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Can AERONET data be used to accurately model the monochromatic beam and circumsolar irradiances under cloud-free conditions in desert environment?

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Abstract

Routine measurements of the beam irradiance at normal incidence (DNI) include the irradiance originating from within the extent of the solar disc only (DNI_S) whose angular extent is 0.266° ± 1.7%, and that from a larger circumsolar region, called the circumsolar normal irradiance (CSNI). This study investigates if the spectral aerosol optical properties of the AERONET stations are sufficient for an accurate modelling of the monochromatic DNI_S and CSNI under cloud-free conditions in a desert environment. The data from an AERONET station in Abu Dhabi, United Arab Emirates, and a collocated Sun and Aureole Measurement (SAM) instrument which offers reference measurements of the monochromatic profile of solar radiance, were exploited. Using the AERONET data both the radiative transfer models libRadtran and SMARTS offer an accurate estimate of the monochromatic DNI_S, with a relative root mean square error (RMSE) of 5%, a relative bias of +1% and a coefficient of determination greater than 0.97. After testing two configurations in SMARTS and three in libRadtran for mod-

elling the monochromatic CSNI, libRadtran exhibits the most accurate results when the AERONET aerosol phase function is presented as a Two Term Henyey–Greenstein phase function. In this case libRadtran exhibited a relative RMSE and a bias of respectively 22 and –19% and a coefficient of determination of 0.89. The results are promising and pave the way towards reporting the contribution of the broadband circumsolar irradiance to standard DNI measurements.

1 Introduction

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The direct, or beam, normal irradiance (DNI) is the radiant flux per unit area received on a plane normal to the sun rays from a small solid angle centered to the solar disc (ISO-9488, 1999; WMO, 2010). The DNI plays a role in various domains, such as natural biomass development, climate, daylighting, or concentrated solar technologies (CST) in electricity production. In the ISO definition of the DNI the "small solid angle" is





not defined. The World Meteorological Organization (WMO) recommends measuring instruments with aperture (or opening) half-angles between 2.5 and 5°, respectively equivalent to solid angle apertures of 6 and 24 msr. For an observer at the surface of the Earth, the Sun has an angular radius of $0.266^{\circ} \pm 1.7$ % (Jilinski et al., 1998).

- ⁵ CST systems have aperture half-angles larger than the angular radius of the solar disc, but usually smaller than those of the measuring instruments (Blanc et al., 2014). This implies that the irradiance originating from within the extent of the solar disc only (DNI_S) and that from a larger circumsolar region defined by the solid angle aperture, called the circumsolar normal irradiance (CSNI), are intercepted within the aperture of the measuring instrument or concentrating system. This paper deals with the modelling
- of the DNIs and CSNI.

To tackle the ambiguity of the "small solid angle", Blanc et al. (2014) recommend reporting the viewing angles of the measuring instrument along with the sunshape and contribution of the circumsolar irradiance in addition to the DNI measured by pyrhe-

- liometers or equivalent pyranometric systems. The circumsolar contribution may be provided in terms of CSNI defined for the solid angle aperture, or in terms of the circumsolar ratio (CSR), which is the ratio of the CSNI to the sum of the CSNI and DNI_S (Buie et al., 2003). The sunshape is the azimuthally averaged profile of solar radiance normalized with respect the central, i.e. maximum, radiance reading. The solar
 radiance profile represents the angular distribution of the sky radiance from which the
- CSNI is computed.

Reporting the sunshape and the circumsolar contribution are not straightforward if no coinciding measurements of such are available. Several ground measurement campaigns of the solar radiance profile have taken place, but the data sets are limited ²⁵ in space and time (Neumann et al., 2002; Noring et al., 1991). More recent and still ongoing campaigns have measured or are still measuring the monochromatic profile of solar radiance at a resolution of 0.015° up to an angular distance of 8° from the center of the solar disc with the Sun and Aureole Measurement (SAM) instrument. SAM only measures the monochromatic radiance at 670 nm with a full spectral width





at half-maximum of 10 nm. Other spectral filters exist at 440 and 870 nm. This instrument is manufactured by Visidyne Inc., and the data is available for public access (http://www.visidyne.com/). Out of the nine instruments reported on the website, six of them have data available for download, for three instruments located in France, Spain,

- and the United Arab Emirates (UAE) and three in the USA. Wilbert et al. (2013) propose a method to convert the monochromatic measurements of the profile of solar radiance to broadband profiles using a modified – but not explicitly described – version of the radiative transfer model (RTM) SMARTS (Simple Model of the Atmospheric Radiative Transfer of Sunshine, Gueymard, 1995, 2001). Other preliminary works (Eissa et al., 2012) Our base at al. 2010) have medalled the breadband CONL but the results have
- ¹⁰ 2013; Oumbe et al., 2012) have modelled the broadband CSNI, but the results have not been compared with reference measurements.

AERONET (Aerosol Robotic Network) products provide the aerosol optical properties at numerous locations globally and for varying time periods (Holben et al., 1998). Masdar City, located in the suburbs of Abu Dhabi, UAE, is the seat of both AERONET

- and SAM measurements. It offers the opportunity to study the potentials of AERONET data in modelling the DNI_S and CSNI. The objective of this article is to answer the following question: can AERONET data be used to accurately model the monochromatic beam and circumsolar irradiances under cloud-free conditions in desert environment? A desert environment is of interest because countries in the Middle East and North
- Africa region, where the environment is mostly dominated by desert surroundings, have set ambitious plans to install CST systems in the upcoming years (Brand and Zingerle, 2011; Griffiths, 2013). In desert environments the circumsolar radiation may be significant under turbid cloud-free skies, implying that information of the CSNI and DNI_S is essential for an improved assessment of the DNI (Blanc et al., 2014; Thomalla et al., 1983).

To that extent, several parameterizations of the monochromatic phase function, asymmetry parameter and single scattering albedo available in the RTMs libRadtran (Mayer and Kylling, 2005; Mayer et al., 2012) and SMARTS are tested against SAM measurements, where the aerosol optical properties are extracted from the products of



AERONET. The article is organized as: theoretical background (Sect. 2), aerosol optical properties from AERONET data (Sect. 3), SAM data (Sect. 4), cross-comparison between AERONET and SAM data (Sect. 5), AERONET data in the parameterizations of the RTMs (Sect. 6), results and discussion (Sect. 7), and conclusions (Sect. 8).

