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Global and diffuse solar radiation in Spain: Building a homogeneous dataset and assessing their trends

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ABSTRACT

There is a growing interest in the study of decadal variations in surface solar radiation during the last decades, although the analyses of long-term time series in some areas with major gaps in observations, such as in Spain, are still pending. This work describes for the first time the development of a new dataset of surface solar radiation in Spain based on the longest series with records of global solar radiation (*G*), most of them starting in the early 1980s. Additional records of diffuse solar radiation (*D*), which is a component of *G* much less studied due to the general scarcity of long-term series, are available for some of these series. Particular emphasis is placed upon the homogenization of this dataset in order to ensure the reliability of the trends, which can be affected by non-natural factors such as relocations or changes of instruments. The mean annual *G* series over Spain shows a tendency to increase during the 1985–2010 period, with a significant linear trend of +3.9 $W m^{-2}$ per decade. Similar significant increases are observed in the mean seasonal series, with the highest rate of change during summer (+6.5 $W m^{-2}$ per decade) and secondly in autumn (+4.1 $W m^{-2}$ per decade) and spring (+3.2 $W m^{-2}$ per decade). These results are in line with the widespread increase of *G*, also known as brightening period, reported at many worldwide observation sites. Furthermore, the annual mean *D* series starts without relevant variations during the second half of the 1980s, but it is disturbed by a strong increase in 1991 and 1992, which might reflect the signal of the Pinatubo volcanic eruption. Afterwards, the mean series shows a tendency to decrease up to the mid-2000s, with a significant linear trend of −2.1 $W m^{-2}$ per decade during the 1985–2010 period. All these results point towards a diminution of clouds and/or aerosols over the area.

1. Introduction

Incident sunlight at the Earth's surface, or surface solar radiation, is the fundamental source of energy in the climate system, and consequently a key component for life on our planet. Due to its central role in the Global Energy Balance (Trenberth et al., 2009; Stephens et al., 2012; Wild et al., 2013), knowledge on the variations of solar radiation plays a crucial role in a large number of processes. Moreover, it is a crucial element for a number of socioeconomic sectors of principal importance, such as agriculture, tourism, solar energy production, or even health care, e.g. due to its links with ultraviolet radiation and the associated risk of skin cancer.

Although traditionally solar radiation was assumed to be constant over the years, nowadays there is a growing interest in the impact of the decadal variations of this magnitude during recent decades. In fact, a widespread reduction of about 3–9 $W m^{-2}$ in the global solar radiation (*G*) from the 1950s to the 1980s has been well documented (Stanhill and Cohen, 2001; Liepert, 2002; Wild, 2012), a phenomenon that was called *global dimming* (Stanhill and Cohen, 2001). Since the 1980s, a stabilization and increase in *G* have been detected in many regions of the World, especially in the industrialized nations, with an overall increase of about 1–4 $W m^{-2}$ (e.g. Hatzianastassiou et al., 2005; Wild, 2012), which was coined as *brightening* (Wild et al., 2005) period. As a result of these trends in *G*, changes in different components of the climate system have also been reported, such as impacts on surface temperatures and global warming (Wild et al., 2007), the intensity of the hydrological cycle (e.g. Ramanathan et al., 2001; Wild and Liepert 2010), the melting processes in glaciers and snow cover (e.g. Ohmura et al., 2007), or the terrestrial carbon cycle and plant growth through the regulation of the photosynthesis (e.g. Gu et al., 2002; Wild et al., 2012).

