UNIVERSIDAD DE EXTREMADURA

TESIS DOCTORAL

Análisis de las tendencias de la radiación solar en la Península Ibérica desde finales del siglo XIX

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PROGRAMA DE DOCTORADO EN MODELIZACIÓN Y EXPERIMENTACIÓN EN CIENCIA Y TECNOLOGÍA

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A mis padres, a mi hermana y a mi pareja.

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"El sol y las nubes, dos actores en el escenario celestial, entablan una eterna danza de luces y sombras, tejiendo historias de cambio y transformación en el lienzo azul del cielo."
- Rachel Carson

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Resumen

El estudio de la radiación solar implica medir la cantidad de energía solar que llega a la superficie terrestre, su distribución en diferentes longitudes de onda y su variabilidad a lo largo del tiempo. Estas mediciones proporcionan información valiosa sobre el balance radiativo terrestre, lo cual permite entender los patrones de calentamiento y enfriamiento en la atmósfera y la superficie, siendo esto esencial para monitorizar el cambio climático. Además, la nubosidad también juega un papel crucial en el clima, reflejando la radiación solar al espacio y enfriando la Tierra. La cantidad y el tipo de nubes, así como su distribución, tienen una influencia determinante en el balance de energía de la Tierra.

El análisis de la radiación solar requiere observaciones precisas, para lo cual se emplea una amplia variedad de instrumentos en superficie y a bordo de satélites. Estos datos se utilizan para monitorizar tendencias a largo plazo, identificar patrones climáticos y comprender cómo los cambios en la radiación solar afectan al clima regional y global. Sin embargo, cuando no se disponen de medidas directas de radiación solar es necesario recurrir a otra variable (*proxy*) a partir de los cual estimar dicha variable. En este contexto, los registros de insolación se han convertido en una herramienta muy útil en la evaluación de la variabilidad a largo plazo de radiación solar en diferentes ubicaciones, más aún cuando se recuperan series temporales antiguas de insolación, como es el caso de esta tesis.

En este contexto, el objetivo principal de esta tesis es analizar la variabilidad temporal de la radiación solar y nubosidad en la Península Ibérica desde finales del siglo XIX hasta principios del siglo XXI. Para ello, se han usado datos de insolación registrados mediante heliógrafos y observaciones de cubierta nubosa tomados de forma continua

durante más de 100 años en tres observatorios de la Península Ibérica (Lisboa desde 1890, Coímbra desde 1891 y Badajoz desde 1929). Inicialmente, se han recuperado y digitalizado datos de insolación y nubosidad recogidos en publicaciones internas de los observatorios para poder completar los registros disponibles de los servicios meteorológicos de España y Portugal. En una segunda etapa, se han construido las series temporales de las variables de estudio en cada emplazamiento, y se ha analizado la calidad y homogeneidad de las mismas. Posteriormente, se ha evaluado las tendencias que presentan las series, comparándolas con otros estudios en diferentes localizaciones del planeta. Además, se ha estudiado las series en condiciones de cielo despejado, lo cual permite analizar el posible impacto de los aerosoles en las tendencias de radiación solar.

El análisis de las tendencias de las series temporales de los valores radiativos en las tres localizaciones de estudio ha permitido identificar cuatro periodos. Inicialmente, se observa en Lisboa y Coímbra un descenso en los valores de insolación (*early dimming)* desde finales del siglo XIX hasta la década de 1910s. Así, se ha determinado una tendencia estadísticamente significativa en la insolación de -0.51±0.32 horas de sol por década en Coímbra. A continuación, se ha constatado en Badajoz un aumento significativo (+4.18 W/m^2 por década) de la radiación solar en superficie hasta mitad del siglo XX (*early brightening*), aunque este fenómeno no se ha observado en las dos estaciones portuguesas. Posteriormente, en las tres estaciones analizadas se observa un nuevo descenso (*dimming*) hasta los 1980s, seguido de un aumento (*brightening*) hasta comienzo del siglo XXI. Así, por ejemplo, la serie de Lisboa muestra un descenso de -0.28 ± 0.07 horas de sol por década y un aumento de +0.20 ± 0.05 horas de sol por década, respectivamente. Por otro lado, el análisis de las tendencias de nubosidad en cada periodo muestra que los aumentos de radiación pueden deberse parcialmente al descenso de la cobertura nubosa en las tres localidades, y viceversa. Además, el estudio de las tendencias de los valores radiativos en días de cielo despejado indica que la presencia de aerosoles en la atmósfera tiene una influencia relevante en la variabilidad a largo plazo de la radiación solar recibida en superficie.

Finalmente, se han comparado las series temporales de radiación solar en superficie proporcionadas por satélite con medidas registradas por piranómetros en 12 estaciones de la Península Ibérica para el periodo 1985-2015. Aunque la correlación entre los datos medios anuales es aceptable (coeficientes de determinación de 0.8), las tendencias obtenidas a partir de datos satelitales son notablemente inferiores a las tendencias determinadas mediante piranómetros, principalmente en verano. Estas discrepancias están probablemente relacionadas con la inclusión de valores climatológicos promedios del aerosol atmosférico en los modelos de estimación de los satélites, los cuales no recogen la notable disminución de la carga de aerosol observada en la Península Ibérica desde finales del siglo XX hasta la actualidad.

Summary

The study of solar radiation involves measuring the amount of solar energy reaching the Earth's surface, its distribution across different wavelengths, and its variability over time. These measurements provide valuable information about the Earth's radiative balance, helping to understand patterns of heating and cooling in the atmosphere and on the surface, essential for monitoring climate change. Additionally, cloud cover plays a crucial role in climate, reflecting solar radiation back into space and cooling the Earth. The quantity, type, and distribution of clouds have a determining influence on Earth's energy balance.

The analysis of solar radiation requires precise observations, for which a wide variety of instruments are used both on the surface and aboard satellites. These data are used to monitor long-term trends, identify climate patterns, and understand how changes in solar radiation affect regional and global climate. However, when direct measurements of solar radiation are not available, it is necessary to resort to another variable (proxy) from which to estimate that variable. In this context, insolation records have become a very useful tool in evaluating the long-term variability of solar radiation in different locations, especially when recovering historical insolation time series, as in the case of this thesis.

In this context, the main objective of this thesis is to analyze the temporal variability of solar radiation and cloudiness in the Iberian Peninsula from the late 19th century to the early 21st century. Data from sunshine duration recorded by heliographs and observations of cloud cover taken continuously for over 100 years at three observatories in the Iberian Peninsula (Lisbon since 1890, Coimbra since 1891, and Badajoz since 1929) have been used. Initially, insolation and cloudiness data collected in internal

publications of the observatories were recovered and digitized to complete the available records from the meteorological services of Spain and Portugal. In a second stage, time series of the study variables at each location were constructed, and their quality and homogeneity were analyzed. Subsequently, trends in the series were evaluated, comparing them with other studies in different locations worldwide. Additionally, the series were studied under clear sky conditions, allowing an analysis of the potential impact of aerosols on solar radiation trends.

The analysis of trends in the time series of radiative values in the three study locations has allowed the identification of four periods. Initially, a decrease in sunshine duration values (early dimming) is observed in Lisbon and Coimbra from the late 19th century until the 1910s. A statistically significant trend in sunshine duration of -0.51±0.32 hours of sunshine per decade in Coimbra has been determined. Next, a significant increase (+4.18 W/m2 per decade) in surface solar radiation is observed in Badajoz until the mid-20th century (early brightening), although this phenomenon has not been observed in the two Portuguese stations. Subsequently, a new decrease (dimming) is observed in the three stations analyzed until the 1980s, followed by an increase (brightening) until the beginning of the 21st century. For example, the Lisbon series shows a decrease of -0.28 ± 0.07 hours of sunshine per decade and an increase of +0.20 ± 0.05 hours of sunshine per decade, respectively. On the other hand, the analysis of cloudiness trends in each period shows that increases in radiation may be partially due to a decrease in cloud cover in the three locations, and vice versa. Additionally, the study of trends in radiative values on clear sky days indicates that the presence of aerosols in the atmosphere has a relevant influence on the long-term variability of received surface solar radiation.

Finally, time series of surface solar radiation provided by satellites have been compared with measurements recorded by pyranometers at 12 stations in the Iberian Peninsula for the period 1985-2015. Although the correlation between mean annual data is acceptable (determination coefficients of 0.8), trends obtained from satellite data are notably lower than trends determined by pyranometers, especially in summer. These discrepancies are probably related to the inclusion of average climatological values of atmospheric aerosol in satellite estimation models, which do not capture the significant decrease in aerosol load observed in the Iberian Peninsula from the late 20th century to the present.

1. Introducción

1.1. Marco de trabajo

La radiación solar, energía electromagnética emitida por el Sol, es el motor de la vida en la Tierra y juega un papel fundamental en una amplia gama de procesos naturales y tecnológicos (Stephens et al., 2012; Wild et al., 2015). Esta radiación es la fuente primaria de energía que alimenta la fotosíntesis, el proceso mediante el cual las plantas convierten la energía solar en materia orgánica y oxígeno. Esto sustenta la cadena alimentaria y proporciona el oxígeno que respiramos. Además de mantener la vida, la radiación solar es fundamental para la tecnología solar. Los paneles solares fotovoltaicos aprovechan la radiación solar para generar electricidad mediante el efecto fotoeléctrico, mientras que los sistemas de calefacción solar utilizan la radiación solar para calentar agua y espacios. Estas tecnologías son esenciales para la transición hacia fuentes de energía renovable y sostenible, lo que contribuye a la mitigación del cambio climático.

La radiación solar que llega a la Tierra se puede dividir en tres componentes:

Radiación Solar Directa: radiación que llega directamente del Sol a la superficie terrestre sin ser dispersada ni absorbida por la atmósfera.

Radiación Solar Difusa: aquella que ha sido dispersada en varias direcciones por partículas en la atmósfera, como moléculas de aire y aerosoles. Esta radiación proviene de todas las direcciones del cielo.

Radiación Solar Reflejada: parte de la radiación solar que llega a la Tierra es reflejada tanto por la atmósfera como por la superficie terrestre. La razón entre la cantidad de radiación reflejada y la radiación incidente se denomina albedo.

Además, la radiación solar se compone de una variedad de longitudes de onda, que abarcan desde la radiación ultravioleta (UV) de alta energía hasta la radiación infrarroja (IR) de baja energía. La mayor parte de la radiación solar que llega a la superficie de la Tierra (denominada de onda corta) se encuentra en el rango espectral del visible e infrarroja cercana (NIR). La Figura 1 muestra la radiación solar dentro del espectro electromagnético completo.

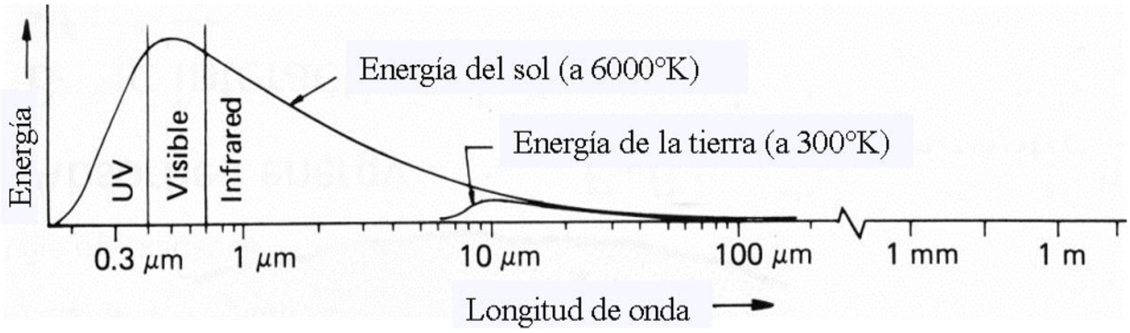

Figura 1. Espectro de emisión de energía de la radiación solar (onda corta) y de la radiación terrestre (onda larga) en función de la longitud de onda.

Cuando la radiación solar atraviesa la atmósfera terrestre, sufre una serie de procesos de interacción con sus constituyentes. Así, ciertas longitudes de onda de la radiación solar son absorbidas por gases en la atmósfera, como el oxígeno, el ozono y el vapor de agua. Esta absorción tiene consecuencias importantes, como la formación y destrucción de ozono estratosférico y la consiguiente atenuación de la radiación UV que llega a la superficie terrestre. La radiación solar también se dispersa en diferentes direcciones debido a partículas en la atmósfera, como moléculas de gases y aerosoles. Además, las nubes atenúan notablemente la radiación solar mediante procesos combinados de absorción, dispersión y reflexión. Todos estos factores moduladores hacen que la radiación solar en superficie sea considerablemente menor de la que llega al tope de la atmósfera.

Los cambios temporales de los constituyentes atmosféricos que atenúan la radiación solar provocan que los valores radiativos registrados en la superficie terrestre presenten una gran variabilidad. Además, la radiación solar en superficie varía a lo largo del día y a lo largo de las estaciones debido a la rotación de la Tierra y su inclinación axial.

La radiación solar ha sido objeto de estudio durante décadas. Los científicos han desarrollado instrumentos para realizar mediciones precisas en superficie, y así poder analizar su variabilidad, su impacto en el clima y su aplicación en tecnologías solares (Wild, 2009; 2016). Además, los avances en la observación por satélite han permitido la monitorización precisa de los valores de radiación solar en superficie a nivel global. En este contexto, el estudio de la evolución de la radiación solar incidente en la superficie desde la segunda mitad del siglo XX, cuando comenzaron a registrarse medidas continuas, ha sido un asunto de gran interés para la comunidad científica (Stanhill y Achiman, 2017). Así, numerosos estudios han observado en distintos lugares del planeta un período de descenso en los valores radiativos en superficie de alrededor de 3-9 W/m^2 desde la década de 1950 hasta la década de 1980, fenómeno conocido como *global dimming* (Stanhill y Cohen, 2001; Ohmura, 2007). Además, se ha constatado un período de aumento de aproximadamente 1-4 W/m^2 desde la década de 1980 hasta la actualidad, especialmente en las naciones industrializadas, fenómeno conocido como *brightening* (Wild, 2009; Wild et al., 2005; Sanchez-Lorenzo et al., 2015). La Figura 2 muestra como ejemplo la evolución del promedio anual de los valores de radiación solar en superficie en W/m^2 en Potsdam (Alemania) durante el periodo 1937-2014 (Wild, 2016), observándose los fenómenos comentados anteriormente. Más concretamente, se pueden apreciar fases distintas de aumento de la radiación solar (décadas de 1930-1940, *early brightening*), de descenso (décadas de 1950-1980, *dimming*), y nuevas subidas (desde la década de 1980, *brightening*). Además, se puede notar una estabilización desde alrededor de 2010.

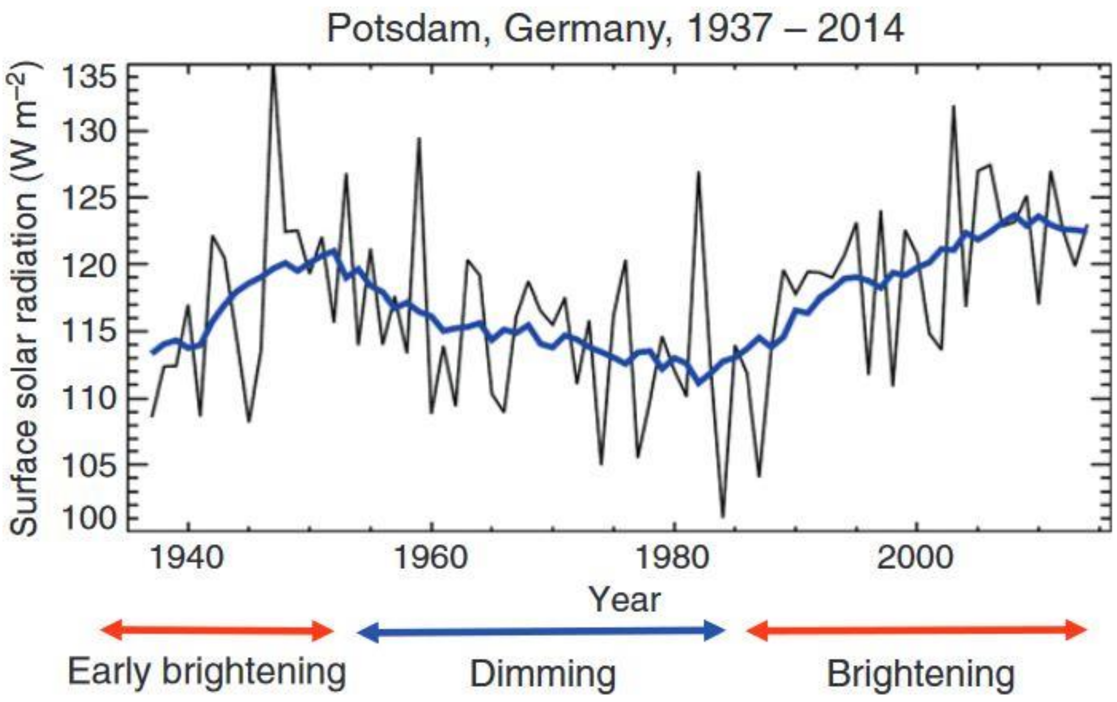

Figura 2. Valores anuales de radiación solar sobre la superficie terrestre medidas en W/m^2 en Potsdam (Alemania) durante parte del siglo XX y XXI. La línea azul representa una media móvil a cinco años (Wild, 2016).

Igualmente, desde finales del siglo XIX se ha podido estudiar la evolución de la radiación solar a partir de la insolación (*sunshine duration*). Esta magnitud se define como la cantidad de tiempo, en número de horas por día, en la que la radiación solar directa supera un cierto umbral (generalmente tomado en 120 W/m^2). Así, la insolación se ha usado ampliamente como *proxy* para reconstruir y analizar la variabilidad a largo plazo de la radiación solar en la superficie en numerosos emplazamientos del planeta: Estados Unidos (Stanhill y Cohen, 2005), Japón (Stanhill y Cohen, 2008), Suiza (Sanchez-Lorenzo y Wild, 2012), Italia (Manara et al., 2015), etc. Particularmente, para la Península Ibérica (Sánchez-Lorenzo et al. 2007; Sánchez-Lorenzo et al., 2009) estudiaron en numerosas localizaciones la evolución de la insolación desde la década de

1930, cuantificando los fenómenos *global dimming* y *brightening* en esta región. Además, Antón et al. (2017) recuperaron la serie de insolación de Madrid desde 1887, que muestra una disminución en la radiación solar en la superficie hasta la década de 1930 (*early dimming*), seguida de un aumento progresivo hasta 1950 (*early brightening*). Los primeros registros de insolación en la Península Ibérica se realizaron en el Observatorio de San Fernando (sur de España) en 1881, los cuales constituyen la serie más larga disponible, aunque no se considera homogénea entre 1891 y 1933 (Wheeler, 2001). Obregón et al. (2020) digitalizaron los registros diarios de insolación en esta estación singular durante el período 1881-1890, mostrando la primera evidencia de los efectos de la erupción del volcán Krakatoa de 1883 en datos de insolación.

En la última década, se ha realizado un esfuerzo para recuperar datos meteorológicos del pasado a nivel mundial (Domínguez-Castro et al., 2017; García-Herrera et al., 2018; Brönnimann et al., 2019). Las fuentes documentales de la Península Ibérica también han proporcionado series meteorológicas antiguas tanto de España (Domínguez-Castro et al., 2014; Vaquero et al., 2021) como de Portugal (Alcoforado et al., 2011). En particular, también se ha prestado atención a la recuperación de series de medida de radiación solar, insolación y nubosidad en la Península Ibérica (Antón et al., 2014, 2017; Aparicio et al., 2019; Bravo-Paredes et al., 2019; Obregón et al., 2020). En este contexto, en la presente tesis se ha tratado de seguir esta línea, recuperar valores de insolación y nubosidad con el fin de analizar la evolución de la radiación solar en los últimos 130 años.

1.2. Justificación de la coherencia e importancia unitaria de la tesis

La presente tesis doctoral se centra en el análisis temporal de datos de radiación solar y nubosidad registrados en diversos emplazamientos de la Península Ibérica, haciendo especial hincapié en los nuevos datos recuperados y digitalizados para las localidades de Coímbra, Badajoz y Lisboa a lo largo de varios periodos comprendidos entre finales del siglo XIX y comienzos del siglo XXI.

