Atmospheric Research 290 (2023) 106804

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Analysis of sunshine duration and cloud cover trends in Lisbon for the period 1890–2018

A.J.P. Aparicio [a,b,c,*], V.M.S. Carrasco [a,b], J. Montero-Martín [a], A. Sanchez-Lorenzo [a], M. J. Costa [c,d], M. Antón [a,b]

[a] Departamento de Física, Universidad de Extremadura, 06006 Badajoz, Spain
[b] Instituto Universitario de Investigación del Agua, Cambio Climático y Sostenibilidad (IACYS), Universidad de Extremadura, 06006 Badajoz, Spain
[c] Earth Remote Sensing Laboratory (EaRSLab) and Institute of Earth Sciences—ICT (Polo de Évora), Instituto de Investigação e Formação Avançada (IIFA), Universidade de Évora, 7000-671 Évora, Portugal
[d] Departamento de Física, Escola de Ciências e Tecnologia, Universidade de Évora, 7000-671 Évora, Portugal

ARTICLE INFO

Keywords:
Sunshine duration
Cloud cover
Dimming
Brightening
Portugal

ABSTRACT

Sunshine duration (SD) represents a valuable parameter for early years when few or none measurements of surface solar radiation (SSR) are available. In the present work, daily and monthly SD records registered in Lisbon (Portugal) for the period 1890–1940 have been digitized to expand the data series available in electronic format, which starts in 1941. The resulting series for the period 1890–2018 can be considered as the earliest one in Portugal and the second one in the Iberian Peninsula. Cloud cover (CC) data for the same period have also been digitized. The SD series exhibits a weak negative trend (without statistical significance) from the 1890s to the 1910s, which is in line with the early dimming period in SSR reported in some regions. Subsequently, no trends are obtained for the period 1910s–1950s, which indicates that the early brightening is not observed in Lisbon unlike other locations in the Iberian Peninsula. After that, two strong statistically significant trends are found for the periods 1950s–1980s and 1980s–2010s in line with the well-known global dimming and brightening periods in SSR, respectively. On the other hand, the CC series presents an increase from 1890 to the 1980s, followed by a decrease up to 2018 (both being statistically significant), which may partially explain the reported SD trends. An analysis of SD under cloudless conditions proved the utility of this quantity to track long-term changes in atmospheric aerosol load. In addition, this analysis and a seasonal one pointed out that aerosols seem to play a relevant role in SD long-term variability.

1. Introduction

Solar radiation is crucial in many natural processes in our planet. In addition, current concerns such as climate change and solar energy resources require knowledge on the variability of solar radiation reaching the Earth's surface (Ramanathan and Carmichael, 2008; Wild, 2016).

Widespread measurements of surface solar radiation (SSR) started in the late 1950s (Stanhill and Achiman, 2017). The analysis of these time series showed a global decrease in SSR until the 1980s called “global dimming” (Liepert, 2002; Ohmura, 2009; Stanhill and Cohen, 2001), followed by an increase up to the present time, known as “brightening” (Sanchez-Lorenzo et al., 2015; Wild, 2005).

Despite the large amount of SSR data after the 1950s, the number of series prior to that decade is scarce. In Europe, there are only two stations with data since the 1920s (Stockholm and Wageningen) and three ones since the 1930s (Davos, Locarno-Monti and Potsdam), none being in the southern regions (Sanchez-Lorenzo et al., 2015). Some of these early series present an increase in SSR until the 1940s (Ohmura, 2007; Sanchez-Lorenzo et al., 2015; Stanhill and Achiman, 2017). This period is called “early brightening” (Wild, 2009). On the contrary, other series do not show this behavior (Hoyt, 1979; Ohvril et al., 2009; Roosen and Angione, 1984).

Due to the scarcity of SSR measurements and the different results found before the 1950s, the use of related variables is of great importance to complement and extend the available data series (Stanhill, 2005). In this respect, sunshine duration (SD) is one of the most useful historic proxies for SSR with measurements starting in the last part of the 19th century (Stanhill and Cohen, 2008; Wild, 2009). This variable is

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* Corresponding author at: Departamento de Física, Universidad de Extremadura, 06006 Badajoz, Spain.
E-mail address: ajpa@unex.es (A.J.P. Aparicio).

https://doi.org/10.1016/j.atmosres.2023.106804
Received 1 February 2023; Received in revised form 5 May 2023; Accepted 8 May 2023

usually defined as the number of hours that direct solar radiation surpasses 120 W·m^{-2}. There is a large number of studies analyzing long-term changes of SD during the last decades (He et al., 2018; Ohmura, 2009; Sanchez-Lorenzo et al., 2007; Wild, 2016; Wild, 2009). Specifically, we can find numerous studies for Europe (e.g., Bartoszek et al., 2021; He et al., 2018; Kazadzis et al., 2018; Sanchez-Lorenzo et al., 2008), as well as United States (e.g., Angell, 1990; He et al., 2018; Stanhill and Cohen, 2005), China (e.g., He et al., 2018; Kaiser and Qian, 2002; Wang et al., 2012), or Japan (e.g., Ma et al., 2022; Stanhill and Cohen, 2008). In Sanchez-Romero et al. (2014) a summary of the main devices used to record SD is presented among other limitations of the measurements.

For the Iberian Peninsula, Sanchez-Lorenzo et al. (2007, 2009) analyzed SD measurements since the 1930s and reported a period of dimming for 1950s–1980s, followed by a brightening period up to the end of the 20th century. Román et al. (2014) reconstructed SSR from SD records since 1950 for Spanish stations finding tendencies matching the global dimming and the subsequent brightening. Antón et al. (2017) followed the same procedure to reconstruct SSR in Madrid (Spain) for the period 1887–1950 and identified an early dimming from the beginning of the series until the 1910s, followed by an early brightening. Similarly, reconstructed SSR in Badajoz (Spain) over 1929–2015 was inferred by Montero-Martín et al. (2023) presenting an early brightening period (1929–1950), followed by a dimming (1951–1984) and a subsequent brightening (1985–2015). Montero-Martín et al. (2021) studied SD records for the period 1891–1950 in Coimbra (Portugal) and found an early dimming from the beginning of the series up to the 1910s. Lastly, it is worth mentioning that early trends in the Iberian Peninsula have also been analyzed using other variables related to solar radiation such as actinometric measurements (Bravo-Paredes et al., 2019) and atmospheric transparency (Antón et al., 2014; Aparicio et al., 2019).

In the present work, we have digitized daily and monthly records of SD registered in Lisbon for the period 1890–1942. Thus, this work expands the data series available in electronic format for this location (period 1941–2018) creating the earliest continuous SD series in Portugal and the second one in the Iberian Peninsula (Madrid series starts in 1887). Note that the earliest SD data series in the Iberian Peninsula is that at San Fernando with data since 1881. Unfortunately, that series is not homogeneous for the 1891–1933 period (Wheeler, 2001). We have also digitized cloud cover (CC) records and expanded the available data series for the same location and period. Thereby, the present work aims to study the evolution of SD in Lisbon, the long-term trends and the factors that may explain the behavior of this data series for the period 1890–2018.

The data used in the present study are described in Section 2. Section 3 contains an explanation of the methodology followed to process the data and create the temporal series that are shown and analyzed in Section 4. Lastly, conclusions are presented in Section 5.

2. Data

The Instituto Dom Luiz (IDL) is a research center for the study of Earth and Atmospheric Sciences hosted by the University of Lisbon. It was founded under the name Observatório Meteorológico da Escola Politécnica in 1853. In the course of time, it has had other names such as Observatório do Infante D. Luiz, Observatório do Infante D. Luís, Observatório Central Meteorológico do Infante D. Luiz and Instituto Geofísico do Infante D. Luís (Batlló et al., 2014). The coordinates of the IDL meteorological observatory are 38° 42′ 59.4″ N in latitude and 9° 08′ 56.7″ W in longitude, and its altitude above sea level is 77.1 m. The IDL have performed systematic meteorological observations in Lisbon since 1856. Some of the first records contain data on atmospheric pressure, precipitation, temperature, cloud cover and wind speed, among others (Silveira, 1863). The measurements are published in bulletins called "Anais do Observatório do Infante D. Luiz" or similarly, depending on the denomination of the institution at the time. With the passage of time, the bulletins have incorporated measurements of other variables.

SD measurements in the IDL started in 1890. The first device employed was a Jordan heliograph (Capello, 1893). In January 1913, it was replaced by a more modern device: a Campbell-Stokes heliograph (Lima, 1915). Over the whole study period (1890–2018) the heliograph altitude has been 22.8 m above ground (and the location of the observatory has not changed). The first bulletins with SD records only contain monthly data on this variable (period 1890–1917). From 1918, daily data is available too. Fig. 1 shows an example page with daily SD measurements for January 1918. First column represents the days of the month, columns 2–17 contain SD in intervals of one hour (expressed in hours and minutes), column 18 is the total SD for each day (expressed in hours and minutes) and column 19 includes the percentage of SD with respect to the theoretical number of daylight hours. All the rows show daily data except for the last one, which contains the sum for the month. In the present work, daily and monthly SD records have been digitized from IDL bulletins (in pdf format) since the beginning of the series (1890) up to 1942. Most of the bulletins are available on the website of the project SIGN (http://sign.fc.ul.pt/index.html), and the ones missing in that website (bulletins with data for the period 1921–1925) have been provided by the Portuguese Institute for Sea and Atmosphere (Instituto Portugués do Mar e da Atmósfera, IPMA).