The causes of the dimming/brightening are very complex, although changes in the transparency of the atmosphere due to changes in anthropogenic aerosol emissions and variations in cloud characteristics are considered the most probable factors explaining these trends (for a review, see Stanhill and Cohen, 2001; Wild, 2009). Regarding the changes in cloudiness, it has been suggested that the dimming and brightening periods were linked to an increase and decrease in cloud cover, as well as changes in the cloud types, respectively (e.g. Russak, 1990, 2009; Liepert, 1997, 2002; Liepert and Kukla, 1997; Stjern et al., 2009). However, this fact is not always obvious due to a disagreement

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in the trends of both *G* and cloudiness variables found in other studies (e.g. Stanhill and Moreshet, 1994; Kaiser, 2000; Norris and Wild, 2007, 2009; Chiacchio and Wild, 2010). Equally, changes in *G* under clear sky conditions have also been observed (e.g. Wild et al., 2005; Qian et al., 2007; Ruckstuhl et al., 2008), emphasizing the important role of atmospheric aerosols in the dimming/brightening phenomenon, which is also supported by the fact that observed and modeled decadal changes in anthropogenic aerosol emissions and concentrations are in line with the trends in *G* (e.g. Stern, 2006; Streets et al., 2006, 2009; Cermak et al., 2010; Folini and Wild, 2011). However, both global dimming and brightening still have major uncertainties in their explanation and quantification, as it was stated by the IPCC Fourth Assessment Report (Trenberth et al., 2007, p. 279), or recently pointed out by Wild (2012).

Additionally, changes in the diffuse part of the solar radiation (*D*), or the diffuse fraction (*D*/*G*), have also been observed during the last decades over Europe (e.g. Russak, 1990, 2009; Stanhill, 1998; Liepert and Tegen, 2002; Power, 2003; Black et al., 2006; Abakumova et al., 2008; Mercado et al., 2009), United States (Liepert and Tegen, 2002), China (e.g. Liang and Xia, 2005; Qian et al., 2007; Mercado et al., 2009), South Africa (Power and Mills, 2005), or India (Soni et al., 2012). Overall, there is a tendency towards an increase (decrease) of the *D*/*G* during the dimming (brightening) period due to the enhanced (reduced) scattering in the atmosphere as a response to the increase (decrease) of aerosols and clouds. Among other processes, a relevant impact of changes in *D* has been demonstrated for plant photosynthetic activity, which tends to increase in dense vegetation canopies with an increase of *D* and *D*/*G* (e.g. Gu et al., 2002; Mercado et al., 2009).

One of the most important issues when analyzing the decadal evolution of *G* is the lack of long-term series of surface solar radiation in vast areas of the World (e.g. Africa, South America, Middle East), as well as the low number of stations even over the areas with the highest density of series, such as Europe (Stanhill, 1983). Thus, for example, in Europe currently there are less than about 80 stations with more than 25–30 years of data for *G* series in the Global Energy Balance Archive (GEBA) (Gilgen et al., 1998), which on the other hand are mainly concentrated over central Europe, without any of these stations available over the Iberian Peninsula (Chiacchio and Wild, 2010). Furthermore, the limited number of stations with long-term measurements is even more evident for *D* series. Thus, in the GEBA database there are less than about 20 stations providing *D* series over Europe (e.g. see Table S1 in Mercado et al., 2009), mostly located in Germany and other areas of Central Europe and none in Spain. Equally, another open issue in the global dimming/brightening topic is the lack of a comprehensive evaluation of the temporal homogeneity of the solar radiation series (Wild, 2009), which are often affected by spurious data and temporal inhomogeneities (e.g. Shi et al., 2008; Sanchez-Lorenzo et al., 2011; Tang et al., 2011; You et al., in press), despite the recent efforts for quality control of these measurements (e.g. at Baseline Surface Radiation Network stations, e.g. Long and Dutton, 2002).

Although previous attempts have been made to collect solar radiation records in Spain in order to study their statistical characterization and to produce solar radiation maps (e.g. Baldasano et al., 1988; Santabarbara et al., 1996; Moreno et al., 2011; Sancho et al., 2012), a systematic assessment of the homogeneity and analysis of the trends in the *G* and *D* series available over Spain is still lacking. Thus, the main objective of this study is to generate a long-term dataset of homogeneous *G* and *D* series over Spain, and secondly to study their temporal changes during the last decades. The dataset used in this study is described in Section 2, whereas the results of the quality controls and homogeneity assessment of the *G* and *D* series are presented in Section 3. The results for the trend analysis of the mean *G* and *D* series over Spain and site by site during the last decades are shown and discussed in Sections 4 and 5, respectively. Finally, conclusions of this study are presented in Section 6.

