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Sunbelt Spectra Comparison with Standard ASTM G173: the Chilean Case

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Abstract. Two spectra of solar direct normal irradiance (including circumsolar) are estimated based on spatio-temporal averages of the relevant atmospheric parameters extracted from two different databases: MODIS satellite sensor retrievals and AERONET sun photometer network. The satellite database is used to calculate an average spectrum for the area of the Atacama Desert. The AERONET database is used for two purposes: (i) to apply bias-removal linear methods to correct the MODIS parameters over Atacama Desert, and (ii) to calculate an average local spectrum for the Paranal station. The SMARTS radiative transfer model is used to obtain the three representative spectra developed in this study. Both the Atacama Desert and Paranal spectra are compared against each other and also to the world reference, ASTM G173. In one of the cases, significant differences are found for short wavelengths. In order to quantify the relative importance of these spectral differences, the propagation of errors due to the use of each spectrum is evaluated for CSP applications over the Atacama Desert, considering twelve different scenarios involving the reflectance, transmittance or absorptance of various materials.

INTRODUCTION

Under clear-sky conditions, the solar spectrum strongly varies over space and time—daily and seasonally. On one hand, the shape (or spectral distribution) of the spectrum depends on the atmospheric conditions that prevail at the specific moment and location. These conditions are defined mainly by the total ozone column (TOC), precipitable water (PW), aerosol optical depth (AOD) at various wavelengths, surface pressure, and reflectance from the ground (albedo). On the other hand, the radiation path length through the atmosphere, or air mass (*M*), is another important factor, which magnifies the effects of each above-mentioned variable.

Taking into account the influence of each parameter separately, the direct normal irradiance (DNI) received at ground level at wavelength, λ, may be described as:

$$DNI_\lambda = E_{0n\lambda} T_{1\lambda} T_{2\lambda} \dots T_{n\lambda} \tag{1}$$

where $E_{0n\lambda}$ is the extraterrestrial irradiance and $T_{n\lambda}$ is the atmospheric transmittance due to the *n*th considered extinction process. For most extinction processes, $T_{n\lambda}$ can be determined from the Bouguer-Lambert-Beer law:

$$T_{n\lambda} = e^{-M_n \tau_{n\lambda}} \tag{2}$$

where M_n is the optical mass of extinction process *n*, and $\tau_{n\lambda}$ is its spectral optical thickness.

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Information about the spectral distribution of the incident irradiance is essential for the design and study of numerous technologies based on the use of the solar resource. In spite of this, there is not enough information about the spectral irradiance for most regions that have the highest potential for CSP deployment, mainly due to the high costs of installing specialized instrumentation, including their operation and maintenance.

Many research centers use the ASTM G173 reference spectrum to obtain useful information for a variety of solar energy applications. However, the current G173 standard was created by ASTM (http://www.astm.org/) based on North American geographic and atmospheric conditions [1]. Therefore, taking into account the variability of the climatic conditions over the Sunbelt region—which is well illustrated by the Köppen-Geiger climatic map [2,3]—it is clear that the standard spectrum may not be appropriate under all conditions, so that additional spectra based on local climatic conditions would be very useful. More specifically, using a unique standard spectrum for the evaluation of solar technologies behavior under a variety of atmospheric conditions can be a source of error since these spectra typically differ substantially. This issue was demonstrated in previous studies [4–6]. This concern has led the solar industry to become increasingly interested in how the spectral distribution of the incident spectrum could vary with geography, topography or climate.

Over the Atacama Desert, the atmospheric and environmental conditions are particular and differ substantially from what is usually found in other regions, and particularly the northern hemisphere. This is conducive to altered spectral distributions relative to the G173 standard. The key factors that may induce differences in spectrum are the high mean elevation (hence low pressure), a large number of days with very clear conditions (low AOD), and low absorption due to the reduced ozone and water vapour columns [7]. This is why this area benefits from the world's highest solar resource. It has been determined that the Direct Normal Irradiation (DNI) can reach more than 9 kWh/m^2 per day on average, resulting in more than 3300 kWh/m^2 per year [8].