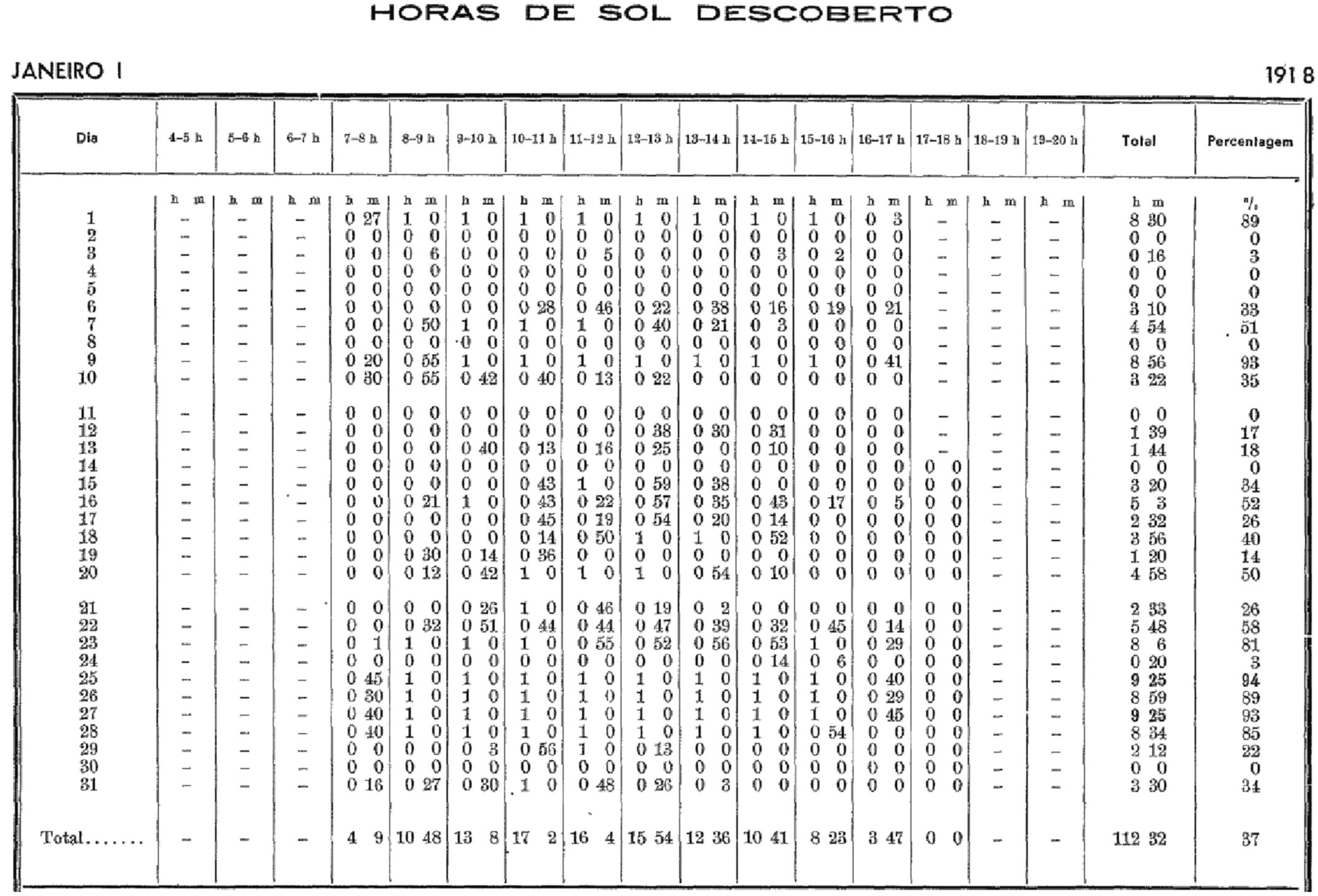
After digitization, an exhaustive quality control has been performed to detect digitization errors and inconsistences in the bulletins. We checked that all the values were inside coherent intervals. For example, we checked that there were no negative values and that SD was lower than the theoretical number of daylight hours. In addition, for the period 1918–1942 (1890–1917) monthly (yearly) averages from daily (monthly) records were calculated and compared with monthly (yearly) averages of the bulletins. When the averages did not match, we consulted the bulletins and checked if the cause of the error was the digitization or an inconsistency in the bulletin. Later, we corrected the error.

As mentioned above, the bulletins of the IDL contain CC records since 1856. The measurements of CC were carried out by human observations. Numbers 0–10 represent the number of tenths of the sky covered with clouds. The values of CC used in the present study are averages of CC measurements at 9:00, 12:00 and 15:00 (local time of Lisbon until 1946 and local time of Greenwich since 1947, being 37 min the difference between the two times). In line with our retrieval of SD records, we have digitized monthly CC data for 1890–1917 and daily data for 1918–1941 (although the bulletins contain daily CC data for the whole study period). A quality control similar to that applied to the SD data was also applied to the CC values.

As mentioned in the previous section, daily SD and CC data series since 1941 for Lisbon (digitized from the IDL bulletins) are available in machine-readable format from the IPMA. For the present study, we joined the SD (CC) data series digitized in the present work for the period 1890–1942 (1890–1941) with the digital records of the IPMA for the period 1943–2018 (1942–2018). Thereby, we obtain SD and CC data series for Lisbon for the period 1890–2018. The temporal coverage of the data is 100% for the monthly part of the SD and CC series (period 1890–1917), and 99.2% and 99.6% for the daily part of the SD and CC series (period 1918–2018), respectively. Machine-readable versions of these data series are made available to the scientific community as supplementary material of this paper. Note that the CC data from IPMA are expressed in oktas of sky covered by clouds (scale 0–8). Then, with the goal of merging the CC series digitized in the present work for the period 1890–1941 (which contains values expressed in tenths of sky) with that from the IPMA for the period 1942–2018, the values in tenths of sky were converted into oktas.

3. Corrections applied to the series

Aiming to have series with the same periodicity, for the daily part of the SD and CC series (1918–2018), monthly averages are computed from



HORAS DE SOL DESCOBERTO

JANEIRO I 1918

Dia	4–5 h	5–6 h	6–7 h	7–8 h	8–9 h	9–10 h	10–11 h	11–12 h	12–13 h	13–14 h	14–15 h	15–16 h	16–17 h	17–18 h	18–19 h	19–20 h	Total	Percentagem
	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m	°/₀
1	–	–	–	0 27	1 0	1 0	1 0	1 0	1 0	1 0	1 0	1 0	0 3	–	–	–	8 30	89
2	–	–	–	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	–	–	–	0 0	0
3	–	–	–	0 0	0 6	0 0	0 0	0 5	0 0	0 0	0 3	0 2	0 0	–	–	–	0 16	3
4	–	–	–	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	–	–	–	0 0	0
5	–	–	–	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	–	–	–	0 0	0
6	–	–	–	0 0	0 0	0 0	0 28	0 46	0 22	0 38	0 16	0 19	0 21	–	–	–	3 10	33
7	–	–	–	0 0	0 50	1 0	1 0	1 0	0 40	0 21	0 3	0 0	0 0	–	–	–	4 54	51
8	–	–	–	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	–	–	–	0 0	0
9	–	–	–	0 20	0 55	1 0	1 0	1 0	1 0	1 0	1 0	1 0	0 41	–	–	–	8 56	93
10	–	–	–	0 30	0 55	0 42	0 40	0 13	0 22	0 0	0 0	0 0	0 0	–	–	–	3 22	35
11	–	–	–	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	–	–	–	0 0	0
12	–	–	–	0 0	0 0	0 0	0 0	0 0	0 38	0 30	0 31	0 0	0 0	–	–	–	1 39	17
13	–	–	–	0 0	0 0	0 40	0 13	0 16	0 25	0 0	0 10	0 0	0 0	–	–	–	1 44	18
14	–	–	–	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	–	–	0 0	0
15	–	–	–	0 0	0 0	0 0	0 43	1 0	0 59	0 38	0 0	0 0	0 0	0 0	–	–	3 20	34
16	–	–	–	0 0	0 21	1 0	0 43	0 22	0 57	0 35	0 43	0 17	0 5	0 0	–	–	5 3	52
17	–	–	–	0 0	0 0	0 0	0 45	0 19	0 54	0 20	0 14	0 0	0 0	0 0	–	–	2 32	26
18	–	–	–	0 0	0 0	0 0	0 14	0 50	1 0	1 0	0 52	0 0	0 0	0 0	–	–	3 56	40
19	–	–	–	0 0	0 30	0 14	0 36	0 0	0 0	0 0	0 0	0 0	0 0	0 0	–	–	1 20	14
20	–	–	–	0 0	0 12	0 42	1 0	1 0	1 0	0 54	0 10	0 0	0 0	0 0	–	–	4 58	50
21	–	–	–	0 0	0 0	0 26	1 0	0 46	0 19	0 2	0 0	0 0	0 0	0 0	–	–	2 33	26
22	–	–	–	0 0	0 32	0 51	0 44	0 44	0 47	0 39	0 32	0 45	0 14	0 0	–	–	5 48	58
23	–	–	–	0 1	1 0	1 0	1 0	0 55	0 52	0 56	0 53	1 0	0 29	0 0	–	–	8 6	81
24	–	–	–	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 14	0 6	0 0	0 0	–	–	0 20	3
25	–	–	–	0 45	1 0	1 0	1 0	1 0	1 0	1 0	1 0	1 0	0 40	0 0	–	–	9 25	94
26	–	–	–	0 30	1 0	1 0	1 0	1 0	1 0	1 0	1 0	1 0	0 29	0 0	–	–	8 59	89
27	–	–	–	0 40	1 0	1 0	1 0	1 0	1 0	1 0	1 0	1 0	0 45	0 0	–	–	9 25	93
28	–	–	–	0 40	1 0	1 0	1 0	1 0	1 0	1 0	1 0	0 54	0 0	0 0	–	–	8 34	85
29	–	–	–	0 0	0 0	0 3	0 56	1 0	0 13	0 0	0 0	0 0	0 0	0 0	–	–	2 12	22
30	–	–	–	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	–	–	0 0	0
31	–	–	–	0 16	0 27	0 30	1 0	0 48	0 26	0 3	0 0	0 0	0 0	0 0	–	–	3 30	34
Total.......	–	–	–	4 9	10 48	13 8	17 2	16 4	15 54	12 36	10 41	8 23	3 47	0 0	–	–	112 32	37