Esta tesis consta de cuatro publicaciones científicas, tres de las cuales han seguido una pauta común. En una primera fase se han recopilado series de datos de insolación y cubierta nubosa en formato digital de los servicios meteorológicos de España y Portugal, las cuales comienzan a mediados del siglo XX. Además, se han recuperado datos de esas dos variables registrados entre finales del siglo XIX y mediados del XX a partir de diversas publicaciones internas de los propios observatorios, los cuales han sido digitalizados. Posteriormente, con toda esta información, se han construido series temporales de insolación y nubosidad para cada emplazamiento de estudio, evaluando la calidad y homogeneidad de las mismas. A continuación, se ha analizado la evolución temporal de las series, con la finalidad de determinar tendencias y sus correspondientes interpretaciones físicas. Por último, se han escrito cada uno de los tres artículos, los cuales se han enviado a las revistas científicas y, tras pasar la correspondiente revisión por pares, se ha llegado finalmente a su publicación. En este último proceso, las series de datos se han puesto disponibles a la comunidad científica.

La cuarta publicación de esta tesis analiza las tendencias de radiación solar en 12 emplazamientos de España para el periodo 1985-2015 usando datos medidos por piranómetros y observaciones satelitales, siendo su objetivo principal determinar las posibles discrepancias entre las tendencias que muestras ambas series.

Por lo tanto, la coherencia e importancia unitaria de la presente tesis doctoral queda justificada, puesto que los cuatro artículos que en ella se recogen tienen una misma finalidad: alcanzar un mejor conocimiento de las variabilidad y tendencias de la radiación solar y nubosidad en la Península Ibérica desde finales del siglo XIX a la actualidad.

1.3. Objetivos

Esta tesis doctoral tiene como objetivo principal el análisis de la variabilidad temporal de la radiación solar y nubosidad en la Península Ibérica desde finales del siglo XIX hasta principios del siglo XXI. Para alcanzar este objetivo, se han recuperado datos de fuentes documentales de tres observatorios meteorológicos: Coímbra, Badajoz y Lisboa. Además, se ha trabajado con datos proporcionados por los servicios meteorológicos de España y Portugal, así como con observaciones satelitales. Este objetivo principal se concreta mediante los siguientes objetivos específicos:

- Recuperar datos de insolación y cubierta nubosa impresos en fuentes documentales de tres observatorios meteorológicos (Coímbra, Badajoz y Lisboa) desde finales el siglo XIX hasta mediados del siglo XX.
- Analizar las tendencias de la radiación solar en superficie y nubosidad en las tres estaciones de estudio desde el inicio de sus series de medida hasta la actualidad.
- Estudiar el impacto de los aerosoles en las tendencias de radiación solar en las tres estaciones mediante el uso de series temporales de insolación en condiciones de cielo despejado.
- Comparar las tendencias de radiación solar en la Península Ibérica estimadas a partir de observaciones satelitales con las tendencias obtenidas a partir de datos medidos en superficie.

1.4. Estructura de la tesis

La presente tesis doctoral se estructura en cinco capítulos del siguiente modo:

- El Capítulo 1 presenta el marco de trabajo y los antecedentes bibliográficos. Además, argumenta la motivación por la cual esta tesis se presenta como compendio de publicaciones, y describe los objetivos de esta.
- El Capítulo 2 detalla las medidas usadas en esta tesis, los instrumentos utilizados para su observación, las fuentes documentales a partir de las que se han recuperado datos, así como las características de los emplazamientos de estudio.
- El Capítulo 3 presenta las publicaciones que forman parte de esta tesis y se adjunta una copia de las mismas. Por una parte, el Artículo 1 compara las tendencias de la radiación solar en superficie medida por piranómetros en 12 estaciones de España, con las tendencias obtenidas en estos emplazamientos con registros satelitales. Por otra parte, en los Artículos 2, 3 y 4 se analizan en detalle las tendencias de las series temporales de insolación y de nubosidad construidas en los observatorios de Coímbra, Badajoz y Lisboa, respectivamente, desde finales del siglo XIX.
- El Capítulo 4 recoge una discusión de los principales resultados reportados por las cuatro publicaciones que componen esta tesis.
- Finalmente, el Capítulo 5 recoge las conclusiones más importantes extraídas del trabajo realizado en la presente tesis doctoral.

2. Medida de insolación, radiación solar y nubosidad

2.1. Medida de la insolación mediante heliógrafos

El heliógrafo es un instrumento que mide la insolación proyectando la radiación solar directa en una tira de papel graduado en horas. Cuando la intensidad de esta radiación es lo suficientemente alta (umbral de 120 W/m^2), se quema dicho papel proporcionando las horas a la que ocurre este fenómeno. Así, la insolación diaria será el resultado de sumar las horas marcadas en la tira de papel (conocidas como horas de sol) para cada día del año.

A continuación, se detallan las características de los observatorios en los que se han recuperado datos de insolación, las fuentes documentales utilizadas, así como los modelos de heliógrafo usados en cada estación de medida.

<u>Coímbra (Artículo 2)</u>:

Coímbra es una de las ciudades más pobladas de Portugal, situada en el noreste de ésta. El Observatorio Meteorológico de la Universidad de Coímbra se encuentra a las afueras de la ciudad cerca del río Mondego. El observatorio se construyó en 1863, presentando observaciones meteorológicas continuas desde 1864. Este observatorio perteneció al 'Instituto Geofísico da Universidade de Coimbra (IGUC)' entre 1963 y 2013, año en el que pasó al 'Observatório Geofísico e Astronómico da Universidade de Coimbra'. En abril de 1996, la estación meteorológica del IGUC ya no formó parte de la red de estaciones meteorológicas portuguesas, y la estación oficial se trasladó al aeródromo de Cernache, en las afueras de Coímbra, a unos 10 km al suroeste del IGUC. Las observaciones de insolación utilizando un heliógrafo modelo Campbell-Stokes se detuvieron en 2007 en Cernache, retomándose posteriormente con un equipo automático.

Se recuperaron y digitalizaron datos diarios de insolación de varios volúmenes publicados anualmente por la Universidad de Coímbra de 1891 a 1950. Cada volumen contiene además mediciones de cubierta nubosa, presión atmosférica, temperatura, presión de vapor atmosférico, humedad relativa, viento, lluvia, y ozono.

Los registros de insolación comenzaron con un heliógrafo modelo Jordan construido por Negretti y Zambra (Sánchez-Romero et al., 2014). Fue adquirido a finales de 1889, pero solo comenzó a utilizarse regularmente en enero de 1891. Los metadatos encontrados en los volúmenes publicados anualmente informan que se produjo un cambio de instrumento de medida de la insolación en febrero de 1940, remplazando el heliógrafo modelo Jordan por un heliógrafo Campbell-Stokes (Sánchez-Lorenzo et al., 2013).

Badajoz (Artículo 3):

Badajoz se encuentra en el suroeste de la Península Ibérica, a orillas del río Guadiana. La primera ubicación del Servicio Meteorológico Español en Badajoz fue el edificio del Instituto de Educación Secundaria 'Bárbara de Braganza', ubicado en el centro de la ciudad de Badajoz. La serie de registros de insolación comenzó en septiembre de 1928 mediante un heliógrafo Campbell-Stokes, y continuó sin interrupciones ni cambio de instrumento hasta 1984. Se recuperaron y digitalizaron datos diarios de insolación de 1928 a 1950 a partir de varios volúmenes publicados por el Servicio Meteorológico Español.

Además, existe en Badajoz otro observatorio en el que se registró la insolación, el aeropuerto de la ciudad, situado en Talavera de la Real a 13 km al este del centro de

Badajoz. Los registros de insolación en este observatorio se realizaron también mediante un heliógrafo Campbell-Stokes entre 1955 y 2016.

Lisboa (Artículo 4):

El observatorio meteorológico de Lisboa se sitúa el Instituto Dom Luiz (IDL), el cual es un centro de investigación para el estudio de Ciencias de la Tierra y Ciencias Atmosféricas de la Universidad de Lisboa. Fue fundado bajo el nombre "Observatório Meteorológico da Escola Politécnica" en 1853. Con el tiempo, ha tenido otros nombres como "Instituto Geofísico do Infante D. Luís" (Batlló et al., 2004). El IDL ha realizado observaciones meteorológicas sistemáticas en Lisboa desde 1856. Los primeros registros contienen datos de presión atmosférica, precipitación, temperatura, cobertura de nubes y velocidad del viento, entre otros (Sá y Silveira, 1863).

Las mediciones de insolación en el IDL comenzaron en 1890. El primer dispositivo empleado fue un heliógrafo Jordan (Capello, 1893), siendo remplazado en enero de 1913 por un heliógrafo Campbell-Stokes (Lima, 1915). Los primeros boletines con registros de insolación solo contienen datos mensuales sobre esta variable (período 1890-1917). A partir de 1918, también se dispone de datos diarios.

2.2. Medida de la radiación solar mediante piranómetros

En esta tesis se han usado datos de radiación solar en superficie proporcionadas por la Agencia Estatal de Meteorología de España (AEMET) usando piranómetros Kipp and Zonen. Estos instrumentos proporcionan valores de radiación solar integrados en un amplio intervalo de longitudes de onda (aproximadamente desde 300 nm a 3000 nm).

Concretamente, estas medidas de radiación solar en superficie mediante piranómetros se han utilizado con el fin de validar las tendencias obtenidas a partir de medidas de satélite en 12 estaciones de medida de la Península Ibérica (Artículo 1). Además, también se han usado para generar los coeficientes en el modelo de reconstrucción de la radicación solar a partir de las medidas de insolación en Badajoz (Artículo 3).

2.3. Medida de radiación solar mediante satélites

A partir de la década de los años 80, la comunidad científica dispone de datos continuos y globales de radiación solar en superficie por medio de satélites. Concretamente, en esta tesis (Artículo 1) se han usado los datos de dos productos satelitales: CLARA-A2 y SARAH-2.

El producto CLARA-A2 (Karlsson et al., 2017) generado por el satélite AVHRR, tiene una cobertura global que abarca desde 1982 hasta 2015, con una resolución temporal diaria y una resolución espacial de 0.25° x 0.25°.

El producto el SARAH-2 (Pfeifroth et al., 2017) es un producto basado en el satélite geoestacionario Meteosat. Este producto abarca Europa, África, el Océano Atlántico y algunas partes de América del Sur, con una cobertura temporal que se extiende desde 1983, una resolución temporal de 30 minutos y una alta resolución espacial de 0.05° x 0.05°.

2.4. Medida de la nubosidad

Históricamente, la medida de la nubosidad se ha hecho a través de observaciones humanas diarias. La cubierta nubosa se puede definir como la parte del cielo que está cubierta cuando se realizan las observaciones. Así, los valores de cubierta nubosa se miden en décimas o en octas: 0 define un cielo despejado para ambas unidades, mientras que un cielo completamente cubierto viene definido por 8 octas o 10 décimas.

El número y la hora de las observaciones de cubierta nubosa en cada emplazamiento de estudio han sido las siguientes;

- En Coímbra (Artículo 2): cinco observaciones por día (9h, 12h, 15h, 18h y 21h) desde 1881 hasta 1922, cinco observaciones por día (7h, 9h, 12h, 15h y 18h) desde 1923 hasta 1928 y cuatro observaciones por día (9h, 12h, 15h y18h) desde 1929 hasta 1950.
- En Badajoz (Artículo 3): tres observaciones por día (7h, 13h y 18h).
- En Lisboa (Artículo 4): tres observaciones por día (9h, 12h y 15h).

3. Resultados

3.1. Artículo 1.

Título: Comparison of long-term solar radiation trends from CM SAF satellite products with ground-based data at the Iberian Peninsula for the period 1985–2015

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Aspectos destacables del artículo:

El objetivo fundamental de este estudio es realizar un análisis exhaustivo sobre la calidad de las tendencias a largo plazo de la radiación solar en superficie medida por satélites. Para alcanzar este objetivo, se emplean como datos de referencia las medidas de piranómetros ubicados en 12 estaciones de la Península Ibérica durante el periodo comprendido entre 1985 y 2015. En este trabajo se analizan dos productos satelitales del CM-SAF de EUMETSAT: 1) CLARA-A2 obtenido a partir del satélite AVHRR, y 2) SARAH-2 obtenido por el satélite Meteosat.

Los productos satelitales presentan un buen acuerdo con las mediciones en la superficie: correlación de R= 0.83 para SARAH-2 y de R=0.80 para CLARA-A2 a nivel anual. Sin embargo, los dos productos satelitales subestiman significativamente las tendencias que proporcionan las medidas de los piranómetros. Así, mientras que los datos de piranómetros indican tendencias en el rango de -0.5 a +6.5 $Wm^{-2}década^{-1}$, con un nivel de significancia estadística del 95% en la mayoría de las estaciones, los productos satelitales presentan tendencias menores, sin alcanzar niveles estadísticamente significativos. Las tendencias se sitúan en el intervalo de -0.4 a +3.8 $Wm^{-2}década^{-1}$ para CLARA-A2, y entre +0.2 y +2.8 $Wm^{-2}década^{-1}$ para SARAH-2.

Este estudio también pone de manifiesto la importancia de analizar las tendencias estacionales de la radiación solar en superficie. Dichas tendencias, tanto en los datos de piranómetros como de los productos satelitales, revelan un acuerdo óptimo en primavera, caracterizada por relevantes tendencias positivas. Esta correspondencia se puede relacionar con la notable disminución de la nubosidad en la región de estudio durante esa estación. Sin embargo, las discrepancias se hacen más evidentes en verano. Los productos satelitales muestran anomalías bajas en comparación con los piranómetros, especialmente a partir de principios de la década de 2000. Esta particularidad podría estar vinculada a que los productos satelitales no recojan la conocida disminución de la carga de aerosoles en la Península durante ese período, ya que los modelos de estimación de los satélites usan valores climatológicos.

En resumen, este trabajo ofrece una evaluación minuciosa de la calidad de las tendencias de radiación solar en superficie proporcionada por dos productos satelitales sobre la Península Ibérica.

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Comparison of long-term solar radiation trends from CM SAF satellite products with ground-based data at the Iberian Peninsula for the period 1985–2015

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ABSTRACT

The aim of this work is to analyse the quality of long-term trends of surface incoming shortwave solar radiation (SIS) derived from two satellite datasets from the EUMETSAT Satellite Application on Climate Monitoring (CM SAF): the SIS Data Set from the Advanced Very High-Resolution Radiometer (AVHRR) data, Edition 2 (CLARA-A2), and the SIS Data Set-Heliosat, Edition 2 (SARAH-2). In order to achieve this goal, reference ground-based SIS measurements recorded at 12 stations over the Iberian Peninsula for the period 1985–2015 are used in this study. Firstly, the two satellite datasets have been compared against ground-based SIS measurements at 12 surface sites, showing a good agreement (i.e., $R = 0.83$ in SARAH-2 and $R = 0.80$ in CLARA-A2 on an annual basis). However, the two satellite datasets substantially underestimate the SIS trends found for the ground-based measurements. Thus, while the ground-based SIS data reported trends between -0.5 and $+6.5$ $Wm^{-2}decade^{-1}$ (with statistical significance at 95% level at most stations), the satellite datasets gave trends lower for all locations (without statistical significance); between -0.4 and $+3.8$ $Wm^{-2}decade^{-1}$ for CLARA-A2, and between $+0.2$ and $+2.8$ $Wm^{-2}decade^{-1}$ for SARAH-2. It is worth to mention that the seasonal analysis of the SIS trends for both ground-based and satellite data displays a reasonably good agreement in spring (i.e., high positive trends), in accordance with the notable decline in the cloudiness for this season in the study region. By contrast, satellite products exhibit smaller SIS anomalies than ground-based data in summer, particularly from the beginning 2000s, which could be related to well-known decrease in the aerosol load over the study region.

1. Introduction

Solar radiation is a crucial climate variable to understand changes in the Earth-atmosphere system (Hartmann et al., 1986; Ohmura and Gilgen, 1993; Wild et al., 2015). It is well-known that solar radiation variability affects many relevant fields such as solar energy production (Huld et al., 2017; Wild et al., 2015), agriculture (Stanhill and Cohen, 2001), tourism (Mieczkowski, 1985) or even health care (Vyssoki et al., 2014). Thus, it is a priority to analyse the temporal variations of surface incoming shortwave solar radiation (SIS) (Sanchez-Lorenzo et al., 2015; Wild, 2016).

Several studies have examined SIS changes (e.g. Stanhill and Cohen, 2001; Wild, 2009, 2012), which have reported a widespread decrease of about 3–9 Wm^{-2} (dimming period) from the 1950s to the 1980s and an increase around 1–4 Wm^{-2} (brightening period) from the 1980s until now, especially in the industrialized nations (Wild, 2009). Dimming and brightening periods have been reported in different regions of the world using ground-based SIS measurements, such as for example in Europe (Norris and Wild, 2007; Sanchez-Lorenzo et al., 2015), United States (Liepert, 2002; Long et al., 2009), Japan (Tanaka et al., 2016) or China (Wang et al., 2015; Wang and Wild, 2016; Yang et al., 2018). In addition, there has also been a decrease in SIS over the past few decades in some areas (Antuña-Marrero et al., 2019; Jahani et al., 2018; Soni et al., 2019); which is most likely due to a recent increase in anthropogenic aerosol emissions in developing economies. These changes in SIS produce important effects on other climate issues like global warming (Wild et al., 2007), melting of snow cover and glaciers (Ohmura et al., 2007) or the hydrological cycle (Ramanathan, 2001). Possible causes of the dimming and brightening periods are mainly related to changes in cloud cover (Kambezidis et al., 2016; Long et al., 2009; Parding et al., 2016; Sanchez-Lorenzo et al., 2017) and anthropogenic aerosol concentration (Nabat et al., 2014; Ruckstuhl et al., 2008; Ruckstuhl and Norris, 2009; Sanchez-Lorenzo and Wild, 2012).

However, SIS variations still have strong uncertainties due to the

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Nomenclature

MABE	Mean absolute bias error.
MBE	Mean bias error.
SIS	Surface incoming shortwave solar radiation.
R	coefficient of correlation.
RMSE	Root mean square error.

lack of ground-based stations in particular regions of the Earth (Wild, 2009, 2016). Additionally, the location of many stations nearby cities can produce local effect caused by pollution (Alpert et al., 2005). An alternative methodology that tries to reduce these uncertainties involves using satellite-based products. Thus, for instance, CM SAF satellite climate products (CLARA-A2 and SARAH-2) from EUMETSAT have been used to estimate SIS trends over Europe since the 1980s (Pfeifroth et al., 2018a, 2018b; Sanchez-Lorenzo et al., 2013, 2017). These products have been validated using ground-based data (Müller et al., 2015; Urraca et al., 2017a, 2017b), showing a good agreement, although CLARA-A2 product suffers from missing data before 1992 which increases data uncertainty (Pfeifroth et al., 2018a, 2018b). However, Pfeifroth et al. (2018b) found discrepancies between satellite-derived SIS data from CM SAF products and ground-based observations to reproduce SIS variability, especially in Southern Europe.

In this context, the present work evaluates the consistency and accuracy of these two CM SAF climate data records against reference ground-based measurements, focusing on the long-term analysis over the Iberian Peninsula for the period 1985–2015. The temporal variability and the spatial distribution of long-term SIS trends have been analysed in detail. The used data sources and methodologies are explained in Sections 2 and 3, respectively. In Section 4 the results are presented together with a discussion about the quality of the products and an evaluation of the variability and trends observed over the Iberian Peninsula. Finally, conclusions are described in Section 5.

2. Datasets

The data used in this study comes from two different sources. On the one hand, two satellite-based climate data records from the CM SAF are used, called the SIS Data Set from the advanced very high-resolution radiometer (AVHRR) data - Edition 2 (CLARA-A2), and the SIS Data Set-Heliosat, Edition 2 (SARAH-2). On the other hand, ground-based solar radiation measurements, provided by the Spanish *Agencia Estatal de Meteorología* (AEMET) are used in order to validate CM SAF datasets.

