Atmos. Meas. Tech. Discuss., 7, 4191–4227, 2014
www.atmos-meas-tech-discuss.net/7/4191/2014/
doi:10.5194/amtd-7-4191-2014

Atmospheric Measurement Techniques
Discussions
Open Access

Re-construction of global solar radiation time series from 1933 to 2013 at the Izaña Atmospheric Observatory

R. D. García[1,2], E. Cuevas[1], O. E. García[1], V. E. Cachorro[2], P. Pallé[3], J. J. Bustos[1], P. M. Romero-Campos[1], and A. M. de Frutos[2]

[1]Izaña Atmospheric Research Center (IARC), Agencia Estatal de Meteorología (AEMET), Santa Cruz de Tenerife, Spain
[2]Atmospheric Optics Group, Valladolid University, Valladolid, Spain
[3]Instituto Astrofísica de Canarias (IAC), Santa Cruz de Tenerife, Spain

Received: 22 March 2014 – Accepted: 15 April 2014 – Published: 25 April 2014

Correspondence to: R. D. García (rgarciac@aemet.es)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

This paper presents the re-construction of the 80 year time series of daily global shortwave downward radiation (SDR) at the subtropical high-mountain Izaña Atmospheric Observatory (IZO, Spain). For this purpose, we combine SDR estimates from sunshine duration (SD) data using the Ångström–Prescott method over the 1933/1991 period, and SDR observations directly performed by pyranometers between 1992 and 2013. Since SDR measurements have been used as a reference, a strict quality control has been applied, when it was not possible data have been re-calibrated by using the LibRadtran model. By comparing to high quality SDR measurements, the precision and consistency over time of SDR estimations from SD data have successfully been documented. We obtain a overall root mean square error (RMSE) of 9.2 % and an agreement between the variances of SDR estimations and SDR measurements within 92 % (correlation coefficient of 0.96). Nonetheless, this agreement significantly increases when the SDR estimation is done considering different daily fractions of clear sky (FCS). In that case, RMSE is reduced by half, up to about 4.5 %, when considering percentages of FCS > 40 % (90 % of days in the testing period). Furthermore, we prove that the SDR estimations can monitor the SDR anomalies in consistency with SDR measurements and, then, can be suitable for re-constructing solar radiation time series. The re-constructed IZO global SDR time series between 1933 and 2013 confirms discontinuities and periods of increases/decreases of solar radiation at Earth's surface observed at a global scale, such as the early brightening, dimming and brightening. This fact supports the consistency of the IZO SDR time series presented in this work, which may be a reference for solar radiation studies in the subtropical North Atlantic region.

AMTD
7, 4191–4227, 2014

1 Introduction

Solar radiation controls the energy radiative balance in the Earth and, thus, our weather and climate. For this reason, its study has been one of the main objectives of the research community during the last decades. Recently, the focus is on evaluating the long-term trends of solar radiation reaching the Earth's surface (shortwave downward radiation, SDR) as well as on identifying the variability driven by climate change (Stanhill and Cohen, 2001; Sanroma et al., 2010; Wild, 2009). Observational evidences of changes on SDR trends have already been reported at a global scale. A decrease of the solar radiation at surface has been observed between the 1960s and the 1990s, effect known as *dimming*, with a general decline between 4 and 6 % over 30 years considering worldwide distributed stations (e.g. Ohmura and Lang, 1989; Gilgen et al., 1998; Stanhill and Cohen, 2001; Liepert, 2002; Pinker et al., 2005; Wild et al., 2005; Wild, 2009). On the contrary, since the 1980s a partial recovery has been documented, with an increase of the solar radiation known as *brightening* (Wild et al., 2005, 2007, 2008, 2012; Gilgen et al., 2009). Trends between +1.0 and +10.7 %/decade have been reported from the 1980s onwards (Wild, 2009, and references herein).

The causes of the *dimming/brithening* phenomena are not well understood yet (IPCC, 2007; Wild et al., 2012), but some authors link them to changes in the global cloud cover, on the atmospheric aerosol content (natural or anthropogenic), and on the interplay of direct and indirect aerosol effects (Stanhill and Cohen, 2001; Ramanathan et al., 2001; Wild et al., 2005; Wild, 2009). The relative importance of these factors may differ depending on region and pollution level (Wild, 2009). In this context, some authors point out that the *dimming* may only be a local effect, associated with urban environments (e.g. Alpert and Kishcha , 2008), or that tendencies over land and over ocean can differ in sign and in magnitude (e.g. Pinker et al., 2005). For a better understanding of these global effects and reduce the uncertainties that still remain, long-term SDR time series in regions representative of background signals are fundamental.

AMTD
7, 4191–4227, 2014

Reliable solar radiation studies need of high-quality, long-term and worldwide distributed SDR measurements. Although the SDR instruments exist since the 1920s, regular and coordinated SDR observations are not well established until the 1950s within the framework of the International Geophysical Year (IGY) (Nicolet, 1982). In order to complete gaps in these SDR time series, to correct erroneous records, or to extend them over time, SDR estimations from other climate variables, such as sunshine duration (onwards, SD), cloud cover or visibility, are very valuable. For this purpose, the most extended approach is to estimate the global SDR from SD data (Iziomon and Mayer, 2002; Sivamadhavi and Selvaraj, 2012), since it combines long-term records available (SD measurements started in the 19th century, Butler and Hoskin, 1987; Pallé and Butler, 2001), simplicity and reliable results. The relation between SD and global SDR observations have been described by using several mathematical relations, including linear, the so-called Ångström–Prescott relation (Angstrom, 1924; Prescott, 1940), cubic (Samuel, 1991), logarithmic (Ampratwum and Dorvlo, 1999) and exponential (Almorox and Hontoria, 2004) relations. In all of these equations, a set of coefficients are calculated in a simultaneous period of SD and global SDR measurements. The comparison of the aforementioned approaches conclude that the use of complex relations instead of the simple linear relation proposed by Ångström–Prescott does not significant improve the global SDR estimates (Almorox and Hontoria, 2004; Yorukoglu and Celik, 2006).

In this context, the goal of this work is to re-construct the time series of the global SDR between 1933 and 2013 at the Izaña Atmospheric Observatory (IZO), representative of subtropical North Atlantic free troposphere, by using the Ångström–Prescott method on SD measurements (1933/1991), and SDR observations performed by pyranometers (1992/2013). For this purpose, this work is divided in six sections. Section 2 describes the different instruments and measurements used (radiation and SD data) as well as the main characteristics of IZO. Section 3 shows the re-calibration of measured global SDR at IZO between 1992 and 2005, when no strict quality controls were applied on SDR measurements, by using the LibRadtran model. Section 4 explains the method applied to estimate the global SDR from SD records and documents the precision and consistency of our SDR estimates, while the re-construction of the whole global SDR time series from 1933 to 2013 is addressed in Sect. 5. Finally, summary and conclusions are given in Sect. 6.

2 Site description, measurements and tools

This study has been performed at the high-mountain Izaña Atmospheric Observatory (IZO, http://izana.aemet.es), located in Tenerife (The Canary Islands, Spain; 28.3° N, 16.5° W, 2373 m a.s.l.). This station is managed by the Izaña Atmospheric Research Center (IARC) from the Meteorological State Agency of Spain (AEMET). IZO is a world-wide reference station. Since almost three decades, the IARC aims at monitoring atmospheric constituents that are capable of forcing changes in the climate of the Earth, through modification of the atmospheric radiative environment (greenhouse gases and aerosols), and those that may cause depletion of the global ozone layer. IZO is part of the WMO-GAW programme (World Meteorological Organization-Global Atmospheric Watch) since 1984 and part of the NDACC (Network for the Detection of Atmospheric Composition Change) since 2001. Also, it actively contributes to international aerosols and radiation networks such as AERONET (Aerosol Robotic Network) and BSRN (Baseline Surface Radiation Network). IZO is a suitable site for in-situ and remote sensing observations and optimal for calibration and validation activities due to a high atmospheric stability, high frequency of clean and pristine skies, a stable total column ozone, very low column water content and low aerosols content.

2.1 Global SDR data

Between 1992 and 2013 the global SDR measurements have been performed with different pyranometers at IZO (Table 1).

AMTD
7, 4191–4227, 2014

- Before 2005, the measurements were taken with two instruments (Kipp & Zonen CM-5 and CM-11), but they were not subject to strict quality controls. According to manufacturer, daily uncertainties of ±5 % and ±2 % can be expected, respectively (http://www.kippzonen.com).

- Since August 2005 IZO belongs to Broadband Radiation Network (BRN), managed by the Spanish National Radiometric Centre (NRC-AEMET). The NRC is operating since mid 1970's, and currently is comprised by 60 radiation measuring stations at Spain. These instruments are routinely calibrated under ISO9001:2000 quality standards. Daily uncertainty of ±2 % are expected (Sancho et al., 2011).