Fig. 1. Example page of a bulletin "Anais do Observatório Central Meteorológico do Infante D. Luiz" with measurements of sunshine duration in Lisbon for January 1918 (source: Ferreira, 1948, LVI, p. 47).

the daily data. After that, we have monthly series of SD and CC for the whole study period 1890–2018. Further calculations and analyses are performed over these series. Fig. 2 (continuous lines) contains the time evolution of SD (top panel) and CC (bottom panel) series (annual averages, calculated from monthly values, are presented to have a clear view of the data).

3.1. *Homogenization*

The temporal homogeneity of the series is evaluated through the Standard Normal Homogeneity Test (SNHT), which is applied to the annual series to detect potential inhomogeneities (Alexandersson, 1986). Note that data of the year 1919 is not taken into account when the test is applied. For this year, there is a gap in the series from March to August. These months of the year contain the days with the highest number of hours of daylight. For this reason, Fig. 2 (top panel) shows a dip for 1919. This anomalous behavior is corrected in the following subsection. According to the test, there is a statistically significant break ($p < 0.05$) in the SD series in 1913 and another in 1958. Looking at Fig. 2 (top panel, continuous line) there is an evident shift in 1913. As mentioned in Section 2, in 1913 the Jordan heliograph was replaced by a Campbell-Stokes one. Then, this break represents an inhomogeneity that must be corrected. For that, using the monthly series, the average values of the periods 1890–1912 and 1913–1936 are calculated. Then, the difference between the two averages is added to the monthly values prior to 1913. In relation to the break in 1958, after consulting the bulletins, we verified that no changes took place around this date that could cause an inhomogeneity in the SD series. Moreover, according to Miranda et al. (2002), who presented the time evolution of SD measurements for six Portuguese stations (Lisbon included) from the 1940s to the 1990s, the evolution over time of the six series around 1958 is similar. This implies that the break detected by the test is not a real inhomogeneity (due to an artefact) but the natural behavior of SSR in that period. Then, the SD series does not need to be corrected for this break.

The SNHT was also applied to the CC annual series. A statistically significant break was detected in 1957. Fig. 2 (bottom panel, continuous line) reveals a clear shift in CC values in that date. The bulletins do not register any changes in the observers, the measurement process, etc. that can cause an inhomogeneity around 1957. However, Miranda et al. (2002) show the evolution over time of four Portuguese CC measurements series (Lisbon included) from the 1940s to the 1990s. From that work, we can see that the only series with a shift is that of Lisbon. Then, we consider that the break in 1957 represents an inhomogeneity in the CC series. To correct it, average values for the periods 1896–1956 and 1857–2017 in the monthly CC series are computed, and the difference between the two values is added to the data prior to 1957 (period 1890–1956).

The temporal evolution of SD and CC series before and after correcting for inhomogeneities is shown in Fig. 2.

3.2. *Correction for seasonal variations*

Once the inhomogeneities have been corrected in the monthly SD and CC series, we have homogeneous series. However, before performing long-term trend analyses, the series require a correction for seasonal

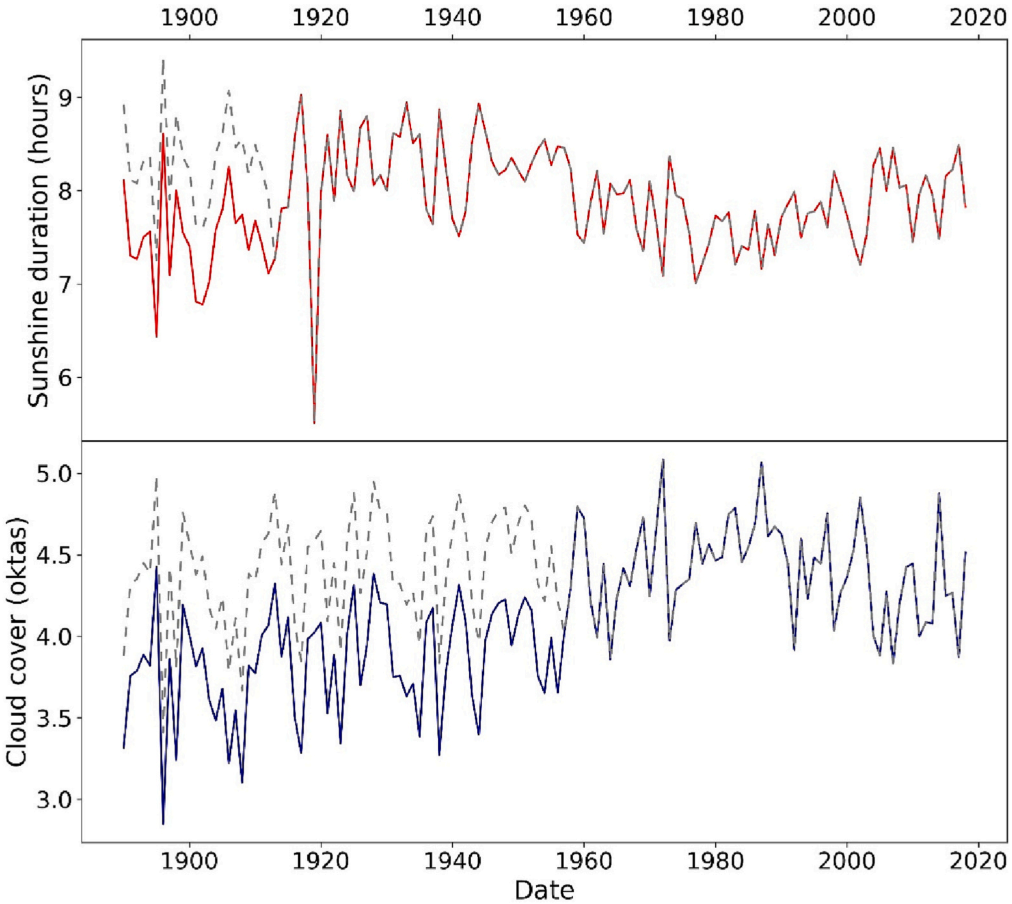


Fig. 2. Time evolution of annual series of sunshine duration (SD, top panel) and cloud cover (CC, bottom panel) in Lisbon for the period 1890–2018 before (continuous lines) and after (dashed lines) correcting for inhomogeneities.

variations. Firstly, the average seasonal cycle needs to be calculated. This cycle consists of 12 values: one average for each month of the year. For example, the first value represents the average SD value of January and is calculated by averaging all the monthly SD data corresponding to January for the period 1890–2018. Then, the deseasonalized monthly SD series is obtained by subtracting the corresponding value of the average seasonal cycle to each month of the initial series. The following equation summarizes the operation:

$$D^{i,j} = I^{i,j} - S^{j}$$

where D represents the series corrected for seasonal variations (anomalies), I the initial uncorrected series, S the average seasonal cycle, the superscript i the year (ranging from 1890 to 2018) and the superscript j the month of the year (from 1 to 12). The same procedure is followed to deseasonalize the CC monthly series.

