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Variability analysis of the reconstructed daily global solar radiation under all-sky and cloud-free conditions in Madrid during the period 1887–1950

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ABSTRACT

This study focuses on the analysis of the daily global solar radiation (GSR) reconstructed from sunshine duration measurements at Madrid (Spain) from 1887 to 1950. Additionally, cloud cover information recorded simultaneously by human observations for the study period was also analyzed and used to select cloud-free days. First, the day-to-day variability of reconstructed GSR data was evaluated, finding a strong relationship between GSR and cloudiness. The second step was to analyze the long-term evolution of the GSR data which exhibited two clear trends with opposite sign: a marked negative trend of −36 kJ/m^2 per year for 1887–1915 period and a moderate positive trend of +13 kJ/m^2 per year for 1916–1950 period, both statistically significant at the 95% confidence level. Therefore, there is evidence of "early dimming" and "early brightening" periods in the reconstructed GSR data for all-sky conditions in Madrid from the late 19th to the mid-20th centuries. Unlike the long-term evolution of GSR data, cloud cover showed non-statistically significant trends for the two analyzed sub-periods, 1887–1915 and 1916–1950. Finally, GSR trends were analyzed exclusively under cloud-free conditions in summer by means of the determination of the clearness index for those days with all cloud cover observations equal to zero oktas. The long-term evolution of the clearness index was in accordance with the "early dimming" and "early brightening" periods, showing smaller trends but still statistically significant. This result points out that aerosol load variability could have had a non-negligible influence on the long-term evolution of GSR even as far as from the late 19th century.

1. Introduction

Solar radiation reaching the Earth's surface plays a key role in the energy budget of the Earth–atmosphere system, being fundamental for diverse processes such as evaporation, water cycle and plant photosynthesis (e.g., Stephens et al., 2012; Wild et al., 2013). The assessment of the long-term variation of solar radiation at surface is required for various issues such as global warming, glacier retreat, water resources and solar energy applications (for a review, we refer to Wild, 2009, 2016).

Widespread measurements of the global (direct plus diffuse) solar radiation (GSR) at surface were not initiated until 1957/58 within the framework of the International Geophysical Year (Stanhill and Achiman, 2016). Since then, several ground-based networks have provided high-quality GSR data using well-characterized instrumentation (e.g., Gilgen et al., 1998; Ohmura et al., 1998). From all these measurements recorded for the last decades, a widespread decrease in GSR from the 1950s to the 1980s (a phenomenon called "global dimming") has been detected in numerous locations worldwide (e.g., Stanhill and Cohen, 2001 and references therein; Liepert, 2002; Ohmura, 2009). Additionally, it has also been observed a partial recovery of GSR values at surface from the middle 1980s to nowadays, a phenomenon known as "brightening" (e.g., Hatzianastassiou et al., 2005; Wild et al., 2005; Sanchez-Lorenzo et al., 2013a).

Unfortunately, few ground-based stations have reliable GSR data before the 1950s, even in areas with the highest density of long-term series such as Europe or Japan (e.g., De Bruin et al., 1995; Gilgen et al., 1998; Ohmura, 2006, 2009; Stanhill and Achiman, 2016). Thus, for example, there are only around five stations in Europe that provide data before the 1950s, none of them located in Southern Europe

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(Sanchez-Lorenzo et al., 2015). Some of these scarce datasets have shown an increase of the radiative values in the first part of the 20th century (Wild, 2009; Ohmura, 2006, 2009; Lachat and Wehrli, 2011; Sanchez-Lorenzo et al., 2015; Stanhill and Achiman, 2016). However, this "early brightening" is not evident for other datasets (e.g., Ohvril et al., 2009; Sanchez-Lorenzo and Wild, 2012; Tanaka et al., 2016), making of this phenomenon a controversial issue (Antón et al., 2014).

To overcome the limited number of GSR datasets before 1950s, several proxies, such as sunshine duration (SD), daily temperature range and visibility among others, have been tested for the reconstruction of the surface solar radiation (Wild, 2009, 2012). Among these variables, SD has been successfully proved as an excellent proxy measure allowing long-term reconstructions of GSR at different sites. For instance, Stanhill and Cohen (2005) estimated GSR data from SD records in several sites at the US from 1891 to 1987 using a linear relationship between the two variables. Stanhill and Cohen (2008) performed a similar study for numerous sites in Japan being the study period 1890–2002. More recently, García et al. (2014) reconstructed GSR time series at Izaña (Canary Islands, Spain) for the period 1933–1991 using the linear Ångström–Prescott model. Román et al. (2014a) estimated GSR data in nine locations at the Iberian Peninsula (including Madrid) from long-term SD measurements after 1950s by means of a semi-empirical method based on a combination of radiative transfer and empirical relationships.

It must be noted that SD measurements started in the 19th century (Pallé and Butler, 2001; Stanhill, 2003; Sanchez-Lorenzo et al., 2013b; Magee et al., 2014). However, the estimation of GSR data from SD records extending back over the last part of 19th century are really scarce in Europe; only reconstructions since 1885 in Switzerland (Sanchez-Lorenzo and Wild, 2012), since 1884 in Krakow (Poland) (Matuszko, 2014) and since 1893 in Potsdam (Germany) (Stanhill and Achiman, 2016) can be found in the literature. Moreover, there is a remarkable lack of studies focusing on the long-term reconstruction of GSR data under cloud-free conditions before 1950s, which requires collocated cloud cover information together with SD records (Sanchez-Lorenzo and Wild, 2012).