- Since 2009 IZO belongs to BSRN (BSRN station #61, IZA). In 2004 the BSRN was designated as the global baseline network for surface radiation for the Global Climate Observing System (GCOS) with the main objective of providing measurements of the best quality for shortwave and longwave surface radiation fluxes, with high temporal resolution. For this purpose, the BSRN establishes exigent quality controls for its products (Long and Dutton, 2002; Long and Shi, 2006). Applying the BSRN quality controls aforementioned to the Izaña SDR measurements for solar zenith angles (SZA) $< 90^{\circ}$, R. D. García et al. (2012) found that the IZO measurements largely satisfy the quality controls recommended by the BSRN. The estimated uncertainties for the instantaneous global irradiances indicated by BSRN in 1997 are $\pm 5\,\mathrm{W\,m^{-2}}$ (±2 %) (Ohmura et al., 1998; McArthur, 2005). These values account for calibration uncertainties and were estimated from standard deviation of the calibration coefficients.

Since 2009 the BSRN and NRC networks co-exist at IZO, showing an excellent consistency (Pearson and Kendall correlation coefficients of > 0.99 and > 0.98, respectively). The RMSE of the daily differences between 2009 and 2013 is of $0.34\,\mathrm{MJ\,m^{-2}}$ (1.1 %), within the instrumental expected uncertainty. This confirms the high-quality of the IZO global SDR measurements. Note that the different pyranometers acquire global SDR records on a 1 min basis. But, in this work, we use daily SDR calculated according

AMTD
7, 4191–4227, 2014

to Eq. (1):

$$H_\mathrm{d} = \int_\mathrm{sr}^\mathrm{ss} I(t) \cdot \mathrm{d}t \tag{1}$$

where $I(t)$ is the instantaneous values of the solar irradiance ($\mathrm{W\,m^{-2}}$) and the time (t) is computed from sunrise (sr) to sunset (ss), every 1 min.

There are short gaps in the long-term SDR time series at IZO. To complete these time intervals, we have used the SDR measurements taken at the Teide Observatory (OT, http://www.iac.es) managed by the Instituto de Astrofísica de Canarias (IAC). OT is only 1.3 km far away from IZO and at same altitude (28.3° N, 16.5° W, 2371 m a.s.l.). The global SDR measurements at OT were performed with a Silicon Cell Pyranometer (SCP, Model 3120), with an expected uncertainty of ±3 % for daily values (see http://www.allweatherinc.com/). The periods in which we used these measurements were April 2000–August 2000, January 2001–July 2002 and September 2003–July 2005. Nonetheless, a difference $< 0.5\,\%$ between the global SDR in the range 250–1500 nm and in the range 310–2800 nm are observed.

2.2 Radiation transfer model and input parameters

LibRadtran model is a complete free software package containing a suite of tools for radiative transfer calculations in the Earth's atmosphere (freely available from http://www.libradtran.org) (Mayer and Kylling, 2005).

The global and direct SDR estimations were computed as described in García et al. (2014). The radiative transfer calculation is addressed by a multi-stream discrete ordinates algorithm (Stamnes et al., 1988) (DISORT for $\mathrm{SZA} \leq 70°$ and SDISORT for $\mathrm{SZA} > 70°$) and the input model parameters (atmosphere gas composition, surface albedo, aerosol optical properties, ...) are directly measured at IZO.

The most significant changes with regard to García et al. (2014) are related to aerosol optical depth (AOD) and total precipitable water vapour (PWV) observations.

Since 1994 the AOD values have been measured with different sun-photometers (in brackets the expected uncertainty is given for each instrument): a PMOD/Rocket between 1994–1996 (±0.013 at 368 nm, Diaz et al., 2000), a MFRSR (Multifilter Rotating Shadowband Radiometer) between 1996–2001 (±0.03, Pedro Miguel Romero, private communication, 2014), a PFR (Precision Filter Radiometer) between 2001–2004 developed at the World Radiation Center Physikalish-Meteorologisches Observatorium in Davos, Switzerland (WRC/PMOD) (±0.01, Wehrli, 2000), and finally with CIMEL sun-photometer within AERONET (Holben et al., 1998) since 2005 onwards (±0.01, Eck et al., 1999). In this study, we have considered the daily AOD value at 500 nm. For 1992 and 1993 there is not AOD data, thereby we considered a constant AOD value of 0.02 that represents ~ 80 % of the days at IZO. The differences found with an AOD of 0.01 and 0.03, with respect to simulations with an AOD of 0.02 are 0.32 % and −0.18 %, respectively. Hence, the total precipitable water vapour (PWV) is obtained from Vaisala radiosonde (Miloshevich et al., 2009), launched twice a day (~ 23:15 and ~ 11:15 UTC) very close to IZO. Between 1992 and 2002 Vaisala RS80 radiosondes were daily launched from the radiosonde station of Santa Cruz de Tenerife (36 m a.s.l.) and since October 2002 onwards Vaisala RS92 radiosondes are launched from the radiosonde station of Güimar (WMO station #60018) (Romero et al., 2011). Schneider et al. (2010) found a RS92's PWV precision of 15 % by comparison with FTIR (Fourier Transform Infrared) PWV data.

2.3 Sunshine duration data

The SD is defined by WMO as the period during which direct solar irradiance exceeds a threshold value of 120 W m^{-2}. This value is equivalent to the level of solar irradiance shortly after sunrise or shortly before sunset in cloud-free conditions (WMO, 1982).

At the IARC, the SD observations started in 1933 with a Campbell–Stokes sunshine record (CS). The CS focuses the direct solar beam through a glass sphere, mounted concentrically in a section of a spherical bowl, on a burn card located begin the sphere. The card is provided with a time indication, which makes it possible to determine the

AMTD
7, 4191–4227, 2014

SD from the length of the burn when the card is removed from the instrument at the end of the day (Painter, 1981; WMO, 1996; Sanchez-Lorenzo et al., 2013). During the last years, this traditional sunshine recorder has been replaced by electronic devices. At IARC, the CS instrument was replaced by a Kipp and Zonen Sunshine Duration Sensor (CSD) in 2001, which operates until now. This instrument is formed by three detectors that cover part of sky, one detects all the direct and diffuse solar radiation, while the other two detectors only cover 1/3 of the sky (Kipp and Zonen, 2003).

The CS presents several disadvantages against CSD record, being the most important ones: (1) the instrument must be operated manually and a new card strip mounted every morning before sunrise, (2) the card strip responds in a different manner to solar irradiance whether the ambient air is humid or dry, (3) the burning of band are not well defined at sunrise and sunset, (4) different operators reading the same cards may get very different totals. As a consequence, Massen (2011) found the CS measurements suggest a systematic overestimation of sunshine hours by up to ±10 % over a 11 year period.

Although the CSD measurements will not be used in the re-construction of global SDR time series, this work provides an excellent opportunity for documenting their quality and robustness for this kind of studies. For this reason, we present similar analysis and discussion for the two SD recorders.

In order to document the precision of the IZO SD measurements as observed by the two SD instruments, we have compared these measurements to those obtained from direct SDR data when exceed a threshold value of 120 $\mathrm{W\,m^{-2}}$. As direct SDR measurements are not available during the CS time series, we have simulated them with the LibRadtran model (see Sect. 2.2 for details about the model and its inputs) for all the cloud-free days between 1997–1999 for CS and 2006–2008 for CSD. Notice that these periods have been selected throughout this work as testing periods (see Sect. 4.1). The comparison shows a good agreement between both datasets (see Fig. 1), obtaining correlation coefficients, RMSE and SEM (standard error of the mean) of 0.95, 0.52 $\mathrm{MJ\,m^{-2}}$ (4.8 %) and 0.06 $\mathrm{MJ\,m^{-2}}$ (0.53 %) respectively, for CS, and 0.99,

AMTD
7, 4191–4227, 2014

0.26 $MJ m^{-2}$ (2.3 %), and 0.02 $MJ m^{-2}$ (0.20 %) respectively, for CSD. The CS record tends to overestimate SD by 5.6 % from October to February and 2.4 % from March to September and the CSD record by 3.1 % and 0.7 % in the same periods. This seasonal difference can partly be attributed to the different response of the CS recorder to typical measurement conditions in the winter months (high humidity and low temperature conditions). Furthermore, the CS design by using a glass sphere that concentrates radiances coming from the whole sky on the card (not only the direct solar irradiance) may cause differences between CS and direct SDR simulations depending on cloud conditions.

3 Re-calibration of measured global SDR

The global SDR measurements between January 1992 and July 2005 did not belong to any network and were not subject of any specific quality control. Therefore, a re-calibration the corresponding data is mandatory to be reliably used in the reconstruction of the IZO SDR time series. The re-calibration was done using the LibRadtran model, which has demonstrated to be a very useful tool as a measurement quality control (García et al., 2014). The latter study observed an excellent agreement between BSRN measurements and LibRadtran simulations at IZO between 2009 and 2012: the scatter (one standard deviation) of the daily differences is $< 2\%$ for global and direct SDR.