As a summary of the methodology followed in this work, Section 2 described how records of SD and CC for the period 1890–1942 and 1890–1941, respectively, have been digitized in this work. Then, these data were merged with those available in machine-readable format from the IPMA (1943–2018 for SD and 1942–2018 for CC) to obtain series for the period 1890–2018 (see Fig. 2, continuous lines). Subsequently, these two data series are corrected for inhomogeneities (see Fig. 2, dashed lines) and seasonal variations (see resulting series in Fig. 3), which has been explained in Section 3. Once the data series have been both constructed and corrected, it is possible to detect trends in SD and CC, as described in the following Section 4.

4. Results and discussion

Fig. 3 depicts the resulting annual SD (top panel) and CC (bottom panel) series after applying the two aforementioned corrections. The figure also contains 11-year running averages to highlight the long-term behavior of the series.

Firstly, we look at SD series (Fig. 3, top panel). At first glance, two clear periods are distinguished. An early period from the beginning of the series up to the 1950s, followed by a modern period. The early period presents stable values with short decreases and increases whereas the modern period contains a long decline followed by a long partial recovery. Performing linear regressions on the monthly SD time series, statistically significant trends (at the 95% confidence level) covering the whole early period, that is, spanning from 1890 up to any of the years of the 1950s are not detected. An almost statistically significant negative trend ($p = 0.06$) is found for the period 1890–1915 with a value of -0.17 ± 0.09 h per decade (slope ± standard error), which could indicate the existence of a weak early dimming in the study location. After this period and until the late 1940s, there are short increases and decreases (for example 1910s–1930s) without statistically significant trends. Therefore, there is no evidence for an early brightening in the study location. These results derived from the trend analysis for the period that spans between the last decade of the 19th century and the first half of the 20th century are similar to those obtained by Montero-Martín et al. (2021) who detected an early dimming period in SD data from Coimbra (a Portuguese location too) for a similar period without finding an early brightening period until the 1950s. In Spain, other studies obtained an early dimming period (Antón et al., 2017; Aparicio et al., 2019; Bravo-Paredes et al., 2019), and outside the Iberian Peninsula too (Kazadzis

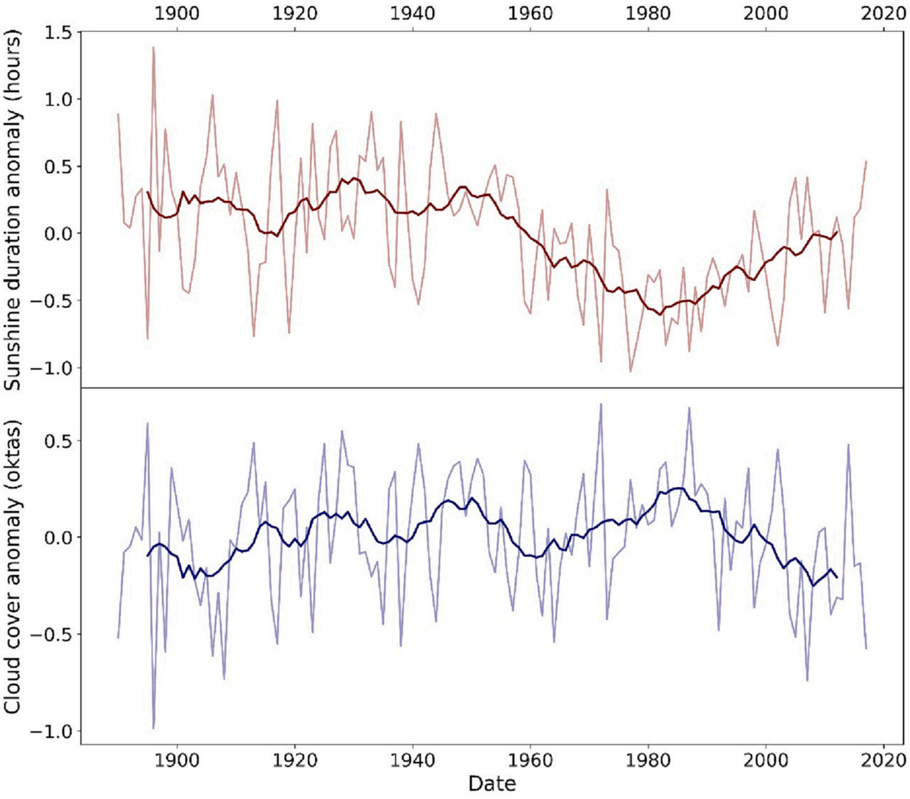


Fig. 3. Time evolution of homogenized and deseasonalized annual anomalies of SD (red thin line, top panel) and CC (blue thin line, bottom panel) in Lisbon for the period 1890–2017. Thick lines represent 11-year running averages. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2018; Matuszko, 2014; Stanhill and Achiman, 2017; Stanhill and Cohen, 2008). On the contrary, there is no evidence of this trend in the US (Stanhill and Cohen, 2005) and mixed evidence in Ireland (Pallé and Butler, 2002). In relation to the second quarter of the 20th century, other works reported early brightening periods in Spain (Antón et al., 2017; Aparicio et al., 2019; Curto et al., 2009; Montero-Martín et al., 2023) as well as outside the Iberian Peninsula (Matuszko, 2014; Ohmura, 2009; Ohmura, 2007; Sanchez-Romero et al., 2014; Stanhill et al., 2018), whereas other studies did not find that trend (Manara et al., 2015; Sanchez-Lorenzo and Wild, 2012; Stanhill and Cohen, 2005).

With respect to the modern period (1950s–2010s), statistically significant trends with a value of −0.28 ± 0.07 h per decade for the period 1953–1982 and 0.20 ± 0.05 h per decade for the period 1982–2017 are obtained. Both trends are in line with the well-known dimming and brightening periods in SSR found in the Iberian Peninsula (Montero-Martín et al., 2023; Román et al., 2014; Sanchez-Lorenzo et al., 2013; Sanchez-Lorenzo et al., 2007) and other locations around the world (Sanchez-Lorenzo et al., 2015; Wild, 2016; Wild, 2009).

Regarding the CC series (Fig. 3, bottom panel), an increase is apparent from the beginning of the series up to the 1980s, followed by a decline until the end of the series (statistically significant trends of 0.02 ± 0.01 and − 0.16 ± 0.05 oktas per decade for 1890–1982 and 1982–2017, respectively). The increase for the 20th is common in the literature (Pallé and Butler, 2002; Sanchez-Lorenzo and Wild, 2012) and, in addition, there are also some studies in line with the decrease since the second half of the 20th century (Manara et al., 2023; Mateos et al., 2014; Sanchez-Lorenzo et al., 2017; Sanchez-Lorenzo et al., 2009). Sanchez-Lorenzo et al. (2012) provide a detailed review of studies dealing with trends in CC using visual observations covering the whole 20th century. Unfortunately, there are few works studying long term trends of CC and cloud genera, being Matuszko (2003) one of the few exceptions covering the 20th century in Cracow (Poland).

Looking at the relationship between SD and CC, it can be seen from Fig. 3 that the minimum values of SD are associated with maximum values of CC (years 1895, 1913, 1919, 1972, 1977) and vice versa (1896, 1906, 1917, 1933, 1944). On the decadal scale (see Table 1), during the

Table 1

Values of trends (slope ± standard error) in sunshine duration (SD) and cloud cover (CC) in Lisbon for different subperiods obtained through linear regression analyses. The upper part of the cells contains SD expressed in units of hours per decade, CC in units of oktas per decade and SD fraction in units of decade^{-1}, whereas the lower part in terms of percentage per decade.

Series	1890–1915	1915–1953	1953–1982	1982–2017
SD	−0.17 ± 0.09 −2.1 ± 1.1	−0.02 ± 0.05 −0.3 ± 0.6	**−0.28 ± 0.07** **−3.6 ± 0.9**	**0.20 ± 0.05** **2.6 ± 0.7**
CC	0.10 ± 0.08 2.3 ± 1.8	0.07 ± 0.04 1.5 ± 0.9	0.09 ± 0.06 2.0 ± 1.3	**−0.16 ± 0.05** **−3.6 ± 1.0**
Cloudless SD fraction	no data	0.002 ± 0.002 0.2 ± 0.2	**−0.018 ± 0.003** **−1.9 ± 0.4**	**0.011 ± 0.003** **1.2 ± 0.3**
Spring SD	0.06 ± 0.20 0.7 ± 2.3	−0.02 ± 0.11 −0.2 ± 1.3	−0.28 ± 0.15 −3.4 ± 1.8	0.15 ± 0.11 1.9 ± 1.3
Summer SD	−0.30 ± 0.17 −2.6 ± 1.5	**−0.18 ± 0.06** **−1.6 ± 0.5**	**−0.41 ± 0.10** **−3.7 ± 0.9**	**0.33 ± 0.08** **3.0 ± 0.7**
Autumn SD	−0.15 ± 0.16 −2.0 ± 2.2	0.07 ± 0.08 1.0 ± 1.1	−0.19 ± 0.12 −2.7 ± 1.7	0.11 ± 0.11 1.6 ± 1.6
Winter SD	−0.27 ± 0.20 −4.9 ± 3.7	0.06 ± 0.11 1.1 ± 2.0	−0.26 ± 0.17 −5.1 ± 3.5	0.21 ± 0.11 4.1 ± 2.2