In this context, the present contribution attempts to evaluate the limitations of relying on a unique (standard) DNI spectrum, which may not represent the typical conditions of the Atacama Desert, or even of Chile, to evaluate various optical properties in solar applications. A few local spectra are derived from the available information in Chile by using appropriate atmospheric radiative transfer models. These results are then compared to the ASTM G173 reference spectra of DNI in order to gather useful information on the impact of using G173 rather than a local solar spectrum on various solar energy applications, particularly CSP.

METHODOLOGY AND DATA

The most accurate information on the key atmospheric constituents that attenuate the solar spectrum can be extracted from the AERONET database [9]. AERONET is a worldwide sun photometer network that provides high-quality data of AOD, various other aerosol optical properties, and precipitable water (PW) at a few hundred sites. In the case of Chile, only a few AERONET stations are operational. Among them, Arica has the longest record (14.8 years as of this writing). Besides Arica, the limited experimental data on aerosols and water vapor available in the region makes the use of satellite retrievals like MODIS (Moderate Resolution Imaging Spectroradiometer) particularly attractive. However, the spatial resolution of daily-average MODIS Coll. 6 data (1°x1°) appears quite low considering the rapid variations in elevation over Chile and the steep decrease in AOD and PW with elevation, see Fig. 1 [7]. Moreover, the MODIS retrieval algorithms are known to introduce errors over arid areas or when the ground albedo is high. These facts can explain the large discrepancies that are found here between the values of AOD and PW retrieved by MODIS and those measured by the AERONET stations in the area: Paranal_CTA, Paposo, Crucero and Arica (Fig. 2, left columns).