1992–2005 time series of re-calibrated global SDR

This section presents the re-calibration of global SDR data between January 1992 and July 2005. To do so, we calculated the new sensitivity of our pyranometers (hereafter re-evaluated sensitivity, Table 2) as the mean of ratio between the global SDR measurements and simulations in a time interval of 5 min from the solar noon (WMO, 1996). These SDR estimations were done using the Libradtran model for cloud-free

AMTD
7, 4191–4227, 2014

days, selected by using the method of Long and Ackerman (2000) in the months from October to February to assure very stable atmospheric conditions (without aerosols and very low PWV). This approach was tested with BSRN measurements between 2009 and 2013, obtaining a difference $< 3\,\%$ between the original sensitivity given by the manufacturer and the re-evaluated one.

The re-calibrated daily global SDR measured at IZO and OT between 1992 and 2005 is illustrated in Fig. 2. The relative difference between re-evaluated and original calibration is, on average, $< 7\,\%$, except from April 1997 to August 1998 (Fig. 2a). In this period the re-evaluated calibration decreases by $15\,\%$ compared to the original calibration, with the consequent increase of the daily global SDR (see Fig. 2b). Figure 2b and c show the time series of the daily global SDR from 1992 to 2005 at IZO (red squares represent original SDR and blue squares represent re-evaluated SDR) and OT (red squares original SDR and green squares re-evaluated SDR), respectively, and the whole re-calibrated time series is plotted in Fig. 2d. Note that the global SDR measured from CSP instrument was extended to 2800 nm with LibRadtan model to be comparable to the wavelengths range of others pyranometers measurements.

4 Estimation of global SDR from sunshine duration

Several types of regression models have been proposed for estimating global SDR on a horizontal surface at the Earth's surface from SD records. One of the most extended and used approaches was developed by Ångström (Angstrom, 1924, 1956) and later modified by Prescott and Rietveld (Prescott, 1940; Rietveld, 1978). This model allows the global SDR from SD to be determined by using the following equation:

$$\frac{H}{H_o} = a\frac{n}{N_d} + b \qquad (2)$$

where H and H_0 are the daily global SDR ($\mathrm{MJ\,m^{-2}\,day^{-1}}$) and the daily extraterrestrial SDR, respectively, on a horizontal surface ($\mathrm{MJ\,m^{-2}\,day^{-1}}$), n and N_d are the number

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD

7, 4191–4227, 2014

Re-construction of global solar radiation time series at Izaña station

R. D. García et al.

of hours measured by the SD recorder and the maximum daily SD, respectively, and a and b are coefficients to be determined by using regression fit.

The value of H_0 is calculated as:

$$H_o = \frac{24}{\pi} I_{sc} E_o [\omega_s (\sin\delta \sin\phi) + (\cos\delta \cos\phi \sin\omega_s)] \quad (3)$$

where I_{sc} is solar constant (1367 W m^{-2}, Frohlich and Brusa, 1981), E_o is the eccentricity correction factor of the Earth's orbit (Eq. 4), ω_s is sunrise hour angle, δ is solar declination (Eq. 5) and ϕ is the geographic latitude.

$$E_o = 1 + 0.033 \cos[2\pi d_n/365] \quad (4)$$

where d_n is the day number of the year.

$$\begin{aligned}\delta =& (0.006918 - 0.399912 \cos\eta + 0.070257 \sin\eta \\ & - 0.006758 \cos 2\eta + 0.000907 \sin 2\eta - 0.002697 \cos 3\eta \\ & + 0.000148 \sin 3\eta)(180/\pi)\end{aligned} \quad (5)$$

where η is called the day angle and is represented by:

$$\eta = 2\pi(d_n - 1)/365 \quad (6)$$

In addition to meteorological variables (temperature, humidity ...), the SD mainly depends on the fraction of clear sky (FCS, see Fig. 3). The FCS, defined by Eq. (7), accounts for reductions of SD due to clouds and aerosols ((mainly mineral dust particles at IZO (Rodríguez et al., 2011; O. E. García et al., 2012)). In Fig. 3a five regions (in intervals of 20 %) can clearly be distinguished, with a very low overlapping among them. Similar stratification is observed in the measured global SDR time series (Fig. 3b). Therefore, the subsequent estimation of global SDR from SD records, by using Ångström–Prescott's Eq. (2), will be performed considering the dependence on FCS.

$$FCS = (SD_{exp}/SD_{max}) \cdot 100 \tag{7}$$

where SD_{exp} and SD_{max} are the observed and the maximum possible SD, respectively.

As aforementioned, the 1933/1992 SD time series (when solar pyranometers are not available) were recorded with CS instruments. Therefore, in order to be consistent, the *a* and *b* coefficients used to re-construct the 1933/1991 SDR time series are those computed only considering a common period of SD from CS records and global re-evaluated SDR measurements (1992/2000). In the next sections we will evaluate the accuracy of our approach by comparing the SDR estimations from SD records and SDR measurements in the period between 1992 and 2013 when simultaneous SDR and SD measurements are available.

4.1 Validation of SDR estimations

We have split the SD series (1992/2013) from the two SD recorders (CS and CSD) in two periods: one for calculating the Ångström–Prescott's coefficients ("calculation periods"), and another for testing them ("testing periods"). Once the coefficients *a* and *b* are evaluated in the calculation period, we computed daily global SDR estimates using the Eq. (2) for the testing periods. As calculation periods we consider periods with high-quality SDR measurements to assure very reliable coefficients: for 1992/1996 for CS (where minor post-corrections were applied, recall Fig. 2) and 2009/2013 for CSD (when the SDR data corresponded to BSRN). As testing periods we use the 1997/1999 and 2006/2008 periods for CS and CSD, respectively. In accordance with Fig. 3, the Ångström–Prescott's coefficients in the calculating periods have been computed by grouping FCS values into 20 % intervals. Table 3 lists the obtained coefficients for the two SD instruments. Note that the coefficients are significantly different depending on the instrument, what supports our decision of using only CS measurements to determinate the Ångström–Prescott's coefficients in the reconstruction of the 1933/2013 global SDR time series.

Theoretically, the expected uncertainty on the SDR estimations can be determinated by doing an error propagation on Eq. (2). Thus, assuming the errors given in Table 3 for the Ångström–Prescott's coefficients and the errors given in Sect. 4 for the SD measurements, we obtain that the SDR estimations can be provided with a RMSE of 4.0 % and 2.7 % for corresponding testing periods of the CS and CSD recorders, respectively.

This theoretical quality estimation has been completed by a detailed experimental intercomparison summarised in Fig. 4 and Table 4. Figure 4 displays the annual cycle of the bias between SDR estimations and measurements (estimations – measurements) for the testing periods of the two SD instruments as well as the dependence of the bias on the FCS intervals. As expected, the CS shows more systematic bias and scatter than electronic CSD device for both cases. The intra-annual bias (Fig. 4a) revels that the SD recorders provide more accurate SDR estimations in summer (RMSE of 3.1 % and 1.5 % for CS and CSD, respectively) than in winter, when the meteorological conditions are less favourable (RMSE of 3.1 % and 1.5 % for CS and CSD, respectively). This is in line with the dependence observed on the FCS values (Fig. 4b): the lower FCS values (i.e. high presence of clouds or aerosols) are observed, the larger systematic bias and scattering are found. This leads to a decrease of correlation between estimations and measurements (Table 4). Both SD instruments show very consistent behaviours for FCS values > 60 %, where we have more ∼ 80 % of the days, with median biases very close to zero and correlations > 90 % (Table 4). However, for FCS values lower than this limit, poorer correlations are found (< 0.80). SDR values from the CS recorder are systematically high ∼ 1 MJ m^{-2} than SDR measurements, while the CSD estimations underestimate the SDR measurements by ∼ 0.4 MJ m^{-2}.

The overall systematic bias (median bias) is estimated to be < 0.30 and 0.02 for the CS and CSD instruments, respectively, while the precision, given by the RMSE, reaches 1.33 MJ m^{-2} (5.5 %) for the CSD and 2.16 MJ m^{-2} (9.2 %) for the CS (see

Table 4). However, when considering FCS values $> 40\%$, where $\sim 90\%$ of days are concentrated, the RMSE values are limited to 3.0 % and 4.5 % for the CSD and CS, respectively. These values perfectly agree with our theoretical error estimation and are comparable to previous studies. Several authors reported RMSE of 1.26 $MJ\,m^{-2}$ in the city of Toledo, Spain (Almorox et al., 2005), between 1.49 and 1.65 $MJ\,m^{-2}$, in Ankara, Turkey (Yorukoglu and Celik, 2006), and between 1.39 and 3.08 $MJ\,m^{-2}$ in 31 sites around China, between the observed global SDR and the estimated ones using Ångström–Prescott method.