5 2 Theoretical background

2.1 The beam irradiance

The monochromatic DNI_{S} is represented by the Beer–Bouguer–Lambert law (Liou, 2002) as:

 $B_{n,\lambda}^{Sun} = E_{0,n,\lambda} \exp(-\tau_{\lambda} m),$

¹⁰ where $B_{n,\lambda}^{Sun}$ is the monochromatic DNI_S, $E_{0,n,\lambda}$ is the monochromatic extraterrestrial irradiance received on a plane normal to the Sun rays, τ_{λ} is the monochromatic optical depth of all attenuating factors present in the atmosphere and *m* is the pressurecorrected relative optical air mass (Kasten and Young, 1989). $E_{0,n,\lambda}$ and *m* are well described in the literature. Therefore, the accurate modelling of $B_{n,\lambda}^{Sun}$ requests an ac-¹⁵ curate retrieval of τ_{λ} within the extent of the solar disc only.

The monochromatic DNI_S may also be computed from the beam radiance within the solar disc as (Blanc et al., 2014; Buie et al., 2003):

$$B_{n,\lambda}^{Sun} = \int_{0}^{2\pi\delta_{S}} \int_{0}^{\delta_{S}} L_{\lambda}(\xi,\varphi_{n})\cos(\xi)\sin(\xi)d\xi d\varphi_{n},$$
(2)

where $L_{\lambda}(\xi, \varphi_n)$ is the monochromatic beam radiance, ξ is the scattering angle, φ_n is the azimuth angle on the plane normal to the Sun and $\delta_{\rm S}$ is the angular radius of the Sun corrected with respect to the Sun–Earth distance. For the small ξ of the solar



(1)



and circumsolar regions the deviation from 1 of the $cos(\xi)$ term can be considered negligible. Also, under the assumption of radial symmetry of the sky radiance in the vicinity of the Sun under cloud-free conditions, Eq. (2) simplifies to:

$$B_{n,\lambda}^{Sun} = 2\pi \int_{0}^{\delta_{S}} L_{\lambda}(\xi) \sin(\xi) d\xi.$$

5 2.2 The circumsolar irradiance

Ignoring the multiple scattering effects and in the near vicinity of the solar disc the circumsolar diffuse radiance can be computed with a certain level of accuracy for an observer at ground level as (Dubovik and King, 2000; Liou, 2002; Wilbert et al., 2013):

$$L_{\lambda}(\xi) = E_{0,n,\lambda} m \exp(-\tau_{\lambda} m) P_{\lambda}(\xi) \omega_{\lambda} \tau_{\lambda} / (4\pi),$$

where $P_{\lambda}(\xi)$ is the monochromatic phase function and ω_{λ} is the monochromatic single scattering albedo. Therefore, the uncertainty associated with modelling the circumsolar diffuse monochromatic radiance is associated mainly with the uncertainties in τ_{λ} , $P_{\lambda}(\xi)$ and ω_{λ} .

The CSNI is computed from the circumsolar diffuse radiance as (Blanc et al., 2014; ¹⁵ Buie et al., 2003):

$$\mathsf{CS}_{\mathsf{n},\lambda}(\delta,\alpha) = 2\pi \int_{\delta}^{\alpha} L_{\lambda}(\xi) \sin(\xi) \mathsf{d}\xi,$$

where $CS_{n,\lambda}(\delta, \alpha)$ is the monochromatic CSNI in the interval $[\delta, \alpha]$, δ is the inner limit of the circumsolar region and α is the outer limit of the circumsolar region.



(3)

(4)

(5)

3 Aerosol optical properties from AERONET data

The environment of interest is that of Masdar City, located in the suburbs of Abu Dhabi, UAE. The site is described as near-coastal, desert and urban, with frequent cloud-free but turbid skies due to natural and anthropogenic dust emissions (Gherboudj and Ghedira, 2014). It has an altitude above mean sea level of 7 m, and is located

at 24.420° N and 54.613° E. Coinciding AERONET and SAM measurements were performed from June 2012 to May 2013.

The CIMEL CE-318 Sun photometer of the AERONET station has an aperture halfangle of 0.6° (Holben et al., 1998). The monochromatic aerosol optical depth, abbreviated in AOD and noted $\tau_{a,\lambda}$, is provided at the following wavelengths: 1640, 1020, 870, 675, 500, 440, 380, and 340 nm, from the Version 2 Direct Sun Algorithm (DSA) products. The total column content in water vapor and the solar zenith angle θ_S are also reported. In this work, only Level 2.0 DSA products were used to ensure cloud-free and quality assured observations. The cloud-screening algorithm of the AERONET data only filters out the cloud-contaminated observations in the direction of the Sun (Smirnov et al., 2000).

Version 2 Inversion products are also available from the AERONET data. They include the monochromatic radiance measurements as a function of the scattering angle *ξ* in the almucantar plane, measured at the following wavelengths: 1020, 870, 675, and 440 nm. The measurements in the almucantar plane are carried out at an air mass of 4, 3, 2 and 1.7 in the morning and the afternoon and hourly between 09:00 and 15:00 true solar time (Holben et al., 1998). In the near vicinity of the solar disc the almucantar measurements of radiance are provided over Masdar City at *ξ* of: ± 3; ± 3.5; ± 4; ± 5; ± 6°. The measurements exceed 6°, but for the sake of the discussion on circum²⁵ solar radiation the cutoff here is made at 6°. From June 2012 to May 2013 there are 2241 profiles of the diffuse radiance notably at 675 nm in the almucantar plane, all in Level 2.0. The wavelength of 675 nm is of specific interest in this study because it al-





most coincides with the radiance measurements of the SAM instrument, discussed in Sect. 4.

The AERONET Version 2 Inversion products also include (Dubovik and King, 2000; Dubovik et al., 2002; Holben et al., 1998):

- the monochromatic aerosol single scattering albedo $\omega_{a,\lambda}$;
 - the monochromatic aerosol phase function $P_{a,\lambda}(\xi)$;
 - the monochromatic asymmetry parameter g_{λ} .

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For this time period, and in Level 2.0, there are 1068 observations of $\tau_{a,\lambda}$, $P_{a,\lambda}(\xi)$ and g_{λ} covering the whole 12 months of this study period. The months with the smallest number of observations are November, December 2012 and May 2013, with respectively 4, 5 and 4% of the 1068 observations. For the remaining months the number of observations ranges between 8 and 14% of the 1068 observations. Only 491 from the 1068 observations include $\omega_{a,\lambda}$, and in this case the distribution of the samples amongst the months varies widely. There are two samples in November, October, December 2012, and May 2013 offer a small number of samples smaller than

January, February, March, and May 2013 offer a small number of samples, smaller than26. The five remaining months offer statistically significant number of samples.