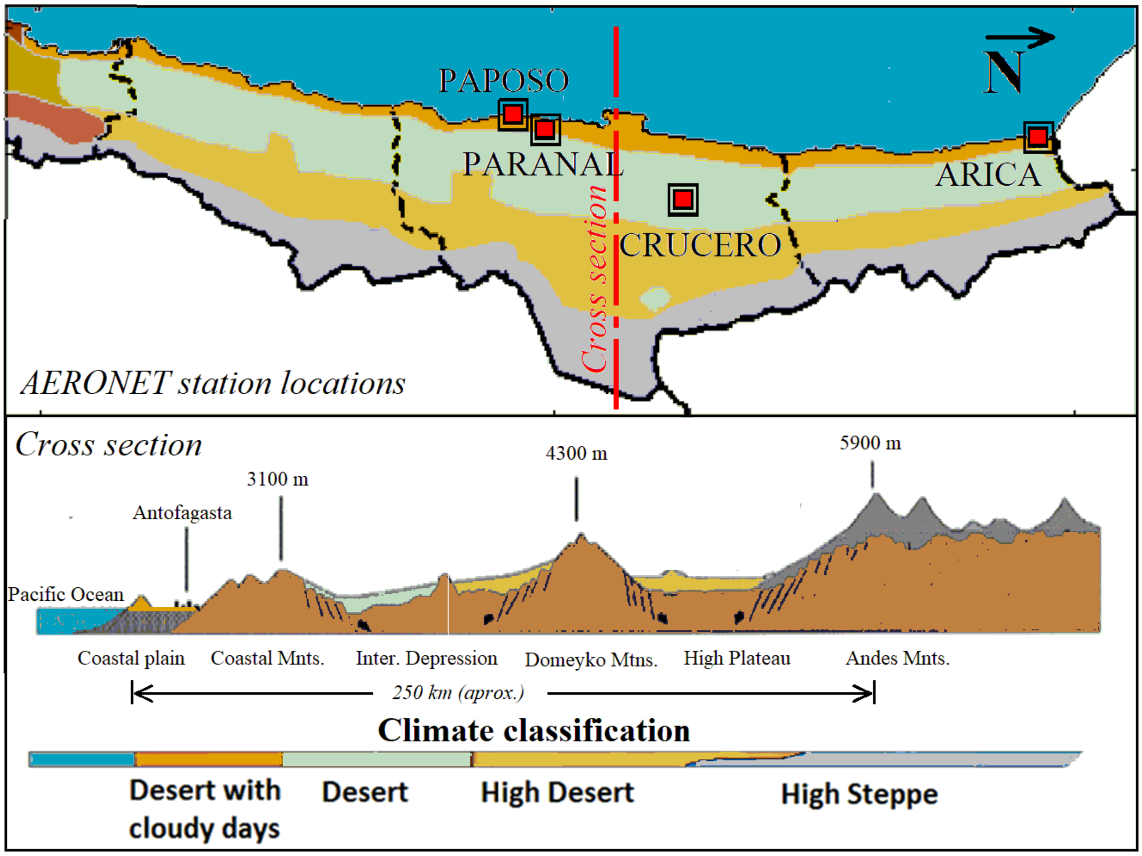

FIGURE 1. Upper figure: Approximate locations of the AERONET station in northern Chile, with colours representing different types of climate. Lower figure: Cross-section of the desert region in Antofagasta, Chile, and climate classification as defined in [10].

Bias-removal linear methods can be applied to correct the gridded MODIS AOD and PW data using ground observations from AERONET stations, with the goal to perform a "site adaptation", similar to what is done for solar irradiance [11]. The difference here is that the cell size (≈100 km) of the gridded MODIS data is much larger than that (≈3–4 km) of gridded irradiance products derived from geostationary satellite sensors, while the decrease of AOD and PW with elevation is much steeper than the change of irradiance with elevation. Hence, the AOD and PW data of the grid cell containing the ground station must first be corrected with the scale-height technique, which accounts for the difference between the station's elevation and the cell's mean elevation [12]. For simplification, a uniform scale height of 2.1 km is used here for both AOD and PW.

Daily AOD and PW data provided by a MODIS Atmosphere Daily Global Product (MOD08_D3_6) were used in this study (URL to Reproduce Results: [13]). The bias correction for the MODIS AOD and PW retrievals is extended to the whole region of Northern Chile. Figure 2 also shows scatter plots of MODIS vs. AERONET for both AOD and PW after this correction. Although satellite retrievals provide considerably more spatial coverage than ground-based stations, it is obvious from Fig. 2 that the latter are still necessary to calibrate the former.