4.2 Long-term consistency of SDR estimations

In order to reliably use our global SDR estimations from SD recorders for solar radiation trends studies, it is indispensable to document their homogeneity and long-term stability. To do so, we examine possible drifts and discontinuities in the times series of the differences between the SDR estimations and measurements in the common period (1992/2013). We defined a drift as the linear trend of the annual mean bias (estimations – measurements), while the change-points (changes in the median of the bias time series) are analysed by using a robust rank order change-point test (Lanzante, 1996). Note we have applied the Ångström–Prescott's coefficients obtained by separating the periods of SD records between 1992/2000 (CS) and 2001/2013 (CSD).

The straightforward comparison between the annual mean anomalies reveals a rather consistent agreement (correlation coefficient of 0.86, Fig. 6a), which is translated into the bias time series. Thus, we observe that the bias time series is homogeneous (i.e. no change points were identified) as well as there is no significant drift (linear trend is $+0.03 \pm 0.05\,MJ\,m^{-2}\,year^{-1}$) at 99 % confidence level. Furthermore, no significant autocorrelation of the bias time series with itself was detected. These findings document that the SDR estimations are consistent over time with SDR measurements and, then, they are valid for re-constructing the global SDR time series and for trends studies.

AMTD
7, 4191–4227, 2014

5 1933–2013 times series of estimated global SDR

The re-constructed SDR time series between 1933 and 2013 at IZO is shown in Figs. 6 and 7. The SDR estimations between 1933 and 1991 were calculated by using the Ångström–Prescott's coefficients given in Table 5 and the measured SDR data from 1992 to 2013 (in grey dots). For trend studies, the SDR anomalies are more representative than the absolute values (Sanchez-Lorenzo and Wild, 2012), thereby the whole time series has been deseasonalised by subtracting the averaged SDR annual cycle, obtaining the anomalies time series (Figs. 6b and 7). This anomalies time series reveals phenomena detected at a global scale, such as the beginning of the dimming period at the end of 1950s, the strong increase of global SDR values since middle of 1980s (brightening) and the recent and important volcanic eruptions of Arenal and Fernandina Island in 1968, El Chichón in 1982 and Pinatubo in 1992. It is remarkable that the maximum value of SDR corresponds to year 2013. The latter will be our global SDR times series of reference.

By using the Lanzante's method (Lanzante, 1996) on the annual mean anomalies time series, we confirm three change-points about 1953, 1968 and 2000 at 99 % of confidence level. The change-point signal-to-noise ratios, which quantify the magnitude or relative importance of each discontinuity, are 2.3, 0.8 and 1.5, respectively, indicating that the breaks in 1950s and 2000s may be considered as principal transition dates and 1968 as a secondary change-point. These two principal discontinuities define three periods:

1. *Early brightening*: from the 1930s to the early 1950s, the few historic data available suggest an increase of the SDR in the first part of the 20th century, known as *early brightening* (De Bruin et al., 1995; Gilgen et al., 1998; Ohmura, 2006), with a peak about the late 1940s/early 1950s. This phenomenon is also confirmed by the IZO anomalies time series considering all-sky conditions, and especially visible for mostly cloud-free situations (FCS > 40 %, Fig. 7b). However, we observe a delay of between 5–10 years for the transition from the early brightening to the

dimming period and from the dimming period. This delay is generally observed throughout the whole anomalies time series and may be partly attributed to free troposphere conditions of IZO. Note that between 1933 and 1953 the cloudy and cloud-free anomalies time series show opposite trends, with an anti-correlation of ~ 25 % (Fig. 7).

2. *Dimming*: from the 1950s to the ending of the 1990s a gradual decrease of SDR is observed, which is in accordance with the widespread period of reduced solar radiation at a global scale, extensively reported by the literature in the second half of the 20th century and known as the *dimming* (Stjern et al., 2009; Gilgen et al., 1998; Stanhill and Cohen, 2001; Wild et al., 2005; Ohmura, 2006; Wild, 2009).

3. *Brightening*: from the ending of the 1990s onwards, we document the partial recovery of SDR measurements, *brightening*, also reported at many globally distributed locations (Wild et al., 2005, 2008; Wild, 2009). The *dimming/brightening* phenomena have consistently been detected both under cloudy and also under cloud-free conditions, as shown in Fig. 7. This fact points out that the dimming and brightening phenomena might be associated with, among others, changes on atmospheric aerosols concentrations due to anthropogenic activities (Wild, 2009, and references herein). In accordance with previous studies, significant signatures of these events are not well recognized on global SDR anomalies time series (Ohmura, 2006; Wild, 2009). Note the cloudy and cloud-free anomalies time series show an acceptable agreement from the 1960s onwards, with a positive and significant correlation of ~ 50 %.

6 Summary and conclusions

The global SDR times series between 1933 and 2013 has been successfully reconstructed combining SDR estimates from SD measurements (1933/1991) using the

AMTD
7, 4191–4227, 2014

Ångström–Prescott method and SDR observations performed by different pyranometers (1992/2013) at IZO.

The quality of the SDR and SD databases have been assessed. Since 2005, the global SDR measurements taken at IZO are under strict quality controls in the framework of the CNR and BSRN networks. Nonetheless, before 2005, the re-calibration of the SDR measurements was needed. This re-calibration was made with the LibRadtran model, obtaining differences $< 7\,\%$ between the original and the re-evaluated calibration.

The SD measurements taken by Campbell–Stokes recorders (CS) between 1993 and 2000 and by Sunshine Duration Sensor recorders (CSD) between 2001 and 2013 were also validated against the LibRadtran model direct SDR simulations for cloud-free days. There is a good agreement between both datasets, with a RMSE of $0.52\,\mathrm{MJ\,m^{-2}}$ (4.8 %) for CS and $0.26\,\mathrm{MJ\,m^{-2}}$ (2.3 %) for CSD. Propagating these errors to SDR estimations from SD records, an expected precision of 4.0 % and 2.7 % for CS and CSD, respectively, have been found. By comparing with global SDR, we obtain a precision, given by the RMSE, of $2.16\,\mathrm{MJ\,m^{-2}}$ (9.2 %) for the CS and $1.33\,\mathrm{MJm^{-2}}$ (5.5 %) for the CSD. Although the CSD observations were not used to re-construct the IZO global SDR time series, this study provides an excellent opportunity for documenting their quality and examining the dependence of the Ångström–Prescott method on the SD instruments. The consistency over time series of the SDR estimations has been documented by comparing these to SDR measurements on a 20 years period (1992/2013), obtaining that the bias time series is homogeneous as well as there is not present significant drift.

The resulting annual time series SDR confirms a period of *early brightening* from the 1930s to the early 1950s, a period of *dimming* from the 1950s to the ending of the 1990s followed by a period of *brightening* in the most recent decades. All of these findings demonstrate the consistency of the IZO SDR time series presented in this work, which may be a reference for solar radiation studies in the Subtropical North Atlantic Region. Future works will analyze in depth the long-term trends and their interplay

AMTD
7, 4191–4227, 2014

with variations of the solar constant, the cloud cover, and the atmospheric aerosols concentrations. The joint analysis with dust AOD is critical in our region since dust intrusions, which undergo interannual and decadal variations, module AOD and hence solar radiation.

Acknowledgements. This work was developed under the Specific Agreement of Collaboration between the Meteorological State Agency (AEMET) of Spain and the University of Valladolid regarding radiometry, ozone and atmospheric aerosol programmes conducted at Izaña Atmospheric Observatory (IZO), and for the adaptation and integration of the AEMET CIMEL network following the AERONET-RIMA standards. Financial supports from the Spanish Ministry of Economy and Competitiveness (MINECO) and from the "Fondo Europeo de Desarrollo Regional" (FEDER) for projects CGL2011-23413, CGL2012-33576 and CGL2012-37505 are gratefully acknowledged. The authors are grateful to the IZO team and especially Ramón Ramos the Izaña's field manager and all observers who have worked in the past for monitoring Campbell–Stokes measurements in 80 years at Izaña. We gratefully acknowledge NRC (AEMET) and IAC for providing the global SDR measurements. This work utilizes data obtained by the Global Oscillation Network Group (GONG) project, managed by the National Solar Observatory which is operated by AURA.

References

Almorox, J. and Hontoria, C.: Global solar radiation estimation using sunshine duration in Spain, Energ. Convers. Manage., 45, 1529–1539, doi:10.1016/j.enconman.2003.08.022, 2004. 4194

Almorox, J., Benito, M., and Hontoria, C.: Estimation of monthly Angstrom–Prescott equation coefficients from measured daily data in Toledo, Spain, Renew. Energ., 30, 931–936, doi:10.1016/j.renene.2004.08.002, 2005. 4205

Alpert, P. and Kishcha, P.: Quatification of the effect of urbanization on solar dimming, Geophys. Res. Lett, 35, L08801, doi:10.1029/2007GL033012, 2008. 4193

Ampratwum, D. B. and Dorvlo, A. S. S.: Estimation of solar radiation from the number of sunshine hours, Appl. Energ., 63, 161–167, doi:10.1016/S0306-2619(99)00025-2, 1999. 4194

Andrews, E., Ogren, J. A., Bonasoni, P., Marinoni, A., Cuevas, E., Rodríguez, S., Sun, J. Y., Jaffe, D. A., Fischer, E. V., Baltensperger, U., Weingartner, E., Collaoud Coen, M., Sharma, S., Macdonald, A. M., Leaitch, W. R., Lin, N.-H., Laj, P., Arsov, T., and Kalapov, I.: Climatology of aerosol radiative properties in the free troposphere, Atmos. Res., 102, 365–393, 2011.