2.1. The AEMET ground-based dataset

It consists of daily mean SIS records (305–2800 nm), expressed as Wm^{-2} and measured by means of Kipp & Zonen pyranometers with an expected daily relative uncertainty < 5%, at 12 different stations in the Iberian Peninsula (Table 1 and Fig. 1), which have been previously described by Sanchez-Lorenzo et al. (2013) and here updated until December 2015. These measurements were periodically calibrated according to the standards for measurements of the World Radiation Centre (Davos, Switzerland) and they were subjected to a quality control check on a daily basis in order to detect and remove gross errors, outliers, false zeros, etc. Equally, the temporal homogeneity of these SIS series has been tested on a monthly basis by means of the Standard Normal Homogeneity Test (SNHT) for single shifts (Alexandersson and Moberg, 1997). In brief, for the SNHT test, each series is tested and corrected against a reference series computed as an average of some nearby stations. For more details about this dataset and the homogenization procedure we refer to Sanchez-Lorenzo et al. (2013).

Despite some of these series being available before 1985, others have missing values. Therefore, in order to unify them, the temporal coverage in this study ranges from 1985 to 2015. In addition, due to the change of the meteorological stations in some sites during this period, a composite series has been determined by assembling series from more than one station. These composites and the year of the relocations of the stations are also detailed in Table 1.

2.2. The CM SAF datasets

The CLARA-A2 product has a global coverage ranging from 1982 to 2015, with a daily temporal resolution and a spatial resolution of 0.25° x 0.25° (Karlsson et al., 2017). It must be noted that since 1992 a second AVHRR instrument has been available improving the spatio-temporal coverage, so missing data can be found mostly in winter before this year. More information can be read in Karlsson et al. (2017).

The SARAH-2 (Pfeifroth et al., 2017) is the latest CM SAF climate SIS record, based on the geostationary Meteosat satellite. This product covers Europe, Africa, the Atlantic Ocean and some parts of South America, with a temporal coverage ranging since 1983, with a 30 min temporal resolution and a high spatial resolution of 0.05° x 0.05°. More details can be found in (Müller et al., 2015).

3. Methodology

The present paper focuses on analysing long-term SIS variations instead of day to day variations. Therefore, monthly mean SIS time-series datasets (M) from 1985 to 2015 were used for both satellite- and ground-based data. Those months with 13 or more days without simultaneous satellite-based products and ground-based data are removed from the analysis.

The first step in the long-term SIS analysis is to deseasonalise the monthly SIS series for each ground-based station. In this work, the annual cycle of SIS data (seasonal pattern) was derived from the averages of M_{SIS} values for each of the twelve months (S) and then subtracted from the monthly SIS dataset in order to obtain deseasonalised monthly values (absolute monthly anomalies, A), as Eq. (1) shows.

$$A^{i,j} = M^{i,j} - S^{j} \quad (1)$$

where the super-index i denotes the year (from 1985 to 2015), and the super-index j the month (from 1 to 12).

Additionally, the relative monthly anomalies (RA) with respect to the long-term SIS mean are also obtained by Eq. (2).

$$RA^{i,j}(\%) = 100 \times (M^{i,j} - S^{j})/S^{j} \quad (2)$$

A detailed linear regression analysis is performed between the monthly SIS anomalies provided by the ground-based data and those derived from the satellite datasets. Slopes of the regression lines, coefficients of determination (R) and the root mean square errors (RMSE) are evaluated in this analysis.

Table 1
Details of the 12 stations in the Iberian Peninsula used in this study. Composite column indicates the year of the station's change.

ID	Station	Longitude (°)	Latitude (°)	Altitude (m)	Composite (Y/N and Year)
1	Albacete	−1.86	38.95	674	N
2	Bilbao	−2.91	43.30	42	N
3	Caceres	−6.34	39.47	405	N
4	Coruña	−8.38	43.30	58	N
5	Logroño	−2.33	42.45	353	Y (1995)
6	Madrid	−3.68	40.41	665	N
7	Malaga	−4.49	36.67	60	Y (1996)
8	Murcia	−0.80	37.39	61	N
9	Oviedo	−5.87	43.35	336	N
10	San Sebastian	−2.04	43.31	251	N
11	Santander	−3.80	43.49	52	Y (1997)
12	Valladolid	−4.77	41.65	735	Y (1992)

Fig. 1. Map of the Iberian Peninsula with the 12 ground-based stations.

Furthermore, the differences between satellite monthly anomalies (A_{Sat}) and ground-based anomalies (A_{ref}) are obtained for each site, calculating the following two statistical parameters:

1. The mean bias error (MBE) provides a measure of overall overestimation or underestimation of the satellite products against ground-based dataset. Eq. (3) defines MBE.

$$MBE = (1/N) \sum_{i,j} (A_{Sat}^{i,j} - A_{Ref}^{i,j}) \quad (3)$$

where N denotes the number of months used in the difference series.

2. The mean absolute bias error (MABE) shows the average magnitude of error between satellite products and ground-based measurements, without taking into account the sign of the error. Eq. (4) defines MABE.

$$MABE = (1/N) \sum_{i} |A_{Sat}^{i,j} - A_{Ref}^{i,j}| \quad (4)$$

where N denotes the number of months used in the difference series.

The study of long-term SIS trends is performed from the linear regression analysis applied on the annual and seasonal time series (derived from the annual average of the deseasonalised monthly SIS values). Additionally, the long-term SIS trends are obtained separately for each season of the year by means of a linear regression analysis applied on four time series inferred from the average of the deseasonalised monthly SIS values for winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug), and autumn (Sept-Oct-Nov).

4. Results and discussion

First, a linear regression analysis between the ground-based and satellite monthly anomalies is performed for each location and for all sites together in order to analyse their proportionality and similarity. Statistical parameters (the slope of the regression, R and RMSE) derived from the linear fitting are shown in Table 2. Additionally, this table also shows the MBE and MABE parameters obtained by Eqs. (3) and (4).

The results show a good correlation of both satellite datasets against reference ground-based data, with correlation coefficients higher than 0.67 for all stations, and values of 0.83 (SARAH-2) and 0.80 (CLARA-A2) when all data from the 12 locations (the "Iberian Peninsula" dataset) are used in the linear regression analysis. Furthermore, these analyses provide slopes higher than 0.7 at most stations, which is a sign of high proportionality between the ground-based and satellite-based SIS anomalies. The MBE values are close to zero for all sites, which means that the satellite data (for both SARAH-2 and CLARA-A2) neither

Table 2
Parameters obtained in the correlation analysis between satellite- and ground-based monthly anomalies during the period 1985–2015. The parameters are: SLOPE, slopes of regression lines; R, correlation coefficients; RMSE, root mean square errors; MBE, mean bias errors; MABE, mean absolute bias errors.

Station	Satellite vs ground-based	Slope	R	RMSE (Wm^{-2})	MBE (Wm^{-2})	MABE (Wm^{-2})
Albacete	SARAH-2	0.64	0.78	9.9	+0.0	8.4
	CLARA-A2	0.72	0.77	11.1	−0.1	8.7
Bilbao	SARAH-2	0.70	0.76	10.1	+0.0	7.9
	CLARA-A2	0.75	0.77	10.6	−0.3	8.0
Cáceres	SARAH-2	0.80	0.88	7.8	+0.0	6.0
	CLARA-A2	0.81	0.85	9.1	−0.4	7.0
Coruña	SARAH-2	0.95	0.91	7.3	+0.0	5.5
	CLARA-A2	0.95	0.88	8.8	−0.1	6.8
Logroño	SARAH-2	0.89	0.85	8.5	+0.0	6.7
	CLARA-A2	0.91	0.84	8.9	−0.3	6.8
Madrid	SARAH-2	0.85	0.91	6.4	+0.0	4.9
	CLARA-A2	0.87	0.86	8.4	−0.7	6.2
Málaga	SARAH-2	0.61	0.74	8.6	+0.0	7.6
	CLARA-A2	0.62	0.67	10.5	−0.2	8.8
Murcia	SARAH-2	0.73	0.86	6.1	+0.0	5.2
	CLARA-A2	0.83	0.84	7.6	−0.1	6.0
Oviedo	SARAH-2	0.67	0.77	10.2	+0.0	6.9
	CLARA-A2	0.70	0.73	12.1	−0.1	7.9
San Sebastián	SARAH-2	0.75	0.79	9.7	+0.0	6.5
	CLARA-A2	0.78	0.79	10.3	−0.2	7.1
Santander	SARAH-2	0.76	0.87	6.8	+0.0	5.8
	CLARA-A2	0.80	0.79	10.0	−0.3	7.4
Valladolid	SARAH-2	0.82	0.85	8.1	+0.0	6.0
	CLARA-A2	0.87	0.82	9.9	−0.2	7.1
Iberian Peninsula	SARAH-2	0.76	0.83	8.5	+0.0	6.4
(All Data)	CLARA-A2	0.80	0.80	9.9	−0.2	7.3

overestimate nor underestimate on average the ground-based anomalies. By contrast, MABE values exhibit a notable station-to-station variation with values between 4.9 and 8.4 Wm^{-2} for SARAH-2 and between 6.0 and 8.8 Wm^{-2} for CLARA-A2. If the MABE values are derived from the relative anomalies (Eq. (2)) instead of absolute anomalies (Eq. (1)), their values vary between 2.7 and 6.1 percentage points for SARAH-2 and between 3.1 and 6.1 percentage points for CLARA-A2. For the "Iberian Peninsula" dataset, the MABE values are 6.4 Wm^{-2} (4.2 percentage points) for SARAH-2, and 7.3 Wm^{-2} (4.6 percentage points) for CLARA-A2. The bias in the satellite anomalies with respect to the reference ground-based anomalies can be mainly associated with the sky conditions during the satellite overpass and the associated uncertainties of comparing point to grid-box averaged data. The water vapor and aerosol climatological data used in the satellite retrieval may also differ from the actual conditions at the stations location which could add additional uncertainties to the inter-comparison.

Fig. 2 shows the relationship between the monthly anomaly series (1985–2015) from ground-based and satellite SIS data for SARAH-2 (top plot) and CLARA-A2 (bottom plot) for the "Iberian Peninsula" dataset. The solid line is the regression line while the dashed line is the zero bias line (unit slope). The plots show a good agreement in the correlation (R~0.8) but with a high degree of spread (RMSE~9 Wm^{-2}) as described above. Additionally, the plots indicate that both satellites tend to underestimate the strong ground-based SIS anomalies. This behaviour produces a balance, resulting in MBE parameters around zero for both satellite products as has been discussed above.

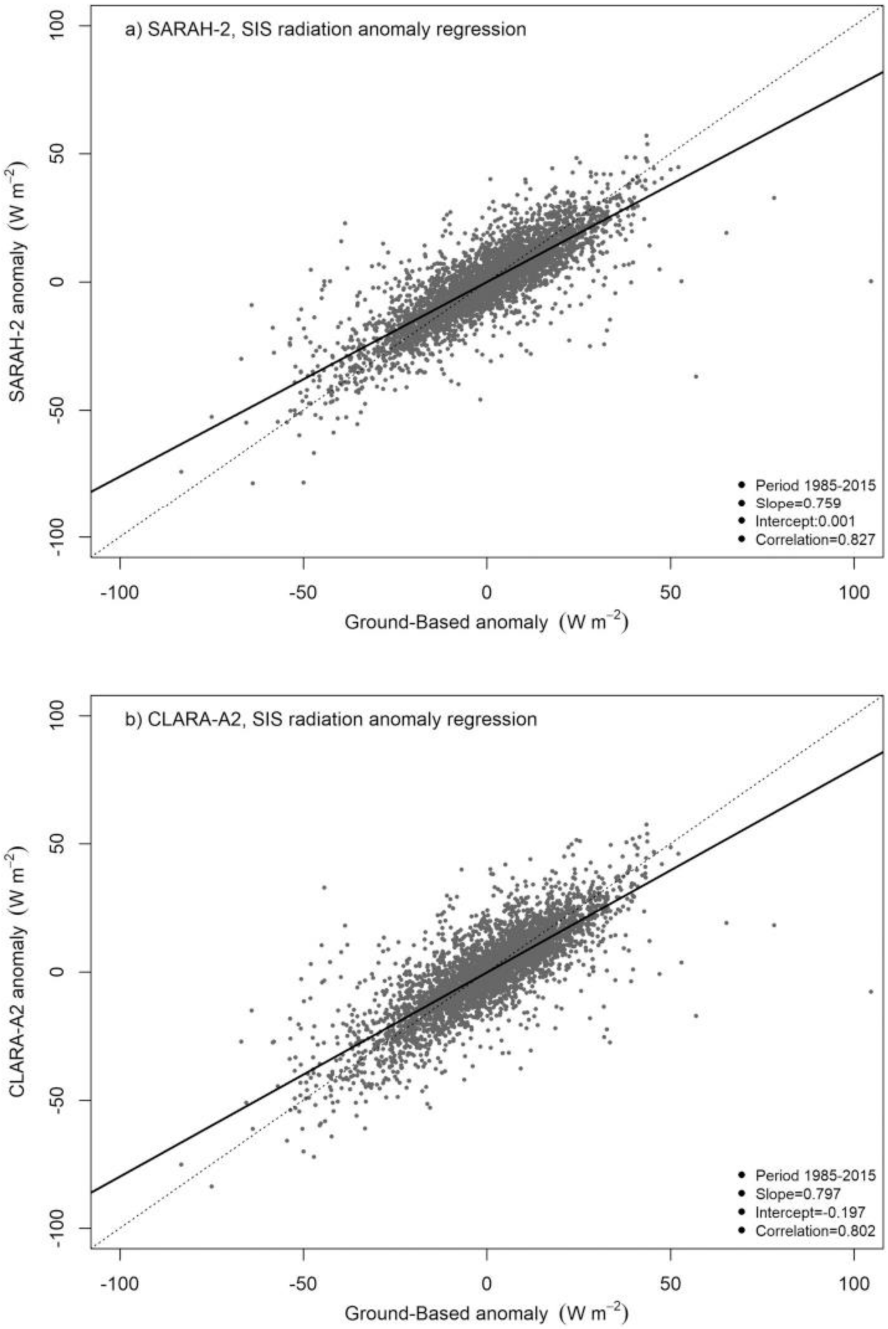

Fig. 2. Plot of monthly SIS anomalies (Wm^{-2}) of a) SARAH-2 and b) CLARA-A2 versus ground-based data, including the slope, intercept and correlation coefficient of the regression line. The solid line is the regression line. The dashed line represents a zero bias line.

In order to analyse seasonally the quality and accuracy of the satellite products with reference to the "Iberian Peninsula" ground-based dataset, statistical parameters (MBE, MABE, RMSE and R) are shown in Table 3. The correlation between both satellite products and the ground-based SIS anomalies is high with correlation coefficients above 0.75 for all seasons. The MABE exhibits the lowest values in winter (4.4 and 5.0 Wm^{-2} for SARAH-2 and CLARA-A2, respectively), while the largest values are found in summer (8.9 and 9.2 Wm^{-2} for SARAH-2 and CLARA-A2, respectively). By contrast, when relative anomalies are used to calculate the MABE, the smallest values are found in summer (3.5 and 3.6 percentage points for SARAH-2 and CLARA-A2, respectively), and the highest values in winter (5.4 and 6.1 percentage points for SARAH-2 and CLARA-A2, respectively). The low MABE values obtained in spring (3.5 and 4.1 percentage points for SARAH-2 and CLARA-A2, respectively) are also remarkable. These results suggest a better agreement between satellite and ground-based anomalies during periods with cloud-free conditions as summer and most of spring in the Iberian Peninsula.

Once the statistical parameters have been studied, it is interesting to analyse the annual and seasonal evolution of the averaged 12 time series for satellite data and for ground-based measurements, shown in Fig. 3. The annual and seasonal linear trends for all averaged time series over the 1985–2015 period are shown in Table 4.

A key characteristic of the anomaly series shown in Fig. 3 is the inter-annual variability. It can be seen that the annual ground-based SIS time series exhibits a slight increase from 1985 to 1996, followed by a strong increase toward the end 1990s. From the early 2000s to 2015 there is another marked increase, which results on a significant positive linear trend over the entire study period 1985–2015 of $+4.4 \pm 1.3$ $Wm^{-2}decade^{-1}$ ($+2.6 \pm 0.8\%$ $decade^{-1}$). This result agrees with the SIS trends over the Iberian Peninsula since the 1980s (Sanchez-Lorenzo et al., 2013; Wild, 2009), as well as with the increasing sunshine duration in the 1980–2000 period reported by Sanchez-Lorenzo et al. (2007).

An increase can also be observed along the annual satellite time series (both CLARA-A2 and SARAH-2) in the period 1985–2015 with a good agreement year by year with ground-based time series. Overall, the increase in satellite time series in the whole period results in a positive linear trend with statistical significance but being substantially lower than the trends reported by ground-based measurements, with values of $+1.5 \pm 1.1$ $Wm^{-2}decade^{-1}$ ($+0.8 \pm 0.7\%$ $decade^{-1}$) for SARAH-2 and $+ 1.9 \pm 1.2$ $Wm^{-2}decade^{-1}$ ($+0.9 \pm 0.8\%$ $decade^{-1}$) for CLARA-2. This result might be related to the 2005–2015 period (see Fig. 3) where the satellite time series show a notably weaker increase than ground-based time series. The disagreement may be mostly due to a stronger positive trend of ground-based data in autumn and, especially, summer during this period of time (Fig. 4).

The four seasons show significant positive linear trends (Table 4), with values between $+7.0 \pm 2.9$ $Wm^{-2}decade^{-1}$ ($+2.6 \pm 1.0\%$ $decade^{-1}$) in summer and $+ 2.8 \pm 1.9$ $Wm^{-2}decade^{-1}$ ($+2.7 \pm 1.9\%$ $decade^{-1}$) in winter. Fig. 4 displays the seasonal evolution of the SIS anomalies time series. Spring and summer series present a similar behaviour to the annual series, with a higher interannual variability than autumn and winter series. It is worth to note that summer series show the lowest anomaly (in 1992), which might be related to the direct effect of the aerosols released during the Pinatubo volcanic eruption (Sanchez-Lorenzo et al., 2013). Autumn series display similar variations to annual series since 1995 but there is a decrease in the 1980s, with a notable minimum in 1992–1994. A steady increase can be observed in winter over the whole period, although a marked minimum is noted in 2010, which might be due to the maximum precipitation registered this year according to an exceptional negative North Atlantic Oscillation index (Vicente-Serrano et al., 2011). Those seasonal variations are also recorded by the two satellite time series. Both SARAH-2 and CLARA-A2 have a high level of agreement with ground-based series in all seasons (Table 2). The disagreement between time series only occurs around 1993 in winter and in late 1990s in summer, causing a slight decrease in correlation.

Table 4 shows that the largest annual trends are visible in Albacete, Cáceres and Bilbao. The strongest trends (> 10 $Wm^{-2}decade^{-1}$) are found in summer in Málaga and Murcia, sites located in the South of the Iberian Peninsula. On the other hand, unlike the positive trends that appear along the most of the Iberian Peninsula, a slight negative trend is found in Coruña for CLARA-A2 and ground-based data. Low trends are also found in Logroño, Oviedo and Valladolid, especially in winter in these sites. Table 4 also shows that there are locations with notably higher trends than others but all locations have in common an underestimation in SIS trends respect to ground-based linear trends. This result may be related to the fact that satellites reproduce weaker SIS anomalies during the period 2005–2015, especially in summer and autumn (Fig. 4). However, there are a few sites (e.g., San Sebastián and Albacete) where satellite annual trends display a good agreement with ground-based trends. Linear trends are better reproduced by satellite products in winter and spring, although they lack statistical significance. Spring is the season of the year when there is a negative trend in cloud cover according to several studies (Calbó and Sanchez-Lorenzo, 2009; Sanchez-Lorenzo et al., 2009, 2017; Trigo et al., 2002; Tzallas et al., 2019). This fact is likely the cause of the increase of solar radiation in spring. In contrast, in autumn and summer no cloudiness trends have been reported in the Iberian Peninsula (Calbó and Sanchez-Lorenzo, 2009; Sanchez-Lorenzo et al., 2009, 2017).