If an atmosphere containing aerosols only is assumed, since the variability of the aerosol optical properties contributes the most to the radiance (Dubovik and King, 2000), Eq. (4) becomes:

²⁰ $L_{\lambda}(\xi) = E_{0,n,\lambda}m\exp(-\tau_{a,\lambda}m)P_{a,\lambda}(\xi)\omega_{a,\lambda}\tau_{a,\lambda}/(4\pi).$

Over this study area, for the selected time period, and for $\lambda = 675$ nm, using Eq. (6) for the 491 observations a simple sensitivity analysis was conducted on the significance of $\tau_{a,675 \text{ nm}}$, $\omega_{a,675 \text{ nm}}$ and $P_{a,675 \text{ nm}}(\xi)$ on $L_{675 \text{ nm}}(\xi)$. By adding to $\tau_{a,675 \text{ nm}}$ its standard deviation computed from the 491 observations, whilst keeping $P_{a,675 \text{ nm}}(\xi)$ and $\omega_{a,675 \text{ nm}}$ at their actual values, $L_{675 \text{ nm}}(\xi)$ was computed once with and once without the deviation



(6)

on $\tau_{a.675}$ nm. The relative error is computed as:

relative error = $|L'_{675 \text{ nm}}(\xi) - L_{675 \text{ nm}}(\xi)|/L_{675 \text{ nm}}(\xi)$,

where $L'_{675 \text{ nm}}(\xi)$ is the radiance computed with the deviation on $\tau_{a.675 \text{ nm}}$. The relative error induced on $L_{675 \, \text{nm}}(\xi)$ reaches up to 100 % in several cases. This gives an insight 5 on the importance of the AOD when modelling the circumsolar diffuse radiance.

- The same analysis was performed for $\omega_{a.675\,\text{nm}}$ and $P_{a.675\,\text{nm}}(\xi)$. The standard deviation of $\omega_{a.675 \text{ nm}}$ is 0.019, or 2% of the mean value, and by adding to $\omega_{a.675 \text{ nm}}$ its standard deviation relative errors of 2% are observed on $L_{675 \text{ nm}}(\xi)$. Indeed, $\omega_{a,\lambda}$ is linearly proportional to $L_{\lambda}(\xi)$, implying that a deviation of 2% from the actual value of $\omega_{a,675\,\text{nm}}$ would only have a modest effect of 2% on the circumsolar diffuse radiance. 10 A practical consequence is that a mean value of $\omega_{a,675\,\text{nm}}$ can be used with an acceptable loss of accuracy. In addition, using a mean value of $\omega_{a,\lambda}$ is a means to tackle the issue of the missing $\omega_{a,\lambda}$ values at instances when $P_{a,\lambda}(\xi)$ data are available. The AERONET retrieval of $\omega_{a,\lambda}$ is not valid under small aerosol loading situations and this causes the gaps in $\omega_{a,\lambda}$ (Dubovik et al., 2000; Yin et al., 2015). The mean value of 15 $\omega_{a,675\,\text{nm}}$ for the available 491 observations over this study area and for this study period is 0.954, this number is fairly close to the monthly mean values of $\omega_{a,675}$ nm, which range from a minimum of 0.917 in December 2012 to a maximum of 0.974 reached in March 2013.
- The aerosol phase function $P_{a,675\,\text{nm}}(\xi)$ is a function of ξ , therefore, the standard 20 deviation was computed for the three ξ available from AERONET which are less than 6°, i.e. 0, 1.71, and 3.93°. The same procedure was applied at each ξ to observe the relative error on $L_{675 \, \text{nm}}(\xi)$. For the three ξ the relative errors on $L_{675 \, \text{nm}}(\xi)$ reach up to 40 %. This indicates the significance of an accurate $P_{a.675 \text{ nm}}(\xi)$ when modelling the circumsolar diffuse radiance.





(7)

ISCUSSION

4 SAM data

The ground measurements of the beam and circumsolar diffuse radiance were collected at Masdar City by the SAM instrument (DeVore et al., 2012a). The instrument is comprised of two cameras (Wilbert et al., 2013). One directly measures the radiance within the solar disc. The solar aureole, also known as the circumsolar region, is

- ⁵ ance within the solar disc. The solar aureole, also known as the circumsolar region, is formed on a screen with a beam dump for the solar disc region and this image is captured by the other camera facing the screen. The monochromatic radiance at Masdar City is measured only at 670 nm with a full spectral width at half-maximum of 10 nm. The angular resolution of the radiance measurements is 0.0217° and the acquisition
- frequency is 4 or 5 times per minute. The relative error of the beam radiance is reported to be less than 1 % for $\tau_{a,670 \text{ nm}} < 0.6$, while that of the aureole radiance is reported to be between 5 and 15 % (Stair and DeVore, 2012). An angular gap exists between the beam and circumsolar radiance measurements to avoid superimposition of the solar disc radiance scattered on the screen with the image of the circumsolar region on that
- screen (Wilbert et al., 2013). DeVore et al. (2012b) suggested that radiance measurements collected by the solar aureole camera for $\xi < 0.64^{\circ}$ are noisy and should be excluded: this suggestion is followed in this study.

There are four main files of SAM data for each day (LePage et al., 2008). One file contains the radial profiles, i.e. azimuthally averaged, of the beam and circumsolar radiance throughout the whole day. A second file contains the horizontal beam and circumsolar radiance measurements throughout the whole day, scanning the Sun in the east and west directions with respect to the center of the Sun (almucantar). A third file contains the vertical beam and circumsolar radiance measurements throughout the whole day, scanning the Sun in the north and south directions with respect to the center of the Sun. The reported angular resolution for the horizontal and vertical

the center of the Sun. The reported angular resolution for the horizontal and ver measurements is also 0.0217°. The last file includes $\tau_{a,670}$ nm and θ_{s} .

The SAM instrument is fairly new. The oldest reference found was that of DeVore et al. (2007) who reported examples of the SAM measurements collected in 2006.