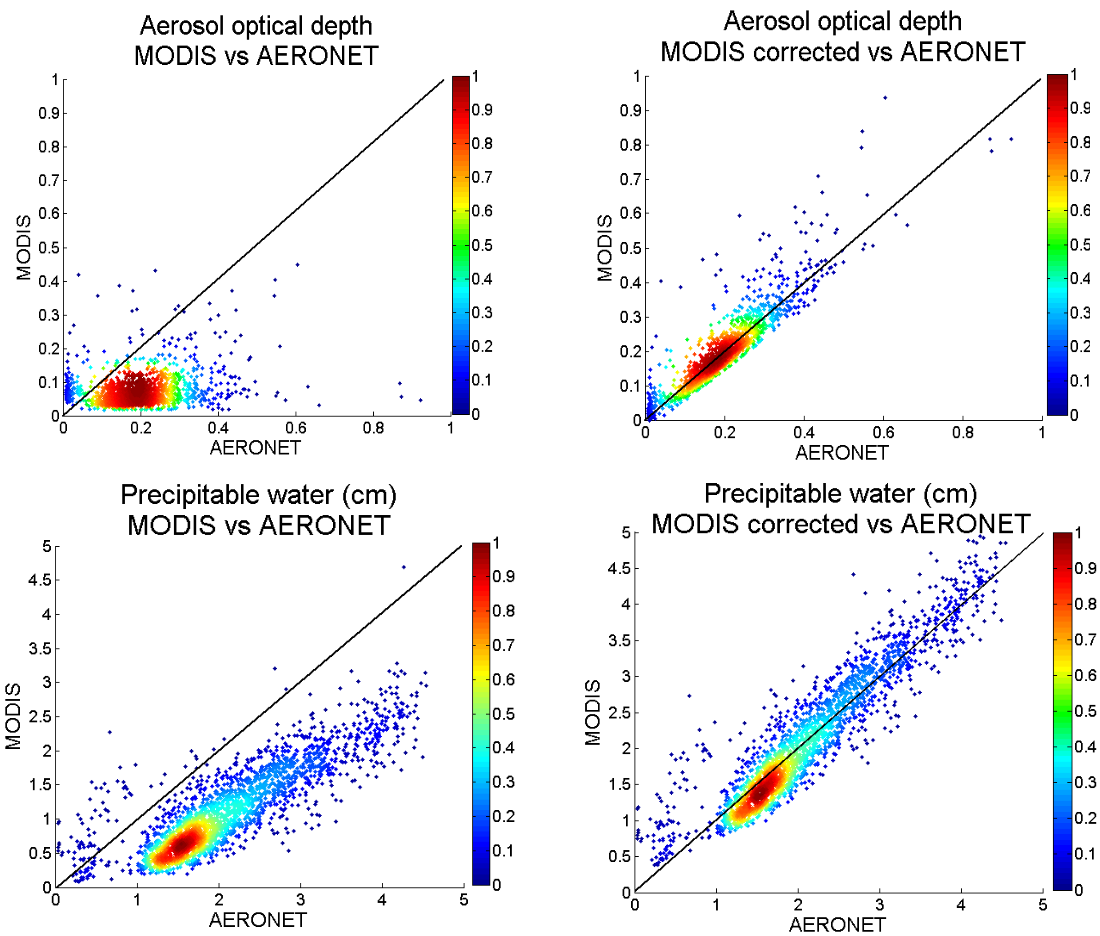

FIGURE 2. Left column: Scatter plots between the original MODIS AOD and PW data and the corresponding AERONET data. Right column: Scatter plots between the corrected ("site adapted") MODIS original AOD and PW data and the corresponding data. The considered AERONET stations are Paranal_CTA, Paposo, Crucero and Arica. Color bars display the relative data densities.

Based on the discussion above, it appears important to evaluate how appropriate the MODIS database can be for the determination of mean values of atmospheric data over the Atacama Desert area. In this respect, two sets of such mean values are calculated in different ways. First, averages of the corrected values of PW and AOD are obtained from MODIS for the Atacama Desert area. Second, local mean values of the same are obtained from the ground-based measurements at the Paranal AERONET station. Both sets are alternatively used as inputs to the SMARTS radiative transfer model, as discussed below. Table 1 presents the average values determined in both cases. Even though the elevations are similar, and Paranal is part of the Atacama Desert, there are significant differences in the AOD and PW values obtained with the two methods, probably related to the low spatial resolution of MODIS and the rapid variations in elevation mentioned above (see Fig.1).

The SMARTS radiative transfer model, v2.9.5 [14,15] is used here to estimate the DNI spectra, including the circumsolar contribution (very low in the present case, i.e. much less than 1%). This is carried out for both Atacama Desert and Paranal using the values in Table 1 as inputs. Note that the ASTM G173 standard has been obtained with SMARTS, which has become an industry standard for solar spectral irradiance computations, based on its ease of use and accuracy [16].

TABLE 1. Main input parameters to the SMARTS model for Paranal and Atacama Desert. The data used for the average calculations at Paranal were recorded at that AERONET station from November 2015 to September 2016. The Atacama Desert-average values are computed from the MODIS daily estimates over the period 2006–2015.

Variable	Paranal (AERONET)	Atacama Desert average (corrected MODIS)
Pressure	780.7 hPa	795.4 hPa
Precipitable Water	0.53 cm	1.7 cm
AOD at 550 nm	0.0145	0.163
Ångström exponent	1.1646	1.2915
Ozone	0.257 atm-cm	0.257 atm-cm
Albedo	0.18	0.18
Air mass	1.5	1.5
Elevation	2154 m	2000 m

RESULTS

Figure 3 shows the DNI spectra obtained for Paranal and Atacama Desert in comparison with the G173 standard. All spectra are normalized to the integral value of the DNI standard, namely 900 W m^{-2}. Larger differences are observed in the Paranal spectrum. It is higher in the ultraviolet region and smaller in the visible and near-infrared bands, mainly due to the differences in the AOD values: 0.017 for Paranal vs. 0.084 for G173, both at the reference wavelength of 550 nm. In addition, the irradiance in water vapor absorption bands (e.g. around 940 nm or 1120 nm) show differences due to differing PW input values (1.42 cm for the standard vs. 0.53 cm in Paranal). In the case of Atacama Desert, the spectrum resulting from the values in Table 1 is closer to the standard.

