**Trends in downward surface solar radiation from satellites and ground
observations over Europe during 1983-2010**

Arturo Sanchez-Lorenzo¹, Aaron Enriquez-Alonso², Martin Wild³,
Jörg Trentmann⁴, Sergio M. Vicente-Serrano¹, Alejandro Sanchez-Romero², Rebekka Posselt⁵,
Maria Hakuba³

¹ *Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE-CSIC),
Zaragoza, Spain*

² *Department of Physics, University of Girona, Girona, Spain*

³ *Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland*

⁴ *Deutscher Wetterdienst (DWD), Offenbach, Germany*

⁵ *Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland*

Corresponding author:

Arturo Sanchez-Lorenzo

Pyrenean Institute of Ecology (IPE)

Spanish National Research Council (CSIC)

Av. Montañana 1005

50059 Zaragoza (Spain)

Email: arturo.sanchez@ipe.csic.es

Abstract

Trends of all-sky downward surface solar radiation (SSR) from satellite-derived data over Europe (1983-2010) are first presented. The results show a widespread (i.e., non-local dimension) increase in the major part of Europe, especially since the mid-1990s in the central and northern areas and in springtime. There is a mean increase of SSR of at least 2 Wm^{-2} per decade from 1983 to 2010 over the whole Europe, which, taking into account that the satellite-derived product lacks of aerosol variations, can be mostly related to a decrease in the cloud radiative effects over Europe. Secondly, residual series have been derived as the result of the difference between ground-based and satellite-derived all-sky SSR data. The residual mean series points to a significant increase during the period 1983-2010, with higher rates of around 2 Wm^{-2} per decade over central and eastern Europe. The spatial variation of these residual time series, which are in line with clear-sky SSR trends over Europe reported in the literature, seem to suggest that these differences in the residual series are not just explained by calibration issues in the satellite-derived product.

Keywords: surface solar radiation, satellite-derived, all-sky irradiance, temporal inhomogeneities, decadal changes, brightening, Europe.

1. Introduction

Downward surface solar radiation (SSR) is a critical part of the Global Energy Balance and the climate system, and consequently, the understanding of changes in SSR are crucial for an improved understanding of climate change issues (IPCC, 2013; Wang and Dickinson, 2013; Wild, 2012). A widespread decrease of SSR from the 1950s to the 1980s has been observed (Liepert, 2002; Stanhill and Cohen, 2001; Wild, 2009), followed by an increase of SSR since the mid-1980s, especially in developed regions such as Europe (Wild, 2009). These periods of decrease and increase of SSR have been named as global dimming and brightening (Stanhill and Cohen, 2001; Wild *et al.*, 2005), respectively. Changes in the transmission of the atmosphere due to variations in cloud properties and aerosols have been suggested as the main causes of these SSR trends (Mateos *et al.*, 2014; Stanhill and Cohen, 2001; Wang *et al.*, 2012; Wild, 2009, 2016).

However, both global dimming and brightening phenomena still have some uncertainties, due to for example the lack of long-term SSR series, especially under clear-sky conditions, which limit the spatial representativeness of the observed changes (Hakuba *et al.*, 2013; Hinkelman *et al.*, 2009; Wild, 2009). Satellite-derived SSR offers an alternative to fill these gaps, at least since the 1980s, as they have a better coverage than ground-based observations. Nevertheless, these satellite datasets are also frequently affected by non-climatic factors due to the use of different instruments to derive the datasets and the temporal degradation of satellite sensors (Sanchez-Lorenzo *et al.*, 2013b; Zhang *et al.*, 2015).

Hinkelman *et al.* (2009) analyzed the trends of the SSR derived from the GEWEX-SRB project (1° resolution) during the period 1983-2004. Their results show a slight increase of 0.25 Wm^{-2} on global scale, with a similar decadal evolution over Europe, which it is not in line with the

ground-based observations (Chiacchio and Wild, 2010; Sanchez-Lorenzo *et al.*, 2015). Pinker *et al.* (2005) used a different product (2.5° resolution) and found that the derived global mean SSR series underwent a significant increase of 1.6 Wm⁻² per decade from 1983 to 2001. Their results highlighted that the positive trends are mainly concentrated over the oceans and not over land areas, in disagreement with the brightening detected in surface observations over land (Wild, 2009). On the other hand, Hatzianastassiou *et al.* (2005) derived a SSR product from 1984 to 2000 (2.5° resolution) and reported a significant increase of +2.4 Wm⁻² per decade in the global mean series, which is considerably higher than the results from Pinker *et al.* (2005) and Hinkelman *et al.* (2009). Overall, the increase in SSR shown by Hatzianastassiou *et al.* (2005) is more in line with the brightening period observed in the surface measurements since the late 1980s (Wild, 2009; Wild *et al.*, 2005), although it is worth noting that trends over different regions, such as Europe, are not reported. Recently, Zhang *et al.* (2015) and Wang *et al.* (2015) reported a disagreement between ground-based records and different satellite-derived products over China.

