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A fast and simple model to estimate the contribution of the circumsolar irradiance to measured broadband beam irradiance under cloud-free conditions in desert environment

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ABSTRACT

Routine measurements of the broadband beam irradiance at normal incidence by means of pyrheliometers or equivalent pyranometric systems include unknown contributions from the irradiance originating from within the extent of the solar disc B_n^{sun}, and that from a larger circumsolar region defined by its solid angle aperture, called the circumsolar normal irradiance CS_n. This article describes a fast and simple parametric model that estimates the beam and circumsolar radiation, for opening half-angles in the interval [0.4°, 5°], under cloud-free conditions in a desert environment. 1 min measurements of the beam normal B_n, global G and diffuse D horizontal irradiances at Solar Village, Saudi Arabia, and Tamanrasset, Algeria, were used for calibration and validation. Using AERONET measurements as inputs to the radiative transfer code libRadtran, it has been checked–through an 'indirect' validation with the ground measured B_n–that the modelled B_n^{sun} and CS_n are accurate. Accordingly, a library of B_n^{sun} and CS_n modelled by libRadtran for varying solid angle apertures was generated. Building on this library, a fast parametric model was developed to estimate B_n^{sun} and CS_n using G, D and B_n as inputs. The coefficients of the model were fitted to a training set of measurements and then validated twice: once at their respective site, and once at the other site. When using the coefficients for their own site for both Solar Village and Tamanrasset for CS_n, the relative bias is respectively −2.7% and −1.5%, the relative root mean square error (RMSE) is 19.9% and 19.6%, and the correlation coefficient is 0.871 and 0.935. As for B_n^{sun}, the relative bias is −2.0% and −2.2%, the RMSE is 2.7% and 3.6%, and the correlation coefficient is 0.999 and 0.998. Applying the coefficients of one site to the other site yields satisfactory results. It is recommended to use the coefficients of Tamanrasset for desert sites exhibiting frequent clear skies, and those of Solar Village for sites exhibiting frequent turbid skies. The coefficients have also been fitted using data from both sites, for a combined model.

1. Introduction

The scattering of the sun rays by molecules, aerosols and particular cloud coverage, e.g., ice crystals such as cirrus, transfers part of the energy from the exact direction of the sun to the circumsolar region, also known as the solar aureole (Blanc et al., 2014; Buie et al., 2003; Noring et al., 1991; Thomalla et al., 1983). The direct, or beam, irradiance at normal incidence, denoted B_n, is the radiant flux per unit area received on a plane normal to the sun rays from a small solid angle centred to the solar disc (ISO-9488, 1999; WMO, 2010). B_n plays a role in various domains, such as natural biomass development, climate, daylighting or concentrated solar technologies (CST) in electricity production. The CST systems generally exhibit solid angle apertures larger than the angular radius of the solar disc, but smaller than those of pyrheliometers and radiometers meant to measure B_n (Blanc et al., 2014). This implies an overestimation of the solar resource for electricity production if measurements of B_n are not corrected for the intercepted radiation from the circumsolar region, i.e., taking into account the parts of the circumsolar normal irradiance CS_n that are intercepted by the measuring system on the one hand and the CST system on the other hand.

This study contributes to an improved assessment of the broadband

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Nomenclature

Acronyms

AOD	aerosol optical depth
BSRN	Baseline Surface Radiation Network
CC	correlation coefficient
CI	confidence interval
CST	concentrated solar technologies
DS1	data set 1
DS2	data set 2
LOOCV	leave-one-out cross-validation
LS	least-squares affine regression
MAE	mean absolute error
PCA	first component of principal component analysis
RMSE	root mean square error
SAM	sun and aureole measurement instrument
SSA	single scattering albedo
SSI	surface solar irradiance
SV	Solar Village, Saudi Arabia
TAM	Tamanrasset, Algeria
WMO	World Meteorological Organization

Symbols

B_n	direct, or beam, irradiance at normal incidence
B_n^{sun}	B_n from the extent of the solar disc only
c	coefficients of the polynomials of the model
CSC	circumsolar contribution
CS_n	circumsolar normal irradiance
CSR	circumsolar ratio
D	diffuse horizontal irradiance
G	global horizontal irradiance
L	radiance
p	penumbra function
P_{aer}	aerosol phase function
SC	sky clearness
α	opening half-angle
δ_S	angular radius of the sun
ε_L	limit angle
ε_S	slope angle
θ_S	solar zenith angle
λ	wavelength
ν, o, ρ	coefficients of the parametric model
ξ	angular distance from the center of the sun
φ_n	azimuth angle on a plane normal to the sun

beam and circumsolar radiation, for varying solid angle apertures, under cloud-free conditions in a desert environment. The interest for such an environment is because CST systems, including the concentrated solar thermal electric and concentrated photovoltaic systems, are installed and planned in areas where cloud-free conditions are frequent and the beam irradiance is large, such as desert areas in the Middle East and North Africa.