Angstrom, A. K.: Solar and terrestrial radiation, Q. J. Roy. Meteorol. Soc., 50, 121–126, 1924. 4194, 4201

Angstrom, A. K.: On computation of global radiation from records and sunshine, Arkiv Geophysik, 3, 471–479, 1956. 4201

Butler, C. J. and Hoskin, M. A.: The archives of Armagh Observatory, Journal of History of Astronomy, 18, 295–307, 1987. 4194

Dahlback, A. and Stammes, K.: A new spherical model for computing the radiation field available for photolysis and heating at twilight, Planet. Space Sci., 39, 671–683, 1991.

De Bruin, H. A. R., Van den Hurk, B. J. J. M., and Welgraven, D.: A series of global radiation at Wageningen for 1928–1992, Int. J. Climatol., 15, 1253–1272, doi:10.1002/joc.3370151106, 1995. 4206

Díaz, J. P., Expósito, F. J., Torres, C. J., and Carreño, V.: Simulation of mineral dust effects on UV irradiance level, J. Geophys. Res., 105, 4979–4991, 2000. 4198

Dubovik, O. and King, M.: A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements, J. Geophys. Res., 105, 673–696, doi:10.1029/2000JD900282, 2000.

Eck, T. F., Holben, B. N., Reid, J. S., Dubovik, O., Smirnov, A., O'Neill, N. T., Slutsker, I., and Kinne, S.: Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols, J. Geophys. Res., 104, 31333–31349, doi:10.1029/1999JD900923, 1999. 4198

Fröhlich, C. and Brusa, R. W.: Solar radiation and its variation in time, Sol. Phys., 74, 209–2158, 1981. 4202

García, O. E., Díaz, J. P., Expósito, F. J., Díaz, A. M., Dubovik, O., Derimian, Y., Dubuisson, P., and Roger, J.-C.: Shortwave radiative forcing and efficiency of key aerosol types using AERONET data, Atmos. Chem. Phys., 12, 5129–5145, doi:10.5194/acp-12-5129-2012, 2012. 4202

García, R. D., Ramos, R., Cuevas, E., Cachorro, V., and de Frutos, A. M.: Status of the Izaña BSRN station, Optica Pura y Aplicada, 45, 51–55, 2012. 4196

García, R. D., García, O. E., Cuevas, E., Cachorro, V. E., Romero-Campos, P. M., Ramos, R., and de Frutos, A. M.: Solar radiation measurements compared to simulations at the BSRN Izaña station, mineral dust radiative forcing and efficiency study, J. Geophys. Res., 119, 179–194, doi:10.1002/2013JD020301, 2014. 4197, 4200

Gilgen, H., Wild, M., and Ohmura, A.: Means and trends of shortwave irradiance at the surface estimated from GEBA, J. Climate, 11, 2042–2061, 1998. 4193, 4206, 4207

Gilgen, H., Roesch, A., Wild, M., and Ohmura, A.: Decadal changes of shortwave irradiance at the surface in the period 1960 to 2000 estimated from Global Energy Balance Archive, J. Geophys. Res., 114, D00D08, doi:10.1029/2008JD011383, 2009. 4193

Holben, B. N., Eck, T. F., Slutsker, I., Tanré, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y. J., Nakajima, T., Lavenu, F., Jankowiak, I., and Smirnov, A.: AERONET – a federated instrument network and data archive for aerosol characterizarion, Remote Sens. Environ., 66, 1–16, 1998. 4198

Iziomon, M. G. and Mayer, H.: Assessment of some global solar radiation parametrizations, J. Atmos. Sol.-Terr. Phy., 64, 1631–1643, doi:10.1016/S1364-6826(02)00131-1, 2002. 4194

Intergovernmental Panel on Climate Change (IPCC): Climate Change 2007: The Physical Science Basis, Working Group I Contribution to the Fourth Assessment Report of the IPCC, edited by: Solomon, S., Qin, S., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge Univ. Press, New York, 2007. 4193

Kandler, K., Benker, N., Bundke, U., Cuevas, E., Ebert, M., Knippertz, P., Rodríguez, S., Schütz, L., and Weinbruch, S.: Chemical composition and complex refractive index of Saharan Mineral Dust at Izaña, Tenerife (Spain) derived by electron microscopy, Atmos. Environ., 41, 8058–8074, 2007.

Kerr, A. and Tabony, R.: Comparison of sunshine recorded by Campbell–Stokes and automatic sensors, Weather, 59, 90–95, doi:10.1256/wea.99.03, 2004.

Khem, P. N., Binod, K. B., Sapkota, B., and Kjeldstad, B.: Estimation of global solar radiation using sunshine duration in Himalaya Region, Research Journal of Chemical Sciences, 2, 20–25, 2007.

Kipp and Zonen: CSD1 Sunshine Duration Meter, Instruction Manual, available at: http://www.kippzonen.com (last access: 24 April 2014), 2003. 4199

Lanzante, J. R.: Resistant, robust and nonparametric techniques for the analysis of climate data: theory and examples including applications to historical radiosonde station data, Int. J. Climatol., 16, 1197–1226, 1996. 4205, 4206

AMTD
7, 4191–4227, 2014

Liepert, B. G.: Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990, Geophys. Res. Lett., 29, 1421, doi:10.1029/2002GL014910, 2002. 4193

Liu, X., Mei, X., Li, Y., Zhang, Y., Wang, Q., Jensen, J., Porter, J.: Calibration of the Angstrom–Prescott coefficients (a, b) under different time scales and their impacts in estimating global solar radiation in the Yellow River basin, Agr. Forest Meteorol., 149, 697–710, doi:10.1016/j.agrformet.2008.10.027, 2009.

Long, C. and Ackerman, T.: Identification of clear skies from broadband pyranometer measurements and calculation of downwelling shortwave cloud effects, J. Geophys. Res., 105, 15609–15626, doi:10.1029/2000JD900077, 2000. 4201

Long, C. and Dutton, E.: BSRN Global Network recommended QC tests, V2.0, Tech. rep., BSRN Technical Report, 2002. 4196

Long, C. and Shi, Y.: The QCRad Value Added Product: Surface Radiation Measurement Quality Control Testing, Including Climatologically Configurable Limits, Atmospheric Radiation Measurement Program Technical Report, ARM TR-074, 2006. 4196

Louche, A., Notton, G., Poggi, P., and Simonnot, G.: Correlations for direct normal and global horizontal irradiation on a French Mediterranean site, Sol. Energy, 46, 261–266, doi:10.1016/0038-092X(91)90072-5, 1991.

Massen, F.: Sunshine Duration From Pyranometers Readings, available at: http://meteo.lcd.lu/papers/sunshine_duration_from_pyranometer/Sunshine_duration_from_pyranometer_readings.pdf (last access: 24 April 2014), 2011. 4199

Mayer, B. and Kylling, A.: Technical note: The libRadtran software package for radiative transfer calculations – description and examples of use, Atmos. Chem. Phys., 5, 1855–1877, doi:10.5194/acp-5-1855-2005, 2005. 4197

McArthur, L.: Baseline Surface Radiation Network (BSRN), Operations Manual Version 2.1, wmo/td-no. 1274 ed., WCRP-121, 2005. 4196

Miloshevich, L. M., Vömel, H., Whiteman, D. N., and Leblanc, T.: Accuracy assessment and correction of Vaisala RS92 radiosonde water vapor measurements, J. Geophys. Res., 114, D11305, doi:10.1029/2008JD011565, 2009. 4198

Nicolet, M.: The international geophysical year 1957/58, World Meteorological Organization Bulletin, 31, 222–231, 1982. 4194

Ohmura, A.: Observed long-term variations of solar irradiances at the Earth's surface, Space Sci. Rev., 125, 111–128, 2006. 4206, 4207

AMTD

7, 4191–4227, 2014

Re-construction of global solar radiation time series at Izaña station

R. D. García et al.

Ohmura, A. and Lang, H.: Secular variation of global radiation over Europe, in: Current Problems in Atmospheric Radiation, edited by: Lenoble, J. and Geleyn, J. F., 298–301, 1989. 4193

Ohmura, A., Dutton, E., Forgan, B., Fröhlich, C., Gilgen, H., Hegner, H., Heimo, A., Langlo, G., McArthur, B., Müller, G., Philipona, R., Pinker, R., Whitlock, C., Dehne, K., and Wilda, M.: Baseline Surface Radiation Network (BSRN/WCRP): new precision radiometry for climatic research, B. Am. Meteorol. Soc., 79, 2115–2136, 1988. 4196

Painter, H. E.: The performance of a Campbell–Stokes sunshine recorder compared with a simultaneous record of the normal incidence irradiance, Meteorol. Mag., 110, 102–109, 1981. 4199