The Satellite Application Facility for Climate Monitoring (CM SAF) has generated a product of SSR based on the instruments on-board the geostationary Meteosat First Generation satellites covering the period 1983-2005 (Mueller *et al.*, 2011; Posselt *et al.*, 2011a). Over Europe, considering a subset of grid points, this dataset shows a significant annual increase of 1.8 Wm⁻² per decade over the whole period which increases up to 4.5 Wm⁻² per decade if only the 1994-2005 period is considered (Sanchez-Lorenzo *et al.*, 2013b). More recently, this dataset has been extended by using records from the Meteosat Second Generation satellites until 2010 by Posselt *et al.* (2014), who reported a mean increase of 4.4 Wm⁻² per decade over the whole Europe

during the 1994-2010 period, but without an analysis of the spatial and seasonal differences in the trends (Posselt *et al.*, 2014).

The main goal of this work is to study the changes of the annual and seasonal SSR over Europe by using the CM SAF SSR product extended until 2010, with special emphasis on the spatial and seasonal differences of these trends as previous literature mainly focused on the average over the whole of Europe on an annual basis. In addition, this work studies the residual series obtained by subtracting the high spatial resolution satellite-based all-sky data from a homogeneous dataset of ground-based of all-sky SSR on monthly basis. The datasets used in this study are described in Section 2. The trends of all-sky SSR over Europe are detailed in Section 3, whereas the residual series are shown in Section 4. Finally, conclusions of this paper are presented in Section 5.

2. Datasets and analysis

The satellite-based data set used in this study is based on the CM SAF Surface Radiation data set derived from the Meteosat geostationary satellites of the First Generation (MFG, Meteosat 2-7 in operation between 1982 and 2005) (Posselt *et al.*, 2011b, 2012) and the Second Generation (MSG, >2005) (Posselt *et al.*, 2014) and covers the time period from 1983 to 2010 with a spatial resolution of 0.03° in latitude and longitude. The MFG and MSG satellites, which are located at a longitude of 0° over the equator in an altitude of around 36,000 km, are equipped with the Meteosat Visible and Infrared Imager (MVIRI) radiometers and Spinning Enhanced Visible and Infrared Imager (SEVIRI), respectively. In brief, the satellite-derived SSR is first derived by making use of the Heliosat algorithm (e.g., Hammer *et al.*, 2003) that determines the effective cloud albedo, which afterwards is combined with estimated clear-sky irradiances using the Mesoscale Atmospheric Global Irradiance Code (MAGIC) (Mueller *et al.*, 2009). To derive the

clear-sky irradiances monthly-averages of the integrated water vapour from the ERA-Interim reanalysis (Dee *et al.*, 2011) as well as a monthly climatology of the aerosol properties based on Kinne *et al.* (2006) have been used (Posselt *et al.*, 2011b). Particular care was taken in Posselt *et al.* (2014) to ensure a homogeneous transition from the MVIRI instruments (until 2005) and the SEVIRI instruments (starting 2006). The broadband visible channel information from MVIRI was reproduced by a linear combination of the two narrow band visible channels available from SEVIRI following the methodology of Cros *et al.* (2006). Additional details about the dataset can be found in Posselt *et al.* (2011b, 2012, 2014).

The ground-based all-sky SSR measurements used to be compared with the satellite-derived product were obtained from the Global Energy Balance Archive (GEBA, <http://www.geba.ethz.ch/>), which is a database maintained at ETH Zurich that stores worldwide monthly means of different energy fluxes measured at the surface, mainly SSR measurements (Gilgen and Ohmura, 1999). A subset of series over Europe with monthly homogenized records of SSR (expressed in Wm^{-2}) was considered. This dataset has been previously checked for temporal homogeneity by Sanchez-Lorenzo *et al.* (2013b), and contains the longest SSR series over Europe, with series starting before 1971 and with at least 30 years of data up to 2007. For this study, the records have been updated from January 2008 to December 2010 where possible by using the data available in the World Radiation Data Center (WRDC, <http://wrdc.mgo.rssi.ru/>). For more details about the name of the stations, and homogenization and gap filling procedures, we refer to Sanchez-Lorenzo *et al.* (2013b).

