF for each wavelength is obtained by a statistical analysis as the average of all the ($\ln I_0(\lambda)$) determinations accepted by the selection criteria in the chosen time interval. The standard deviation of the mean value ($\sigma/\sqrt{n}$) is considered as its absolute error.
The approach done by Sellitto et al. (2006) uses a special measurement schedule to obtain the interfilter calibration between filter #2 and #3 and several instrumental corrections to carry out the modified LP. The AOD retrieval is performed in the second step. The second approach was run using the O3baod software package developed by Martin Stanek. It uses the five neutral density filter determined in the Brewer calibration procedures to operate also in two steps. The first step allows obtain the CF using O3betc routine and the second step is to retrieve the AOD running the O3baod routine.

4. Results and discussion

The calibration was performed using only the days which satisfy the LP criteria and the number of the selected days is very different for both codes. Sellitto et al. code uses 108 days, while the Stanek one only accepts 40 days. The differences between both codes become also evident in the CF: those obtained by Stanek and Sellitto et al. are around 8 and 15 respectively (Table 1). The latest values are closer to those found in the literature (which fall in the 15-17 range) even if were obtained using different methodologies, locations, and different version of the Brewer (Marenco et al., 2002, Chemol & De Backer, 2003; and Kazdazis et al., 2005). However, it seems to be a relationship between the CFs from both codes, since the ratio ($\ln(I_0)_{Stanek}/\ln(I_0)_{Sellitto}$) is almost constant around 0.539 for all the wavelengths (Table 2), suggesting some systematic deviation. The linear fit between the CF obtained by both approaches shows a correlation of 0.997 for all wavelengths. We use these relationships to transform the

Sellitto CFs (around 15) to those accepted by Stanek code (around 8) in order to minimize the calibration effect on the following AOD retrieval.
A cloud screening and AOD quality check algorithm was applied on the basis of Smirnov et al. (2002). It is an iterative algorithm working in several steps that essentially limits the daily AOD variability through its standard deviation at 320 nm ($\sigma_{320} \leq 0.015$). If σ_{320} is larger than the limit, a smoothness criterion is applied to remove the highest instantaneous AOD values associated to thin clouds. The 3σ criterion is applied later to eliminate the outliers which are highly improvable values. The further AOD analysis was done using only the screened data for both approaches.
Since the channels used by the Brewer are centered at close wavelengths, the spectral variation of AOD is small. The average of the spectral deviation ($\max(AOD_\lambda) - \min(AOD_\lambda)$) is less than 0.03 and 0.006, which represents 12% and 4%, respectively for Sellitto and Stanek approaches. The spectral deviation relative to the mean AOD value for all wavelength increases as the AOD_{320} decrease. The code by Sellitto is more sensible to the spectral deviation, especially when AOD_{320} becomes smaller than 0.1.
The AOD evolution for channel 320.1 nm is shown in Figure 1. The AOD obtained by Stanek code is always smaller than Sellitto's values. Large deviations between the two datasets exist. Figure 2 shows the evolution of these deviations at 306.3 and 320.1 nm, showing highly variability from 0.02 to 0.7, which are very similar at all wavelengths. The seasonal evolution of AOD retrieved using the Sellitto software in 2008 follows the same trend found at Lampedusa in different years (Sellitto et al., 2006).

Table 1. Spectral calibration factors. N is the number of days used in LP..

Channel	$\ln(I_0)_{Stanek}$	$\ln(I_0)_{Sellitto}$	$\ln(I_0)_{Stanek} / \ln(I_0)_{Sellitto}$
306.3	8.095±0.015	14.938±0.015	0.542
310.1	8.027±0.016	14.816±0.010	0.542
313.5	8.266±0.016	15.393±0.010	0.537
316.8	8.296±0.016	15.457±0.014	0.537
320.1	8.334±0.016	15.563±0.014	0.536
N	40	108	

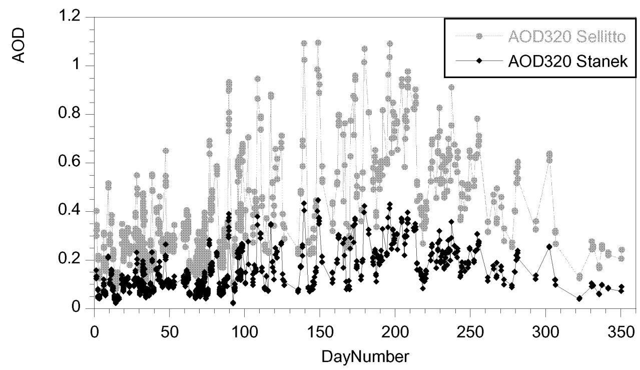

Figure 1. Aerosol optical depth at 320.1 nm retrieved with the algorithm by Sellitto et al. (grey dots), and by Stanek (black diamonds).