However, no article has been found which clearly defines quality control procedures for the SAM measurements. There are also several gaps in the downloaded data. Therefore, a set of quality control procedures are defined herein to retain only the high quality measurements:

⁵ i. the number of profiles of solar radiance and $\tau_{a,670 \text{ nm}}$ observations do not match. Therefore, the radial, horizontal and vertical profiles were matched to the $\tau_{a,670 \text{ nm}}$ observations which have the same time stamp. With this test 229561 observations of the profiles and $\tau_{a,670 \text{ nm}}$ remain from originally 244 609 profiles;

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ii. any radial profile with negative values in the solar disc region is removed: 222742 observations remain:

iii. the monochromatic radiance of the radial profile should decrease with an increasing angular displacement in the solar disc region, i.e. the condition $dL_{\lambda}(\xi)/d\xi < 0$ must be fulfilled. This procedure is similar to that proposed by Buie et al. (2003) when performing the quality checks on the profiles of solar radiance measured by the Lawrence Berkeley National Laboratory. With this test 222714 observations remain;

iv. according to Buie et al. (2003) and Neumann et al. (2002) the variations in the solar disc region of the sunshape are low for CSRs ranging between 0.05 and 0.4. When comparing the solar disc region of the CSR 0 and CSR 40 sunshapes proposed by Neumann et al. (2002) a relative root mean square error (RMSE) of 4% is observed when taking the CSR 0 sunshape as the reference. The RMSE was constructed from the relative intensity of each sunshape at the different ξ . To this end, each SAM radiance measurement in the solar disc region was normalized between 0 and 1. In the solar disc region, a mean normalized solar radiance profile was generated from all the available measurements resulting from point (iii), which was then matched to the closest actual normalized profile in terms of Euclidean distance. Then the relative RMSE was computed for each normalized





solar radiance profile with respect to the actual mean normalized profile. The 90th percentile of the RMSE was chosen as the cutoff; it also coincides with a relative RMSE of 4 %. 200 443 profiles pass this quality check;

v. as pointed out by Noring et al. (1991), the circumsolar radiance and ξ exhibit a linear relation in the log-log space. Therefore, the correlation coefficient in the log-log space was computed between the circumsolar radiance of each of the radial profiles and ξ in the interval [0.64, 6°]. Any radial profile exhibiting a correlation coefficient less than 0.990 was eliminated. 191 812 observations remain.

5 Cross-comparison between AERONET and SAM data

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- ¹⁰ Both SAM and AERONET data include L_{λ} and $\tau_{a,\lambda}$. Comparing them is a way to remove inconsistent outliers from measurements from either instruments. To compare the AERONET and SAM radiance measurements, the AERONET almucantar radiance measurements were matched to the SAM horizontal monochromatic radiance measurements in terms of time stamp. In the temporal matching process, the measure-
- ¹⁵ ments between the two different instruments had to be at most 1 min apart and $\theta_{\rm S}$ reported by the two instruments had to match: the bias between the matched $\theta_{\rm S}$ was found to be 0.00° and the maximum absolute error in angle for all observations was 0.22°.

The SAM radiance measurements were then angularly aggregated to match the 20 0.6° half field of view of the CIMEL 318 Sun photometer. After matching the measurements, 1117 AERONET and SAM profiles remained. Ideally for these 1117 profiles there should be 11 170 measurements of radiance corresponding to ξ of: ± 3 , ± 3.5 , ± 4 , ± 5 , and $\pm 6^{\circ}$. Instead there is a lower number of observations due to missing data in the almucantar measurements from AERONET which could occur at any ξ . The 25 standard deviation of the differences between these remaining pairs of observations was computed. In a second step, all samples with a difference greater than three times





the standard deviation were filtered out. 253 samples matched this criterion. This test is meant to filter out extreme cases which could occur if one instrument is shaded by clouds while the other is not. This situation can occur since the two instruments are not exactly at the same place and the time matching is in minutes.

- Figure 1 exhibits the density scatter plot (or 2-D histogram, Eilers and Goeman, 2004) of the SAM and AERONET radiance measurements. Red dots correspond to regions with high densities of samples and the dark blue ones to those with very low densities of samples. The relative RMSE is 18 %, the relative bias is 0 % and the coefficient of determination R^2 is high at 0.894. The observations are well-scattered around the 1 : 1 line. The comparison results are good, implying reliable measurements from
- both instruments. The AERONET measurements were collected at 675 nm while those of SAM were collected at 670 nm. This may induce minor errors in this comparison. Also shown in Fig. 1 are the mean value of the observables on the x axis, the correlation coefficient (CC), the 1 : 1 line, the least-squares (LS) affine regression, the robust affine regression, and the first axis of inertia, also known as the first component in
- principal component analysis (PCA).

The AERONET AOD is not provided at the specific wavelength of the SAM instrument of 670 nm. Therefore, the AERONET AOD at this specific wavelength was computed using the Ångström law (Ångström, 1964) as:

²⁰ $\tau_{\mathbf{a},\lambda} = b\lambda^{-a},$ $\ln(\tau_{\mathbf{a},\lambda}) = \ln(b) - a\ln(\lambda),$

where *b* is $\tau_{a,1000 \text{ nm}}$ and *a* is the Ångström parameter.

5130 pairs of coincident observations remain, for which the maximum difference in time stamp of both instruments is 1 min. To remove any further outliers between the two instruments, the reported accuracy (±0.03) of the SAM $\tau_{a,670\,\text{nm}}$ is accounted for (DeVore et al., 2012a), which is greater than the reported accuracy (±0.01 for $\lambda \ge 440\,\text{nm}$) for the AERONET $\tau_{a,\lambda}$ (Holben et al., 1998). Therefore, any coinciding SAM and AERONET $\tau_{a,670\,\text{nm}}$ which do not agree within ±0.03 of each other were



(8)

(9)



eliminated. 3723 pairs of observations were kept. This number is guite large: 73% of the observations agree in both instruments.

Figure 2 exhibits the density scatter plot of the 3723 pairs of SAM vs. AERONET AOD at 670 nm. The relative RMSE is 6% and the relative bias is +5% meaning that the

- ⁵ SAM $\tau_{a 670 \text{ pm}}$ is greater in average than the AERONET $\tau_{a 670 \text{ pm}}$. The R^2 value is high at 0.998. Even though AOD values exceed 0.8, the limits of the axes have been set to have a maximum value of 0.8 in order to better examine the regions with higher sample densities. The observed underestimation of the AERONET $\tau_{a.670 \text{ nm}}$ compared to SAM (cf. Fig. 2) is due to the field of view of the different instruments. Indeed, the AERONET
- Sun photometer has an aperture half-angle of 0.6°. This implies that the circumsolar 10 radiance from the edge of the solar disc up to a scattering angle of 0.6° is intercepted within the aperture of the Sun photometer, which would imply an underestimation in the AERONET AOD, because the measured irradiance is greater than that within the extent of the solar disc alone. On the contrary, due to the finer resolution of the SAM
- instrument the AOD is retrieved within the extent of the solar disc only (DeVore et al., 15 2012a). In other words, the CSNI at 0.6° has a significant effect on the AOD retrieval for AERONET.

For calibration purposes, the 3723 samples presented in Fig. 2 were randomly split into two subsets:

- 80% of the samples were used to correct the AERONET $\tau_{a,670\,\text{nm}}$ with respect to 20 the SAM reference values via a robust fit,
 - the remaining 20% of the samples were used to test the correction and assess the calibration errors.