In order to compare the satellite-derived and the ground-based datasets, a subset of 47 time series was selected over the 1983-2010 period (Figure 1). We have excluded the stations at both high altitudes and latitudes as in Sanchez-Lorenzo *et al.* (2013b) due to the well-known problems to

derive SSR in mountain areas (Posselt *et al.*, 2012), as well as the limitations of the geostationary satellites to observe high-latitude areas (Schulz *et al.*, 2009). In addition, we have also excluded some stations that were subjected to numerous statistical corrections (e.g., Rome) during the homogenization of the series (Sanchez-Lorenzo *et al.*, 2013b). The 47 satellite-derived grid points closest to the 47 ground-based stations have been extracted in order to compare both SSR datasets. December 1988 that is missing in the satellite-derived records was not considered in the ground-based series, as well as all the months missing in the ground-based stations (which have no complete records for all stations after 2000), in order to use the same number of months for the comparison of both datasets.

The linear trends of the series shown in this paper were calculated by means of least squares linear fitting and where required their significance assessed by the Mann-Kendall nonparametric test (Kendall, 1955) at the 95% confidence level. Gaussian low-pass filters were used in order to smooth time series, which improves the visualization of the decadal variability when plotted together. The filter only considers the values on one side at the start and end of the series in order to filter the full period.

3. Trends of the satellite-derived all-sky SSR over Europe

Trends of the annual and seasonal SSR derived from the satellite data over Europe (from 35° N to 60° N and 15°W and 35° E) are presented for both the 1983-2010 and 1994-2010 periods. This is due to the fact that data previous to 1994 suffer from temporal inhomogeneities, which has been suggested to be the result of artefacts in the raw data and instrument failures (Krähenmann *et al.*, 2013; Posselt *et al.*, 2011a). Nevertheless, the neglect of time varying aerosols, both from anthropogenic and natural (e.g., derived from large volcanic eruptions such

as the Pinatubo) sources in the satellite-derived product has been also suggested as a reason in order to explain the observed breaks, among other possible causes (Sanchez-Lorenzo *et al.*, 2013b). Consequently, and taking into account the results shown in Section 4, we show also the trends over the whole 1983-2010 period.

Time series of annual and seasonal mean values of SSR were derived for each grid point. The seasons are defined as spring (MAM), summer (JJA), autumn (SON), and winter (DJF). Winter is dated according to the year in which January and February fall, and for 1983 is calculated only considering January and February, as well as for 1989 as December 1988 is missing in the satellite-derived dataset. Then, the linear trends of the series were calculated by means of least squares linear fitting and annual and seasonal maps have been produced with the obtained trend rates. The grid values have been regridded from the 0.03° resolution to 0.1° in order to improve the visualization of the maps as the original trends show evidences of artifacts (not shown), which was the result of the regridding of the data from the original satellite grid to the 0.03° long-lat grid on which the data is provided. We confirm that these artifacts do not affect the following results and regridding was just performed for visualization purposes.

Figure 2 shows the trends of the annual SSR series from the satellite-derived product during the periods 1983-2010 (left) and 1994-2010 (right). The SSR trends highlight a widespread increase in the major part of Europe from 1983 to 2010 (Figure 2, left), with rates between 1 and 3 Wm^{-2} per decade in most of the areas. Also worth noting is the tendency to neutral trends in the areas around the southeastern Iberian Peninsula, southern Italy, central parts of France, southeastern Europe, and southern parts of the United Kingdom. The mean of the trend values in the whole window is $+2.2$ per decade Wm^{-2} , and a slightly lower value of $+1.8 \text{ Wm}^{-2}$ if only land areas are considered.