According to Pfeifroth et al. (2018b), summer season SIS trends in Southern Europe are not properly reproduced by satellite products. Fig. 5 shows the summer season anomaly time series plots for the 12 individual stations. In most sites, it can be seen that both satellite products display substantially smaller SIS anomalies than ground-based data, especially during the period 2005–2015. This result could be associated with the changes in the aerosol load over the study region and the fact that satellite retrievals do not take into account aerosol variations (Karlsson et al., 2017; Pfeifroth et al., 2017) except for heavy aerosol events like dust storms (Müller et al., 2015). Mateos et al. (2014a, 2014b, 2015) reported a notable reduction of the aerosol load over the Iberian Peninsula from the beginning 2000s which can be due to a mix of anthropogenic and natural reasons. Thus, for instance, the particulate matter (PM) emissions in this region decreased around 25% between 2000 and 2011 (Aas et al., 2013), and numerous observational PM series exhibited decreasing trends in the 2000s (e.g., Barmpadimos et al., 2012; Cusack et al., 2012; Pey et al., 2013). Additionally, natural aerosols such as desert dust episodes in the western Mediterranean Basin, which occur mainly in summer, substantially decreased in 2000s (Gkikas et al., 2013; Cachorro et al., 2016). On the other hand, the disagreement between satellite and ground-based data may be due to an overestimation of ground-based data, but we have already seen that in spring, when cloud coverage is more determining than aerosols, surface and satellites reproduce similar trends. Consequently, a possible

Table 3
Statistical indicators (SLOPE, R, RMSE, MBE, MABE) between satellites and ground-based data in all stations together for MAM, JJA, SON, DJF and annual situation.

Statistic	Satellite vs ground-based	Annual	MAM	JJA	SON	DJF
SLOPE	SARAH-2	0.76	0.80	0.69	0.78	0.77
	CLARA-A2	0.80	0.82	0.76	0.78	0.82
R	SARAH-2	0.83	0.86	0.77	0.83	0.83
	CLARA-A2	0.80	0.83	0.77	0.79	0.82
RMSE (Wm^{-2})	SARAH-2	8.5	9.8	10.2	7.1	6.0
	CLARA-A2	9.9	11.5	11.6	8.4	6.9
MBE (Wm^{-2})	SARAH-2	+0.0	+0.0	+0.0	+0.0	+0.0
	CLARA-A2	−0.2	−0.1	−0.1	−0.3	−0.6
MABE (Wm^{-2})	SARAH-2	6.4	6.9	8.9	5.5	4.4
	CLARA-A2	7.3	8.3	9.2	6.5	5.0

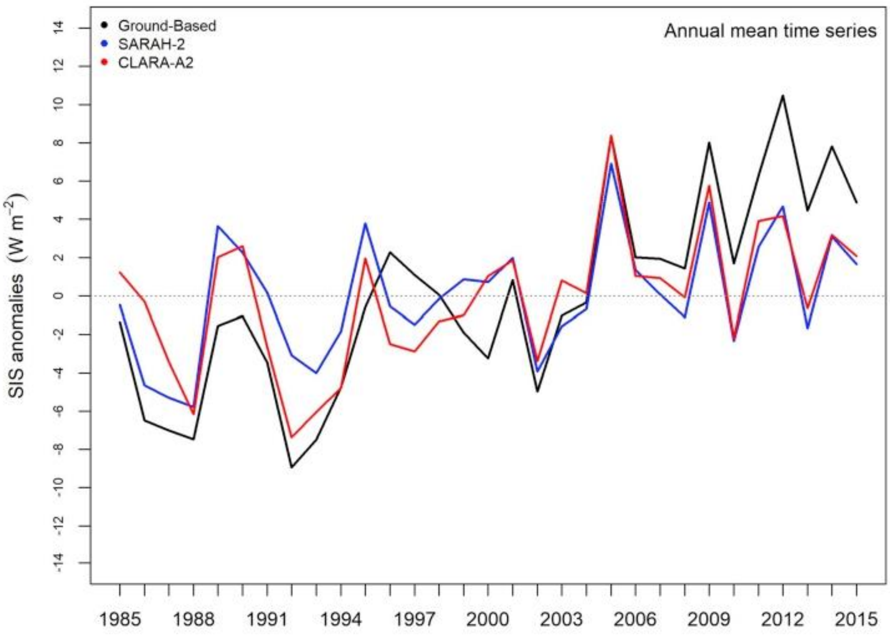

Fig. 3. Averaged annual SIS anomalies series (1985–2015) from ground-based measurements of 12 stations in Iberian Peninsula (black lines), plotted together with averaged SIS anomalies series from satellite data of the 12 stations (red lines for CLARA-A2 series and blue lines for SARAH-2 series). SIS anomalies are represented as Wm^{-2}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Annual and seasonal (MAM, JJA, SON, DJF) linear trends (± 2·standard deviation) from 1985 to 2015 [$Wm^{-2}decade^{-1}$] of the 12 stations in the Iberian Peninsula.

Station	Dataset	Annual	MAM	JJA	SON	DJF
Albacete	GB	**+6.5 (2.6)**	+3.8 (6.5)	**+9.9 (4.2)**	**+6.8 (3.7)**	**+5.4 (3.4)**
	SARAH-2	**+2.0 (1.7)**	+1.9 (4.4)	+1.6 (3.4)	**+2.7 (2.6)**	+2.1 (3.0)
	CLARA-A2	**+3.1 (2.1)**	+2.5 (4.9)	**+5.6 (4.2)**	+2.6 (3.1)	+1.5 (3.6)
Bilbao	GB	**+5.6 (3.3)**	**+5.7 (4.9)**	**+8.5 (6.0)**	**+6.2 (3.9)**	+1.6 (2.7)
	SARAH-2	+0.2 (1.8)	+1.9 (4.4)	+0.4 (4.9)	+0.1 (3.2)	−1.4 (2.3)
	CLARA-A2	+1.3 (2.0)	+4.0 (4.5)	+3.3 (5.4)	+0.9 (4.8)	−2.5 (3.1)
Cáceres	GB	**+5.8 (1.7)**	+3.5 (4.5)	**+9.8 (3.4)**	**+5.4 (3.6)**	**+6.5 (5.0)**
	SARAH-2	**+1.9 (1.8)**	+1.2 (4.1)	+3.1 (3.5)	+1.4 (3.1)	+2.1 (3.3)
	CLARA-A2	**+2.3 (2.1)**	+2.8 (5.1)	**+3.8 (3.7)**	+0.9 (3.9)	+1.1 (4.5)
Coruña	GB	−0.5 (2.1)	+1.1 (4.7)	−3.2 (4.6)	+0.9 (3.4)	−0.8 (3.1)
	SARAH-2	+0.5 (2.0)	+3.1 (4.7)	−2.5 (4.2)	+1.2 (3.6)	+0.1 (2.5)
	CLARA-A2	−0.3 (2.2)	+2.2 (4.9)	−3.3 (4.7)	+0.5 (4.3)	+0.1 (4.0)
Logroño	GB	**+3.4 (2.1)**	+3.4 (4.5)	**+7.3 (3.9)**	+2.1 (2.9)	+0.8 (2.2)
	SARAH-2	+1.2 (1.8)	+2.2 (4.9)	+2.0 (5.2)	+0.3 (3.1)	+0.1 (2.5)
	CLARA-A2	+1.6 (2.0)	+2.3 (4.9)	+3.5 (5.1)	+0.3 (3.6)	−0.6 (2.7)
Madrid	GB	**+5.6 (1.9)**	+2.9 (4.6)	**+7.8 (3.8)**	**+5.7 (3.1)**	**+7.1 (3.7)**
	SARAH-2	**+2.4 (1.7)**	+1.7 (4.4)	+2.6 (3.5)	+2.5 (3.0)	**+2.8 (2.7)**
	CLARA-A2	**+2.7 (1.9)**	+3.2 (4.7)	+3.5 (3.7)	+2.2 (3.5)	+1.7 (3.3)
Málaga	GB	**+5.4 (2.1)**	+2.9 (3.6)	**+10.4 (3.8)**	**+4.1 (2.7)**	**+6.2 (5.1)**
	SARAH-2	**+1.6 (1.5)**	−0.6 (3.5)	**+3.1 (2.2)**	+1.0 (2.8)	+3.0 (3.2)
	CLARA-A2	−0.4 (1.7)	−2.7 (3.9)	−0.9 (2.9)	−1.3 (3.7)	+2.5 (4.3)
Murcia	GB	**+5.5 (1.7)**	+3.5 (3.9)	**+10.7 (2.7)**	**+4.0 (2.2)**	**+4.6 (3.2)**
	SARAH-2	**+2.8 (1.4)**	+2.3 (4.0)	**+3.6 (2.1)**	+1.8 (2.3)	**+3.4 (2.1)**
	CLARA-A2	**+2.6 (1.7)**	+2.3 (4.2)	**+5.4 (2.8)**	+0.9 (3.2)	+1.3 (3.3)
Oviedo	GB	**+2.3 (2.2)**	+1.5 (5.5)	+3.6 (5.8)	**+4.3 (3.0)**	+0.0 (2.3)
	SARAH-2	+1.2 (1.8)	+1.9 (4.5)	+1.4 (5.3)	+1.9 (3.0)	−0.6 (2.1)
	CLARA-A2	**+3.8 (2.1)**	**+5.4 (4.4)**	**+6.6 (5.2)**	**+3.8 (3.6)**	−0.8 (2.9)
San Sebastián	GB	**+3.5 (2.3)**	+2.5 (5.0)	**+6.0 (5.3)**	**+5.2 (3.0)**	−0.3 (2.6)
	SARAH-2	+0.9 (1.8)	+2.3 (5.1)	+1.5 (5.1)	+0.8 (3.1)	−1.0 (2.3)
	CLARA-A2	**+2.9 (2.0)**	+4.0 (5.3)	**+6.5 (5.4)**	+2.6 (4.5)	−1.8 (3.0)
Santander	GB	**+5.6 (2.1)**	**+7.3 (4.2)**	**+7.0 (4.9)**	**+6.7 (2.8)**	+1.1 (2.0)
	SARAH-2	**+1.6 (1.5)**	+3.6 (3.8)	+1.0 (4.7)	+2.4 (2.8)	−1.1 (1.8)
	CLARA-A2	+0.5 (1.9)	+0.5 (4.8)	+0.5 (6.5)	+3.5 (5.0)	−2.1 (2.9)
Valladolid	GB	**+3.8 (2.4)**	+3.1 (4.6)	**+5.9 (5.1)**	**+4.9 (3.9)**	+1.7 (2.4)
	SARAH-2	**+1.8 (1.7)**	+1.2 (4.5)	+2.3 (4.4)	+2.9 (3.5)	+1.1 (1.9)
	CLARA-A2	**+2.6 (2.0)**	+3.1 (4.6)	+4.0 (4.7)	+3.0 (4.3)	+0.0 (2.6)
Iberian Peninsula (all data)	GB	**+4.4 (1.3)**	**+3.4 (3.0)**	**+7.0 (2.9)**	**+4.7 (2.0)**	**+2.8 (1,9)**
	SARAH-2	**+1.5 (1.1)**	+1.9 (3.1)	+1.7 (3.1)	+1.5 (2.1)	+0.9 (1.6)
	CLARA-A2	**+1.9 (1.2)**	+3.0 (3.1)	+3.2 (3.3)	+1.6 (2.9)	+0.3 (1.9)

The trends with a significance level equal or higher than 95% are in bold.

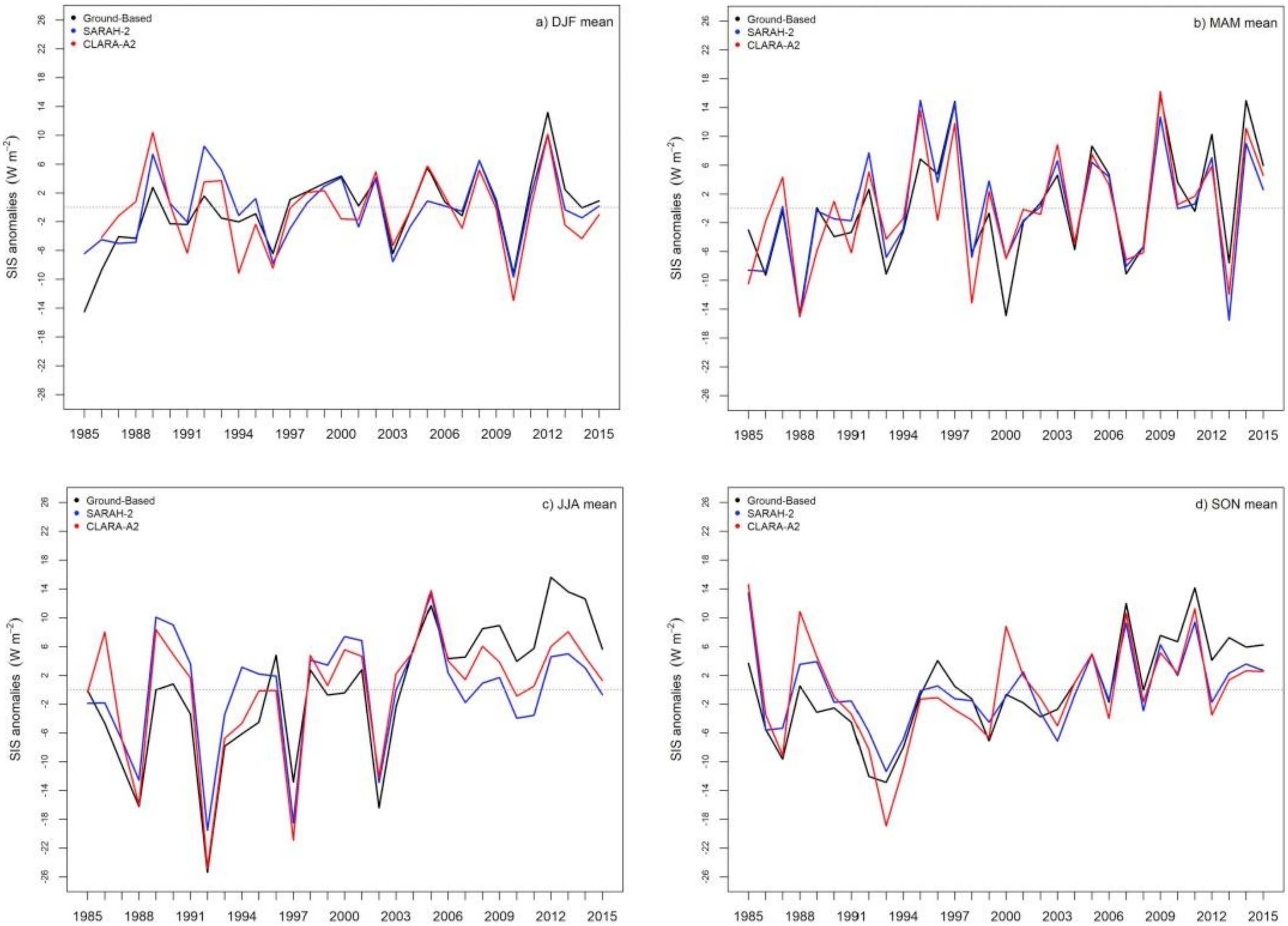

Fig. 4. Averaged seasonal SIS anomalies series (1985–2015) from ground-based measurements of 12 stations in Iberian Peninsula (black lines), plotted together with averaged SIS anomalies series from satellite data of the 12 stations (red lines for CLARA-A2 series and blue lines for SARAH-2 series). SIS anomalies are represented as Wm^{-2}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reason of the disagreement in trends between satellite and reference ground-based SIS data over the Iberian Peninsula may be related to the aerosols, in line with recent results over China (Wang et al., 2018).

Finally, Fig. 6 shows the variability of SIS anomalies linear trends in the 1985–2015 period in the 12 locations. Each box shows the mean of the trends as well as quartiles and outliers. There are slight differences in the mean spatial trends between CLARA-A2 and SARAH-2, but CLARA-A2 shows a higher spatial variability than SARAH-2 and higher variability along the seasons. Nevertheless, the three datasets show that winter and summer have higher variability than autumn and spring in the linear trend. From this plot we can also confirm that satellite linear trends are better reproduced in spring and fairly reproduced in winter, while in summer and autumn do not reproduce properly the ground-based linear trends.

5. Conclusions

Some relevant conclusions can be drawn from the analysis of the variability and trends of the surface incoming shortwave solar radiation over the Iberian Peninsula in the 1985–2015 using satellite and ground-based data. We have found that satellite anomalies time series have a relatively high degree of correlation with ground-based anomalies series, with a small bias in all locations. In addition, a widespread increase of the SIS in the Iberian Peninsula from 1985 to 2015 has been observed, although satellite-based SIS trends overall underestimate these ground-based trends, especially in the summer season, which is in line with other studies in Europe.

Winter and summer have higher spatial variability in SIS trends than autumn and spring. Besides, CLARA-A2 shows more spatial and seasonal variability than SARAH-2. Nevertheless, it must be highlighted that, in the Iberian Peninsula, surface and satellite data (even CLARA-A2) reproduce similar trends in spring. In this way, it is worth to note that satellites are able to reproduce interannual and decadal variability in the Iberian Peninsula, at least in those seasons where variations in SIS are mostly due to clouds. Additionally, the decrease in the aerosol load over the study region reported in the literature might partially explain the differences in the SIS anomalies trends between satellites and stations data records, especially in summer.

Author statement

All coauthors agree with the content of this new version.

Declaration of Competing Interest

The authors have no conflict of interest to declare.

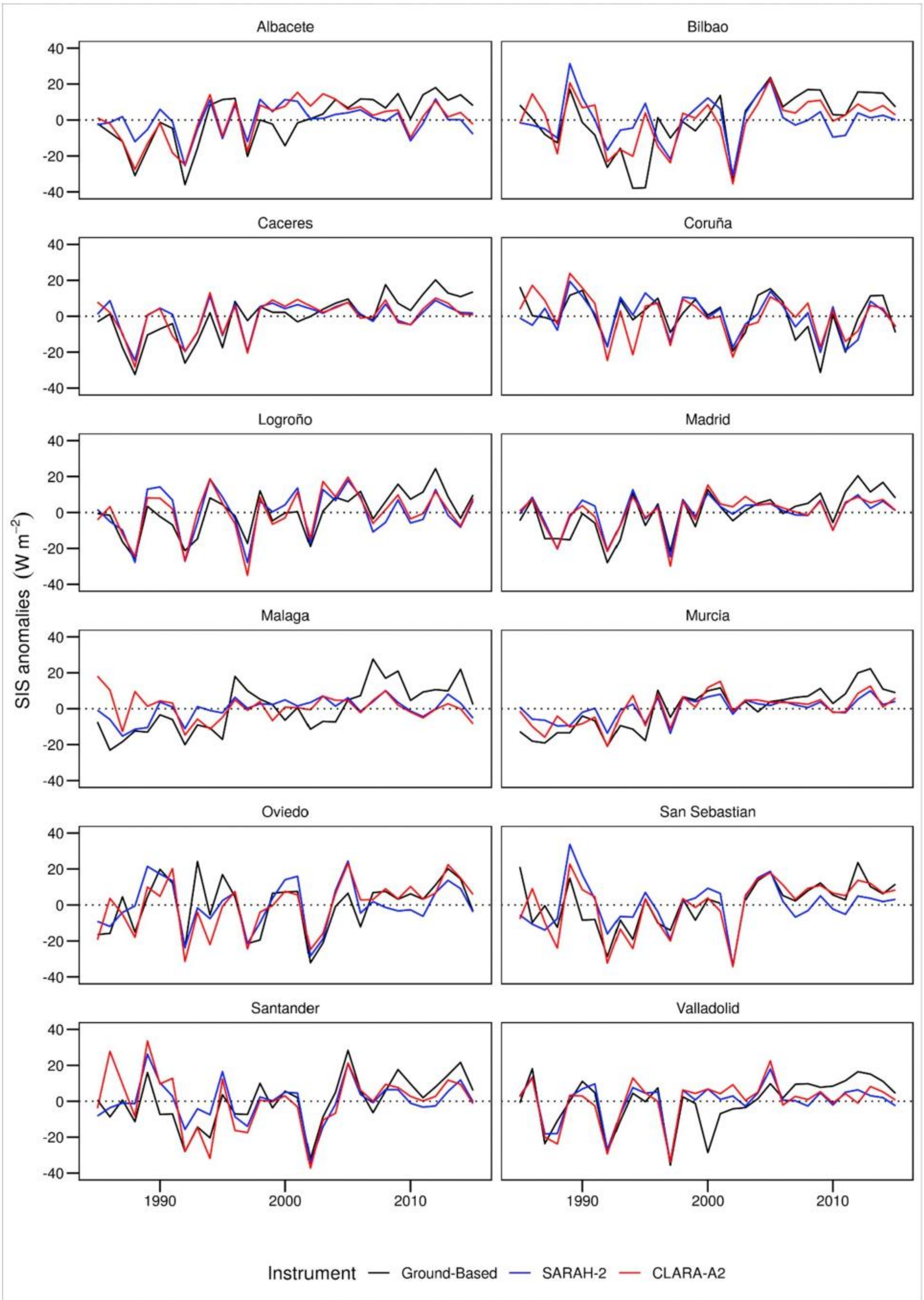

Fig. 5. Summer season SIS anomalies (Wm^{-2}) time series (1985–2015) for the studied locations.