It turns out that the LS, PCA and robust affine regressions of the fitting subset have very similar coefficients as those of Fig. 2. As per the robust affine regression of the 25 fitting subset, it is therefore proposed to correct the AERONET $\tau_{a.670}$ nm as:

 $\tau_{a,670 \text{ pm}}$ (corrected AERONET) = 0.992 $\tau_{a,670 \text{ pm}}$ (AERONET) + 0.016.

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Applying Eq. (10) on the testing samples and comparing with the reference SAM values, the relative bias of the corrected AERONET $\tau_{a,670 \text{ nm}}$ is 0%, the relative RMSE is 3% and the R^2 value is 0.998. The set of the 3723 samples does not cover the full twelve months: August 2012 is missing from the SAM measurements; no SAM and AERONET data coincide in May 2013; there are relatively lower numbers of coinciding samples for June 2012 (176 samples) and July 2012 (17 samples), while for the remaining eight months the number of samples varies from a minimum of 251 in December 2012 to a maximum of 804 in September 2012. No seasonal dependency is nevertheless observed with respect to the bias computed for each month (excluding

¹⁰ August 2012 and May 2013) from the testing data set; it ranges between ± 3 %. Therefore, it is assumed that this correction works well for the samples having different time stamps and the same wavelength over this location.

After running the quality check procedures on the SAM data, matching the SAM and AERONET data, and removing the outliers of the AOD from both instruments, two main data sets remain which are used in the remainder of this article:

data sets remain which are used in the remainder of this article:

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- i. data set 1, abbreviated in DS1, already used in Fig. 2 for the AOD comparison. It comprises 3723 observations of the SAM beam and circumsolar radiance measurements along with their corresponding AERONET $\tau_{a,\lambda}$ and total column content in water vapor, extracted from the DSA Level 2.0 product. DS1 is used in the following when modelling the monochromatic DNI_S with the RTMs;
- ii. data set 2, abbreviated in DS2, comprises 425 observations of the SAM beam and circumsolar radiance measurements along with their corresponding AERONET $\tau_{a,\lambda}$, total column content in water vapor, $P_{a,\lambda}(\xi)$ and g_{λ} , extracted from the Version 2 Inversion products in Level 2.0. A mean value of 0.954 for $\omega_{a,675 \text{ nm}}$ is used along with DS2. There is no data for August 2012 and May 2013 in DS2, only one observation exists for July 2012 and 17 for June 2012, whereas for the remaining eight months the number of samples varies from 22 in October 2012 to 94





in March 2013. DS2 is used when modelling the monochromatic CSNI with the RTMs.

Figure 3 displays the days of the study period which comprise coinciding SAM and AERONET observations. It illustrates the periods with data available in DS1 and DS2.

6 AERONET data in the parameterizations of the radiative transfer models

The AERONET parts of the two data sets are used as input to a RTM which in turn delivers the monochromatic DNI_S and CSNI which are compared against SAM measurements. Two different RTMs were used, libRadtran and SMARTS. The software libRadtran comprises a number of solvers for radiative transfer calculations in the atmosphere of the Earth (Mayer and Kylling, 2005). The most popular solver of the radiative transfer equation is DISORT (Discrete-Ordinate-Method Radiative Transfer, Stamnes et al., 1998, 2000), which according to Mayer et al. (2012) is "*probably the most versa-tile, well-tested and mostly used 1-D radiative transfer solver on this planet.*" It solves the radiative transfer equation in 1-D geometry assuming a plane-parallel atmosphere of DISORT is that it allows for the computation of the radiance at multiple viewing directions using one input file. In this work the libRadtran version 1.7 was used (Mayer et al., 2012), libRadtran version 2.0 *beta* is currently available (Mayer et al., 2014).

SMARTS is a physical model able to predict either the monochromatic or broadband direct, diffuse and global irradiances received on the surface of the Earth (Gueymard, 1995, 2001). It is also capable of simulating the irradiance that would be measured by a radiometer by defining the viewing angles of the radiometer.

Both SMARTS and libRadtran assume the solar disc is a point source, i.e. a Dirac function. Therefore, the monochromatic DNI_{S} is provided as a direct output by both RTMs.





In libRadtran the diffuse radiance is modelled at the viewing angles specified by the user. Therefore, in the cases of the libRadtran outputs and SAM measurements the monochromatic CSNI is computed by Eq. (5) in the interval [$\delta = 0.64^\circ$, $\alpha = 6^\circ$]. In SMARTS the monochromatic CSNI is an output of the model. Therefore, to compute the CSNI from SMARTS in this same interval the code is run twice, once to compute the CSNI up to 6° and once up to 0.64° and then the final CSNI is their difference. The parameterizations of the two RTMs are presented in the following sections.

6.1 libRadtran

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libRadtran offers the flexibility of a user-defined $P_{a,\lambda}(\xi)$. $P_{a,\lambda}(\xi)$ can be expressed as a series of Legendre polynomials:

$$p_0(x) = 1, \quad p_1(x) = \frac{1}{(2'/!)} \frac{d'}{dx'} (x^2 - 1)' \text{ for } l = 1, 2, ...,$$
 (11)

where p_l is the *l*'th Legendre polynomial as a function of *x* (Courant and Hilbert, 1953). One way is to use the pmom tool in libRadtran that computes the Legendre moments of the measured $P_{a,\lambda}(\xi)$ (Mayer et al., 2012). It takes hundreds of Legendre moments to describe $P_{a,\lambda}(\xi)$ with a sufficient accuracy, especially for small values of the scattering angle.

Practically, the simplest and most common representation of $P_{a,\lambda}(\xi)$ is the Henyey–Greenstein (HG) phase function, which is based on g_{λ} only (Henyey and Greenstein, 1941; Liou, 2002):

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$$P_{\text{HG}}(\xi,g) = (1-g^2)/(1+g^2-2g\cos(\xi))^{1.5}$$

where P_{HG} is the HG phase function and g is the asymmetry parameter – to be replaced with g_{λ} for monochromatic phase functions.

However, the HG phase function does not properly reproduce the scattering patterns which are strongly peaked in the forward direction (Liou, 2002). An accurate represen-





(12)

tation of the sharp peaks of $P_{a,\lambda}(\xi)$ is very important for an accurate estimate of the circumsolar diffuse monochromatic radiance.