182 The mean trend values in the window over land from 45° N to 55° N and 10°W and 20° E
 183 (Central Europe domain, CED) is +1.4 Wm⁻² per decade, which is around 2 Wm⁻² per decade
 184 lower than the trend of the annual mean series obtained using the 47 ground-based series over
 185 Europe (+3.3 Wm⁻²), which are located mainly over central Europe (Figure 1). This difference
 186 has also been reported for the CM SAF dataset limited to the period of the MFG satellites from
 187 1983 to 2005 (Sanchez-Lorenzo *et al.*, 2013b). Equally, a similar underestimation of the trends in
 188 the satellite-derived SSR has been found using a dataset derived from the ISCCP data over
 189 Europe during the periods 1984-2000 (Petrenz *et al.*, 2007) and 1994-2009 (Alexandri *et al.*,
 190 2013).
 191 Figure 2 (right) shows a widespread tendency for higher rates of increase of SSR over Europe
 192 since 1994 as compared to the period 1983-2010, especially in the central and northern regions.
 193 Nevertheless, a strong decrease is also observed around the Western Mediterranean area. The
 194 mean of the trend in the whole window since 1994 is +3.1 Wm⁻² per decade, +2.8 Wm⁻² per
 195 decade if only land areas are considered, which is higher than during the period 1983-2010. The
 196 trend in the CED is +3.8 Wm⁻² per decade, very similar to the trend value of the mean series
 197 obtained using the 47 series from the ground-based stations (+3.5 Wm⁻² per decade).
 198 Overall, the observed annual trends in satellite-derived SSR are in line with previous studies
 199 using surface observations over Europe (Chiacchio and Wild, 2010; Norris and Wild, 2007;
 200 Ohmura, 2009; Philipona *et al.*, 2009; Ruckstuhl *et al.*, 2008; Sanchez-Lorenzo *et al.*, 2013b,
 201 2015; Wild, 2009; Wild *et al.*, 2009), as well as with the results obtained with model simulations
 202 (Folini and Wild, 2011; Nabat *et al.*, 2014; Ruckstuhl and Norris, 2009; Turnock *et al.*, 2015),
 203 although there is a tendency to underestimate the trends in the satellite-derived product,

especially before 1994, possibly due to artifacts or the lack of information regarding aerosol changes.

On the other hand, it is interesting to highlight that the trends in the satellite-derived product show that most of Europe experienced a widespread increase of SSR since the 1980s, which confirm a large-scale dimension of the brightening in Europe, in line with results shown by Wang *et al.* (2014). Other authors have argued that the widespread dimming phase was mainly a local phenomenon due to urban effects (Alpert and Kishcha, 2008; Alpert *et al.*, 2005).

The observed decrease over the Mediterranean region and eastern Iberian Peninsula seems to contradict previous studies showing a brightening period in Spain since the late 1980s (Mateos *et al.*, 2013, 2014; Sanchez-Lorenzo *et al.*, 2007, 2013a). However, a closer look at a SSR series from surface observations taken at Palma de Mallorca (Balearic Islands, Spain, in the Western part of the Mediterranean Sea), extracted from a dataset in Spain (Sanchez-Lorenzo *et al.*, 2013a), indicates a slight decrease of around -1 Wm^{-2} per decade in SSR (period 1994-2010), especially due to a first drop from the late 1990s to the mid-2000s and a second around 2007-2010, in agreement with the data of the satellite-derived extracted over this ground-based station (Figure 3). On the other hand, the linear trend of the ground-based SSR in Palma de Mallorca is clearly positive and significant ($+4.7 \text{ Wm}^{-2}$ per decade) if the period 1985-2010 is considered (Table 5 in Sanchez-Lorenzo *et al.*, 2013a), which highlights the problems caused by the study of trends in short time-series (i.e., 17 years, 1994-2010) that can reflect only part of the decadal variability of the series.

On a seasonal basis (Figure 4), the satellite-derived SSR trends show interesting spatial and temporal variations throughout the year as compared to the trends on annual basis. In general, the spring map is the most similar to the annual map previously described, and shows the strongest

rates considering all seasons (i.e. more than 10 Wm^{-2} per decade) over the central and eastern sectors of Europe particularly in the 1994-2010 period. Equally, the negative trends during the period 1994-2010 are also observed in spring over the western Mediterranean basin. The mean trend values for the whole (land) window in spring over the periods 1983-2010 and 1994-2010 is $+5.2 \text{ Wm}^{-2}$ per decade ($+4.9 \text{ Wm}^{-2}$ per decade) and $+7.1 \text{ Wm}^{-2}$ ($+6.8 \text{ Wm}^{-2}$ per decade), respectively. The rates for the CED are higher, $+5.7 \text{ Wm}^{-2}$ (1983-2010) and $+10.4 \text{ Wm}^{-2}$ (1994-2010) per decade. Overall, these findings (i.e., stronger brightening in springtime) are in line with the results found using SSR and sunshine duration series from surface observations over Europe, possibly due to a decrease in cloudiness as a result of an increase in the anticyclonic activity since the 1980s (Chiacchio and Wild, 2010; Sanchez-Lorenzo *et al.*, 2008).