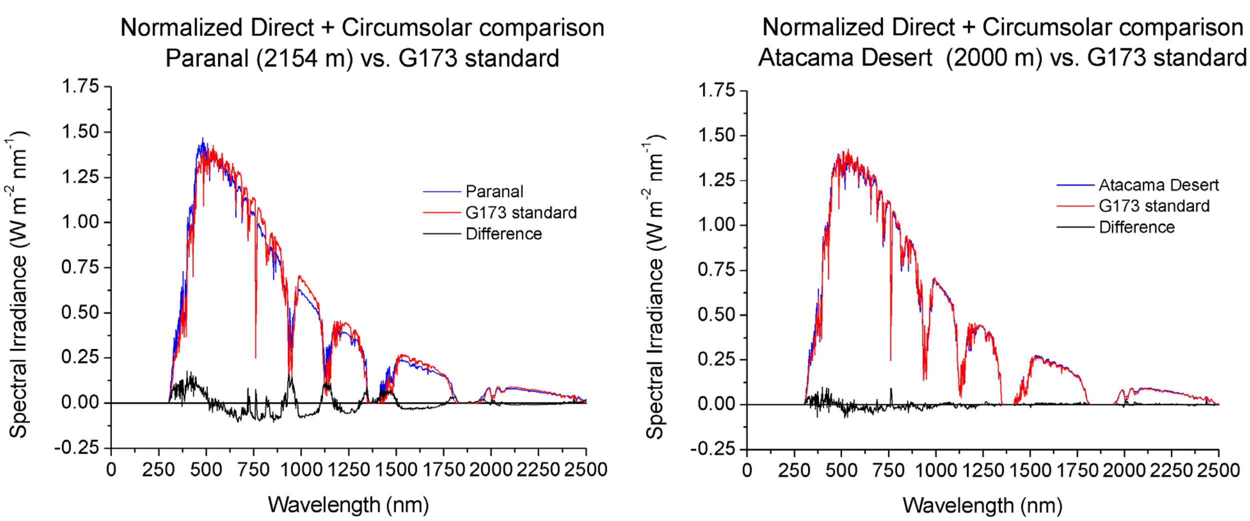

FIGURE 3. Direct normal spectra estimated for Paranal and Atacama Desert, and their departure from the G173 standard.

Figure 4 shows a comparison of the absolute (non-normalized) spectra obtained for Paranal (using average local ground measurements) and Atacama Desert (wide-area satellite-based average). The difference between the two spectra is striking, due to the differences in the AOD and PW inputs noted above. The spectral distributions are particularly different at shorter wavelengths (due to AOD disagreement) and in water vapour absorption bands (due to PW disagreement). In terms of broadband irradiance calculated over the 280–2500 nm spectral range, the estimated DNI at Paranal is 1.24 times greater than for Atacama Desert.

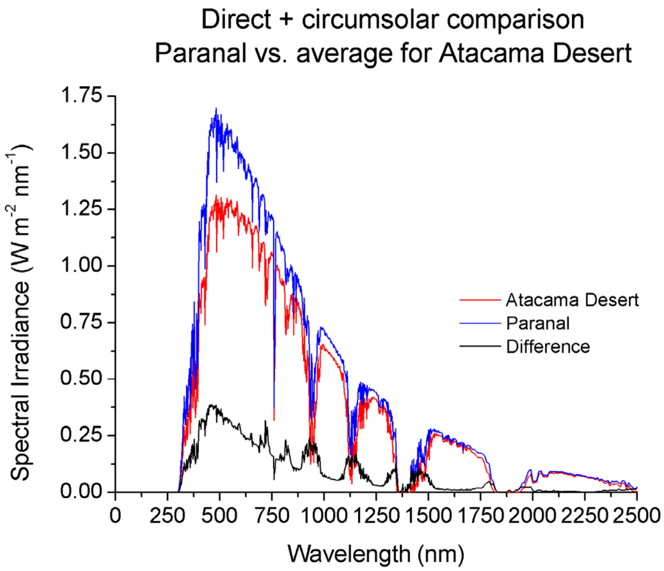

FIGURE 4. Comparison of the direct normal irradiance spectra obtained for Atacama Desert and Paranal.