Statistically significant trends at the 95% confidence level are highlighted in bold.

first quarter of the study period (1890–1915), a weak dimming in SD is detected whereas no trends in CC are found. Subsequently, during the second quarter of the study period (1915–1953), there are no trends in both SD and CC. During the third quarter (1953–1982), a clear dimming in SD is obtained whereas there are no trends in CC. Lastly, during the fourth quarter (1982–2017) when an evident brightening in SD is found, a statistically significant decrease in CC is obtained. Therefore, the above suggests that there is an inverse relationship between SD and CC (which is confirmed by CC vs SD linear regressions showing statistically significant negative correlations for the four aforementioned periods) and, in general, many changes (especially in the short term) in the time evolution of SD could be explained in terms of CC variability. However, especially on the decadal scale, not all the changes in SD can be attributed to CC. In fact, considering the whole study period, a decline in both variables is observed. On average, values at the end of the series are lower than those at the beginning. Thus, there seems to be another variable with notable influence over the long-term evolution of SD. Note that, according to some works, the multi-year variability of SD and SSR is influenced by atmospheric circulation conditions, which affect not only the variability of CC, but also the occurrence of cloud genera (e.g., Clement et al., 2009; Marsz et al., 2022; Matuszko, 2014). In our above analysis, cloud genera have not been considered since this information is not available for Lisbon. However, as an example, a decline in the frequency of stratiform clouds and an increase in convective and stratocumulus clouds have been noted in certain regions of Europe (Liepert, 1997; Wibig, 2008) and on a global scale (e.g., Dübal and Vahrenholt, 2021; Pokrovsky, 2019; Veretenenko and Ogurtsov, 2016) since the second half of the 20th century, which would imply an increase in SSR.

Thus, we investigated if changes in atmospheric aerosol load can affect the evolution of our SD data series by trying to remove cloud effects. For that, a cloudless SD series is obtained by selecting daily SD records that correspond with a CC value of zero oktas (Sanchez-Lorenzo et al., 2009). It was observed that the months of the year contained 2, 3 or 4 days of this type on average, except for July and August that contained 8. Then, we selected the cloudless days of these two months to construct the cloudless SD series. It was seen that the data for the year 2018 produced a huge dip in the cloudless SD series, which is not associated with any changes reported in the metadata or a powerful volcanic eruption. Then, with the objective of constructing a more robust series without the seasonal influence of the different number of daylight hours over the year, the cloudless SD fraction series was calculated, in which all the daily cloudless SD data are divided by their theoretical maximum SD value (the theoretical SD value was defined as the time span from solar zenith angle 90° at sunrise to solar zenith angle 90° at sunset). The dip of the year 2018 was reduced significantly in the cloudless SD fraction series. However, that dip still represented the largest change in value from one year to the next. Data for the year 2018 were removed in all the series because the measurements of that year may be affected by a problem in the heliograph (not registered in the metadata) as they correspond to the last year with SD data. In addition, all the calculations and figures of all the data series were redone without considering data for the year 2018. In fact, the analyses and figures presented in this section are the ones after discarding data of the year 2018.

Fig. 4 (top panel) displays the cloudless SD fraction data series (annual averages are shown to have a clear view of the data). Note that the series starts in 1918 since we did not find daily SD measurements before that date, which are necessary to select cloudless days. The cloudless SD fraction series exhibits a clear shift from the beginning of the series up to 1937. In fact, we assessed the homogeneity of the series by applying the SNHT test in the same way as explained in Section 3. The test detected a strong break in 1937 and two minor ones in 1975 and

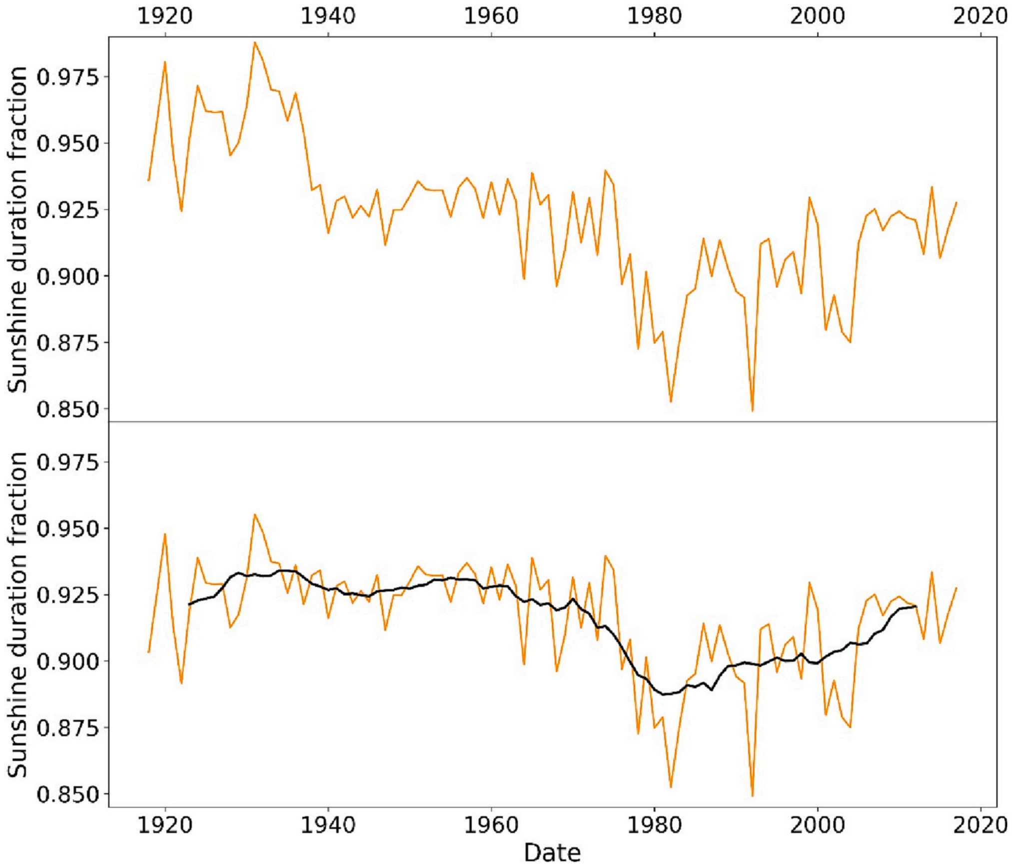


Fig. 4. Time series of raw (top panel) and homogenized (bottom panel) cloudless SD fraction in Lisbon for the period 1918–2017. The thick black line represents 11-year running averages.

2004. The bulletins containing the original data do not register any changes in the heliograph, its location, the observers, the measurement process, etc. that can cause inhomogeneities around the mentioned years. However, after comparing our series with other cloudless SD series from nearby stations (Montero-Martín et al., 2021; Sanchez-Lorenzo et al., 2009), it was concluded that the break in 1937 represented an inhomogeneity that needed to be corrected because the shift is evident in the Lisbon series and it does not represent the natural behavior of SSR in that period (the shift only appears in the Lisbon series), whereas the breaks in 1975 and 2004 are not inhomogeneities because they are smaller and the evolution of the series around those dates is natural and observed in other nearby stations.

Fig. 4 (bottom panel) depicts the resulting time evolution of the cloudless SD fraction series after correcting the inhomogeneity in 1937. Comparing the corrected SD time series (Fig. 3, top panel) with the corrected cloudless SD fraction time series (Fig. 4, bottom panel), it can be seen that they are similar both in the oscillations of the annual series and in the long-term trend behavior highlighted by the 11-year running averages. In fact, the corrected cloudless SD fraction series presents similar statistically significant trends to those found in the corrected SD series (see Table 1), i.e., no trends for the second quarter of the study period (there are no cloudless SD fraction data for the first quarter of the period), followed by a negative trend during 1950s–1980s, and by a positive trend until the 2010s. Moreover, looking at the time series of the corrected SD (Fig. 3, top panel), CC (Fig. 3, bottom panel) and cloudless SD fraction (Fig. 3, bottom panel), and the results of the trend analyses for these series exposed in Table 1, it can be seen:

1) Second quarter of the study period (1915–1953): there is a stabilization of SD values, a slight increase of CC (not statistically significant) and a slight increase in cloudless SD fraction (not statistically significant). Therefore, the slight increase in CC does not imply a decline in SD because there seems to be a decrease in atmospheric aerosol load (indicated by the slight increase in cloudless SD fraction).
2) Third quarter of the study period (1953–1982): there is a negative trend in SD, no trends in CC and a negative trend in cloudless SD fraction. Thus, the decline in SD is not caused by CC, but probably by an increase in atmospheric aerosol load.
3) Fourth quarter of the period (1982–2017): there is a positive trend in SD, a negative one in CC and a positive one in cloudless SD fraction. Thereby, the increase in SD is probably caused by both a decrease in CC and a decline in atmospheric aerosol load.