In autumn, the observed trends since 1983 are usually weaker, with a tendency to negative rates over the Mediterranean area, in line with Chiacchio and Wild (2010), but a widespread increase is observed during the period 1994-2010, with a mean trend of around $+3 \text{ Wm}^{-2}$ per decade for the whole window, increasing to $+4.4 \text{ Wm}^{-2}$ per decade if only the CED is considered. In summer there is widespread increase of SSR across Europe from 1983 to 2010, except for some areas of the UK and France, with a mean trend rate of $+4.8 \text{ Wm}^{-2}$ per decade ($+4.3 \text{ Wm}^{-2}$ per decade) for the whole window (over land), $+2.1 \text{ Wm}^{-2}$ per decade over CED. The spatial distribution of the trends are different for the period 1994-2010, with almost an opposite spatial pattern, i.e. negative (positive) trends in the northern (southern and eastern) land areas of Europe, respectively. Thus, the mean trend value for the CED from 1994 to 2010 in summer is close to zero (0.4 Wm^{-2} per decade).

The winter map shows a completely different spatial pattern, with a tendency to negative or neutral trends over the whole area. In fact, the mean trend values for all grid points are negative

for both periods (-1.0 and -2.1 Wm^{-2} per decade for the 1983-2010 and 1994-2010, respectively), in contrast to the results previously described. The trend for the mean series obtained for the CED shows a decrease of around 1.3 Wm^{-2} per decade for both periods, which is also in line with the lack of a clear brightening signal in ground-based observations (Chiacchio and Wild, 2010).

In order to test the role of cloud changes in the seasonal differences of the SSR trends reported in this study, Figure 5 shows the seasonal trends in total cloud cover over the period 1983-2009. The dataset is built upon human observations of cloud cover from the surface of the Extended Edited Synoptic Cloud Reports Archive (Warren *et al.*, 2007). This dataset in the latest version available provides a collection of individual cloud reports from 1971 to 2009 (Eastman and Warren, 2013). In this study, a grid of $2^\circ \times 2.5^\circ$ (latitude x longitude) has been created in order to minimize biases due to the non-homogeneous spatial distribution of the stations (Enriquez-Alonso *et al.*, 2015), and then we have only selected those grid cells that have data available at least 80% of the period. The results show that spring is the season with the strongest decrease in cloud cover, especially over Central Europe, in line with the strongest increase reported in SSR (Figure 4). On the other hand, autumn cloud cover shows a tendency to increase, especially in southeastern Europe, in general agreement with the decreasing trends observed in SSR for this season (Figure 4). In conclusion, it seems that the seasonal differences in the SSR trends are mainly influenced by changes in cloud cover, although further research is needed for a quantitative estimation of the different drivers, including different cloud properties, of SSR trends.

Finally, in order to show the feasibility of the satellite-derived dataset to reproduce the interannual and decadal variations of SSR over Europe, Figure 6 shows the arithmetic mean of

the 47 monthly anomaly series for the ground-based series (blue) and the records extracted from the 47 satellite-derived grid points (red). For more details about the data, see Section 2. These series are expressed as anomalies from the 1983-2000 mean (which has complete records for the ground-based dataset), and are plotted together with a 36-month Gaussian low-pass filter from 1983 to 2010.

Both time series show a very similar time evolution on monthly ($r=0.94$, $p<0.05$) and decadal time scales. Equally, both time series exhibit significant increases, as assessed by the Mann-Kendall nonparametric test at the 95% confidence level, although the rate of the increase is slightly higher for the ground-based ($+3.2 \text{ Wm}^{-2}$ per decade) than for the satellite-derived ($+2.1 \text{ Wm}^{-2}$ per decade) over the period 1983-2010. On the other hand, the rates of increase are almost the same for both datasets (around 3.5 Wm^{-2} per decade) if only the period 1994-2010 is considered, in line with previous results reported by Sanchez-Lorenzo *et al.* (2013b) based on records from 1983 to 2005. Figure 7 shows in addition the annual mean series for both time series over the period 1994-2010, which highlights that there is a consistency between the satellite-derived product and the surface observations across the two Meteosat satellite generations, in agreement with Posselt *et al.* (2014), with no evidences of temporal inhomogeneities before and after 2006.