Irvine (1965) and Kattawar (1975) proposed a Two Term HG (TTHG) phase function to better depict phase functions with sharp peaks. To the best of the knowledge of
 the authors, no articles have been found on the direct application of the TTHG phase function to model the circumsolar radiation under turbid cloud-free skies. The TTHG phase function is computed as (Haltrin, 2002; Kattawar, 1975):

$$P_{\text{TTHG}}(\xi, c_1, c_2, c_3) = c_1 P_{\text{HG}}(\xi, c_2) + (1 - c_1) P_{\text{HG}}(\xi, c_3),$$
(13)

where P_{TTHG} is the TTHG phase function and c_1 , c_2 and c_3 are three parameters describing P_{TTHG} . In this study each AERONET $P_{a,\lambda}(\xi)$ was used to fit the three parameters c_1 , c_2 and c_3 of Eq. (13) using the nonlinear least-squares Levenberg–Marquardt method (Marquardt, 1963).

Practically, the RTM libRadtran expects Legendre moments. Therefore, knowing the c_1 , c_2 and c_3 parameters, the TTHG phase function must be expanded as a series of Legendre polynomials as:

$$P_{\text{TTHG}}(\xi, c_1, c_2, c_3) = \sum_{\ell=0}^{\infty} (2\ell+1) \left(c_1 c_2^{\ell} + (1-c_1) c_3^{\ell} \right) p_{\ell}(\cos(\xi)), \tag{14}$$

where $(c_1c_2' + (1 - c_1)c_3')$ is the *l*'th Legendre moment and p_l is the *l*'th Legendre polynomial as a function of $\cos(\xi)$, to compute hundreds of Legendre moments before passing them on to libRadtran. Another possible solution, not tested here, is that in principle, one could run twice libRadtran to obtain $P_{\text{HG}}(\xi, c_2)$ and $P_{\text{HG}}(\xi, c_3)$ and then use Eq. (13).

The following were the specific inputs to libRadtran:

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- i. $\theta_{\rm S}$, computed by the SG2 algorithm of Blanc and Wald (2012);
- ii. $\lambda = 670$ nm, to compute the corresponding monochromatic radiance/irradiance;





- iii. $\tau_{a,670}$ nm, corrected as per Eq. (10);
- iv. the total column content in water vapor;
- v. $\omega_{a,675 \text{ nm}}$, only needed for radiance modelling;
- vi. the moments of the $P_{a.675 \text{ nm}}(\xi)$, only needed for radiance modelling;
- vii. the mid-latitude summer atmospheric profile from Anderson et al. (1986);
 - viii. the extraterrestrial spectrum, atlas_plus_modtran;
 - ix. the day of the year, i.e. 1 to 365 or 366 for a leap year, to correct for the Sun–Earth distance;
 - x. the altitude of the site above mean sea level;
- 10 xi. the altitude of the sensor above ground level;
 - xii. the sky element zenith angle θ ;

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- xiii. the sky element azimuth angle φ ;
- xiv. the radiative transfer equation solver, DISORT;
- xv. default value of 16 for the number of streams to be used in DISORT. An increase in the number of streams, 32 was tested, causes significantly longer computational timings with no effects on the results.

In libRadtran if the asymmetry parameter $g_{675 \text{ nm}}$ is defined instead of the moments of $P_{a,675 \text{ nm}}(\xi)$, then a HG phase function is assumed. When $\omega_{a,675 \text{ nm}}$ and $P_{a,675 \text{ nm}}(\xi)$ are both not available as inputs, another option is to define the aerosol type and retrieve their corresponding typical values from the OPAC (Optical Properties of Aerosols and Clouds) library (Hess et al., 1998; Mayer and Kylling, 2005).



6.2 SMARTS

In the RTM SMARTS, the inputs are extracted from 17 "cards" defined by the user (Gueymard, 2006). Several cards are not related to the context of this work, while others were kept at their default values. The relevant "cards" are:

- 5 i. ISPR: the pressure at the site, defined by the latitude, the altitude of the site above mean sea level and the altitude of the sensor above ground level;
 - ii. IATMOS: the atmospheric profile, chosen as mid-latitude summer;
 - iii. IH20: the total column content in water vapor;

iv. qCO_2 : the concentration of carbon dioxide, the default value was selected.

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- ISPCTR: the extraterrestrial spectrum, selected as MODTRAN (Spctrm_4.dat which is the one closest to that used in libRadtran);
- v. AEROS: the aerosol model. Once it was selected as "DESERT_MAX" and once it was user-defined as:
 - ALPHA1 (Ångström wavelength exponent for wavelength less than 500 nm), ALPHA2 (Ångström wavelength exponent for wavelength greater than 500 nm), OMEGAL (the aerosol single scattering albedo), and GG (the asymmetry parameter);
- vi. ITURB: turbidity data. Selected as $\tau_{a,550 \text{ nm}}$, and corrected as per Eq. (10);
- vii. WLMN, WLMX, SUNCOR, SOLARC: for the broadband irradiance they respectively correspond to the minimum wavelength, the maximum wavelength, the Sun– Earth distance correction, and the solar constant;
- viii. IPRT: to print broadband and monochromatic results to the output file.





- WPMX, WPMX, INTVL: minimum wavelength for monochromatic irradiance (set to 670 nm), maximum wavelength for monochromatic irradiance (also set to 670 nm), interval (set to an arbitrary value of 1 nm, since only one wavelength was specified);
- 5 ix. ICIRC: option to compute the circumsolar irradiance.
 - SLOPE, APERT, LIMIT: slope angle of the instrument (set to 0 in SMARTS if unavailable), aperture half-angle α of the instrument, limit angle ε_{L} of the instrument (set to 0 in SMARTS if unavailable);
 - x. IMASS: solar position and air mass m:

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– ZENIT, AZIM: respectively $\theta_{\rm S}$ and the solar azimuth angle $\varphi_{\rm S}$.

Even though SMARTS requires the broadband asymmetry parameter and the broadband aerosol single scattering albedo, such broadband values were not available. Therefore, $g_{675\,\text{nm}}$ and the mean value of $\omega_{a,675\,\text{nm}}$ were used instead. Also, it is not possible to specify $P_{a,\lambda}(\xi)$ in the SMARTS version 2.9.5 which is automatically selected from tables when selecting the aerosol model.

7 Results and discussion

The results of the modelled DNI_S at 670 nm of data set DS1 are presented in Table 1. Both RTMs exhibit a relative RMSE of 5 % and a relative bias of +1 %. The R^2 is 0.972 for libRadtran and 0.974 for SMARTS. The scatter density plots are exhibited in Figs. 4 (libRadtran) and 5 (SMARTS). The same atmospheric profile (mid-latitude summer) was defined in both RTMs. The very minor difference in the bias between both models may be due to the scaling of $\tau_{a,670\,\text{nm}}$ in the SMARTS model, since $\tau_{a,550\,\text{nm}}$ was provided as an input. Another cause in the difference in the bias is that the correction applied to $\tau_{a,550\,\text{nm}}$ in SMARTS was based on the analysis of $\tau_{a,670\,\text{nm}}$ (Eq. 10). This affine





correction has not been validated for wavelengths other than 670 nm. Other sources of errors may be a miscalibration of the AERONET Sun photometer, or misalignments in the tracking mechanism of the Sun photometer (Dubovik et al., 2000).