This reflects, firstly, the utility of SD in cloudless conditions to track the long-term variability of atmospheric aerosol load, which may be related to changes in the rates of black carbon emissions in Europe since the 1920s (Lamarque et al., 2010; McConnell et al., 2007; Novakov et al., 2003), and, secondly, that cloud changes cannot explain all the changes in SD since the aerosol load seems to play an important role in the long-term evolution of SD (Bartoszek et al., 2020; Sanchez-Romero et al., 2014; Wandji Nyamsi et al., 2020).

Furthermore, Fig. 4 (bottom panel) shows that the lowest values of the cloudless SD fraction series correspond to the years 1982 and 1992. This matches the eruption of the volcano El Chichon in Mexico (March 1982) and Pinatubo in Philippines (April 1991), whose volcanic aerosols seem to have affected the SD measurements in Lisbon. This demonstrates that SD measurements in cloudless conditions can detect the signal of major volcanic eruptions (Montero-Martín et al., 2021; Obregón et al., 2020; Sanchez-Lorenzo et al., 2009).

Lastly, seasonal behaviors are analyzed. Seasonal series are constructed (see Fig. 5) by extracting the values of March, April and May for spring, June, July and August for summer, September, October and November for autumn, and December, January and February for winter from the homogenized and deseasonalized monthly SD series.

Looking at Fig. 5, we can identify similar periods as those in annual SD series (Fig. 3, top panel), i.e., an early period until the 1950s presenting more or less stable values with short declines and increases, followed by a modern period with a clear long decline and a clear long increase. As expected, seasonal series present larger maximum and minimum values. For this reason, the y-axis covers a wider range of values (than in the case of the total SD series) giving the impression that the long-term evolution (represented by the 11-year running averages) varies less. Note that the higher values in the series are associated with minimum values in CC and vice versa. Linear regressions only yield statistically significant trends in the summer series (Table 1). That series presents the same type of trends as those reported from the annual SD series, but in a more prominent way. This indicates that the trends detected in SD are mainly driven by summer measurements, whereas records registered in other seasons tend to soften the trends. Taking into account that summer is the least cloudy season (for example, the average number of cloudless days is 8 in spring, 21 in summer, 10 in autumn and 10 in winter) the above results suggest that the aerosol load appears to play a major role in long-term trends in Lisbon (as concluded from the cloudless SD fraction analysis).

Finally, it is worth highlighting that the fact that the long-term behavior of SD in Lisbon studied in the present study matches those trends in SD and SSR found in other regions of the world proves once again that SD is a good proxy for SSR, being especially useful for early years when there is little or no SSR measurements.

5. Conclusions

This work presents SD and CC data series registered in Lisbon for the period 1890–2018. Daily measurements for the period 1941–2018 were available in electronic format whereas daily and monthly ones from 1890 until 1940 have been digitized in the present work. After a quality control applied to the digitized records, these two periods of data have been joined and machine-readable series of SD and CC for the period 1890–2018 are made available to the scientific community. This represents the earliest continuous SD series in Portugal and the second one in the Iberian Peninsula.

Once the series were corrected for inhomogeneities (one in each series), long-term analyses were carried out. The SD series presents a negative trend without statistical significance compatible with a weak early dimming period in Lisbon from the 1890s to the 1910s, after that, a stabilization of the values (1910s–1950s), and then, two strong statistically significant trends in line with the well-known negative and positive trends called global dimming (1950s–1980s) and brightening period (1980s–2010s), respectively. With respect to CC, the series shows an increase from the beginning of the study period until the 1980s, followed by a decline (both being statistically significant).

An analysis of SD under cloudless conditions revealed that this quantity is useful to track the long-term variability of atmospheric aerosol load, which appears to be responsible for long-term changes in SD (apart from cloud changes) in Lisbon. In addition, the minimum values of the cloudless SD series match the eruptions of El Chichon and Pinatubo demonstrating the potential of SD under cloudless conditions to detect major eruptions.

The seasonal analysis of SD only yields statistically significant trends in the summer series, which are more prominent that the trends in total SD. As summer is the least cloudy season, this indicates, again, that aerosol load seems to have a significant influence on long-term SD variability in Lisbon.

The conclusions drawn from the present work highlight the importance of SD as a proxy for SSR to detect long-term trends in that variable and the value of SD records in combination with CC ones to provide atmospheric aerosol load information for early years and/or locations with a shortage of solar radiation and aerosol measurements.

Lastly, it is worth noting that most works analyzing SD trends in the Iberian Peninsula contain series starting in the second half of the 20th century (almost no series begins in the 19th century or in the first

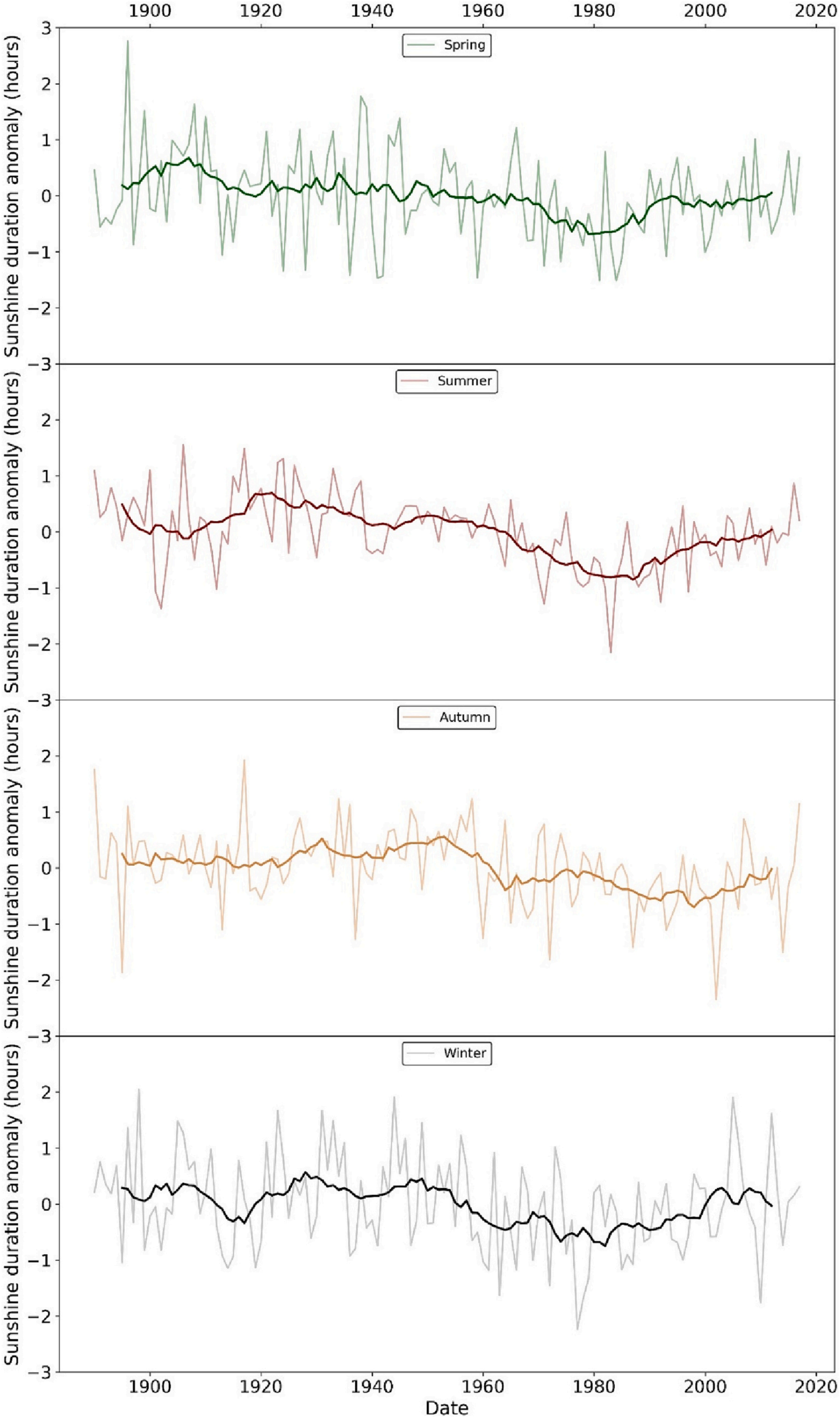


Fig. 5. Time evolution of seasonal anomalies of SD (thin lines) in Lisbon for the period 1890–2017. Thick lines represent 11-year running averages.

decades of the 20th century), and almost all are associated with Spanish locations. The present work improves that spatial and temporal coverage. However, our study is limited to one location and the use of SD as a proxy for SSR. As future work, we intend to recover more Portuguese SD data, digitize them if they are not available in electronic format and analyze their long-term behavior. Other possible future tasks could include the reconstruction of SSR series from SD ones, the study of other meteorological variables that can act as proxies for SSR and the recovery of cloud genera records to study the influence of possible changes in cloud type on SSR variability.