Furthermore, the trends for individual months observed for the mean series of the 47 satellite-derived and ground-based series show an agreement in the signs and values throughout the year for both 1983-2010 and 1994-2010 periods (Figure 8), which proves the consistency between the satellite-derived SSR and the surface observations and increases confidence of the annual and seasonal trends shown in Figure 2 and 4.

4. Trends in the residual series over Europe

In order to study the disagreement in the trends of the surface and satellite-derived observations, we have estimated the differences for both datasets as evidence of possible inhomogeneities in the satellite-derived product, in line with previous studies that compared satellite and ground observations (Brinckmann *et al.*, 2013; Krähenmann *et al.*, 2013; Posselt *et al.*, 2011b, 2012, 2014; Sanchez-Lorenzo *et al.*, 2013b). Specifically, first the mean SSR monthly series has been computed as an arithmetic mean of the 47 monthly anomaly series for both datasets (i.e. the same series as used in Figure 6). Then, the series of monthly differences obtained between the ground-based minus the satellite-based anomalies are calculated, which we will refer to as “residual series”. The use of mean series is recommended, as compared to the use of individual stations, in order to reduce the uncertainties related to the satellite viewing angle and its mismatch between the surface and satellite-derived records.

Figure 9 shows the derived monthly residual series, together with a 36-month Gaussian low-pass filter, from 1983 to 2010. The series points to an increase during the study period, although this tendency is mainly due to the presence of large negative anomalies before 2000, especially around 1984–1986 and 1991–1993 and interrupted during 1987–1990, followed by a period without relevant variations during the early 21th century. The time series shows a significant increase of 1.2 Wm^{-2} per decade over the whole period, a rate that increases up to 2.2 Wm^{-2} per decade if only the period 1983-2000 is considered.

Then we have studied the spatial differences in the residual series trends over Europe. The hypothesis is that if the difference between the changes in the ground-based and satellite-derived data is not only related to an artefact in the satellite product, we should find regional differences across Europe. Specifically, each of the 47 sites were assigned into five different regions across

319 Europe by using the same regionalization defined by Sanchez-Lorenzo *et al.* (2013b), which is
 320 based on a Principal Component Analysis (PCA) that defined the following regions (Figure 10):
 321 the center (region C), the east (region E), the north (region N), the south (region S), and the
 322 northwest (region NW). The mean residual series for the five regions have been computed by
 323 averaging the monthly anomalies residual series of all the available stations in each region.
 324 Figure 10 shows the time evolution of the residual series for each of the five regions, which
 325 highlights that the regions C and E experienced the highest rates of increase from 1983 to 2010.
 326 Specifically, there are significant increases of 1.8 and 1.7 Wm^{-2} per decade for region C and E,
 327 respectively. On the other hand, the other regions show increases below 1 Wm^{-2} per decade, not
 328 reaching the significance level for the N region. These results suggest that at least part of these
 329 differences is likely not related to an artefact in the satellite-derived product.

330 Interestingly, it is worth noting that the regional differences of the residual series across Europe
 331 are in agreement with trends in clear-sky SSR in central and eastern Europe since the 1980s
 332 (Folini and Wild, 2011; Nabat *et al.*, 2014; Norris and Wild, 2007). For example, our results are
 333 in line with the clear-sky SSR trends of around +2 Wm^{-2} per decade reported by Norris and Wild
 334 (2007) in Europe from 1987 to 2002 and with highest rates around the regions C and E defined in
 335 this study. In fact, the trends of the residual series for the regions C and E are 2.7 and 2.3 Wm^{-2}
 336 per decade if the period 1987-2002 used in Norris and Wild (2007) is considered, whereas region
 337 N shows only an increase of 0.5 Wm^{-2} per decade and regions S (-0.1 Wm^{-2} per decade) and NW
 338 (-0.6 Wm^{-2} per decade) have even a slight decrease. It is worth noting that in Norris and Wild
 339 (2007) there is also an evidence of slight decrease in clear-sky SSR during this period 1987-2002
 340 in the stations located in our regions S and NW. In addition, the comparison of the mean annual
 341 series presented by Norris and Wild (2007), which is constructed mainly by using stations in

central Europe, shows that the highest correlation coefficient with the residual series of our study is in region C, with an excellent agreement on interannual ($r=0.81$, $p<0.05$) and decadal time scales on annual basis (not shown).