This result highlights the difficulty of estimating an average DNI spectrum from MODIS data over the Atacama Desert. Northern Chile presents strong morphological features over short distances (400 km at the widest point). These morphological features correspond to five forms of relief with very well-defined climatic characteristics, namely coastal plain, coastal mountain range, intermediate depression, high plateau, and the Andes mountains, see Fig. 1 [10]. The lack of ground measurements of atmospheric aerosols and water vapour outside the coastal zone, and the coarse resolution of the gridded daily MODIS data, which requires topographic and bias corrections, make it difficult to estimate representative averages of the atmospheric inputs that are necessary to derive a reference DNI spectrum for the area.

All CSP technologies use solar collectors to concentrate the incident solar radiation onto a receiver, which sometimes is insulated from the external atmosphere by a transparent cover. The spectral dependence of the system to produce process heat is related to the convolution of the optical properties of all these surfaces with the incident spectrum. The absorbed energy, Q, is estimated here in a simplified manner as follows:

$$Q = \int_0^\infty DNI_\lambda \, R_{m\lambda} \, T_{w\lambda} \, A_{r\lambda} \, d\lambda \tag{3}$$

where $R_{m\lambda}$ is the spectral reflectance of the mirror, $T_{w\lambda}$ is the spectral transmittance of the transparent cover, and $A_{r\lambda}$ is the spectral absorptance of the receiver. Different scenarios are considered here in order to evaluate how much differences in calculated spectral irradiance may affect optical calculations in CSP studies. Four different mirror technologies, three types of quartz cover, and two different normalized DNI spectra are combined to produce 24 different scenarios. A double-layer coating absorber is considered in all calculations. The optical properties of the surfaces are plotted in Fig. 5.

Finally, a relative difference, ΔQ_i, is calculated for each scenario i by comparing it with the corresponding reference value based on the G173 standard. The results in Table 2 show that the resulting error in Q derived from the use of the G173 reference spectrum in the Atacama Desert is less than 0.6% for a typical CSP system (Flagsol mirror with quartz envelope tube). For more selective systems that are used less frequently, the error in Q can reach 1.1%. Additionally, the deviation between the MODIS-derived spectrum and the spectrum derived with the Paranal data reaches 0.5%. Therefore, it can be concluded that the use of site-specific spectra for CSP studies in the Atacama Desert has only a low impact on the yield analysis, and that it cannot reduce the uncertainty in the calculations significantly. The low impact of the changing spectrum on bulk optical properties is explainable by the fact that the materials selected here have only limited spectral selectivity. Adding processes that are more spectrally selective (such as photovoltaic cells in hybrid CSP-PV plants or special UV absorbers in water purification systems) would make the use of a "site-adapted" spectrum more important.

