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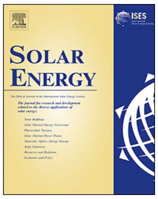

Sources of uncertainty in annual global horizontal irradiance data

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ABSTRACT

The major sources of uncertainty in short-term assessment of global horizontal radiation (G) are the pyranometer type and their operation conditions for measurements, whereas the modeling approach and the geographic location are critical for estimations. The influence of all these factors in the uncertainty of the data has rarely been compared. Conversely, solar radiation data users are increasingly demanding more accurate uncertainty estimations. Here we compare the annual bias and uncertainty of all the mentioned factors using 732 weather stations located in Spain, two satellite-based products and three reanalyses.

The largest uncertainties were associated to operational errors such as shading (bias = −8.0%) or soiling (bias = −9.4%), which occurred frequently in low-quality monitoring networks but are rarely detected because they pass conventional QC tests. Uncertainty in estimations greatly changed from reanalysis to satellite-based products, ranging from the gross accuracy of ERA-Interim ($+\,6.1^{+18.8}_{-6.7}\%$) to the high quality and spatial homogeneity of SARAH-1 ($+\,1.4^{+5.6}_{-5.3}\%$). Finally, photodiodes from the Spanish agricultural network SIAR showed an uncertainty of $^{+6.9}_{-5.4}\%$, which is far greater than that of secondary standards (±1.5%) and similar to SARAH-1. This is probably caused by the presence of undetectable operational errors and the use of uncorrected photodiodes. Photodiode measurements from low-quality monitoring networks such as SIAR should be used with caution, because the chances of adding extra uncertainties due to poor maintenance or inadequate calibration considerably increase.

1. Introduction

Solar resource assessment is essential for many disciplines such as environmental sciences, climatology or energy production. They constantly demand more accurate solar radiation data with high spatial and temporal coverage, but there is also a growing interest on the uncertainty of the data. This information allows performing uncertainty propagation studies of models that use solar radiation as input (Thevenard and Pelland, 2013). A good example of such is yield estimations for new PV systems (Müller et al., 2017), where large uncertainties in solar data lead to high financial costs. A better understanding of these uncertainties would also contribute to mitigate their impact, as well as to select the best source of data for each application.

Uncertainty of solar radiation data depends on the source of data used and the type of radiation analyzed. Data is typically available as global horizontal irradiance (G), that is the surface-downwelling shortwave radiation received on a horizontal plane. For short-term assessments, the uncertainty of G primarily depends on whether the data is measured or estimated. The type of pyranometer and the maintenance procedures are the dominant factors in measured data (McArthur, 2005), while the quality of estimations strongly varies with the modeling approach (Urraca et al., 2017c). For long-term assessments, the inter-annual variability of solar radiation and the decadal trends, known as global dimming and brightening (Wild, 2009; Müller et al., 2014), must be also accounted. Additional uncertainties appear if other variables are used, such as the diffuse (D) and beam (B) components or the irradiance at tilted surfaces (G_t). This is because these variables are rarely measured, especially G_t, and are usually derived from G using decomposition (Gueymard and Ruiz-Arias, 2016; Moretón et al., 2017) and transposition (Ineichen, 2011; Gracia and Huld, 2013) models. Herein we will only address the sources of uncertainty in short-term assessment of G. We refer to the works listed above for evaluations of the uncertainties related to long-term effects, decomposition and transposition models.

Pyranometers are the most accurate source of G data when they are well-calibrated and properly maintained. The main types of outdoor sensors are thermopiles and silicon-based photodiodes (Vignola et al., 2012). Thermopiles are based on the thermoelectric effect and typically

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Nomenclature

Δ	difference between test and reference value
B	beam (direct) surface irradiance received on a horizontal plane
D	diffuse surface irradiance received on a horizontal plane
G	global surface irradiance received on a horizontal plane
u	uncertainty

Subscripts

d	daily
h	hourly
min	minutely
t	tilted
y	annual

Superscripts

est	estimated
meas	measured
ph	photodiode pyranometer
ref	reference value
ss	secondary standard pyranometer
test	test value