Making use of the high-frequency measurements provided by the Baseline Surface Radiation Network (BSRN) (Ohmura *et al.*, 1998), together with a clear-sky detection algorithm (Long and Ackerman, 2000), clear-sky SSR fluxes have been estimated for Toravere (Estonia), which is the only station with more than one decade of measurements in the BSRN dataset at the same location as one of the historical records of SSR used in this study. Specifically, the clear-sky algorithm identifies clear-sky conditions using 1-min measurements of global and diffuse shortwave irradiance to detect clear-sky irradiance situations by using four different tests, which eliminate measurements under cloudy skies from the data. Then, the clear-sky SSR irradiance measurements are used to empirically fit diurnal clear-sky irradiance functions based on the cosine of the solar zenith angle as the independent variable. These fitted functions produce continuous estimates of clear-sky SSR series. For more details, we refer to Long and Ackerman (2000). The comparison shows a coefficient of correlation of 0.70 ($p<0.05$) between the annual series (2000-2010 period) of the estimated residual series at the Toravere site and the one calculated using the high-frequency BSRN measurements at the same site, with both series showing a slight decrease during this short study period (Figure 11).

Consequently, the residual series presented in this study suggest that the differences between ground-based observations and the satellite-derived product are not only due to calibration artefacts in the latter. Thus, other causes, such as the use of time-invariant monthly mean climatological values for tropospheric and stratospheric aerosol (i.e. assuming constant values throughout the years and not including information on disturbances due to volcanoes or biomass

burning or changes in anthropogenic aerosols) or missing/erroneous information of the radiative effects of other radiative gases (e.g., ozone or water vapour) in the satellite-derived product, can at least explain part of the differences in the residual series.

5. Conclusions

In this study, trends of all-sky satellite-derived downward surface solar radiation (SSR) from an extension of a Satellite Application Facility on Climate Monitoring (CM SAF) product over Europe during the period 1983-2010 have been studied first. This satellite product has been derived from the First and Second Generation of the Meteosat satellites and has a spatial resolution of 0.03° of latitude and longitude.

The results suggest that there has been a widespread increase in SSR in the major part of Europe, especially since the mid-1990s. Overall, the satellite-derived product estimates a mean increase of SSR of at least 2 Wm^{-2} per decade during the period 1983-2010 over the whole Europe. Thus, the trends in the SSR from the satellite-derived product suggest that the widespread brightening seen in surface observations is a large-scale phenomenon rather than a consequence of an urbanization/local effect.

There are spatial differences in the observed trends, with a tendency towards highest rates of increase in the central and northern areas of Europe. On a seasonal basis, the decadal variability in spring is the most similar to the annual trends, although with higher rates of increase. Equally, there is a tendency to negative trends around the Mediterranean basin since the early 1990s. Taking into account that the satellite-derived product lacks of aerosol variations, and consequently of changes in direct aerosol effects, these trends should be primarily linked to a

decrease in the cloud radiative effects induced by changes in natural cloud variability and/or aerosol indirect effects on clouds.

Furthermore, the temporal evolution and trends of the satellite-derived SSR has been checked against a dataset of 47 ground-based stations with homogeneous monthly records of SSR from 1983 onwards. The results point to an excellent agreement between both datasets at the month to month scale, as well as with the trends since 1983 although with a tendency to underestimate the rates in the satellite-derived product, especially before the 2000s. The differences in the trends between ground-based and satellite-derived records have been suggested to be related to inhomogeneities due to satellite instruments, but in this study we argue that at least a part of it can be linked to changes in other causes.

Consequently, in addition to the all-sky SSR trends over Europe, a second goal of this study is to derive residual series by combining ground-based and satellite records. Specifically, the residual series have been derived as the difference between monthly anomalies of ground-based and the satellite-derived SSR data. The results highlight that this mean residual series shows a significant increase of more than 1 Wm^{-2} per decade during the period 1983-2010 for the whole Europe, although with rates around 2 Wm^{-2} per decade over central and eastern Europe. The increase in the residual series is mainly due to a strong increase from the mid-1980s to the late 1990s, with a tendency towards stabilization during the early 21st century. These results are in line with previous observations and estimates of clear-sky SSR trends in Europe. Further research is needed to understand the main drivers of the differences between ground-based and satellite-derived products.