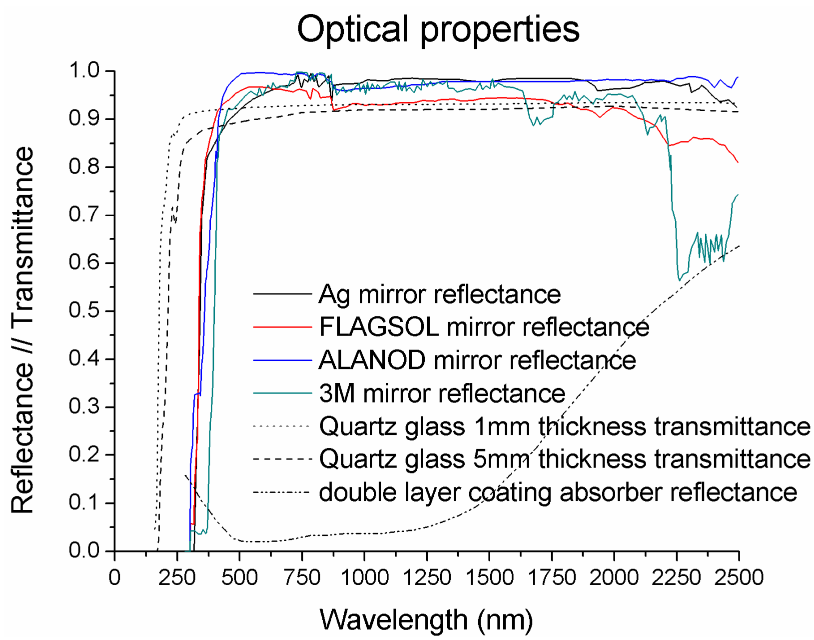

FIGURE 5. Reflectance of different mirrors used in CSP technologies [17], transmittance of quartz windows with 1-mm or 5-mm thickness, and reflectance of an absorber with double-layer coating (SS // Cu-Co-Mn-O // Si-O) [18].

TABLE 2. Relative error, ΔQ_i, for an absorber with double-layer coating (SS // Cu-Co-Mn-O // Si-O).

	Scenario	Atacama Desert at 2000 m	Paranal
i.	Ag mirror - No Window	0.323%	0.625%
ii.	Ag mirror - 1mm quartz window	0.324%	0.639%
iii.	Ag mirror - 5mm quartz window	0.327%	0.671%
iv.	FLAGSOL mirror - No Window	0.313%	0.496%
v.	FLAGSOL mirror - 1mm quartz window	0.314%	0.510%
vi.	FLAGSOL mirror - 5mm quartz window	0.317%	0.543%
vii.	ALANOD mirror - No Window	0.346%	0.666%
viii.	ALANOD mirror - 1mm quartz window	0.347%	0.679%
ix.	ALANOD mirror - 5mm quartz window	0.349%	0.709%
x.	3M mirror - No Window	0.455%	1.012%
xi.	3M mirror - 1mm quartz window	0.455%	1.022%
xii.	3M mirror - 5mm quartz window	0.456%	1.044%

CONCLUSIONS

Two optimized spectra of direct normal irradiance have been obtained with SMARTS, using spatio-temporal averages of atmospheric data from two databases (MODIS and AERONET) as inputs. In a preliminary step, bias-removal linear methods have been applied to correct the MODIS aerosol optical depth (AOD) and precipitable water (PW) according to ground measurements of the same at a few AERONET stations. Data from MODIS have been averaged for the area of the Atacama Desert, and used to obtain a first spectrum that is representative for the Atacama Desert area. Local atmospheric data observed at the AERONET station of Paranal (in Atacama Desert) were also time averaged and used as inputs to SMARTS in order to obtain a second spectrum that is specific to Paranal. Results have been compared against each other and also to the world reference spectrum, ASTM G173.

The averages of AOD and PW derived from MODIS observations substantially disagree with those obtained from the AERONET station at Paranal. Furthermore, the low AOD and PW values at Paranal produce important differences in the spectral irradiance in comparison with the G173 world reference, mainly over short wavelengths and atmospheric water absorption bands in the near-infrared.

Based on all these results, it is concluded that the use of MODIS data is not recommended to calculate direct spectral irradiances from average atmospheric data in the Atacama Desert.

The differences resulting from the use of each one of these three spectra in the calculation of CSP process heat have been obtained for twelve different scenarios describing the combination of several possible mirrors with various spectral reflectances, transparent covers of various transmittances, and an absorber with double-layer coating. In the worst case, the maximum relative difference is only ≈1%. For the most common setups (Flabeg-like mirror and quartz glass envelope) the deviations are below 0.6%.

It is concluded that the ASTM G173 reference DNI spectrum does not necessarily induce a significant error in estimates of CSP plant yield over the Atacama Desert, even though the atmospheric conditions there are significantly different from those of G173. However, the introduction of new technologies that make use of spectrally-selective materials (such as hybrid CSP-PV plants) could justify the use of site-adapted reference spectra.

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