achieve the lowest uncertainty. They are the only ones compliant with the requirements of WMO (WMO, 2008) and ISO 9060:1990 (ISO, 1990), which classifies them from highest to lowest accuracy in (i) secondary standard, (ii) first class and (iii) second class. Photodiode sensors are based on the photovoltaic effect and are an attractive alternative to thermopiles for remote areas and agricultural monitoring stations because of their significantly lower cost and less maintenance. Besides, their fast time response makes them the detectors used by rotating shadowband irradiometers (RSI) with continuous rotation, which provide simultaneous records of G, B and D by shading and unshading the detector periodically (Sengupta et al., 2017). However, photodiodes generally have a lower accuracy than thermopiles, mainly due to the narrow spectral response of silicon. Overall, uncertainty in ground measurements largely varies with the type and cost of the instrument. Some of the factors limiting their accuracy are the cosine error, linearity, spectral effects and temperature dependence (Diresse et al., 2016). The implementation of corrections for these defects becomes essential to achieve acceptable uncertainties (Al-Rasheedi et al., 2018). All these errors are inherent to the sensor and its calibration, and are referred to as *equipment errors* (Younes et al., 2005; Journée and Bertrand, 2011). Excluding large deviations in the calibration constants, equipment errors cannot be detected with quality control (QC) methods and are commonly present in measured data.

The operation conditions of measurement stations introduce additional uncertainties in ground records. This is the case of shading by surrounding objects, accumulation of dust or snow, incorrect leveling of the sensor and electronic problems (Younes et al., 2005; Journée and Bertrand, 2011). All of them are referred to as *operational errors* and are independent of the type of sensor employed. Their magnitude highly varies with the severity of the defect but is generally larger than that of equipment errors. The probability of detecting operational errors should be therefore higher, but common defects, such as shading and soiling, produce acceptable records from a physical perspective. Hence, finding most operational errors in practice is also unlikely (Urraca et al., 2017a) and they are frequent in ground datasets, especially on those from low-quality networks and stations under extreme weather conditions.

Estimations are used in the absence of ground records, which is the most common case due to the sparsity and limited temporal coverage of ground stations. Satellite-based and reanalysis models are the most extended approaches (Bojanowski et al., 2014; Urraca et al., 2017c), as they provide long-time series with spatially continuous estimations. Satellite-based models use images from geostationary and polar-orbiting satellites to estimate cloud properties, and are the most popular method due to their superior quality (Sengupta et al., 2015; Polo et al., 2016). Reanalyses are based on the combination of numeric weather prediction (NWP) models with ground and satellite observations, but they generally have less accuracy than satellite-based models, mainly due to their coarse spatial resolutions (30–80 km). On their plus side, they provide hourly estimations of surface irradiance with global coverage, without gaps and include many other climatic variables. The uncertainty of these products greatly varies spatially because it depends not only on the characteristics of the database but also on the particular conditions of the place being assessed (Urraca et al., 2017b).

The uncertainty in some of the sources of solar radiation data listed above has been analyzed individually. Radiation databases are commonly validated against measurements from high quality ground stations (Suri and Cebecauer, 2014; Ineichen, 2014; Bojanowski et al., 2014; Urraca et al., 2017b, 2018). The uncertainty of thermopiles (Habte et al., 2015; Vuilleumier et al., 2014; Reda, 2012) and photodiodes (Al-Rasheedi et al., 2018; Wilbert et al., 2015; Geuder et al., 2014) has been evaluated with side-by-side comparisons against reference sensors, limiting the number of radiometers used in these studies. The magnitude of cosine errors, linearity effect, temperature dependence and spectral mismatch has also been estimated (Sengupta et al., 2012; Driesse et al., 2015, 2016). Nonetheless, uncertainties in estimated and measured data are rarely evaluated and compared within a common framework, and there is a lack of information about the impact of operational errors because they are rarely detected by QC tests.

Our main goal in this study is to evaluate the uncertainty in annual G associated to (i) estimations, (ii) operational errors and (iii) equipment errors. For that, we use measurements from 732 Spanish stations and estimations from two satellite-based products and three reanalyses. The study is conducted in annual terms from 2005 to 2013 because this is the common temporal resolution used for the prospection of new PV systems (Müller et al., 2017); however daily uncertainties are also reported for the comparison with previous studies. In case of equipment errors, the lack of collocated reference radiometers hinders a strict uncertainty estimation. We assume that the field uncertainty of the 53 secondary standard thermopiles from the national meteorological network should be close to their calibration uncertainty. Based on this, we make a rough estimate of the uncertainty of photodiodes that have a secondary standard closer than 20 km. Note that part of this uncertainty may be due to the reference instrument and to the validation procedure. Finally, using a novel QC method (Urraca et al., 2017a) we detect small operational errors by comparing the measurements against estimations from different independent radiation databases. The cause of each operational error is identified by visual inspection of the plots generated with the QC method, allowing the estimation of the uncertainty associated to each type of operational defect.

2. Data

2.1. Measurements: weather stations

Ground records of G were retrieved from all Spanish weather stations that provided them at no cost (Fig. 1). This results in a ground dataset comprised by 732 stations distributed in 9 networks, including global networks such as the Baseline Radiation Surface Network (BSRN)