Acknowledgments

ASL was supported by a postdoctoral fellowship JCI-2012-12508 from the Spanish Ministry of Economy and Competitiveness. AEA and ASR were supported by the FPI (BES-2011-049095) and FPU (FPU AP2010-0917) programs of the same ministry. This research was supported by the projects CGL2014-55976-R, CGL2014-52135-C3-1-R and *Red de variabilidad y cambio climático* RECLIM (CGL2014-517221-REDT) financed by the Spanish Ministry of Economy and Competitiveness and FEDER and “LIFE12 ENV/ES/000536-Demonstration and validation of innovative methodology for regional climate change adaptation in the Mediterranean area (LIFE MEDACC)” financed by the LIFE programme of the European Commission. This work is partly funded by the Deutscher Wetterdienst (DWD). We acknowledge the provision of the satellite data by EUMETSAT through the Satellite Application Facility on Climate Monitoring (CM SAF) and MeteoSwiss. Dimming/brightening research at ETH has been supported by the National Centre for Competence in Climate Research (NCCR Climate) and by the Swiss National Science Foundation grant 200021 135395. We want to thank R. Stockli for his comments and J. Norris for providing the residual mean series over Europe used in Section 4.

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Figure captions

Figure 1. Location of the 47 stations extracted from the homogenized dataset over Europe used in this study. For more details, see Sanchez-Lorenzo *et al.* (2013b).

Figure 2. Linear trends of the satellite-derived SSR annual series from the satellite-derived over Europe during the periods 1983-2010 (left) and 1994-2010 (right). The values are expressed as Wm^{-2} per decade.

Figure 3. Monthly anomalies series of SSR (thin lines) in Palma de Mallorca (Balearic Islands, Spain) from 1994 to 2010 from satellite-derived (red) and ground-based (blue) data, plotted together with a 12-month Gaussian low-pass filter (thick line). The series are expressed as anomalies from the 1994–2010 mean.

Figure 4. As in Fig. 2, but for the seasonal series.

Figure 5. Linear trends of the total cloud cover seasonal from ground-based observations over Europe during the periods 1983-2009. The values are expressed as % per decade.

Figure 6. Mean monthly SSR anomaly series (dashed lines) of the satellite-derived (red) and ground-based dataset (blue) over 47 locations in Europe from 1983 to 2010, plotted together with a 36-month Gaussian low-pass filter (solid lines). The series are expressed as anomalies from the 1983–2000 mean.

Figure 7. Mean annual SSR anomaly series of the satellite-derived (red) and ground-based dataset (blue) over 47 locations in Europe from 1994 to 2010. The series are expressed as anomalies from the 1994–2010 mean. Dashed vertical line show the change from MVIRI to SEVIRI instruments to infer the satellite-derived product used in this study.

Figure 8. Linear trends of the mean monthly SSR series obtained using the 47 satellite-derived and ground-based series over Europe during the periods 1983-2010 (top) 1994-2010 (middle). Scatter plot of the monthly trends of the satellite-derived and ground-based shown in the top and middle panels (bottom). The values are expressed as Wm^{-2} per decade.

Figure 9. Mean monthly residual series (thin lines), estimated as the difference between the ground-based and satellite-derived mean monthly series over 47 locations in Europe, from 1983 to 2010 with the linear regression line (red line), plotted together with a 36-month Gaussian low-pass filter (thick lines). The series are expressed as anomalies from the 1983–2000 mean.

Figure 10. As in Fig. 7, but for the regional residual series. The five regions have been defined by means of a Principal Component Analysis applied to the 47 ground-based series. A schematic regionalization is shown in the upper-left panel.

Figure 11. Annual residual anomaly series, estimated as the difference between the ground-based and satellite-derived mean monthly series (red line), and clear-sky SSR derived from BSRN measurements and Long and Ackerman (2010) algorithm (blue line), at Toravere (Estonia). The series are expressed as anomalies from the 2000–2010 mean.

1983 - 2010

1994 - 2010

W.m-2/decade