Retrieving information on CS_n is challenging because measurement campaigns of such have been performed in few locations worldwide, and for short periods of time. They were mainly collected in the USA (Noring et al., 1991) and Europe (Neumann et al., 2002; Wilbert, 2014). The only ones, to the knowledge of the authors, collected in the Middle East and North Africa region are the monochromatic measurements collected in Abu Dhabi, UAE using the Sun and Aureole Measurement instrument of Visidyne, Inc. (SAM, http://www.visidyne.com/SAM/index.htm/), and the broadband measurements collected using the BPI circumsolar irradiance sensor CSR460 (Wilbert et al., 2013a) in Oman (http://www.dlr.de/sf/en/desktopdefault.aspx/tabid-10436/12676_read-39752/).

Several methods have been published to estimate CS_n and the circumsolar solar ratio (CSR), which is the ratio of CS_n to the sum of CS_n and B_n^{sun}, where B_n^{sun} denotes the beam irradiance at normal incidence originating from within the extent of the solar disc. Watt (1980)–as explained in Wilbert (2014)–tested several approaches to model the CSR using different meteorological variables. Wilbert et al. (2013b) and Wilbert (2014) propose a method that converts angular profiles of monochromatic radiance measurements of SAM into broadband profiles, from which CS_n may be inferred for a defined aperture angle. The method employs a modified version of the radiative transfer code SMARTS v2.9.5 (Gueymard, 1995, 2001), but unlike SMARTS it is not available for public access. Focusing on cirrus cloudy conditions, Reinhardt (2013) and Reinhardt et al. (2014) propose a method based on look-up-tables established with the radiative transfer code libRadtran (Emde et al., 2016; Mayer and Kylling, 2005) to estimate the circumsolar radiation using cirrus cloud properties retrieved from products of the Meteosat Second Generation satellites. Bugliaro and Wilbert (2016) used the properties of clouds derived from whole-sky images, satellite images, and weather models for the determination of the CSR. Eissa et al. (2014) used the predefined desert aerosol model of the OPAC library (Hess et al., 1998) in libRadtran to estimate the circumsolar radiation. Eissa (2015) and Eissa et al. (2015) tested several methods for describing the aerosol optical properties in libRadtran to model the monochromatic circumsolar radiation.

Focusing on cloud-free skies in a desert environment, in this study a parametric model is developed which is capable of estimating the broadband B_n^{sun} and CS_n using inputs which are more readily available than the specific aerosol optical properties required as inputs when modelling the same using radiative transfer codes.

To achieve the objective of this study, high quality measurements of B_n, global G and diffuse D horizontal irradiances, and aerosol optical properties collected at both Solar Village, Saudi Arabia, and Tamanrasset, Algeria, from the Baseline Surface Radiation Network (BSRN, McArthur, 2005; Ohmura et al., 1998) and AERONET (Holben et al., 1998) networks, were exploited. Firstly, B_n and B_n^{sun} were modelled by the means of libRadtran with the AERONET data as inputs. Modelled B_n and B_n^{sun} were compared against measurements of B_n to assess the accuracy of the modelled values. Due to a lack of CS_n measurements at the sites of interest, the modelled CS_n underwent an 'indirect' validation. Ideally, the modelled B_n^{sun} should be less than the measured B_n, whereas the modelled B_n should exhibit no bias when compared with the measured one. Secondly, a library of B_n^{sun} and CS_n, modelled by libRadtran for varying solid angle apertures was generated. Building on this library, a fast parametric model was developed to estimate B_n^{sun} and CS_n using inputs which are more readily available than the aerosol optical properties, namely measurements of G and D by pyranometers and of B_n by pyrheliometers. The coefficients of the model were fitted at both sites, and each set of coefficients was validated twice: once at its respective site, and once at the other site. The coefficients of the model were then fitted using the data of both sites combined, for a model more applicable globally.

The article is organized as: background (Section 2), data and methods (Section 3), library of reference values (Section 4), model development (Section 5), model for varying solid angle apertures (Section 6), and finally conclusions (Section 7).

2. Background

The solid angle apertures of radiometers meant to measure B_n may be schematically defined by the opening half-angle, denoted α, and the slope and limit angles, respectively denoted ε_S and ε_L (Blanc et al., 2014). α is the average of ε_S and ε_L. The World Meteorological