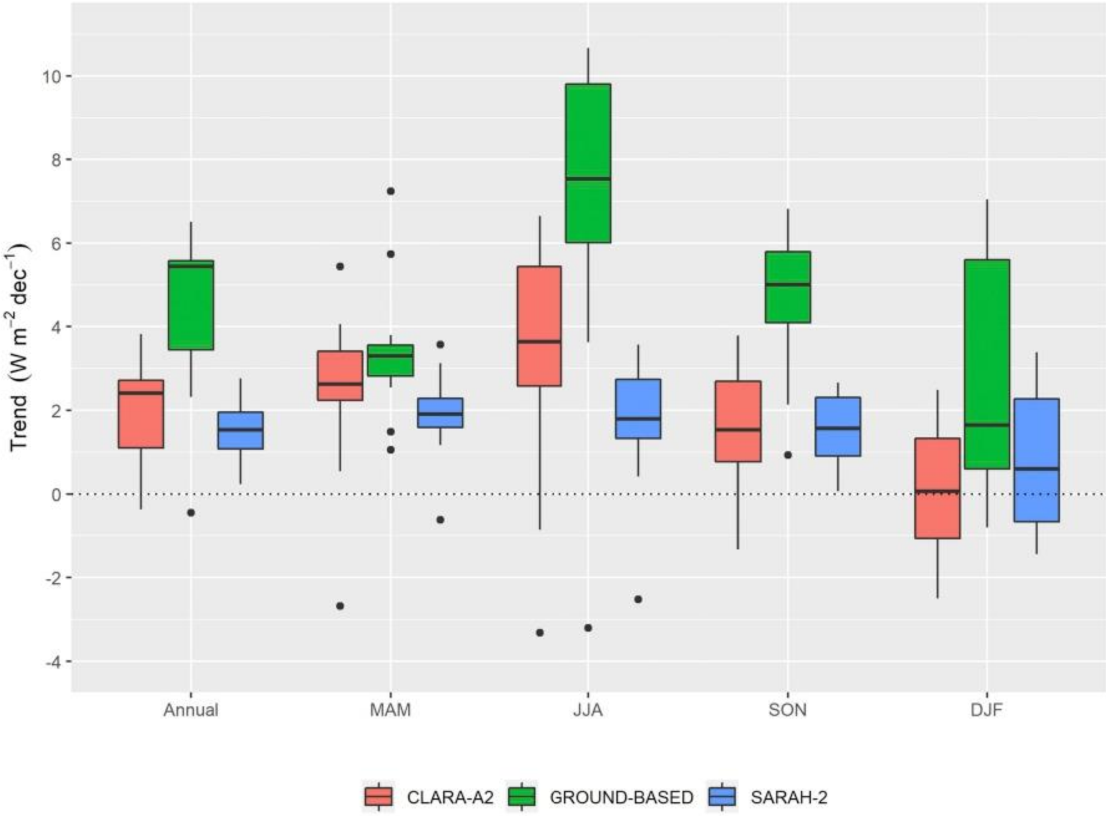

Fig. 6. Boxplots of the satellite and ground-based annual and seasonal SIS anomalies linear trends from 1985 to 2015 in $Wm^{-2}decade^{-1}$.

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3.2. Artículo 2.

Título: Early sunshine duration and cloud cover records in Coimbra (Portugal) for the period 1891-1950.

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Aspectos destacables del artículo:

Este trabajo se centra en un análisis exhaustivo de datos diarios de insolación del Observatorio Meteorológico de Coímbra (Portugal) desde 1891 hasta 1950. Estos datos se han recuperado a partir de fuentes documentales de dicho observatorio, adquiriendo una relevancia significativa al constituir la segunda serie más antigua de Portugal y la tercera de toda la Península Ibérica, por detrás de Madrid y Lisboa. La importancia de esta serie radica en su potencial para proporcionar una visión valiosa de la variabilidad de la radiación solar en la región a lo largo de más de medio siglo.

El análisis de estos registros pone de manifiesto la homogeneidad general de la serie temporal de insolación, con una excepción en el período de 1937-1938, que se presume relacionado con un cambio en el dispositivo de registro de insolación. Tras esto, se observa una tendencia ligeramente negativa de -0.09 ± 0.06 horas por década para el período 1891-1950. No obstante, existe un marcado descenso en los registros de insolación de -0.51 ± 0.32 horas por década observado desde el inicio de la serie temporal hasta la década de 1910, un fenómeno conocido como *early dimming*, que coincide con hallazgos similares en la literatura científica. Estas tendencias son estadísticamente significativas con un nivel de confianza del 95%. Sin embargo, desde 1920 hasta 1950, no se detectan tendencias estadísticamente significativas en los registros de insolación.

Los datos de cubierta nubosa en Coímbra también han sido digitalizados y analizados durante el mismo período. Este análisis arroja una tendencia positiva y estadísticamente significativa de 0.13 ± 0.06 décimas por década para el período completo de 1891-1950. Esta tendencia podría explicar la disminución de los registros de insolación en el mismo período, aludiendo a una posible relación entre el aumento de la nubosidad y una disminución en la insolación.

También se analizó las tendencias de la insolación en condiciones de cielo despejado, observando una fuerte disminución de las anomalías anuales desde el inicio de la serie hasta la década de 1910. Este resultado indica que los aerosoles podrían igualmente jugar un papel muy relevante en el fenómeno de *early dimming.*

Este estudio puso a disposición de la comunidad científica los datos de insolación y cobertura de nubes registrados en Coimbra de 1891 a 1950 en formato digital.

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RESEARCH ARTICLE

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Early sunshine duration and cloud cover records in Coimbra (Portugal) for the period 1891–1950

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Abstract
The recovery of early sunshine duration (SD) records is crucial to improve knowledge of the long-term evolution of incoming solar radiation at the Earth's surface. This work analyses daily SD data digitized from the Meteorological Observatory of Coimbra (Portugal) during 1891–1950. The Coimbra SD records are the earliest series in Portugal and the second one in the whole Iberian Peninsula (i.e., the first being in Madrid, Spain). The analysis shows that SD time series is homogenous except for a break in 1937–1938, which may be likely related to a change of the SD recorder (i.e., Jordan device replaced by a Campbell-Stokes recorder). Once the temporal inhomogeneity has been corrected, a slightly negative trend of -0.09 ± 0.06 hr per decade is found for the whole 1891–1950 period. It must be highlighted the marked decrease in SD records of -0.51 ± 0.32 hr per decade observed from the beginning of the time series until the 1910s ('early dimming') in line with other studies available in the literature. Both trends (whole and 'early dimming' periods) are statistically significant at the 95% confidence level. By contrast, from 1920s until 1950 no statistically significant long-term changes in SD records are found. Additionally, cloud cover data in Coimbra have been also digitized and analysed for the common period. A positive statistically significant trend of 0.13 ± 0.06 tenths per decade is found for the 1891–1950 period which may explain the negative trend of SD records in this same period. Nevertheless, the analysis of SD long-term trends under cloudless conditions suggests that other atmospheric factors such as the aerosol load could likely also play a relevant role on the SD evolution. The SD and cloud cover data from 1891 to 1950 is made available for the scientific community in digital form.

KEYWORDS
cloud cover, early brightening, early dimming, early instrumental data, sunshine duration

1 | INTRODUCTION

Solar radiation plays a key role to understand changes in the Earth-atmosphere system (Stephens *et al.*, 2012; Wild *et al.*, 2015). Many studies have analysed the evolution of incoming solar radiation at surface since the second half of the 20th century when continuous solar radiation measurements began to be recorded. Hence, numerous papers have noticed a dimming period around 3–9 $W \cdot m^{-2}$ from the 1950s to the 1980s and a brightening period of about 1–4 $W \cdot m^{-2}$ from the 1980s until nowadays, especially in the industrialized nations (e.g., Stanhill and Cohen, 2001; Wild, 2009; Sanchez-Lorenzo *et al*., 2015).

Sunshine duration (SD) is a good proxy data in order to reconstruct and analyse the long-term variability of surface solar radiation as it has been reported in the literature (e.g., Stanhill and Cohen, 2005, 2008; Román *et al*., 2014; Antón *et al*., 2017). This magnitude is defined as the amount of time, usually expressed in number of hours per day, that direct solar radiation exceeds a certain threshold (usually taken at 120 $W{\cdot}m^{-2}$). Special attention has been paid to know as much as possible about the long-term evolution of SD records. Specifically for the Iberian Peninsula, Sanchez-Lorenzo et al. (2007; Sanchez-Lorenzo *et al*., 2009) studied in detail the SD evolution since the 1930s. Later on, Antón *et al.* (2017) recovered the Madrid series since 1887, which shows a decrease in the surface solar radiation derived from SD records in Madrid from the 1890s to the 1930s, followed by a progressive increase until 1950, which is in line with the increase in the incoming solar radiation in other sites from the 1930s to the 1950s (Sanchez-Lorenzo *et al*., 2015; Stanhill and Achiman, 2017). It is worth to mention that the SD data at San Fernando (southern Spain) is the longest series over the Iberian Peninsula starting the measurements in 1881. Obregón *et al.* (2020) digitized daily SD records at this singular station during the period 1881–1890, showing the first evidence of the 1883 Krakatoa eruption effects over SD data. Unfortunately, the San Fernando time series is not considered homogeneous between 1891 and 1933 (Wheeler, 2001).

In this context, the two main objectives of this work were (a) to describe in detail the SD data digitized in Coimbra from 1891 to 1950 and (b) to analyse the temporal evolution of this SD series, which is the earliest homogeneous and continuous one in Portugal and the second one in the Iberian Peninsula. Additionally, cloud cover data are also digitized and analysed for the common period in order to be able to understand the causes of the SD evolution. Therefore, is expected that this work will contribute to the understanding of the past evolution of the surface solar radiation over the Iberian Peninsula due to the limited number of SD data sets before 1950s in this region. The data set source and instruments used for the measurements are explained in Section 2. Section 3 explains how the SD records and cloud cover data are recovered. Section 4 shows the analysis of the long-term evolution of both data sets during 1891–1950. Finally, conclusions are described in Section 5.

2 | DATA

In the last decade, an effort has been made to retrieve meteorological data from the past on a global scale (Domínguez-Castro et al., 2017; García-Herrera *et al*., 2018; Brönnimann et al., 2019). Documentary sources from the Iberian Peninsula have also provided ancient meteorological series from both Spain (Domínguez-Castro *et al*., 2014; Vaquero *et al*., 2021) and Portugal (Alcoforado *et al*., 2011). In particular, attention has also been paid to the recovery of long series related to solar radiation in the Iberian Peninsula (Antón *et al*., 2014, 2017; Aparicio *et al*., 2019; Bravo-Paredes *et al*., 2019; Obregón *et al*., 2020). The data recovered and analysed in this work are part of this common effort.

Meteorological Observatory of the University of Coimbra (Figure 1, left) is located outside the city of Coimbra on the top of a ridge around 1,500 m of length near the Mondego River. Within a walled enclosure and insulated on all sides of buildings of the establishment, the Observatory is located in the highest part of the main building, built in 1863. The Observatory belonged to the 'Instituto Geofísico da Universidade de Coimbra (IGUC)' and since 2013 to the 'Observatório Geofísico e Astronómico da Universidade de Coimbra', with continuous meteorological observations since 1864. In April 1996 the IGUC weather station was no longer part of the Portuguese Meteorological station network, being the official station relocated to the aerodrome of Cernache, in the outskirts of Coimbra, ~10 km from southwest of IGUC. Thus, SD and cloud cover observations were moved in 1996 to this new location, but from 1891 to 1950 (i.e., the digitized data of our study) no relevant changes have been detected in the observatory or location of the instruments, except the replacement of the Jordan sunshine recorded by a Campbell-Stokes instrument described below. Observations of SD by using the Campbell-Stokes recorder were stopped in 2007 in Cernache. The geographical coordinates of the Observatory are defined by a longitude of 8° 25′ 10.4″; a latitude of 40° 12′ 25″; and an altitude of 140 m above sea level.

All data were recovered from several volumes published annually by the University of Coimbra from 1891 to 1950. Each volume contains measurements of atmospheric pressure, temperature, atmospheric vapour pressure, relative humidity, wind, rain, ozone, in addition to the two variables analysed in the present work (SD and cloud cover). It is worth noting that data after 1950 is already available in digital format available from the Portuguese Meteorological Service under request.

SD records were recorded on a device of the Jordan's system built by Negretti and Zambra (Sanchez-Romero *et al*., 2014). It was acquired at the end of 1889 but it only started to be used regularly in January 1891. The metadata found in the volumes published annually with the SD records reports that a change of SD recorder takes place in February 1940, using from this date a Campbell-Stokes heliograph (Sanchez-Lorenzo *et al*., 2013) instead

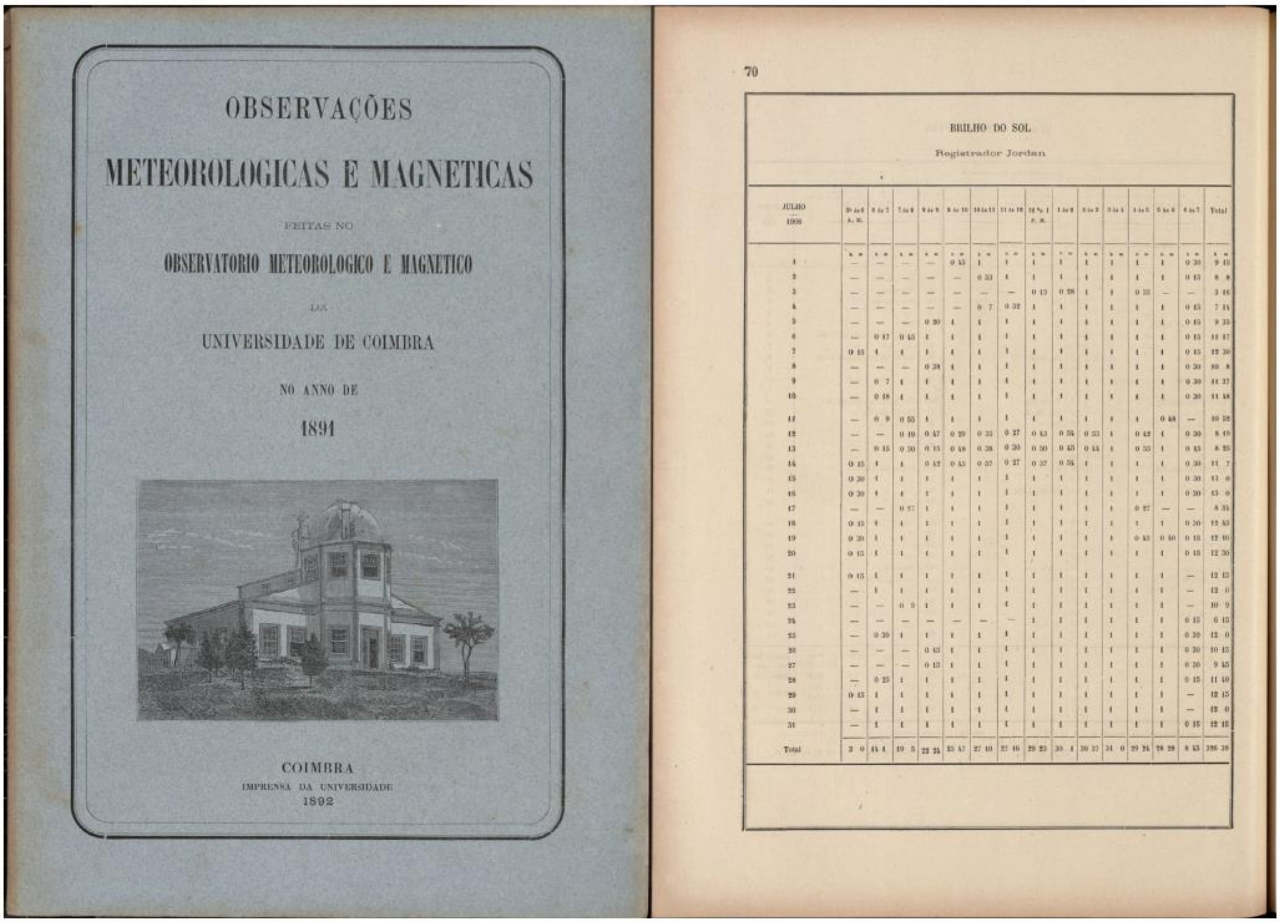
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FIGURE 1 (left) Front page of the log-book of the University of Coimbra published in 1892, which contains the meteorological and magnetics observations in 1891. The picture in the screen capture shows the observatory of the University of Coimbra. (right) Example of SD data published by the Observatory of Coimbra in July 1908. The column on the right hand includes the total daily SD for each day [Colour figure can be viewed at wileyonlinelibrary.com]

of the Jordan device. Both instruments measure the SD by projecting the image of the sun on a strip of sensitized paper. The impression produced on the paper provides us with the time that the sun shines on each hour of the day. For each day, the SD recorded by the Jordan and Campbell-Stokes recorders has been written down hourly, as well as the total daily SD sum (Figure 1, right). Only daily data were digitalized from January 1, 1891 to December 31, 1950, where there is only a 0.4% of missing data.

Additionally, cloud cover data by human observations for the common period (1891–1950) were also recovered. The amount of clouds can be defined as the portion of the sky that covers it when the observations are made. The values of the cloud cover are estimated in tenths: 0 defines a clear sky and 10 define a fully covered sky. It must be noted that four or five observations per day were digitized depending on the date: observations at (local time) 9, 12, 15, 18 and 21 hr from 1881 to 1922; observations at 7, 9, 12, 15 and 18 hr from 1923 to 1928; observations at 9, 12, 15 and 18 hr from 1929 to 1950. There are no gaps in the daily records of cloud cover during the 1891–1950 period.