Pallé, E. and Butler, C. J.: Sunshine records from Ireland: cloud factors and possible links to solar activity and cosmic rays, Int. J. Climatol., 21, 709–729, doi:10.1002/joc.657, 2001. 4194

Pinker, R. T., Zhang, B., and Dutton, E. G.: Do satellites detect trends in surface solar radiation?, Science, 308, 850–854, doi:10.1126/science.1103159, 2005. 4193

Prescott, J. A.: Evaporation from a water surface in relation to solar radiation, Trans. R. Soc. S. Austr., 64, 114–118, 1940. 4194, 4201

Ramanathan, V., Crutzen, P. J., Kiehl, J. T., and Rosenfeld, D.: Aerosol, climate and the hydrological cycle, Science, 294, 2119–2124, doi:10.1126/science.1064034, 2001. 4193

Rietveld, M. R.: A new method for estimating the regression coefficients in the formula relating solar radiation to sunshine, Agriculture Meteorological, 19, 243–252, 1978. 4201

Rodríguez, S., Alastuey, A., Alonso-Pérez, S., Querol, X., Cuevas, E., Abreu-Afonso, J., Viana, M., Pérez, N., Pandolfi, M., and de la Rosa, J.: Transport of desert dust mixed with North African industrial pollutants in the subtropical Saharan Air Layer, Atmos. Chem. Phys., 11, 6663–6685, doi:10.5194/acp-11-6663-2011, 2011. 4202

Romero, P. M., Romero, M. C., and Cuevas, E.: Espesor Óptico de aerosoles a partir de medidas directas del sol y de medidas de irradiancia global y difusa, 3° Asamblea Hispano Portuguesa de Geodesia y Geofísica, 4–8 Febrero, Valencia, 2002.

Romero, P. M., Marrero, C. L., Alonso, S., Cuevas, E., Afonso, S., and Ortiz de Galisteo, J. P.: Una climatología de agua precipitable en la región subtropical sobre la isla de Tenerife basada en datos de radiosondeo, NIPO: 281-12-007-5, Agencia Estatal de Meteorología, Ministerio de Medio Ambiente, y Medio Rural y Marino, Madrid, Spain, 2011. 4198

AMTD
7, 4191–4227, 2014

Re-construction of global solar radiation time series at Izaña station

R. D. García et al.

Sanchez-Lorenzo, A. and Wild, M.: Decadal variations in estimated surface solar radiation over Switzerland since the late 19th century, Atmos. Chem. Phys., 12, 8635–8644, doi:10.5194/acp-12-8635-2012, 2012. 4206

Sanchez-Lorenzo, A., Brunetti, M., Calbo, J., and Martin-Vide, J.: Recent spatial and temporal variability and trends of sunshine duration over the Iberian Peninsula from a homogenized data set, J. Geophys. Res., 112, D20115, doi:10.1029/2007JD008677, 2007.

Sanchez-Lorenzo, A., Calbó, J., Wild, M., Azorin-Molina, C., and Sanchez-Romero, A.: New insights into the history of the Campbell–Stokes sunshine recorder, Royal Meteorol. Society, 68, 327–331, doi:10.1002/wea.2130, 2013. 4199

Sancho, J. M., Sánchez de Cos, M. C., and Jímenez, C.: Comparison of global irradiance measurements of the official Spanish radiometric network for 2006 with satellite estimated data, Journal of Mediterranean Meteteorology & Climatology, Tethys, 8, 43–52, doi:10.3369/tethys.2011.8.05, 2011. 4196

Sanroma, E., Pallé, E., and Sanchez-Lorenzo, A.: Long-term changes in insolation and temperatures at different altitudes, Environ. Res. Lett., 5, 024006, doi:10.1088/1748-9326/5/2/024006, 2010. 4193

Samuel, T. D. M. A.: Estimation of global radiation for Sri Lanka, Sol. Energy, 47, 333–337, doi:10.1016/0038-092X(91)90026-S, 1991. 4194

Schneider, M., Romero, P. M., Hase, F., Blumenstock, T., Cuevas, E., and Ramos, R.: Continuous quality assessment of atmospheric water vapour measurement techniques: FTIR, Cimel, MFRSR, GPS, and Vaisala RS92, Atmos. Meas. Tech., 3, 323–338, doi:10.5194/amt-3-323-2010, 2010. 4198

Sivamadhavi, V. and Selvaraj, R.: Robust regression technique to estimate the global radiation, Indian J. Radio Space, 41, 17–25, 2012. 4194

Stamnes, K., Tsay, S. C., Wiscombe, W. J., and Jayaweera, K.: A numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media, Appl. Optics, 27, 2502–2509, 1988. 4197

Stanhill, G. and Cohen, S.: Global dimming: a review of the evidence for a widespread and significant reduction in global radiation, Agr. Forest Meteorol., 107, 255–278, doi:10.1016/S0168-1923(00)00241-0, 2001. 4193, 4207

Stjern, C. W., Kristjansson, J. E., and Hansen, A. W.: Global dimming and global brightening: an analysis of surface radiation and cloud cover data in northern Europe, Int. J. Climatol., 29, 643–653, doi:10.1002/joc.1735, 2009. 4207

AMTD

7, 4191–4227, 2014

Re-construction of global solar radiation time series at Izaña station

R. D. García et al.

Wehrli, C.: Calibrations of filter radiometers for determination of atmospheric optical depth, Metrologia, 37, 419–422, 2000. 4198

Wild, M.: Global dimming and brightening: a review, J. Geophys. Res., 114, D00D16, doi:10.1029/2008JD011470, 2009. 4193, 4207

Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C. N., Dutton, E. G., Forgan, B., Kallis, A., Russak, V., and Tsvetkov, A.: From dimming to brightening: decadal changes in surface solar radiation, Science, 308, 847–850, doi:10.1126/science.1103215, 2005. 4193, 4207

Wild, M., Ohmura, A., and Makowski, K.: Impact of global dimming and brightening on global warming, Geophys. Res. Lett., 34, L04702, doi:10.1029/2006GL028031, 2007. 4193

Wild, M., Grieser, J., and Schär, C.: Combined surface solar brightening and increasing greenhouse effect support recent intensification of the global land-based hydrological cycle, Geophys. Res. Lett., 35, L17706, doi:10.1029/2008GL034842, 2008. 4193, 4207

Wild, M., Roesch, A., and Ammann, C.: Global dimming and brightening evidence and agricultural implications, CCAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 7, 1–7, doi:10.1079/PAVSNNR20127003, 2012. 4193

World Meteorological Organization (WMO): Commission for Instruments and Methods of Observation, Abridged Final Report of the Eighth Session, WMO Ser., 950, Genova, 1982. 4198

World Meteorological Organization (WMO): Guide to Meteorological Instruments and Methods of Observation, 6th Edn., WMO no. 8, Secretariat of the World Meteorol. Organ., Geneva, Switzerland, 1996. 4199, 4200

Yorukoglu, M. and Celik, A. N.: A critical review on the estimation of daily global solar radiation from sunshine duration, Energ. Convers. Manage., 47, 2441–2450, 2006. 4194, 4205

AMTD

7, 4191–4227, 2014

Re-construction of global solar radiation time series at Izaña station

R. D. García et al.

Table 1. Pyranometers installed between 1992 and 2013 at IZO and OT.

Time	Instrument (Network)	Station	Spectral Range (nm)	Uncertainty Daily values (%)
Jan 1992–Jun 1999	CM-5	IZO	310–2800	±5
Jul 1999–Aug 2003	CM-11	IZO	310–2800	±2
Aug 2005–Dec 2008	CM-21(NCR)	IZO	305–2800	±2
Jan 2009–Dec 2013	CM-21(BSRN)	IZO	305–2800	±2
Jan 1995–Dec 2013	SCP	OT	250–1500	±3

AMTD
7, 4191–4227, 2014

Table 2. Calibration of the different pyranometers installed at IZO and OT between 1992 and 2005.

Time	Instrument (Station)	Original calibration*	Re-evaluated calibration Mean ± Std*
Jan 1992–Jun 1999	CM-5 (IZO)	95.42	93.02 ± 4.65
Jul 1999–Aug 2003	CM-11 (IZO)	193.05	195.05 ± 6.61
Apr 2000–Aug 2000 Jan 2001–Jul 2002 Sep 2003–Jul 2005	SCP (OT)	73.50	75.29 ± 1.04

* $Wm^{-2}\,mV^{-1}$.

AMTD
7, 4191–4227, 2014

Re-construction of global solar radiation time series at Izaña station

R. D. García et al.

Table 3. Coefficients a and b between 1992 and 1996 (Campbell–Stokes Recorder, CS) and between 2009 and 2013 (Sunshine Duration Sensor, CSD) depending on the FCS.