CRediT authorship contribution statement

A.J.P. Aparicio: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition, Project administration. **V.M.S. Carrasco:** Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **J. Montero-Martín:** Methodology, Writing – original draft, Writing – review & editing. **A. Sanchez-Lorenzo:** Formal analysis, Writing – original draft, Writing – review & editing. **M.J. Costa:** Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition, Project administration. **M. Antón:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data series are made available to the scientific community as supplementary material of this paper

Acknowledgments

We would like to acknowledge Instituto Portugués do Mar e da Atmósfera for providing us with bulletins of the Instituto Dom Luiz for the data period 1921-1925 and sunshine duration and cloud cover data for the period 1941-2018. We also thank project SIGN (http://sign.fc.ul.pt) for making a large amount of bulletins of the Instituto Dom Luiz available to the scientific community. This work was co-funded by National funds through FCT - Fundação para a Ciência e Tecnologia, I.P. (projects UIDB/04683/2020 and UIDP/04683/2020). A. J. P. Aparicio thanks Universidad de Extremadura and Ministerio de Universidades of the Spanish Government for the award of a postdoctoral fellowship “Margarita Salas” (MS-11). A. Sanchez-Lorenzo was supported by a fellowship (RYC-2016-20784) and a project (PID2019-105901RB-I00) funded by the Spanish Ministry of Science and Innovation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2023.106804.

References

Alexandersson, H., 1986. A homogeneity test applied to precipitation data. J. Climatol. 6, 661–675. https://doi.org/10.1002/joc.3370060607.

Angell, J.K., 1990. Variation in United States Cloudiness and Sunshine Duration between 1950 and the Drought year of 1988. J. Clim. 3, 296–308. https://doi.org/10.1175/1520-0442(1990)003<0296:VIUSCA>2.0.CO;2.

Antón, M., Vaquero, J.M., Aparicio, A.J.P., 2014. The controversial early brightening in the first half of 20th century: a contribution from pyrheliometer measurements in Madrid (Spain). Glob. Planet. Chang. 115, 71–75. https://doi.org/10.1016/j.gloplacha.2014.01.013.

Antón, M., Román, R., Sanchez-Lorenzo, A., Calbó, J., Vaquero, J.M., 2017. Variability analysis of the reconstructed daily global solar radiation under all-sky and cloud-free conditions in Madrid during the period 1887–1950. Atmos. Res. 191, 94–100. https://doi.org/10.1016/j.atmosres.2017.03.013.

Aparicio, A.J.P., Antón, M., Gallego, M.C., Sanchez-Lorenzo, A., Vaquero, J.M., 2019. Re-evaluation of trends in atmospheric column transparency from pyrheliometer measurements in Madrid (1910–1929). Atmos. Res. 217, 165–171. https://doi.org/10.1016/j.atmosres.2018.11.003.

Bartoszek, K., Matuszko, D., Soroka, J., 2020. Relationships between cloudiness, aerosol optical thickness, and sunshine duration in Poland. Atmos. Res. 245, 105097 https://doi.org/10.1016/j.atmosres.2020.105097.

Bartoszek, K., Matuszko, D., Węglarczyk, S., 2021. Trends in sunshine duration in Poland (1971–2018). Int. J. Climatol. 41, 73–91. https://doi.org/10.1002/joc.6609.

Batlló, J., Brito, M., Alberto, F., Catita, C., Custódio, S., Domingues, C., Romão, A., Valente, A., 2014. Observatório do Instituto Dom Luiz: um século e meio de história. Gazeta de física 37 (2), 22–26.

Bravo-Paredes, N., Gallego, M.C., Antón, M., Núñez, M., Vaquero, J.M., 2019. Analysis of actinometric measurements under all-sky and cloud-free conditions in Cáceres (Spain) for the period 1913–1920. Tellus Ser. B Chem. Phys. Meteorol. 71, 1–8. https://doi.org/10.1080/16000889.2019.1663597.

Capello, J.C., 1893. Annaes do Observatorio do Infante D. Luiz. XXVIII.

Clement, A.C., Burgman, R., Norris, J.R., 2009. Observational and Model evidence for positive Low-Level Cloud Feedback. Science 325, 460–464. https://doi.org/10.1126/science.1171255.

Curto, J.J., Also, E., Pallé, E., Solé, J.G., 2009. Sunshine and synoptic cloud observations at Ebro Observatory, 1910–2006. Int. J. Climatol. 29, 2183–2190. https://doi.org/10.1002/joc.1841.

Dübal, H.-R., Vahrenholt, F., 2021. Radiative Energy Flux Variation from 2001–2020. Atmosphere (Basel). 12, 1297. https://doi.org/10.3390/atmos12101297.

Ferreira, H., 1948. Anais do Observatório Central Meteorológico do Infante D. Luiz. LVI.

He, Y., Wang, K., Zhou, C., Wild, M., 2018. A Revisit of Global Dimming and Brightening based on the Sunshine Duration. Geophys. Res. Lett. 45, 4281–4289. https://doi.org/10.1029/2018GL077424.

Hoyt, D.V., 1979. Atmospheric transmission from the Smithsonian Astrophysical Observatory pyrheliometric measurements from 1923 to 1957. J. Geophys. Res. https://doi.org/10.1029/JC084iC08p05018.

Kaiser, D.P., Qian, Y., 2002. Decreasing trends in sunshine duration over China for 1954-1998: Indication of increased haze pollution? Geophys. Res. Lett. 29, 38-1–38-4. https://doi.org/10.1029/2002GL016057.

Kazadzis, S., Founda, D., Psiloglou, B.E., Kambezidis, H., Mihalopoulos, N., Sanchez-Lorenzo, A., Meleti, C., Raptis, P.I., Pierros, F., Nabat, P., 2018. Long-term series and trends in surface solar radiation in Athens, Greece. Atmos. Chem. Phys. 18, 2395–2411. https://doi.org/10.5194/acp-18-2395-2018.

Lamarque, J.-F., Bond, T.C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M.G., Shindell, D., Smith, S.J., Stehfest, E., Van Aardenne, J., Cooper, O.R., Kainuma, M., Mahowald, N., McConnell, J.R., Naik, V., Riahi, K., van Vuuren, D.P., 2010. Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. Atmos. Chem. Phys. 10, 7017–7039. https://doi.org/10.5194/acp-10-7017-2010.

Liepert, B.G., 1997. Recent changes in solar radiation under cloudy conditions in Germany. Int. J. Climatol. 17, 1581–1593. https://doi.org/10.1002/(SICI)1097-0088(19971130)17:14<1581::AID-JOC214>3.0.CO;2-H.

Liepert, B.G., 2002. Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990. Geophys. Res. Lett. 29, 61-1–61-4. https://doi.org/10.1029/2002GL014910.

Lima, J.M., 1915. Anais do Observatório Infante D. Luís. LI.

Ma, Q., Wang, K., He, Y., Su, L., Wu, Q., Liu, H., Zhang, Y., 2022. Homogenized century-long surface incident solar radiation over Japan. Earth Syst. Sci. Data 14, 463–477. https://doi.org/10.5194/essd-14-463-2022.

Manara, V., Beltrano, M.C., Brunetti, M., Maugeri, M., Sanchez-Lorenzo, A., Simolo, C., Sorrenti, S., 2015. Sunshine duration variability and trends in Italy from homogenized instrumental time series (1936–2013). J. Geophys. Res. Atmos. 120, 3622–3641. https://doi.org/10.1002/2014JD022560.

Manara, V., Brunetti, M., Wild, M., Maugeri, M., 2023. Variability and trends of the total cloud cover over Italy (1951–2018). Atmos. Res. 285, 106625 https://doi.org/10.1016/j.atmosres.2023.106625.

Marsz, A.A., Matuszko, D., Styszyńska, A., 2022. The thermal state of the North Atlantic and macro-circulation conditions in the Atlantic-European sector, and changes in sunshine duration in Central Europe. Int. J. Climatol. 42, 748–761. https://doi.org/10.1002/joc.7270.

Mateos, D., Sanchez-Lorenzo, A., Antón, M., Cachorro, V.E., Calbó, J., Costa, M.J., Torres, B., Wild, M., 2014. Quantifying the respective roles of aerosols and clouds in the strong brightening since the early 2000s over the Iberian Peninsula. J. Geophys. Res. Atmos. 119, 10,382–10,393. https://doi.org/10.1002/2014JD022076.

Matuszko, D., 2003. Cloudiness changes in Cracow in the 20th century. Int. J. Climatol. 23, 975–984. https://doi.org/10.1002/joc.887.

Matuszko, D., 2014. Long-term variability in solar radiation in Krakow based on measurements of sunshine duration. Int. J. Climatol. 34, 228–234. https://doi.org/10.1002/joc.3681.

McConnell, J.R., Edwards, R., Kok, G.L., Flanner, M.G., Zender, C.S., Saltzman, E.S., Banta, J.R., Pasteris, D.R., Carter, M.M., Kahl, J.D.W., 2007. 20th-Century Industrial Black Carbon Emissions Altered Arctic climate Forcing. Science 317, 1381–1384. https://doi.org/10.1126/science.1144856.