3 | METHODOLOGY

3.1 | Homogenization analysis

Firstly, the temporal homogeneity of the recovered SD series has been evaluated. Figure 2 shows the annual mean time raw SD series in Coimbra during 1891–1950 period. To ensure an objective testing of the homogeneity, the Standard Normal Homogeneity Test (SNHT) (Alexandersson and Moberg, 1997) is applied on the annual series, which implies an absolute homogeneity test using only the data of this site. According to the SNHT, a 95% significant break comes out in January

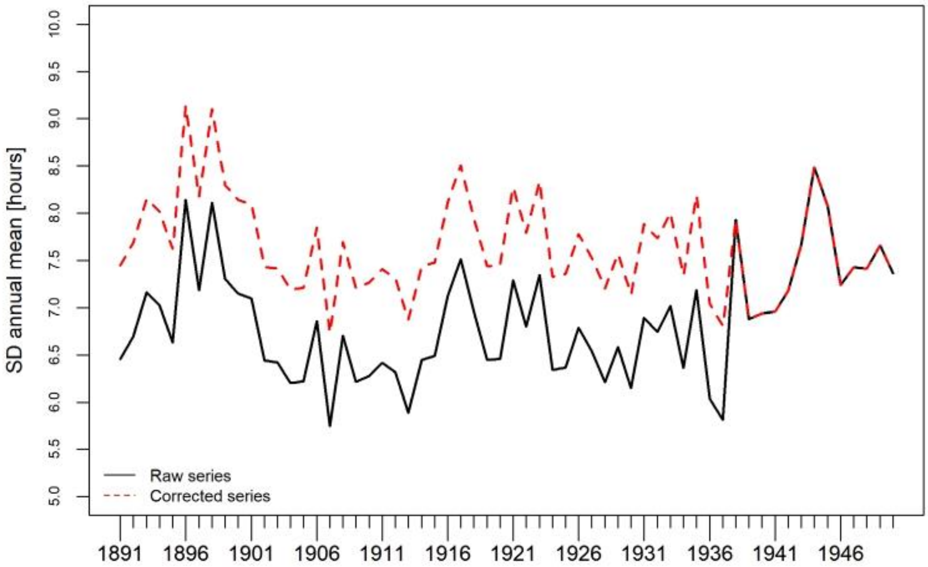

FIGURE 2 Annual mean time series of SD (hours) in Coimbra during the 1891–1950 period. Raw series (continuous line) and corrected series (dashed line) [Colour figure can be viewed at wileyonlinelibrary.com]

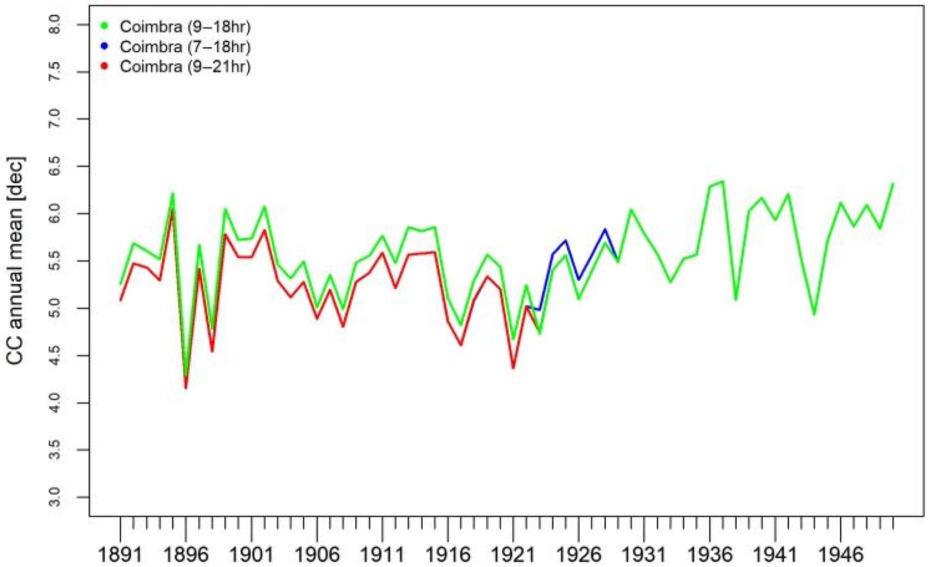

FIGURE 3 Annual mean time series of cloud cover (in tenths) in Coimbra during the 1891–1950 period. Theseries represents the annual series of cloud cover using daily measurements at i) 9, 12, 15 and 18 hr, ii)7, 9, 12, 15 and 18 hr, iii) 9, 12, 15, 18 and 21 hr [Colour figure can be viewed at wileyonlinelibrary.com]

1938. Consequently, it must be highlighted that a statistically significant inhomogeneity appears in January 1938 in the SD data. This break may be likely associated with the replacement of the Jordan device by the Campbell-Stoke heliograph which could have taken place 2 years before the date indicated in the metadata (February 1940) found in the books published by the Observatory of Coimbra.

Therefore, it is necessary to correct the mentioned break in the Coimbra series in order to obtain a homogeneous series. Taking into account that the break is found at the beginning of 1938, the monthly means of the periods 1925–1937 and 1938–1950 have been calculated separately. In addition, the differences between the two monthly means have been obtained, which represent the break between those two periods. Consequently, to eliminate the break, these monthly differences have been added to the daily data over 1891–1937. The homogeneous annual series derived from the corrected daily SD records is also shown in Figure 2.

The cloud cover data for the common period have been recovered, as mentioned in Section 2. Figure 3 shows the annual series of cloud cover based on the number of measurements per day. The green series represents the annual series of cloud cover using daily measurements at 9, 12, 15 and 18 hr. The red series represents the annual series of cloud cover using daily averages of measures at 9, 12, 15, 18 and 21 hr. The blue series represents the annual series using daily averages of measures at 7, 9, 12, 15 and 18 hr. There are small variations between the three series but they are not statistically significant, so we will analyse the evolution of cloud cover as a single annual series.

The homogeneity of the cloud cover data in Coimbra for the period 1891–1950 has been also evaluated by SNHT test confirming that this data set is homogenous at a 95% significance level. Consequently, no adjustments have applied to this series.

It is worth to mention that both the raw and the corrected daily series are available to the scientific community in the Supplementary Information.

3.2 | Long-term analysis method

The first step in the long-term SD analysis is to deseasonalise the corrected SD records. Thus, the monthly SD data set (M) was derived from the average of corrected daily SD records. The evolution of these monthly data set displays a marked seasonal behaviour (not shown) associated with the well-known dependence of incoming solar radiation on the annual cycle of the solar elevation. Hence, the annual cycle of SD data (seasonal pattern) was derived from the averages of daily SD records for each of the 12 months (S). This annual cycle is subtracted from the monthly SD data set in order to obtain deseasonalised monthly values (absolute monthly anomalies, A), as Equation (1) shows:

$$A^{i,j} = M^{i,j} \cdot S^{j} \quad (1)$$

where the super-index i denotes the year (from 1891 to 1950), and the super-index j the month (from 1 to 12). An equivalent deseasonalisation method was also applied to the cloud cover data.

The analysis of long-term trends for both SD and cloud cover data sets is performed from the linear regression analysis applied on the annual time series (derived from the annual average of the deseasonalised monthly values). Thus, the linear trend in functional form is equal to $A \sim a + b \cdot t$; where a is the intercept, b the slope, and t is the time in the units of years. Estimated value of b represents the long-term trend of the annual SD data set. The uncertainty of these trends is given by twice standard deviation of the slope in the linear regression.

4 | RESULTS AND DISCUSSION

Figure 4 (top) shows the evolution of the annual SD anomalies derived from the average of the deseasonalised monthly data from 1891 to 1950 in Coimbra. The trend analysis applied to the annual SD series highlights a decrease over the whole period (1891–1950), with a trend of -0.09 ± 0.06 hr per decade (statistically significant at the 95% confidence level). The highest levels of SD records are found at the end of the 19th century, observing a marked negative trend of -0.51 ± 0.32 hr per decade for the period 1891–1913 with statistical significance at the 95% confidence level. This result could be indicative of a decrease of incoming solar radiation between the last part of the 19th century and the beginning of the 20th century at Coimbra. It is worth mentioning that the short time period used for this latter trend analysis (i.e., 1891–1913, 23 years long) can jeopardize the results and caution is needed interpreting these findings. A similar 'early dimming' has been reported in other studies over the Iberian Peninsula (Antón *et al.*, 2017; Aparicio *et al.*, 2019; Bravo-Paredes *et al.*, 2019) as well as in other regions (e.g., Stanhill and Cohen, 2008; Matuszko, 2014; Stanhill and Achiman, 2017; Kazadzis *et al.*, 2018). On the other hand, there is no evidence of this 'early dimming' in the US (Stanhill and Cohen, 2005), or mixed evidences in Ireland (Pallé and Butler, 2002). Furthermore, the SD evolution shows a stable behaviour without significant long-term trends from 1920s until 1950. Therefore, the analysis of the SD series in Coimbra shows no evidence of an increase of incoming solar radiation throughout the second quarter of the 20th century ('early brightening') reported in other locations (e.g., Ohmura, 2007; Ohmura, 2009; Sanchez-Romero *et al.*, 2014; Stanhill et al., 2014; Stanhill *et al.*, 2018). Specifically, an early brightening have been observed in other locations of the Iberian Peninsula (Curto *et al.*, 2009; Antón *et al.*, 2017), whereas no evidence has been reported for Italy (Manara *et al.*, 2015) or Switzerland (Sanchez-Lorenzo *and Wild*, 2012). Overall, it is worth mentioning that there is a lack of studies analysing the long-term series of SD series, especially since the late 19th century, with common methodologies for homogeneity and trend analyses, which can jeopardize a proper comparison our results with the literature. Further research is needed in order to collect, homogenize, and study the long-term changes of earlier SD measurements.

In order to show the full period of SD records in Coimbra, Figure S1 shows the time evolution from 1891 to 2007, adding the digital records non-freely available from the Portuguese Institute for Sea and Atmosphere (IPMA) since 1950. The extended time series highlights the well-known decrease (i.e., dimming period) of incoming solar radiation from mid-20th century to the 1980s, as well as recovery afterwards (i.e., brightening period). This time evolution since the mid-20th century has been already reported in several studies for the Iberian Peninsula and Europe by using sunshine duration and global

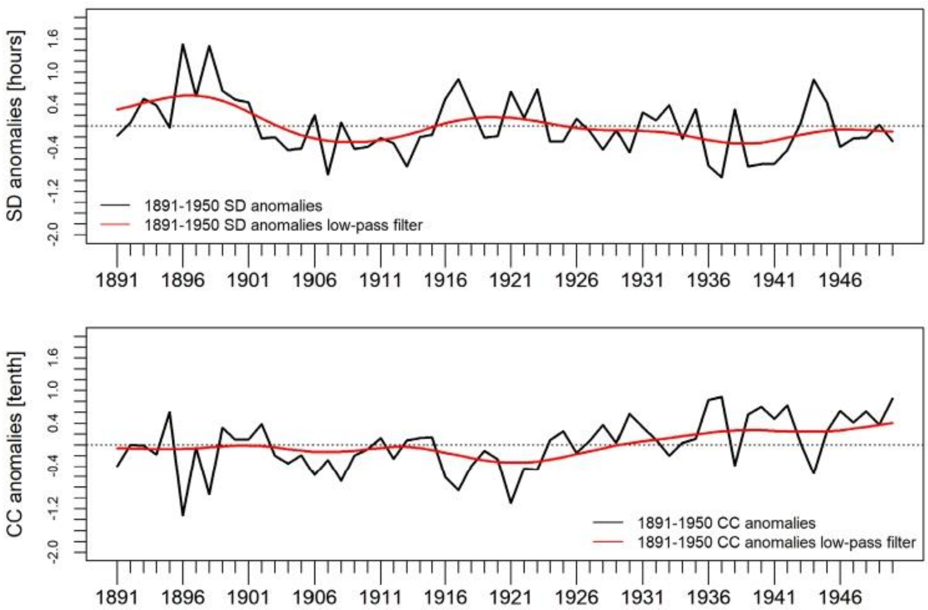

FIGURE 4 Annual mean anomalies series of SD (top) and cloud cover (bottom) from 1891 to 1950 in Coimbra, plotted together with 21-year Gaussian low-pass filter. The series are expressed as anomalies from the 1891–1950 mean [Colour figure can be viewed at wileyonlinelibrary.com]

radiation series (e.g., Sanchez-Lorenzo *et al.*, 2009, 2015; Wild, 2009; Montero-Martín *et al.*, 2020).

Figure 4 (bottom) shows the cloud coverage anomalies time series for the 1891–1950 period in Coimbra, obtaining a positive trend of $+0.13 \pm 0.06$ tenths per decade (statistically significant at the 95% confidence level). This result may explain the slight negative long-term trend found in the same period for the SD records. There is no statistically significant trend during the 1891–1913 period. In addition, it can be noticed that the minimum cloud cover peaks coincide with the maximum SD peaks (e.g., in 1896 and 1898) and vice versa (1937). This positive trend from the late 19th century to the 1950s is in line with the literature, as it is reported a widespread increase of cloud cover over most of the studied regions (Pallé and Butler, 2002; Sanchez-Lorenzo *et al.*, 2012). However, there is no statistically significant negative correlation between SD duration and cloudiness. In fact, at the beginning of the 20th century, there is a decrease in both variables which is contrary to what would be expected. Therefore, it would be possible to assume that the decrease in SD records in Coimbra could be also related to a decrease in other atmospheric variables like the atmospheric aerosol load.

In order to test this hypothesis the SD series under cloudless sky conditions have been checked (Sanchez-Lorenzo *et al.*, 2009; Manara *et al.*, 2017). First, the cloudless days were selected when the average of the mean cloud cover series from four daily observations common for the whole period (i.e., 9, 12, 15 and 18 hr) was 0 tenths. As only July and August have more than 6 days on average considered as cloudless, we have subsequently analysed the average of these 2 months (i.e., summer series hereinafter). Second, the summer mean SD cloudless sky series for Coimbra was obtained by averaging the SD records available for these days with 0 tenths of cloud cover. Third, the mean summer cloudless SD series has been tested for temporal homogeneity with the SNHT as was described in Section 3, and the same significant break has been observed in 1938. Consequently, this break has been corrected as described above for the annual SD series in Section 3. The mean summer SD series under cloudless sky conditions series (Figure 5) shows a statistically significant decrease over the whole 1891–1950 period (-0.09 ± 0.07 hr per decade), although as for the annual SD series (Figure 2) there is a strong decrease in the records in the early 20th century and afterwards a stabilization of the records during the following decades. These results may be likely associated with the black carbon emissions during this period in Europe which suffered a strong increase since mid-19th century that decline after the 1920s (Novakov *et al.*, 2003; McConnell *et al.*, 2007; Lamarque *et al.*, 2010). Additionally, it is worth mentioning that the minimum of the series is reached in 1912, and this anomalous data might be associated to the Katmain eruption in June 1912 in Alaska, which is considered the largest volcanic eruption of the 20th century, in line with results reported by Antón *et al.* (2017) in Madrid (Spain). The signal of the volcanic aerosols emitted by the Katmai in SD records of Coimbra is also in line with the data from pyrheliometer measurements in Madrid (Antón *et al.*, 2014; Aparicio *et al.*, 2019), and its support the ability of SD records under cloudless conditions to detect radiative signal from large volcanic eruptions (Sanchez-Lorenzo *et al.*, 2009; Obregón *et al.*, 2020). Overall, our results also emphasize the potential of SD and cloud cover data to retrieve information of

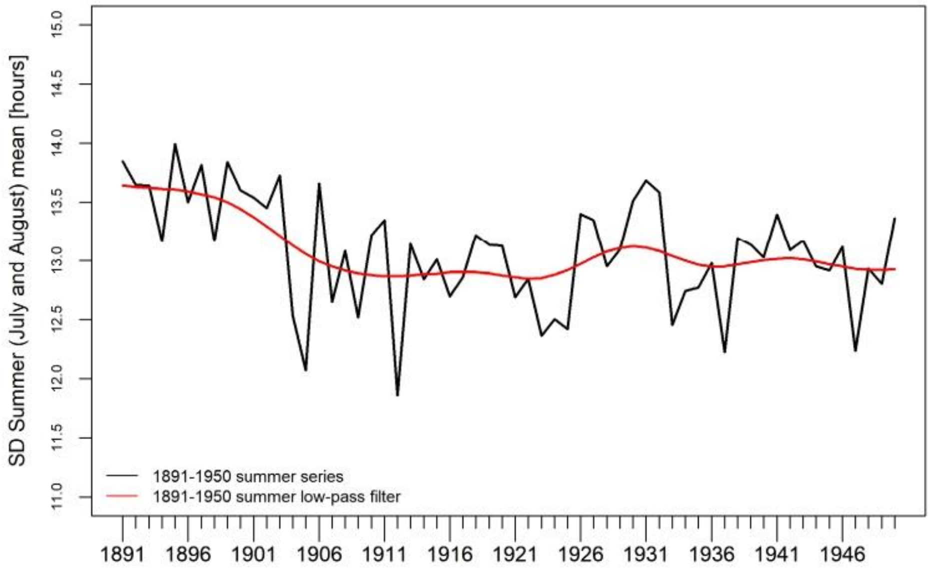

FIGURE 5 Summer (July and August) mean series of homogenized daily mean SD (hours) for cloud-free sky conditions during the 1891–1950 period, plotted together with 21-year Gaussian low-pass filter [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Seasonal linear trends (± 2·*SD*) from 1891 to 1950 (whole period) and from 1891 to 1913 ('early dimming') (hours per decade) in Coimbra

Period	MAM	JJA	SON	DJF
1891–1950	**−0.06 (0.04)**	**−0.03 (0.03)**	−0.01 (0.03)	−0.02 (0.04)
1891–1913	−0.12 (0.17)	**−0.29 (0.12)**	**−0.14 (0.11)**	−0.14 (0.18)

Note: The trends with a significance level equal or higher than 95% are in bold. MAM (March, April, May), JJA (June, July, August), SON (September, October, November), DJF (December, January, February).

the aerosol load in the atmosphere (Sanchez-Romero *et al.*, 2014; Wandji Nyamsi *et al.*, 2020), which it is a crucial issue due to the lack of reliable information about its variation before the satellite era.

Finally, in order to analyse seasonally the evolution of the SD records in Coimbra, linear trends for 1891–1950 (whole period) and 1891–1913 ('early dimming' period) are performed and shown in Table 1. Specifically, linear trends are calculated on seasonal basis for the four time series derived from the average of the deseasonalised monthly data for winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug) and autumn (Sept-Oct-Nov). The results show that there is a slight decrease in all seasons over the whole period, although only statistically significant in spring and summer series. Besides, Table 1 shows that the strongest negative trend in the 'early dimming' period is found in summer (-0.29 ± 0.12 hr per decade), although other seasons also exhibit a decrease in SD anomalies. These results are in line with the annual analysis trend, as well as the seasonal trends reported by Antón *et al.* (2017).

5 | CONCLUSIONS

Some conclusions can be drawn from this study:

1. The earliest series of SD records known in Portugal and the second earliest series in the Iberian Peninsula has been digitized, which begins in 1891.
2. The Coimbra SD series appears to be homogeneous except for one break in 1938, which could be related with a replacement of instrument (Jordan device by Campbell-Stokes recorder). Consequently, the break has been corrected obtaining a homogeneous series over the whole period 1891–1950.
3. A marked negative statistically significant trend in SD records is observed for the period 1891–1913 ('early dimming') followed by a stable period until 1950.
4. The series of cloud cover has also been digitized for the common period and can be considered as homogeneous. It is observed a statistically significant positive trend for the 1891–1950 period, which could explain the slight SD decrease found for this period, although the SD evolution could be also affected by other factors such as atmospheric aerosols.
5. The study carried out in the SD series under cloudless sky conditions supports the hypothesis that the decrease of SD records in Coimbra from 1890s to 1910s might be partially related to an increase in atmospheric aerosol load.

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3.3. Artículo 3.

Título: Reconstruction of daily global solar radiation under all-sky and cloud-free conditions in Badajoz (Spain) since 1929.

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Aspectos destacables del artículo:

Este estudio se centra en el análisis detallado de la variabilidad temporal a largo plazo de la radiación solar en superficie reconstruida en Badajoz (España), abarcando el período de 1929 a 2015. Para ello, se recuperaron y digitalizaron datos de insolación y cubierta nubosa para el periodo 1929-1950. El método de reconstrucción se basa en la relación entre el factor de modificación de nubes (cociente entre medidas de radiación solar y las estimaciones para cielo despejado a partir de un modelo de transferencia radiativa) y los registros de insolación. Además, para seleccionar los días de cielo despejado se emplea información de cobertura de nubes registrada por observaciones desde superficie.

En la evaluación de las tendencias lineales de los valores reconstruidos de radiación solar se distinguen tres períodos distintos. En el intervalo de 1929 a 1950, se evidencia una tendencia positiva y estadísticamente significativa de +4.18 Wm^{-2} por década, indicando un aumento en la radiación solar en superficie durante ese tiempo. A esta etapa le sigue un período de disminución pronunciada, abarcando desde 1951 hasta 1984, con una tendencia negativa de -3.72 Wm^{-2} por década. Esta disminución podría ser atribuible a factores atmosféricos como el aumento en la presencia de aerosoles o una mayor cobertura de nubes que afectan la cantidad de radiación solar alcanzando la superficie. Posteriormente, desde 1985 hasta 2015, se observa un repunte en los niveles de radiación solar, con una tendencia positiva de +2.04 Wm^{-2} por década, lo cual podría estar influenciado por la posible disminución de aerosoles que interfieran con la radiación solar.