- Although there is no observable pattern in the monthly bias, the relative bias is largest during December 2012 (+4% from libRadtran and +5% from SMARTS) and January 2013 (+6% from both RTMs) and smallest during November 2012 (-4% from both RTMs). One hypothesis for this bias is the choice of the atmospheric profile. However, this is disproved as there is a negligible change in the results if the mid-latitude winter profile is defined instead of the mid-latitude summer profile for these months.
- ¹⁰ As there is a disagreement in the sign of the bias for these three consecutive months, no conclusion is drawn with regards to the cause of this bias. The relative bias for the remaining months (excluding August 2012 and May 2013) ranges between ± 3 %. For the overall data set, it may be concluded that both models provide very accurate estimates of the monochromatic DNI_S, where the accuracy of the SAM instrument in the solar disc region is 1 % for $\tau_{a 670 \, \text{nm}} < 0.6$.

The modelling of the CSNI at 670 nm of data set DS2 in the interval [$\delta = 0.64^{\circ}$, $\alpha = 6^{\circ}$] is very strongly dependent on the defined aerosol optical properties. The differences in the results by applying different inputs to the RTMs are summarized in Table 2.

There are several problems concerning a fair comparison of the results of libRadtran and SMARTS. One is that SMARTS does not give the flexibility to input $\tau_{a,\lambda}$ at a user-defined wavelength. The only two options available are either at 500 or 550 nm (although compensated for by the ALPHA parameter), whereas this flexibility is available in libRadtran. Also, SMARTS, at least the publicly available version, does not offer the flexibility of a user-defined $P_{a,\lambda}(\xi)$, while that option is available in libRadtran with the Legendre's moments.

It is clear from the results that the HG phase function is a very bad representation of $P_{a,\lambda}(\xi)$ and its use is not recommended when modelling the CSNI, in a desert environment at least. Even though R^2 is not too low, 0.721 for libRadtran and 0.694 for



SMARTS, a very large negative relative bias is observed in both RTMs when the HG phase function is used.

In the case when using the aerosol models of the predefined libraries available in the RTMs, the bias significantly improves when compared to using the HG phase function ⁵ but still remains negative. However, *R*² becomes lower. When selecting the desert type aerosol of the OPAC library in libRadtran the relative RMSE is 40%, the relative bias is -34% and *R*² is 0.717. Selecting the "DESERT_MAX" aerosol type in SMARTS the relative RMSE is 54%, the relative bias is -39% and *R*² is 0.570. The errors are still high though, and neither the "DESERT_MAX" aerosol model in SMARTS nor the desert type aerosol of the OPAC library in libRadtran provide accurate results of the monochromatic CSNI under cloud-free conditions over the study area.

All statistical indicators show a very significant improvement when using the TTHG phase function determined from the AERONET measurements. The scatter density plot for this case is exhibited in Fig. 6. The relative RMSE is 22%, the relative bias is 10% and P^2 is 0.801. The underestimation is payortheless still per period.

- is -19% and R^2 is 0.891. The underestimation is nevertheless still non-negligible. This bias may partly originate from the phase function $P_{a,675 nm}(\xi)$ used as input. The aperture half-angle of the Sun photometer used in the AERONET stations is 0.6°, which is relatively large considering that the angular radius of the solar disc is 0.266° ± 1.7%, and that the circumsolar region in this context is defined up to 6°. In fact, for $\xi < 6°$ the
- ²⁰ AERONET $P_{a,675 \text{ nm}}(\xi)$ is only provided at three ξ : 0; 1.71; and 3.93°. In addition, for the study area, $P_{a,675 \text{ nm}}(\xi)$ at the first two ξ are actually extrapolated values, because the almucantar radiance measurements were only collected for $\xi \ge 3^\circ$. This is a limitation of using the AERONET $P_{a,675 \text{ nm}}(\xi)$.

It is observed that there is a larger underestimation in the months of October (-31 %), November (-33 %) and December 2012 (-27 %) when compared to the remaining months which have a bias ranging from -20 to -14 % (excluding July 2012 which only has 1 observation, August 2012, and May 2013). The residuals of the libRadtran and SAM monochromatic CSNI vs. the AERONET $P_{a,675 nm}(\xi = 0^{\circ})$ are exhibited in Fig. 7. Although the number of samples is relatively low for the AERONET $P_{a,675 nm}(\xi = 0^{\circ})$



with the sharpest peaks, it is evident that the underestimation is greater in the negative direction for the AERONET $P_{a,675 \text{ nm}}(\xi = 0^{\circ})$ with the sharpest peaks. This observation supports the hypothesis that the AERONET $P_{a,675 \text{ nm}}(\xi)$ might not be very accurate for the smallest scattering angles, especially for those with the sharpest peaks. It is also evident in Fig. 7 that the larger underestimation of October and December 2012 is due to the underestimation in the libRadtran monochromatic CSNI for the $P_{a,675 \text{ nm}}$ with the sharper peaks. However, the same cannot be said for November 2012, because $P_{a,675 \text{ nm}}(\xi = 0^{\circ})$ have relatively moderate values but the modelled libRadtran monochromatic CSNI generally exhibit a larger underestimation than other samples with similar values of $P_{a,675 \text{ nm}}(\xi = 0^{\circ})$. By observing the shapes of the $P_{a,675 \text{ nm}}(\xi)$, the correction of the AERONET $\tau_{a,670 \text{ nm}}$ with respect to the SAM $\tau_{a,670 \text{ nm}}$, and the histogram of the corrected of the AERONET $\tau_{a,670 \text{ nm}}$, nothing seems odd for November 2012. Therefore, no reason is proposed to explain the bias for this month.

Another source of error may be that in the AERONET Version 2 Inversion prod-¹⁵ ucts, including $P_{a,675 \text{ nm}}(\xi)$ and $\omega_{a,675 \text{ nm}}$, the aerosol particle shapes are assumed to be composed of spheres (Dubovik and King, 2000) and spheroids (Dubovik et al., 2002). However, in reality, dust particles have a variety of shapes, not necessarily spheroids, and this may affect the accuracy of the retrieved AERONET aerosol optical properties (Dubovik et al., 2006; Kahnert and Nousiainen, 2006). Nevertheless, given the accu-²⁰ racy of the SAM instrument in the aureole region to be ~15%, it is concluded that defining the moments of the TTHG PFCN in libRadtran provides an overall remarkably accurate and interesting estimates of the monochromatic CSNI under cloud-free conditions over the study area.