In the Iberian Peninsula, previous studies have analyzed the trends in measured GSR since 1980s (Sanchez-Lorenzo et al., 2013c) and reconstructed GSR since 1950s (Román et al., 2014a; Manzano et al., 2015). Therefore, a systematic analysis of the GSR series in this region from the late 19th to the mid-20th centuries is still lacking. In this framework, the present paper analyzes the daily GSR series reconstructed from SD data at Madrid (Spain) for the period 1887–1950. Additionally, GSR trends under cloud-free conditions are also evaluated taking into account cloud cover information, which is also available together with SD records for the whole study period. To our knowledge, these GSR trend analyses for both all-sky and cloud-free condition can be considered as the first one extending back over the last quarter of the 19th century. It is therefore expected that this paper will contribute to the understanding of the past evolution of the surface solar radiation.

2. Data

Astronomical Observatory of Madrid (AOM), currently National Astronomical Observatory, was founded in 1785 and has developed several observational programs in astronomy and meteorology along its history (López Arroyo, 2004). In 1876, AOM staff began a solar observing program, drawing and counting sunspots as occurred in many other astronomical observatories around the world (Vaquero, 2007). Different measurements were performed in several stages including sunspot number and areas (Aparicio et al., 2014), solar protuberances, solar flocculi, and other meteorological readings related to the solar radiation as: pyrheliometrical measurements (Antón et al., 2014), SD and cloud cover data. The datasets of these two latter variables were rescued from annual (or bi-annual) publications made by AOM titled "Observaciones Meteorológicas efectuadas en el Observatorio de Madrid" [Meteorological observations made at the Madrid Observatory] (from 1887 to 1905) and "Anuario del Observatorio de Madrid" [Yearbook of the Madrid Observatory] (from 1906 to 1919). Thus, continuous daily series of both SD and cloud cover data were obtained from 1 January 1887 to 31 December 1919. On the one hand, regarding SD records, it was generally not possible to obtain information on the instruments used in 1887–1919 period; however we know from the metadata that the measurements were started by using a Jordan photographic recorder but possibly soon replaced by a Campbell-Stokes heliograph. On the other hand, the cloud cover data recorded by human observations (tenths of sky covered by clouds) consist of whole numbers from 0 (cloud-free sky) to 10 (overcast sky). The daily values of cloud cover are an average of seven observations made at 6:00, 9:00, 12:00, 15:00, 18:00, 21:00, and 24:00 (Local Time of Madrid).

From 1 January 1920 the measurements of SD and cloud cover were continued at the "Retiro" meteorological observatory, which currently belongs to the Spanish Meteorological Agency (AEMET). This station was located nearby the AOM with very similar environmental conditions and horizon height. The instrument used for SD measurements since 1920 was the Campbell-Stokes heliograph, while the human observations of cloud cover obtained from that year were expressed in oktas of sky covered by clouds, which consist of whole numbers from 0 (cloud-free sky) to 8 (overcast sky). Daily values of cloud cover were obtained from the average of three-daily oktas observations taken at 7:00, 13:00 and 18:00 UTC. The daily values of tenths of sky covered by clouds from 1897 to 1919 were tuned into oktas in order to work with the same variable for the whole study period.

Due to the lack of reference series with SD and cloud cover data in the vicinity of Madrid since the late 19th century, we have used an absolute homogenization method to assess their temporal homogeneity. Thus, the temporal homogeneity of each of the monthly means of SD and cloud cover series was checked by means of the Standard Normal Homogeneity Test (SNHT) (Alexandersson, 1986). The results show that both series from 1887 to 1950 are homogenous at the 95% confidence level, which enable us to study their climate trends.

3. Methodology

3.1. Reconstruction method

The GSR data used in this work were obtained applying the reconstruction method developed by Román et al. (2014a). This method is based on the cloud modification factor of GSR (CMF_{GSR}), which is defined as the ratio of GSR to GSR under cloud-free conditions (GSR_{cf}). The methodology supposes that CMF_{GSR} can be retrieved from SD, and once CMF_{GSR} and GSR_{cf} are obtained, the GSR can be calculated by:

$$GSR = CMF_{GSR} \times GSR_{cf} \tag{1}$$

First, for each day from 1887 to 1950 at Madrid, the GSR under cloud-free conditions was estimated by the two-stream fluxes ("twostr") solver developed by Kylling et al. (1995), which belongs to the UVSPEC tool included in the libRadtran 1.7 package (Mayer and Kylling, 2005). To this end, monthly climatology (given in Román et al., 2014b) of water vapor column, surface albedo, aerosol optical depth at 443 nm and Ångström Exponent were used as input. The detailed description of these simulations together with the analysis of their uncertainties can be found in Román et al. (2014c).

In a second step, the daily sunshine fraction (F) was calculated as the ratio of SD to the theoretical SD under cloudless conditions (SD_0). SD_0 was calculated as the time span from solar zenith angle (SZA) of 87° at sunrise to a SZA of 87° at sunset. CMF_{GSR} was obtained by interpolation of the value of F in a table (see Table 3 in Román et al., 2014a) that contains CMF_{GSR} values for different F values; these CMF_{GSR} values also depend on season. Once all CMF_{GSR} values were obtained from F data, the daily GSR data were obtained multiplying these values by GSR_{cf} as Eq.