Al considerar la variabilidad estacional, se encuentran tendencias estadísticamente significativas sólo durante el verano en los tres subperíodos comentados anteriormente. Esto sugiere una mayor dinámica en la radiación solar durante esta estación, posiblemente vinculada a cambios en la cobertura de nubes y la carga de aerosoles.

Con el objetivo de discernir las causas de las tendencias de radiación solar reconstruidas, se examinó la variabilidad temporal de la cobertura nubosa. Los resultados mostraron que esta variable exhibe una tendencia negativa y estadísticamente significativa entre 1985 y 2015, sugiriendo que una menor cobertura nubosa podría contribuir al aumento de radiación en ese período. Estos resultados ponen de manifiesto la importancia de la interacción entre nubes y radiación solar en la variabilidad temporal de las series de radiación solar en superficie. Sin embargo, con anterioridad a 1985 no se hallaron tendencias estadísticamente significativas en las series anuales y estacionales de cobertura nubosa.

El análisis de la evolución a largo plazo de la radiación solar reconstruida en condiciones de cielo completamente despejado muestra un patrón similar a los obtenidos para todo cielo: un aumento durante 1929-1950, seguido de una disminución en 1951-1984 y finalmente un nuevo aumento de 1985 a 2015. Estos resultados indican que otros factores distintos a los cambios en la nubosidad, como la variabilidad en la carga de aerosoles, juegan un papel relevante en la determinación de las tendencias a lo largo plazo de la radiación solar en la localización de estudio.

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RESEARCH ARTICLE

Reconstruction of daily global solar radiation under all-sky and cloud-free conditions in Badajoz (Spain) since 1929

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Abstract

This work analyses the long-term temporal variability of the annual and seasonal series of reconstructed global solar radiation for both all-sky and cloud-free conditions in Badajoz (Spain) over the 1929–2015 period. Specifically, daily values of global horizontal irradiation (GHI) for all-sky cases are derived from a semiempirical method based on the relationship between the cloud modification factor and sunshine duration records. Additionally, cloud-free situations are selected using cloud cover (CC) information recorded by surface observations. Regarding GHI linear trends for all-sky conditions, three periods are clearly identified: during the 1929–1950 period, there is a positive and statistically significant trend of +4.18 $W{\cdot}m^{-2}{\cdot}decade^{-1}$. It is followed by a significant dimming with a trend of −3.72 $W{\cdot}m^{-2}{\cdot}decade^{-1}$ between 1951 and 1984. GHI levels increase again from 1985 to 2015 with a statistically significant trend of +2.04 $W{\cdot}m^{-2}{\cdot}decade^{-1}$. The seasonal trends are found to be statistically significant only in summer for all the three subperiods. With the goal to find out the possible causes of the reconstructed GHI trends, the temporal variability of the CC was also analysed. It was observed that CC has a statistically significant negative trend between 1985 and 2015 which may partially explain the GHI increase shown for this period. In contrast, not statistically significant trends were found in the annual and seasonal CC series before 1985. The long-term evolution of the GHI under cloud-free conditions exhibits the same pattern as all-sky conditions: an increase during 1929–1950, followed by a decrease in 1951–1984 and then a new increase from 1985 to 2015. Therefore, the positive (negative) linear trends in GHI reported in this study could be partially related to a decrease (increase) in the aerosol load during the analysed three subperiods.

KEYWORDS

atmospheric aerosols, cloud cover, dimming/brightening, early instrumental data, surface solar radiation

1 | INTRODUCTION

Solar radiation is a critical aspect in understanding variations in the Earth-atmosphere system (Stephens et al., 2012; Wild et al., 2015). Since the recording of continuous solar radiation measurements began in the second half of the 20th century, many studies have investigated the evolution of incident surface solar radiation, or global horizontal radiation (GHI). Among these measurements, many papers identified a dimming period from the 1950 s to the 1980s and a brightening period since the 1980s, especially in Europe and North America (e.g., Sanchez-Lorenzo et al., 2015; Stanhill & Cohen, 2001; Stanhill et al., 2018; Wild, 2009). However, a tendency to stabilization and even decrease has also been observed since the 2000s at some regions (Augustine & Hodges, 2021; Wild, 2016; Wild et al., 2021).

Sunshine duration (SD) records are a good proxy data to reconstruct the long-term variability of GHI as reported in several studies (e.g., Antón et al., 2017; Bartoszek et al., 2020; Matuszko et al., 2020; Ohmura, 2007; Román et al., 2014a; Sanchez-Romero et al., 2014; Stanhill & Cohen, 2005, 2008; Wild, 2009, 2016). This parameter is defined as the length of time, usually expressed in hours per day, for which direct solar radiation exceeds a certain threshold (i.e., 120 $W \cdot m^{-2}$).

Attempts have been made to recover past meteorological data (Brönnimann et al., 2019; García-Herrera et al., 2018). Literature on the Iberian Peninsula also provides old data from Spain (Domínguez-Castro et al., 2014; Vaquero et al., 2020) and Portugal (Alcoforado et al., 2011). Specifically, some works have focused on the recovery of long series related to solar radiation in the Iberian Peninsula (Antón et al., 2014, 2017; Aparicio et al., 2019; Bravo-Paredes et al., 2019; Montero-Martín et al., 2021; Obregón et al., 2020). This type of study presents a great interest to understand the past evolution of solar radiation at surface in this region due to the limited number of SD datasets before 1950s. The present work is part of this collaborative effort.

Specifically for the Iberian Peninsula, Sanchez-Lorenzo et al. (2007, 2009) studied the development of SD since the 1930s in detail. Later, Román et al. (2014a) reconstructed the daily GHI from the SD records since 1950 at nine Spanish stations and reported statistically significant dimming and brightening periods in line with the literature. Antón et al. (2017) recovered the Madrid series since 1887, showing a decrease in the GHI (early dimming) derived from SD records in Madrid until the 1910s, followed by a gradual increase up to 1950 (early brightening). The result was also confirmed by analysing the early SD records recovery in Coimbra (Portugal) since 1891 (Montero-Martín et al., 2021). It is worth to notice that SD data series at San Fernando (southern Spain) is the longest in the Iberian Peninsula, measured from 1881. Obregón et al. (2020) analysed daily SD records at this single station from 1881 to 1890 and presented the first evidence of the 1883 Krakatoa eruption effects on SD data. Unfortunately, the San Fernando time series is not considered homogeneous between 1891 and 1933 (Wheeler, 2001). Besides, due to the limited number of SD prior to the 1950s, the recovery and analysis of early SD records over the Iberian Peninsula represents a great interest to understand the past evolution of surface solar radiation in this region.

There are two main goals of this study. The first one is to reconstruct daily global solar radiation values in Badajoz since 1929 using a semiempirical method, based on relationships between SD records and the cloud modification factor (CMF) obtained as the ratio of measured GHI values to the equivalent GHI values but for cloud-free conditions simulated by a radiative transfer code. The second objective is to analyse the temporal evolution of the reconstructed GHI data in Badajoz (for both all-sky conditions and cloud-free cases), which is one of the earliest homogeneous and continuous series in the Iberian Peninsula.

The dataset source and instruments used for the measurements are exposed in detail in section 2. Section 3 describes the reconstruction method to estimate daily values of GHI. Section 4 shows the analysis of the long-term evolution of both datasets during 1929–2015. To sum up, conclusions are written in section 5.

2 | DATA

Badajoz is located in the southwest of the Iberian Peninsula on the bank of the Guadiana River. The first location of the Spanish Meteorological Service in Badajoz was the building of the high school "Bárbara de Braganza" (185 m a.s.l.), located in the city centre of Badajoz (Figure 1). The series of SD records started in September 1928 while the continuous cloud cover (CC) observations started in January 1921. Both series recorded in this observatory (called in this work "Instituto") continued uninterrupted until 1984. Figure 2 shows two images of this early observatory during the first half of the 20th century.

Figure 1 also shows the location of the other observatory used in this study with measurements of both SD and CC data, the Badajoz Airport, sited 13 km east of downtown Badajoz (195 m a.s.l.). The measurements of SD and CC series in this observatory (called in this work "Aeropuerto") started in 1955 and both continue nowadays.

SD records were measured in the two stations with a Campbell–Stokes heliograph (Sanchez-Lorenzo et al., 2013a, 2013b), which obtain this variable by focusing the

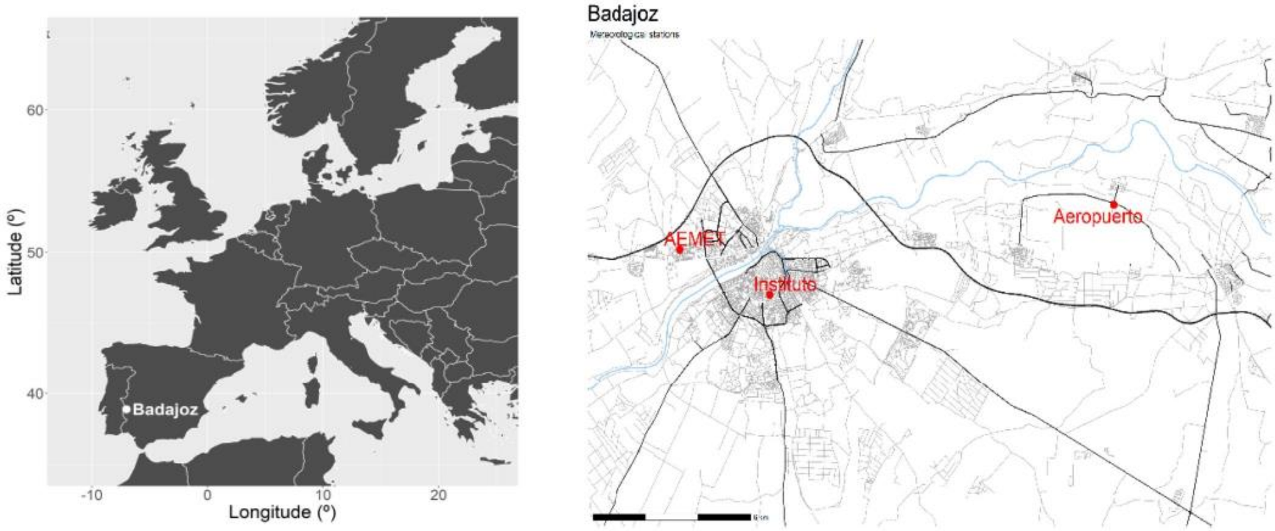

FIGURE 1 (left) Map of Europe including the location of Badajoz (Spain). (right) Location within Badajoz of the three meteorological stations that have been used to obtain the reconstructed GHI data during 1929–2015: High school "Barbara de Braganza" ("*Instituto*" *station*, 1928–1984 period), Airport of the city ("*Aeropuerto*" *station*, 1955–2015 period), and solar radiation station at the current Badajoz meteorological headquarters ("*AEMET*" *station*, 2002–2015 period). The topography of the area where the three close observatories ("Instituto," "Aeropuerto" and "AEMET") are located exhibits a great homogeneity with fertile plains without relevant elevations [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 2 Undated photography of the meteorological observatory in Badajoz (High School "Bárbara de Braganza, Instituto" (left), and the Campbell–Stokes device used to record SD data (right) during the first half of the 20th century [Colour figure can be viewed at wileyonlinelibrary.com]

direct solar beam on a strip of sensitized paper. When the intensity of the direct solar beam is high enough, the focused beam can burn the sensitized paper, which indicates the time, usually expressed in number of hours, when the direct solar beam is above a certain threshold (usually taken at 120 $W\cdot m^{-2}$). For each day, the SD recorded has been written down hourly, as well as the total daily SD sum. SD records from the Campbell–Stokes heliograph in "Aeropuerto" station were replaced by automatic equipment on 1st December, 2016.

CC data by visual observations (three times per day) for the common period (1929–1984 for "Instituto" and 1955–2015 for "Aeropuerto") were also analysed in this work. The values of the CC are recorded in tenths until 31th January 1950: 0 defines a cloud-free sky and 10 defines an overcast sky. Since 1st February 1950 cloud cover values are estimated in oktas (0: cloud-free sky; 8: overcast sky). In this study, all daily mean values were converted to tenths.

SD and CC data for "Instituto" station were rescued by our research team from several handwritten notebooks (Figure 3) of the Spanish Meteorological Service; SD from September 1928 to December 1950 and CC from September 1928 to December 1955. From these dates, SD and CC data for "Instituto" station were already available in digital format. In addition, the whole complete series of SD and CC data for "Aeropuerto" station were available in digital format. It is worth noting that there is a common period of 30 years in which both stations at Badajoz have recorded the same meteorological variables, being possible to compare differences in both series.

Finally, the current location of the official weather station of the Spanish Meteorological Service in Badajoz

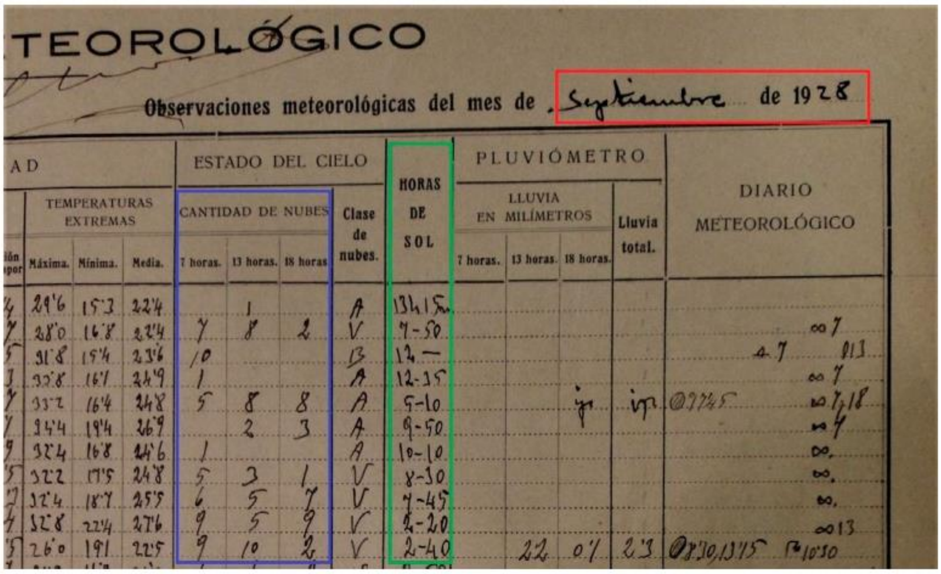

FIGURE 3 Partial view of a page of observations that have been retrieved. The month and year of the observations are highlighted in the red box. The SD and CC records are in the green and blue boxes, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

(called in this work "AEMET" station) is also shown in Figure 1. GHI data have been measured in "AEMET" station since 2002. Unfortunately, no previous records of GHI have been recorded in Badajoz. The daily records are expressed as irradiation units (i.e., $kJ \cdot m^{-2}$) and measured by using Kipp and Zonen pyranometers during the whole period. Although metadata is no available to know changes in the instruments due to replacements or updates, it is important to note that these pyranometers were periodically calibrated according to the standards for measurements of the World Radiation Centre (Sanchez-Lorenzo et al., 2013a, 2013b). Although SD and CC data are available since September 1928, the period of reconstructed GHI series starts in January 1929 in order to analyse whole years. Additionally, considering that SD series from Campbell–Stokes heliograph was interrupted in late 2016, the period of reconstructed GHI series finishes in December 2015.

3 | METHODOLOGY

3.1 | Reconstruction of the GHI

The reconstructed GHI data applied in this study are obtained using the method developed by Román et al. (2014a) and adapted for the study location. This method uses the cloud modification factor of GHI (CMF_{GHI}), which is defined as the ratio of GHI to GHI under cloud-free conditions (GHI_{cf}). The methodology assumes that CMF_{GHI} can be retrieved from SD and, once CMF_{GHI} and GHI_{cf} are obtained, the GHI can be calculated by

$$GHI = CMF_{GHI} \times GHI_{cf}. \qquad (1)$$

3.1.1 | Cloud-free simulations

First, for each day from 1929 to 2015 in Badajoz, the hourly GHI_{cf} is calculated by the two-stream fluxes ("twostr") solver, developed by Kylling et al. (1995), using the UVSPEC radiative transfer tool included in the libRadtran 1.7 package (Mayer and Kylling, 2005). Daily GHI_{cf} values are obtained from hourly estimated ones. These GHI_{cf} values are obtained as the integration of simulated spectral irradiances from 280 to 2800 nm, while the chosen extraterrestrial spectrum is from Kurucz (1992). The pseudo-spectral *k*-distribution "SBDART" from Ricchiazzi et al. (1998) is chosen following the same method as in Román et al. (2014b). All these simulations are run for the Badajoz coordinates.

As input for the GHI_{cf} simulations, the following values are used: the daily values of total ozone column, surface albedo and water vapour column; the three from the Twentieth Century Reanalysis (20CR) Project dataset (Slivinski et al., 2019) over the 1928–2015 period. For the aerosol information in the UVSPEC simulations, monthly climatology tables are used for the Ångström law parameters (Ångström Exponent and turbidity parameter) and the single scattering albedo at 675 nm. These monthly climatology tables were previously calculated using version 3 level 2.0 AERONET data (AErosol RObotic NETwork; Giles et al., 2019; Holben et al., 1998) for the 2012–2021 period at the AERONET Badajoz station. Ångström parameters were obtained by the AERONET aerosol optical depth (AOD) values at 440, 500, 675 and 870 nm. Thus, in the GHI_{cf} simulations of this study there is not time varying aerosol information and consequently it can jeopardize the stability and homogeneity of the decadal variations of the reconstructed GHI data. Nevertheless, it is worth mentioning that aerosol signal is also observed in the variability of SD data (for a review, see Sanchez-Romero et al., 2014).

3.1.2 | Tunning of the model

Once daily GHI_{cf} values are obtained, the measured CMF_{GHI} is calculated for all days with available GHI measurements, as the ratio of GHI to GHI_{cf}. In addition, the daily sunshine fraction (F) is calculated as the ratio of SD to the theoretical maximum SD (SD_0). SD_0 is calculated as the time span from solar zenith angle (SZA) of 87° at sunrise to a SZA of 87° at sunset.

As CMF_{GHI} cannot be calculated when there are not GHI measurements, the reconstruction model of Román et al. (2014a) was chosen to estimate CMF_{GHI}, and hence GHI (Equation (1)), directly from F values since these time series are longer. Román et al. (2014a) calculated some empirical coefficients, which depend on the season of the year, that determine the CMF_{GHI} value for a given F value. These coefficients were calculated using measurements recorded on the Iberian Peninsula, but not at Badajoz. Hence, we recalculate these coefficients using daily CMF_{GHI} and F values, inferred from GHI and SD measurements, in order to tune the reconstruction model to our location.

As a first approximation, we consider the GHI measurements (and hence CMF_{GHI} values) at "AEMET" station and the SD records (and hence F values) at "Aeropuerto" station are collocated. Data from 2002 to 2013 are selected to obtain the new model coefficients, while data from 2014 to 2015 are used to validate the model with the new coefficients. Following the method of Román et al. (2014a), daily CMF_{GHI} is represented as a function of F, separately for the four seasons, in Figure 4. The new model coefficients, shown in black circles in each panel of Figure 4, were obtained for each season as the CMF_{GHI} average in different F bins: $F = 0$; $0 < F \leq 0.2$; $0.2 < F \leq 0.4$; $0.4 < F \leq 0.6$; $0.6 < F < 0.8$; $0.8 < F < 1$ and $F \geq 1$. The differences between the obtained coefficients and those calculated by Román et al. (2014a) are higher for F values equal to zero, showing values between −8% and 44%; while for the rest of F bins the differences range from −6% to 11% (from −2% to 1% for F equal to 1). The irradiation reconstructed using the original and updated coefficients are thus similar since the largest coefficient differences are for low GHI conditions. We decided to use the coefficients obtained in this paper because we considered them more representative of the analysed station.