8 Conclusions

²⁵ The work presented here demonstrates that the AERONET data may very well be used to accurately model the monochromatic beam and circumsolar irradiances under cloud-free conditions in desert environment with a certain degree of accuracy.





In modelling the DNI_S at 670 nm using the corrected AERONET AOD as input to the RTMs, both libRadtran (using $\tau_{a,670 \text{ nm}}$) and SMARTS (using $\tau_{a,550 \text{ nm}}$) provide very similar results. The relative RMSE is 5%, relative bias is +1% and $R^2 \ge 0.972$. For modelling the CSNI at 670 nm in the interval [$\delta = 0.64^\circ$, $\alpha = 6^\circ$] five different configurations of inputs have been tested, two using SMARTS and three using libRadtran. Of the tested configurations, the most accurate is that using libRadtran when defining the corrected AERONET monochromatic AOD $\tau_{a,670 \text{ nm}}$, the mean value of the single scattering albedo $\omega_{a,675 \text{ nm}}$ and the aerosol phase function $P_{a,675 \text{ nm}}(\xi)$ as a 3-parameter TTHG phase function. In this case, the relative RMSE is 22%, relative bias is -19% and R^2 is 0.891. It is believed that a better representation of the aerosol phase function $P_{a,675 \text{ nm}}(\xi)$ for the smallest ξ than the one provided by AERONET would further improve the modelling results of the CSNI. The results are still significantly better than

that obtained when representing $P_{a,675 \text{ nm}}(\xi)$ as a HG phase function or when using the libraries of aerosol optical properties available in both libRadtran and SMARTS. It is

therefore not recommended to use such parameterizations when modelling the CSNI

In the work leading up to these results several other procedures have been proposed.

Firstly, the work exploits measurements made by the SAM instrument. It is fairly new

and no well-established procedure has been published to check the quality of the mea-

surements. This article presents several tests that may contribute to a well-accepted

guality control procedure. Secondly, the work exploits measurements made by a Sun

photometer from the AERONET network. For an accurate modelling of monochromatic DNI_S the monochromatic AOD should be retrieved within the extent of the solar disc only. However, this is not the case with the AERONET monochromatic AOD because

the aperture half-angle of the Sun photometer is 0.6°. The CSNI for this half-aperture

angle induces a significant underestimation of the AOD retrieved by AERONET. Therefore, a correction to the AERONET AOD at 670 nm has been proposed based on SAM

AOD used as reference values. Applying this correction on the testing set reveals a relative RMSE of 3 %, a relative bias of 0 % and R^2 of 0.998. The validity of this correction

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in a desert environment.





for other cases has yet to be studied. Thirdly, modelling the AERONET phase function $P_{a,\lambda}(\xi)$ as a TTHG phase function to compute the CSNI under cloud-free conditions is proposed. This representation has the advantage of accurately reproducing the sharp peaks of $P_{a,\lambda}(\xi)$ for the smallest ξ , whilst being represented by only three parameters.

⁵ This opens up the path for a model to be developed to estimate the three parameters of the phase function, rather than estimating the hundreds of Legendre moments required to accurately represent the phase function.

The next step is to apply this approach to model the broadband DNI_S and CSNI. This would directly contribute to the recommendation of Blanc et al. (2014) to report the sunshape and circumsolar contribution with the standard DNI measurements.

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Discussion

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Paper

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Discussion Paper

Can AERONET data be used to model the monochromatic beam and circumsolar irradiances?

Y. Eissa et al.



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Table 1. Results of libRadtran and SMARTS of data set DS1 for the modelling of the monochromatic ${\sf DNI}_{\sf S}$ at 670 nm.

RTM	Aerosol optical	Mean	Bias		RMSE		R^2
	properties	$W m^{-2} \mu m^{-1}$	$W m^{-2} \mu m^{-1}$	%	$W m^{-2} \mu m^{-1}$	%	
libRadtran	$ au_{ m a,670nm}$	863.9	+4.6	+1	46.9	5	0.972
SMARTS	$ au_{ m a,550nm}$	863.9	+8.5	+1	46.7	5	0.974

Table 2. Results of libRadtran and SMARTS of data set DS2 for the modelling of the monochro
matic CSNI at 670 nm.

RTM	Aerosol optical properties	Mean Wm ⁻² µm ⁻¹	Bias Wm ⁻² µm ⁻¹	%	$\frac{\text{RMSE}}{\text{W}\text{m}^{-2}\mu\text{m}^{-1}}$	%	R^2
libRadtran	$ au_{a,670 \text{ nm}}$; mean $\omega_{a,675 \text{ nm}}$; HG phase function: $g_{675 \text{ nm}}$	84.3	-63.8	-76	68.2	81	0.721
SMARTS	$ au_{ m a,550nm};$ mean $\omega_{ m a,675nm};$ $g_{ m 675nm}$	84.3	-61.6	-73	66.6	79	0.694
libRadtran	$ au_{ m a,670nm}$; OPAC desert type aerosol	84.3	-28.3	-34	33.9	40	0.717
SMARTS	τ _{a,550 nm} ; "DESERT_MAX" aerosol model	84.3	-39.0	-46	45.5	54	0.570
libRadtran	$\tau_{a,670 \text{ nm}}$; mean $\omega_{a,675 \text{ nm}}$; TTHG phase function	84.3	-15.7	-19	18.8	22	0.891



Discussion Paper



Figure 1. Scatter density plot between the SAM $L_{670 \text{ nm}}$ and AERONET $L_{675 \text{ nm}}$ measurements.







Figure 2. Scatter density plot between the SAM and AERONET $\tau_{a,670 \text{ nm}}$ after accounting for the accuracy of the SAM retrievals. The axes are limited to 0.8 for a better view.















Figure 4. Scatter density plot of the libRadtran DNI_{S} at 670 nm (libRadtran $B_{n,670 \text{ nm}}^{\text{Sun}}$) vs. the reference values from the SAM instrument (SAM $B_{n,670 \text{ nm}}^{\text{Sun}}$).

















Figure 7. Residuals (libRadtran CSNI at 670 nm modelled by defining the TTHG phase function minus the SAM reference CSNI at 670 nm) vs. the AERONET aerosol phase function at a scattering angle of 0° (AERONET $P_{a,675 \text{ nm}}(\xi = 0^\circ)$).