FCS (%)	$a \pm$ SEM	$b \pm$ SEM	% days
		CS: 1992/1996	
≤ 20	0.503 ± 0.155	0.342 ± 0.015	9
20–40	0.458 ± 0.178	0.362 ± 0.062	6
40–60	0.476 ± 0.103	0.358 ± 0.058	9
60–80	0.369 ± 0.045	0.434 ± 0.037	23
≥ 80	0.433 ± 0.039	0.386 ± 0.037	53
		CSD: 2009/2013	
≤ 20	0.981 ± 0.269	0.211 ± 0.032	3
20–40	0.391 ± 0.127	0.318 ± 0.044	5
40–60	0.478 ± 0.101	0.299 ± 0.058	5
60–80	0.553 ± 0.061	0.266 ± 0.049	11
≥ 80	0.781 ± 0.021	0.047 ± 0.021	76

AMTD
7, 4191–4227, 2014

Re-construction of global solar radiation time series at Izaña station

R. D. García et al.

Table 4. Statistics for the differences between simulations and measurements at IZ0 (in $MJ\,m^{-2}$) between 1997 and 1999 (Campbell–Stokes Recorder, CS) and between 2006 and 2008 (Sunshine Duration Sensor, CSD) according to seasons and the fraction of clear sky (FCS). (RMSE: Root Mean Square Error; *R*: correlation coefficient. The statistics for the relative bias are in brackets (%)).

	CS: 1997/1999				CSD: 2006/2008			
SEASONS	Median	RMSE	*R*	% days	Median	RMSE	*R*	% days
DJF	0.43	2.06 (6.4 %)	0.91	23	−0.26	1.52 (4.6 %)	0.95	24
MAM	−0.14	2.71 (5.3 %)	0.91	26	−0.34	1.41 (2.5 %)	0.97	25
JJA	0.27	1.87 (3.1 %)	0.85	27	0.20	0.92 (1.5 %)	0.96	25
SON	0.61	1.84 (4.6 %)	0.95	25	0.49	1.38 (3.6 %)	0.98	26
FCS (%)	Median	RMSE	*R*	% days	Median	RMSE	*R*	% days
≤ 20	1.09	4.19 (12.1 %)	0.51	8	−0.41	2.63 (6.8 %)	0.59	5
20–40	0.84	3.33 (4.9 %)	0.69	4	−0.34	1.92 (3.5 %)	0.78	5
40–60	0.96	2.54 (3.6 %)	0.83	6	0.06	1.74 (2.8 %)	0.89	7
60–80	0.35	1.81 (4.2 %)	0.92	23	−0.18	1.84 (3.1 %)	0.93	12
≥ 80	0.17	1.65 (4.5 %)	0.96	59	0.04	0.93 (2.9 %)	0.99	71
Total	0.27	2.16 (9.2 %)	0.96	–	0.02	1.33 (5.5 %)	0.99	–

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD

7, 4191–4227, 2014

Re-construction of global solar radiation time series at Izaña station

R. D. García et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 5. Coefficients *a* and *b* between 1992 and 2000 (Campbell–Stokes Recorder, CS) at IZO as a function of the fraction of clear sky values (FCS). SEM as standard error of the mean.

FCS (%)	$a \pm$ SEM	$b \pm$ SEM	% days
≤ 20	0.304 ± 0.120	0.347 ± 0.012	9
20–40	0.449 ± 0.144	0.348 ± 0.050	5
40–60	0.516 ± 0.085	0.325 ± 0.048	8
60–80	0.402 ± 0.041	0.399 ± 0.033	23
≥ 80	0.475 ± 0.039	0.339 ± 0.038	55

AMTD
7, 4191–4227, 2014

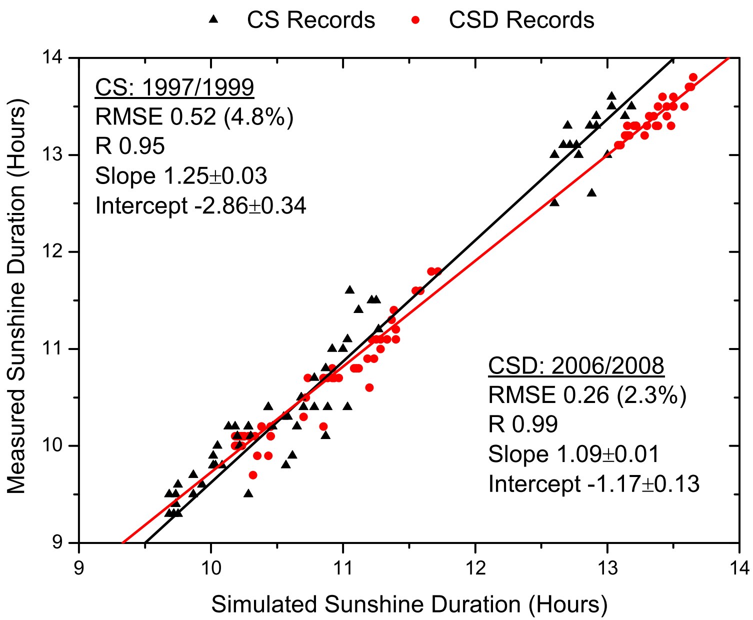

Fig. 1. Scatterplot of the measured SD from CS (black triangles) and CSD (gray dots) instruments vs. SD obtained from LibRadtran model when direct SDR exceeds a threshold value of $120\,\mathrm{W\,m^{-2}}$. The root mean square error (RMSE), and least-square fit parameters are shown in the legend.

AMTD
7, 4191–4227, 2014

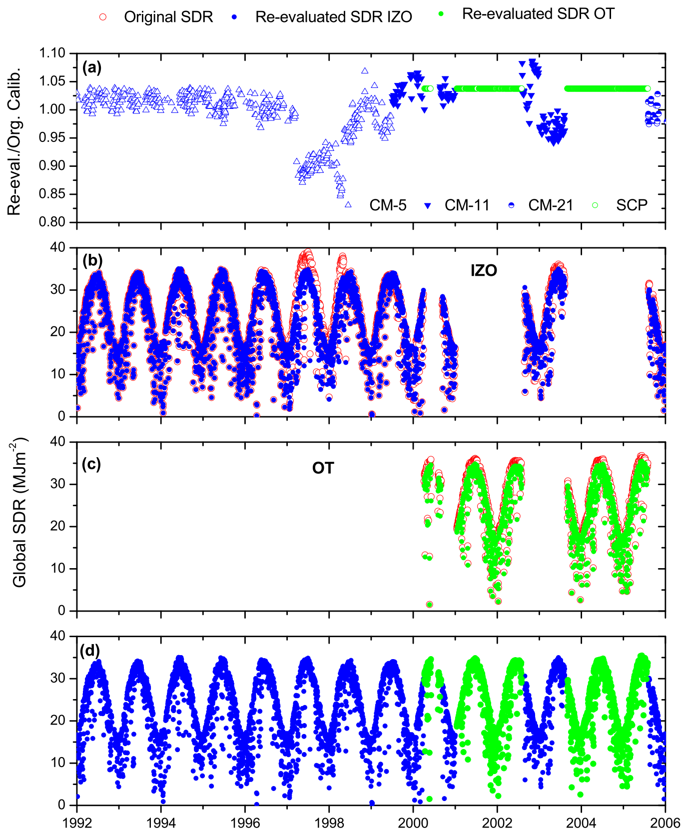

Fig. 2. (a) Evolution of ratio between the re-evaluated calibration and the original calibration for the different pyranometers installed at IZO (blue squares) and at OT (green squares). **(b)**, **(c)** and **(d)** time series of the daily global SDR (MJ m^{-2}) from 1992 to 2005 at IZO, at OT, and the whole re-calibrated time series, respectively (red squares represent original SDR, blue squares represent re-evaluated SDR at IZO and green squares represent re-evaluated SDR at OT).

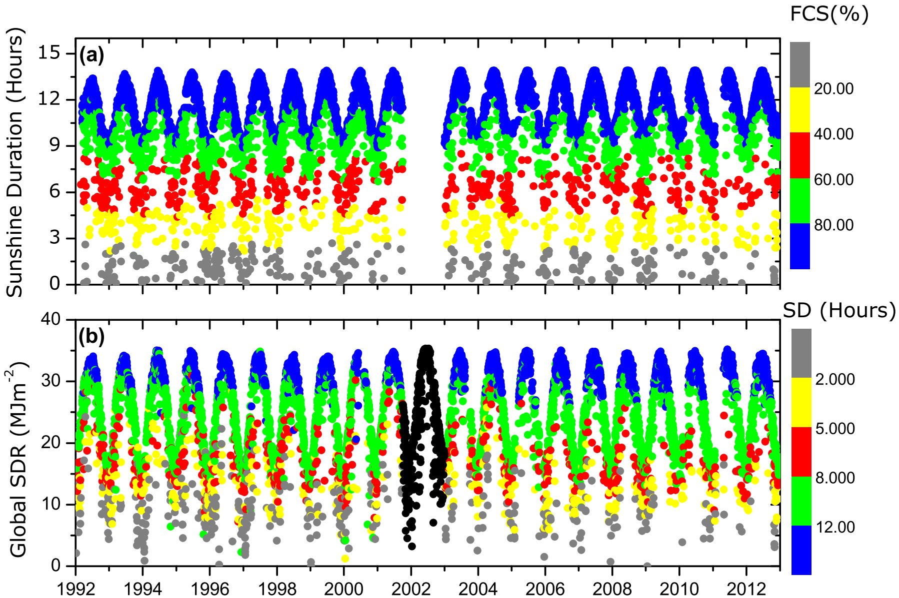

Fig. 3. Time series of **(a)** the sunshine duration (hours). The color scale indicates the fraction of clear sky values (FCS, %) **(b)** the global SDR from 1992 to 2013 at IZ0. The color scale indicates the sunshine duration (hours).