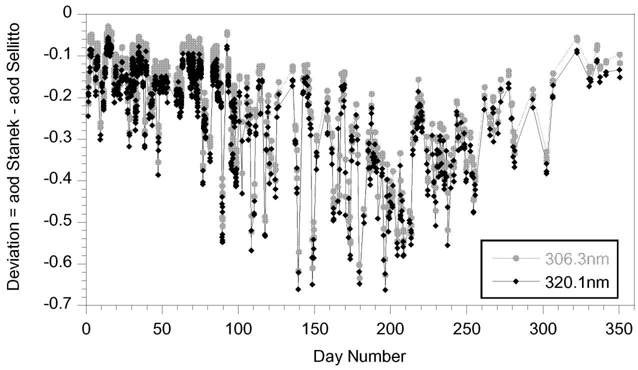

Figure 2. Aerosol optical depth deviation between Stanek and Sellitto et al. on channels 1 and 5 (306.3 and 320.1 nm respectively).

Furthermore, these deviations exhibit also a strong dependence on AOD. The absolute value of differences increases as the AOD increases, showing a strong linear correlation of 0.99 for all the wavelengths. No dependence on the ozone content was observed, suggesting that the deviations are due to the AOD retrieval algorithm.

We have performed also a linear regression between both approaches which have very good correlation at all the wavelengths (R > 0.997). The slope of the fit is slightly spectral varying from 2.411 to 2.466. The intercept is less than 0.036 for all wavelengths, but it is more spectrally variable (Table 2).

We have reprocessed the Stanek values using the slope of the linear regression coefficients, and in this case the absolute differences between both approaches are less than 0.04 with no dependence on the wavelength. The annual averages of these deviations are zero with small annual standard deviations from 0.012 to 0.014. That indicates that the Stanek reprocessed AOD values fall at both sides of the AOD from Sellitto approach and the AOD dependence in the retrieval has been eliminated.

Table 2. Linear regression coefficients $AOD_{Stanek} = f(AOD_{Sellitto})$

Channel	slope	intercept	R
306.3	2.417±0.004	-0.0002±0.0006	0.998
310.1	2.411±0.004	0.0179±0.0006	0.998
313.5	2.438±0.004	0.0008±0.0007	0.998
316.8	2.451±0.005	0.0360±0.0008	0.998
320.1	2.466±0.005	0.0280±0.0008	0.997

5. Conclusions

Two similar codes (Sellitto et al. and Stanek) which reproduce the same methodology to determine AOD from Brewer have been analyzed. The differences found in the calibration routine are associated with a different number of days that pass the LP criteria, and the CF itself. Systematic linear correlations between these CFs from both routines have been found at all wavelengths. Only the screened AOD measurements were used in the comparison. The spectral deviation is larger when the Sellitto et al. approach was used (0.03), while it is only 0.006 for the Stanek code. In both cases the spectral deviation increases with AOD. Large deviation between both approaches has been detected with high variability along the year. The Stanek approach always underestimates the AOD provided by Sellitto et al., and the absolute values vary from 0.02 to 0.7. The deviation shows a large dependence on AOD, increasing as AOD increases, although no dependence on the ozone content is found. Linear regressions between both approaches show a very good AOD correlation at all the wavelengths (R > 0.997). We have reprocessed the Stanek values using the retrieved slopes of the linear regression coefficients, and in this case differences become less than 0.04, which fall wihin the error assigned to the AOD.

These systematic differences between the two approaches for all the wavelengths suggest the possibility of a mathematical error. The Sellitto et al. approach has been tested against other instruments in the UV and visible bands (e.g., di Sarra et al., 2008), yielding very good results. These results highlight the difficulty of deriving aerosol optical depths in the UV, and the necessity of independent verification of the retrieved values before their use for scientific analyses.

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