2. Data

The complete radiation dataset containing measurements of solar radiation in Spain was obtained from the Spanish *Agencia Estatal de Meteorología* (AEMET). It consists of daily records of *G* over a horizontal surface, expressed as irradiation units (kJ m^{-2}), from around 70 stations, most of them with data only for the last 10 years. Only series starting in the late 1970s or the early 1980s, and containing at least 20 years of data up to 2010 (the last year considered in this study), have been selected. For some sites a composite series has been generated using data from more than one station in close proximity, which normally is due to relocations of the meteorological stations (e.g. relocated from the cities to the airports). In total, 4 of the final series within the dataset were reconstructed by assembling two or three series. Taking into account these previous considerations, the final dataset consists of 13 series distributed over Spain, one of them located in the Balearic Islands (Fig. 1). The longest series is located in Madrid, with the records starting in July 1973, while all series are available after 1984. Daily series of *D* are also provided for 5 of the stations considered in this study, with the longest measurements also in Madrid since 1977 and with all series available after 1986. Table 1 shows the main details of the 13 stations used in this study, including the relocations of the stations and the starting year of the measurements for both *G* and *D* series.

Although a complete assessment of the instrumentation changes cannot be performed due to the limited availability of metadata, it is ensured that *G* measurements have been performed by using Kipp & Zonen pyranometers since 1974. These pyranometers were periodically calibrated according to the standards for measurements of the World Radiation Centre in Davos. Correspondingly, *D* measurements have been carried out by means of the same type of pyranometers, but equipped with a device to shadow the instrument from the direct solar radiation. Nowadays, the *D* records in the AEMET network are measured using shadow spheres mounted on sun tracking systems (Sancho et al., 2011), although in former times shadow bands were used. Unfortunately, we do not have information about the year of change of the shading devices of the pyranometers at each station, or the method used to correct the diffuse radiation intercepted by the band, which can introduce a bias in the records, even if the corresponding corrections are applied (e.g. Sánchez et al., 2012). More details about the calibration program and equipment currently installed at the Spanish radiometric network of the AEMET can be consulted in Sancho et al. (2011), although it is obvious that the accuracy of the measurements cannot be assessed for the whole period analyzed in this study. Nevertheless, a homogenization effort has been carried out (see Section 3) to ensure the consistency and quality of the temporal evolution of the time series, such as, for example, to correct a continuous drifting in the series of one station due to an inadequate calibration of the instrument or a possible sudden change of the shading devices of the pyranometers to obtain the *D* records.

An effort has been made to recover and digitize former solar radiation records in Spain, as there are references of previous observations back in time. In fact, there is evidence of pioneer measurements using actinometers since the mid-19th century (Rico Sinobas, 1859), and of systematic measurements of direct solar radiation using well-established pyrheliometers since the beginning of the 20th century in different locations of Spain (e.g. Font Tullot, 1946). Consequently, it is reasonable to assume that observations of *G* were performed in Spain before the 1970s. Unfortunately, it was impossible to find original observations of these previous solar radiation measurements in Spain. Instead, daily data of *G* from 1958 to 1974, currently not available in digital format, were found in different volumes of the publications entitled "Radiación solar en España" (Instituto Nacional de Meteorología, 1974, 1976) edited by the Spanish weather service (currently, AEMET). Among the 15 stations included in the publication, only data of 3 locations were useful for our study; in particular, the data of the Murcia and Oviedo stations allowed us to start these series in 1972 instead of 1975. Equally, for