AMTD
7, 4191–4227, 2014

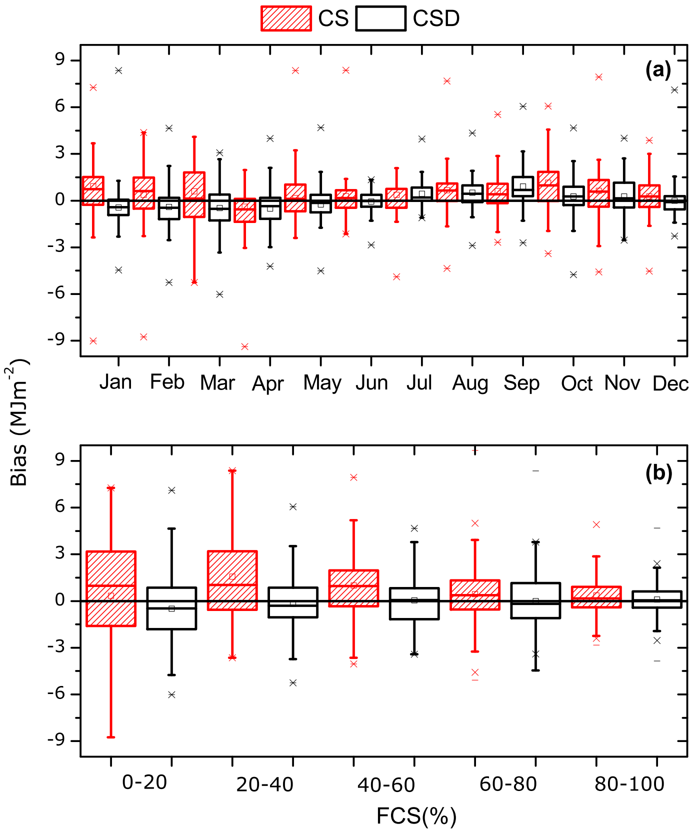

Fig. 4. Box plot of bias (MJ m^{-2}) vs. **(a)** months from 1997 to 1999 (Campbell–Stokes Recorder, CS) and between 2006 and 2008 (Sunshine Duration Sensor, CSD) and **(b)** fraction of clear sky values (FCS) at IZO. Lower and upper boundaries for each box are the 25 and 75 percentiles, the solid line is the median value, the crosses indicate values out of the 1.5 fold box area (outliers).

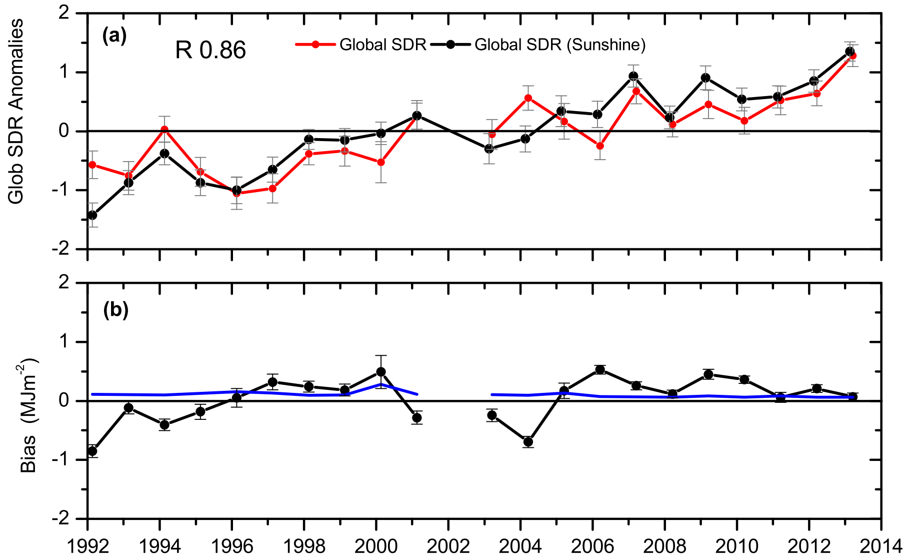

Fig. 5. Times series of annual means of **(a)** the deseasonalized anomalies of global SDR estimations (black line) and measurements (red line) and **(b)** difference between global SDR anomalies estimations and measurements (MJ m^{-2}) from 1992 to 2013 at IZO. The blue solid line represent the linear trend and the error bars indicate ±1 SEM (standard error of the annual means).

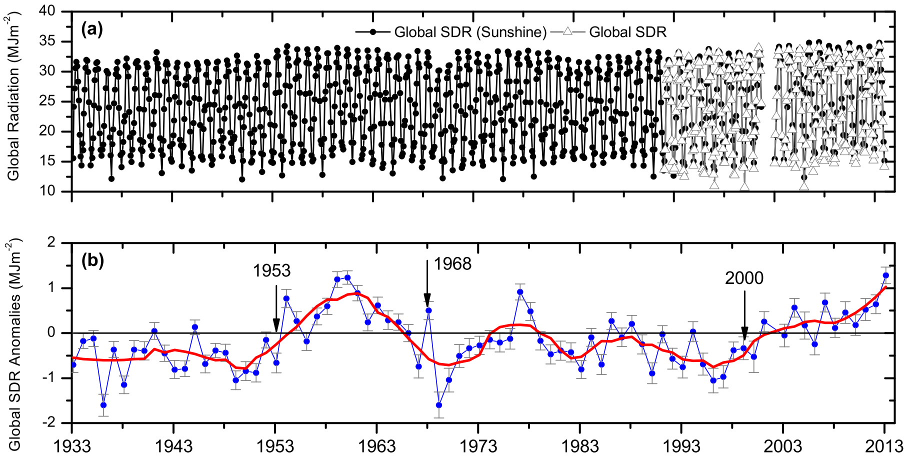

Fig. 6. Time series of the **(a)** monthly means of the global SDR ($MJ m^{-2}$). The black dots represent the global SDR obtained from SD data and the gray triangles represent the global SDR measured between 1992 and 2013 **(b)** annual means of the global SDR anomalies. The arrows indicate the change-point dates. The error bars indicate ±1 SEM (standard error of the mean). Five-year moving average is shown in red.

AMTD
7, 4191–4227, 2014

Re-construction of global solar radiation time series at Izaña station

R. D. García et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

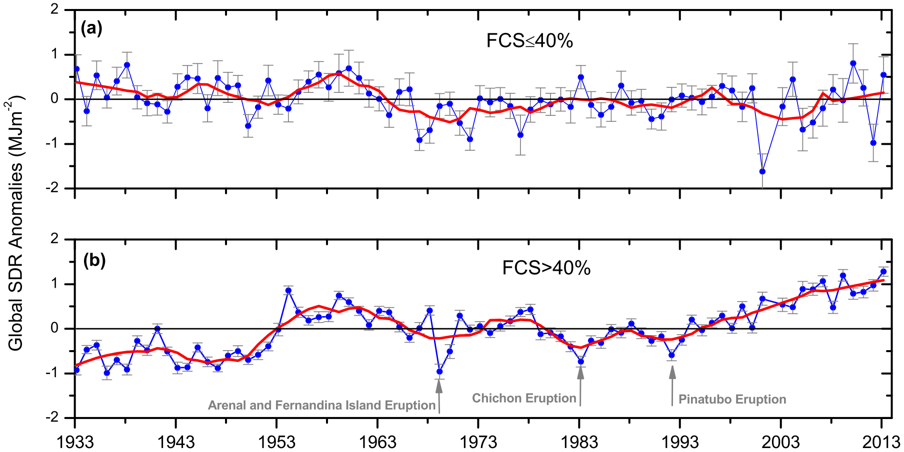

Fig. 7. Time series of the annual means of the global SDR anomalies as a function of **(a)** FCS ≤ 40 % (cloud conditions; 13 % days) and **(b)** FCS > 40 % (cloud-free conditions; 87 % days) from 1933 to 2013 at IZO. The error bars indicate ±1 SEM (standard error of the mean). Five-year moving average is shown in red. The arrows indicate the eruptions: Arenal and Fernandina Island (1968), Chinchón (1982) and Pinatubo (1991).

AMTD
7, 4191–4227, 2014

Re-construction of global solar radiation time series at Izaña station

R. D. García et al.