Miranda, P.M.A., Coelho, F.E.S., Tomé, A.R., Valente, M.A., Carvalho, A., Pires, C., Pires, H.O., Pires, V.C., Ramalho, C., 2002. 20th century Portuguese climate and climate scenarios. In: Santos, F.D., Forbes, K., Moita, R. (Eds.), Climate Change in Portugal: Scenarios, Impacts and Adaptation Measures (SIAM Project), pp. 23–83. Gradiva, 454 pp.

Montero-Martín, J., Antón, M., Vaquero, J.M., Neto, J., Sanchez-Lorenzo, A., 2021. Early sunshine duration and cloud cover records in Coimbra (Portugal) for the period 1891–1950. Int. J. Climatol. 41, 4977–4986. https://doi.org/10.1002/joc.7111.

Montero-Martín, J., Antón, M., Vaquero, J.M., Román, R., Vaquero-Martinez, J., Aparicio, A.J.P., Sanchez-Lorenzo, A., 2023. Reconstruction of daily global solar radiation under all-sky and cloud-free conditions in Badajoz (Spain) since 1929. Int. J. Climatol. https://doi.org/10.1002/joc.8042.

Novakov, T., Ramanathan, V., Hansen, J.E., Kirchstetter, T.W., Sato, M., Sinton, J.E., Sathaye, J.A., 2003. Large historical changes of fossil-fuel black carbon aerosols. Geophys. Res. Lett. 30, 57-1–57-4. https://doi.org/10.1029/2002GL016345.

Obregón, M.A., Gallego, M.C., Antón, M., Vaquero, J.M., 2020. Sunshine duration data in San Fernando (South of Spain) during 1880s: the impact of Krakatoa volcanic eruption. Geosci. Data J. 7, 185–191. https://doi.org/10.1002/gdj3.101.

Ohmura, A., 2007. Observed Long-Term Variations of Solar Irradiance at the Earth's Surface. Space Sci. Rev. 125, 111–128. https://doi.org/10.1007/s11214-006-9050-9.

Ohmura, A., 2009. Observed decadal variations in surface solar radiation and their causes. J. Geophys. Res. 114, D00D05. https://doi.org/10.1029/2008JD011290.

Ohvril, H., Teral, H., Neiman, L., Kannel, M., Uustare, M., Tee, M., Russak, V., Okulov, O., Jõeveer, A., Kallis, A., Ohvril, T., Terez, E.I., Terez, G.A., Gushchin, G.K., Abakumova, G.M., Gorbarenko, E.V., Tsvetkov, A.V., Laulainen, N., 2009. Global dimming and brightening versus atmospheric column transparency, Europe, 1906–2007. J. Geophys. Res. 114, D00D12. https://doi.org/10.1029/2008JD010644.

Pallé, E., Butler, C., 2002. The proposed connection between clouds and cosmic rays: cloud behaviour during the past 50–120 years. J. Atmos. Solar-Terrestrial Phys. 64, 327–337. https://doi.org/10.1016/S1364-6826(01)00105-5.

Pokrovsky, O.M., 2019. Cloud changes in the period of Global Warming: the results of the International Satellite Project. Izv. Atmos. Ocean. Phys. 55, 1189–1197. https://doi.org/10.1134/S0001433819090366.

Ramanathan, V., Carmichael, G., 2008. Global and regional climate changes due to black carbon. Nat. Geosci. 1, 221–227. https://doi.org/10.1038/ngeo156.

Román, R., Bilbao, J., de Miguel, A., 2014. Reconstruction of six decades of daily total solar shortwave irradiation in the Iberian Peninsula using sunshine duration records. Atmos. Environ. 99, 41–50. https://doi.org/10.1016/j.atmosenv.2014.09.052.

Roosen, R.G., Angione, R.J., 1984. Atmospheric Transmission and climate: results from Smithsonian Measurements. Bull. Am. Meteorol. Soc. 65, 950–957. https://doi.org/10.1175/1520-0477(1984)065<0950:ATACRF>2.0.CO;2.

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

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

Sanchez-Lorenzo, A., Calbó, J., Martin-Vide, J., 2008. Spatial and temporal trends in sunshine duration over Western Europe (1938–2004). J. Clim. 21, 6089–6098. https://doi.org/10.1175/2008JCLI2442.1.

Sanchez-Lorenzo, A., Calbó, J., Brunetti, M., Deser, C., 2009. Dimming/brightening over the Iberian Peninsula: Trends in sunshine duration and cloud cover and their relations with atmospheric circulation. J. Geophys. Res. 114, D00D09. https://doi.org/10.1029/2008JD011394.

Sanchez-Lorenzo, A., Calbó, J., Wild, M., 2012. Increasing cloud cover in the 20th century: Review and new findings in Spain. Clim. Past 8, 1199–1212. https://doi.org/10.5194/cp-8-1199-2012.

Sanchez-Lorenzo, A., Calbó, J., Wild, M., 2013. Global and diffuse solar radiation in Spain: building a homogeneous dataset and assessing their trends. Glob. Planet. Chang. 100, 343–352. https://doi.org/10.1016/j.gloplacha.2012.11.010.

Sanchez-Lorenzo, A., Wild, M., Brunetti, M., Guijarro, J.A., Hakuba, M.Z., Calbó, J., Mystakidis, S., Bartok, B., 2015. Reassessment and update of long-term trends in downward surface shortwave radiation over Europe (1939–2012). J. Geophys. Res. Atmos. 120, 9555–9569. https://doi.org/10.1002/2015JD023321.

Sanchez-Lorenzo, A., Enriquez-Alonso, A., Calbó, J., González, J.-A., Wild, M., Folini, D., Norris, J.R., Vicente-Serrano, S.M., 2017. Fewer clouds in the Mediterranean: consistency of observations and climate simulations. Sci. Rep. 7, 41475. https://doi.org/10.1038/srep41475.

Sanchez-Romero, A., Sanchez-Lorenzo, A., Calbó, J., González, J.A., Azorin-Molina, C., 2014. The signal of aerosol-induced changes in sunshine duration records: a review of the evidence. J. Geophys. Res. Atmos. 119, 4657–4673. https://doi.org/10.1002/2013JD021393.

Silveira, J.H., 1863. Annaes do Observatorio do Infante D. Luiz em Lisboa. I.

Stanhill, G., 2005. Global dimming: a new aspect of climate change. Weather 60, 11–14. https://doi.org/10.1256/wea.210.03.

Stanhill, G., Achiman, O., 2017. Early global radiation measurements: a review. Int. J. Climatol. 37, 1665–1671. https://doi.org/10.1002/joc.4826.

Stanhill, G., Cohen, S., 2001. Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. Agric. For. Meteorol. 107, 255–278. https://doi.org/10.1016/S0168-1923(00)00241-0.

Stanhill, G., Cohen, S., 2005. Solar Radiation changes in the United States during the Twentieth Century: evidence from Sunshine Duration Measurements. J. Clim. 18, 1503–1512. https://doi.org/10.1175/JCLI3354.1.

Stanhill, G., Cohen, S., 2008. Solar radiation changes in Japan during the 20th Century: evidence from sunshine duration measurements. J. Meteorol. Soc. Japan. Ser. II 86, 57–67. https://doi.org/10.2151/jmsj.86.57.

Stanhill, G., Paudel, I., Rosa, R., 2018. Solar radiation measurements in the United States between 1916 and 1949 document widespread brightening in the mid-20th century. Int. J. Climatol. 38, 4777–4785. https://doi.org/10.1002/joc.5695.

Veretenenko, S., Ogurtsov, M., 2016. Cloud cover anomalies at middle latitudes: Links to troposphere dynamics and solar variability. J. Atmos. Solar-Terrestrial Phys. 149, 207–218. https://doi.org/10.1016/j.jastp.2016.04.003.

Wandji Nyamsi, W., Lipponen, A., Sanchez-Lorenzo, A., Wild, M., Arola, A., 2020. A hybrid method for reconstructing the historical evolution of aerosol optical depth from sunshine duration measurements. Atmos. Meas. Tech. 13, 3061–3079. https://doi.org/10.5194/amt-13-3061-2020.

Wang, Y., Yang, Y., Zhao, N., Liu, C., Wang, Q., 2012. The magnitude of the effect of air pollution on sunshine hours in China. J. Geophys. Res. Atmos. 117, D00V14 https://doi.org/10.1029/2011JD016753.

Wheeler, D., 2001. Factors governing sunshine in south-West Iberia: a review of western Europe's sunniest region. Weather 56, 189–197. https://doi.org/10.1002/j.1477-8696.2001.tb06568.x.

Wibig, J., 2008. Cloudiness variations in Łódź in the second half of the 20th century. Int. J. Climatol. 28, 479–491. https://doi.org/10.1002/joc.1544.

Wild, M., 2005. From dimming to brightening: decadal changes in solar radiation at earth's surface. Science 308, 847–850. https://doi.org/10.1126/science.1103215.

Wild, M., 2009. Global dimming and brightening: a review. J. Geophys. Res. Atmos. https://doi.org/10.1029/2008JD011470.

Wild, M., 2016. Decadal changes in radiative fluxes at land and ocean surfaces and their relevance for global warming. WIREs Clim. Chang. 7, 91–107. https://doi.org/10.1002/wcc.372.