Once the model coefficients are tuned, they are used to retrieve the CMF_{GHI} value by F measurements in the following way: (1) for a given F measurement, the coefficients of Figure 4 for the same season than the given F measurement are chosen; and (2) CMF_{GHI} is calculated as a linear interpolation between the corresponding coefficients (each one is associated to an F value as Figure 4 shows) to the measured F value. When the F value is higher than 1, the CMF_{GHI} value is assumed equal to the coefficient obtained with $F \geq 1$data. This methodology provides a CMF_{GHI} value for each F measurement available. Once the CMF_{GHI} is retrieved, the GHI value for the F measurement is reconstructed using Equation (1), that is, multiplying CMF_{GHI} by the simulated GHI under cloud-free conditions. The uncertainty on GHI values is propagated from the standard deviation of the reconstruction coefficients (see error bars in Figure 4).

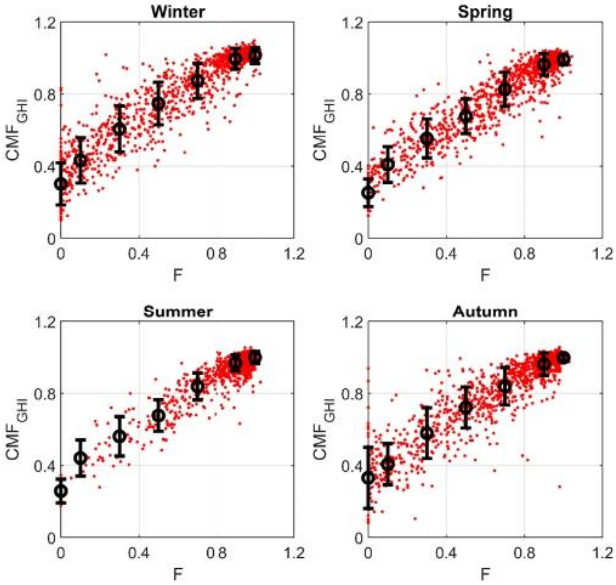

FIGURE 4 CMF_{GHI} at "AEMET" station as a function of F at "Aeropuerto" station for 2002–2013 period at the four different seasons. Circles represent the mean of CMF_{GHI} in different F intervals, and the error bars are the standard deviation [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | Long-term GHI and CC analysis method

The first step in the analysis of the long-term data is to seasonally adjust the GHI and CC records. Therefore, the monthly GHI records (M) are derived from averaging the daily ones. The evolution of this monthly dataset shows the distinct seasonal behaviour (not shown), which is related to the well-known dependence of incoming solar radiation on the annual solar elevation cycle. Furthermore, an annual climatological cycle (seasonal pattern) of the GHI data is derived by averaging all daily GHI records in a given month of the year (*S*). This annual cycle is extracted from the monthly GHI dataset, resulting in deseasonalised monthly values (absolute monthly anomalies, *A*), as shown in Equation (2),

$$A^{i,j} = M^{i,j} - S^{j}, \tag{2}$$

where the superscript i denotes the year and the superscript j the month (from 1 to 12). Equivalent deseasonalisation methods also work for cloud cover data.

Long term trends have been calculated following recommendations from Collaud Coen et al. (2020), using the Python package *mannkendall* developed in the same work over the deseasonalized monthly series of GHI and CC. The method combines three prewhitening methods (i.e., removing autocorrelation in the time-series), since the Mann–Kendall test and Sen's slope estimator assume uncorrelated time-series. The prewhitening is automatically applied when necessary by the algorithm, that is, when the first lag autocorrelation coefficient is statistically significant following a normal distribution at the two-sided test. We have used the temporal aggregation in the four seasons (DJF, MAM, JJA, SON). The test also calculated the global trend in those cases, but only if the seasonal trends are homogeneous. In the cases of inhomogeneity, we have also applied the Mann–Kendall test and Sen's slope without seasonal aggregation to obtain the trend and its statistical significance. The confidence levels are set to the defaults in the package (alpha_MK = 95%, alpha_XHomo = 90%, alpha_CL = 90%, alpha_ak = 95%). It must be noted that the uncertainty in the trends may be higher, since the absolute monthly anomalies have some errors propagated from the reconstruction method.

3.3 | GHI fraction for cloud-free conditions in summer

It is well-known that interannual variability of all-sky GHI is mainly controlled by changes in clouds, and consequently we tried to remove the cloud effect in the time series by selecting only the days with minimal or no cloud cover. Thus, in order to remove the cloud effect and detect a signal linked to other factors, mainly related to direct aerosol effects (Sanchez-Lorenzo et al., 2009; Wild et al., 2021), we have studied the GHI variations under cloud-free conditions. Specifically, we have worked with GHI fraction. The GHI fraction is defined as the daily GHI in Badajoz, divided by the theoretical GHI at the top of the atmosphere over this location. GHI fraction ranges from 0 (no solar radiation reaches the surface) to 1 (all solar radiation at the top of the atmosphere reaches then surface). Nevertheless, GHI fraction for cloudless conditions is notably below 1 due to gases absorption (mainly water vapour) and Rayleigh scattering. The typical annual values of this index for cloud-free conditions at the Iberian Peninsula are between 0.70 and 0.75 (e.g., Antón et al., 2017). Thus, during the period 1929–2015, those days with an average value of the cloud cover smaller than 1 tenth were selected only for summer (i.e., the season with the largest number of clear-sky days; Montero-Martín et al., 2021), obtaining the summer GHI fraction time series.

3.4 | Homogeneity of monthly GHI and CC records

We compute composite series on monthly basis using the two series in Badajoz ("Instituto" 1929–1984 and "Aeropuerto" 1955–2015) to construct a time series covering the whole study period (1929–2015). Due to the overlapping period of almost 30 years between both series (1955–1984), monthly means of this period are calculated for each of the stations and the differences obtained are used to correct the series of Badajoz Institute in order to make both series comparable. Figure 5 shows the evolution of the reconstructed GHI records (top) and CC observations (bottom) at "Instituto" and at "Aeropuerto" observatories for the common measurements period (1956–1984 for GHI records and 1961–1984 for CC records). It can be appreciated the excellent agreement in the pattern of both series at the two stations. The mean relative differences (±one standard deviation) between the two observatories (("Aeropuerto" − "Instituto")/"Instituto") are +1.1 ± 0.8% and +0.02 ± 0.02% for the reconstructed GHI data and CC observations, respectively, which indicate that "Aeropuerto" values slightly overestimate in average the "Instituto" data. The mean absolute relative differences have been also calculated between the two observatories for the common period providing values of 1.4 ± 0.9% for GHI and 7.6 ± 6.4% for CC records.

In addition, to assess the temporal homogeneity of the SD and CC series, we apply an absolute single change-point homogeneity test. Specifically, we use the Standard Normal Homogeneity test (SNHT) (Alexandersson & Moberg, 1997), which detects sudden shifts in the mean as potential evidence of inhomogeneities due to changes in the instrumentation, meteorological station surroundings, observation procedures, changes in observers, among others (Hakuba et al., 2013; Montero-Martín et al., 2021). Overall, according to the SNHT, both SD and CC series can be considered homogeneous at the 95% confidence level except the data after 2015 for SD records. In fact, we have limited our study to the year 2015 as afterwards there

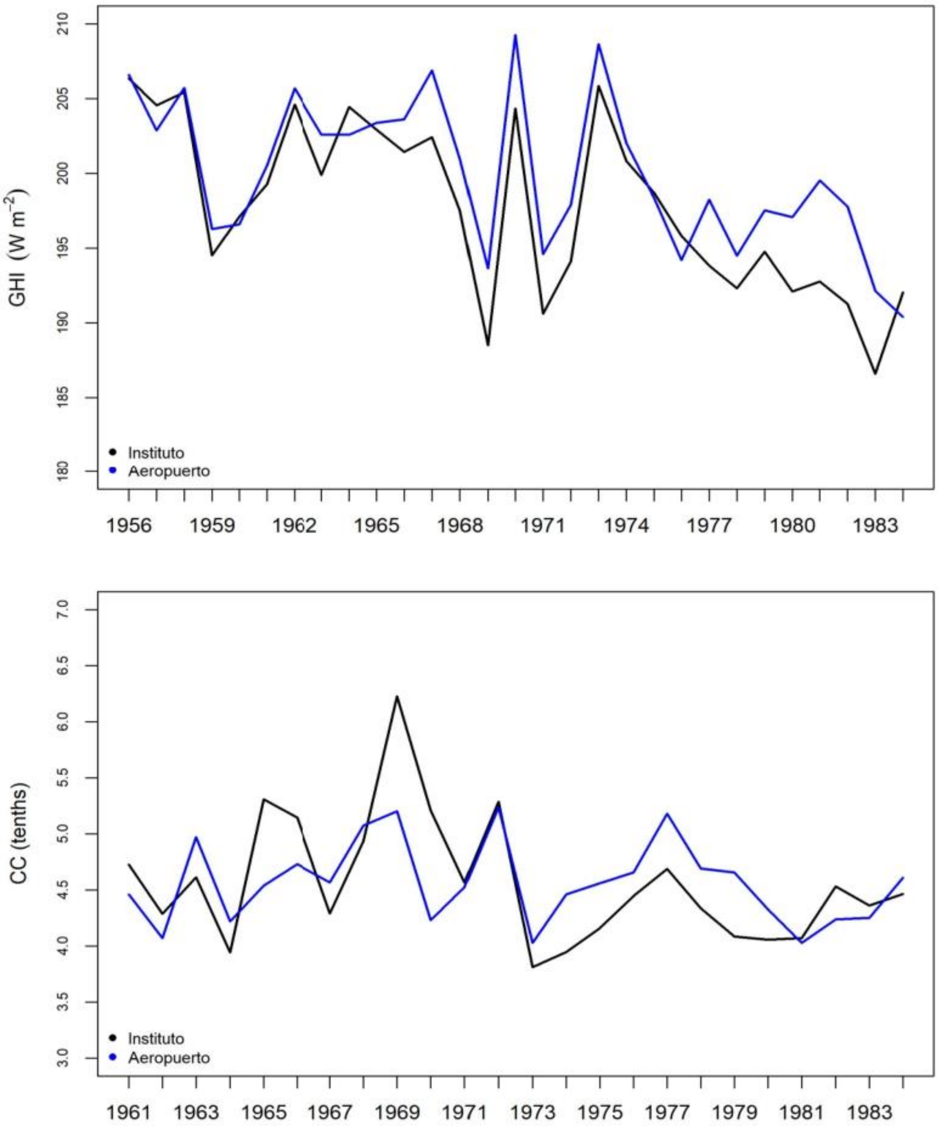

FIGURE 5 Evolution of the reconstructed GHI records (top) and CC observations (bottom) at "Instituto" and at "Aeropuerto" observatories for the common measurements period (1956–1984 for GHI records and 1961–1984 for CC records) [Colour figure can be viewed at wileyonlinelibrary.com]

is a replacement of the Campbell–Stokes recorder by an automatic SD recorder, which is well-known as source of inhomogeneities due to the differences between both types of instruments (Matuszko, 2015). In conclusion, the constructed time series of SD and CC in Badajoz over the 1929–2015 can be considered homogeneous and suitable for the reconstruction of GHI values and their trend analyses.

4 | RESULTS AND DISCUSSION

4.1 | Validation of the reconstruction model

The reconstruction method (section 3.1) was applied to the *F* values to estimate GHI in 2014 and 2015. These reconstructed GHI (GHI_{reco}) were compared against the measured GHI (GHI_{meas}) for the same period to check the reliability of the tunned reconstruction model. This comparison is shown in Figure 6, which shows the daily reconstructed values against the measured ones. The correlation between both data series is high, with a correlation coefficient of 0.99; this correlation coefficient is 0.94 when the reconstructed and measured CMF values are compared instead of GHI ones. About the mean bias error (MBE), which is the mean of the differences between GHI_{reco} and GHI_{meas}, the reconstructed data overestimate the measurements by about 3% in average. The standard deviation (SD) and root-mean-square error (RMSE) of GHI_{reco} and GHI_{meas} differences are both about 1.55 MJ·m^{-2}, pointing out a model precision about 17%. Ninety six percent of the differences between GHI_{reco} and GHI_{meas} are within 2σ; σ being the uncertainty on

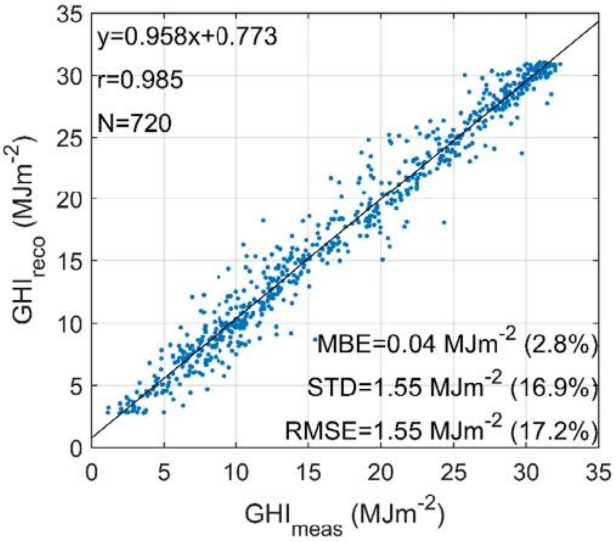

FIGURE 6 Reconstructed GHI as a function of measured GHI at Badajoz for the 2014–2015 period. MBE, correlation coefficient (*r*), standard deviation (SD) and root-mean-square error (RMSE) of the differences between reconstructed and measured GHI values, are included [Colour figure can be viewed at wileyonlinelibrary.com]

GHI_{reco} propagated by the uncertainty on the reconstruction coefficients (error bars in Figure 4). All these results agree with those obtained in Román et al. (2014a).

The results of Figure 6 are similar when the GHI_{reco} is obtained with the original coefficients calculated in Román et al. (2014a), which indicates the robustness of the model; however, in this paper the reconstructed GHI series were calculated using the model coefficients tunned in this work for Badajoz, since they are more representative of the station of interest.

4.2 | Analysis of the GHI trends

In this section, the GHI records were converted into irradiance units (i.e., W·m^{-2}) for a better comparison with previous findings over Spain and worldwide (Wild, 2016). Figure 7 highlights the evolution of the annual GHI anomalies derived from the average of the deseasonalised monthly data from 1929 to 2015 in Badajoz. The trend analysis of the annual GHI anomalies series (Table 1) shows a nonstatistically significant trend over the whole period (1929–2015). The highest levels of GHI anomalies are found in the late 1940s, observing a slightly positive and statistically significant trend of +4.18 W·m^{-2} (95% confidence interval [CI] 1.81–6.52) per decade for the period 1929–1950. This result could be indicative of an increase of incoming solar radiation in the first half of the 20th century at the southwest of Spain. A similar "early brightening" has been reported in other studies over the Iberian Peninsula (e.g., Antón et al., 2017; Aparicio et al., 2019; Sanchez-Romero et al., 2016) as well as in other regions (e.g., Kazadzis et al., 2018; Matuszko, 2014; Przybylak et al., 2021; Stanhill & Achiman, 2017; Stanhill & Cohen, 2008). On the other hand, there is no evidence of this "early brightening" in the US (Stanhill & Cohen, 2005), or mixed evidence in Ireland (Pallé & Butler, 2002).

Furthermore, the analysis of the GHI anomalies series in Badajoz shows a statistically significant decrease of −3.72 W·m^{-2} (95%CI: −5.14 to 2.29) per decade of incoming solar radiation throughout the third quarter of the 20th century which lasted until the 1980s ("dimming") reported in other locations (Sanchez-Lorenzo et al., 2007, 2015; Wild, 2009, 2016). Finally, a new statistically significant increase in GHI anomalies of +2.04 W·m^{-2} (95%CI: 0.55–3.62) per decade can be noted from 1985 to 2015 ("brightening") which is in line with other works (Manara et al., 2017; Montero-Martín et al., 2020; Román et al., 2014a; Sanchez-Lorenzo et al., 2007, 2009; Sanchez-Lorenzo et al., 2013a; Wild, 2009, 2016).

Figure 8 displays the seasonal evolution of the GHI anomalies time series in Badajoz. The four seasons present a similar behaviour to the annual series although spring and winter series show a higher interannual variability than autumn and, specially, summer series. This high interannual variability for spring and winter may likely explain higher uncertainties in the trends for these seasons reported in Table 1. It is worth noting that the spring series shows the highest (1945) and the lowest (1971) anomalies due to that high variability. All seasons have positive linear trends before 1950 although only summer and autumn have statistically significant values at the 95% confidence level (Table 1): +5.83 W·m^{-2} (95% CI: 2.35–9.42) per decade in summer and +5.87 W·m^{-2} (95%CI: 1.96–9.81) per decade in autumn. The dimming between 1951 and 1984 occurs at all seasons, but only the largest decrease of −4.95 W·m^{-2} (95%CI: −7.68 to −2.81) per decade in summer is significant at the 95% confidence level, as well as for the annual trend. Finally, the brightening from 1985 is observed similarly in all seasons but the only statistically significant series is summer as in the annual GHI time series.

Figure 9 shows the CC anomalies time series for 1929–2015 period in Badajoz, with no trend being detectable over the whole period but with a statistically significant negative trend of −0.21 tenths (95%CI: −0.47 to 0.02) per decade between 1985 and 2015 (Table 1). This last result may explain, at least partially, the statistically significant positive trend found in the same period for the GHI anomalies in Badajoz which agrees with other studies in the Iberian Peninsula (e.g., Mateos et al., 2014). In

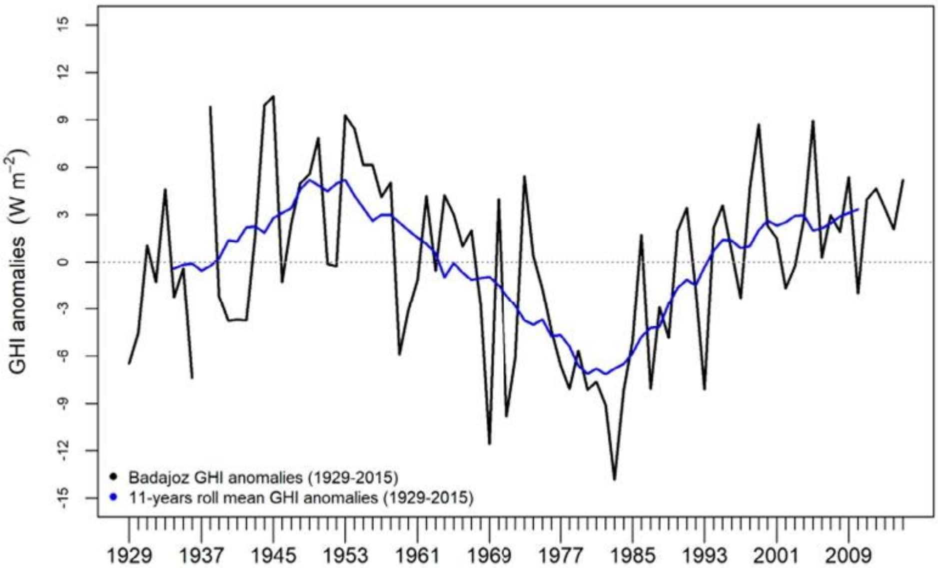

FIGURE 7 Averaged annual GHI anomalies series ($W{\cdot}m^{-2}$) in Badajoz during the 1929–2015 period (black line), plotted together with an 11-year running mean time series (blue line) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Annual and seasonal trends of GHI ($W{\cdot}m^{-2}{\cdot}decade^{-1}$) and CC (tenths per decade) in Badajoz for the whole period 1929–2015, and three subperiods: 1929–1950, 1951–1984, 1985–2015, provided by the *mannkendall* Python package (Collaud Coen et al., 2020)

		GHI ($W{\cdot}m^{-2}{\cdot}decade^{-1}$)		Cloud cover (tenths per decade)	
Period	**Season**	**Trend**	**Confidence interval**	**Trend**	**Confidence interval**
1929–2015	DJF	−0.39	(−1.01, 0.21)	0.03	(−0.03, 0.10)
	SON	−0.05	(−0.63, 0.47)	0.01	(−0.04, 0.06)
	JJA	−0.47	(−0.95, −0.01)	0.01	(−0.03, 0.04)
	MAM	0.89	(−0.08, 1.87)	−0.03	(−0.08, 0.03)
	Annual	−0.09	(−0.42, 0.24)	0.01	(−0.02, 0.03)
1985–2015	DJF	1.84	(−0.52, 4.36)	−0.26	(−0.57, 0.02)
	SON	0.75	(−1.95, 3.55)	−0.17	(−0.43, 0.05)
	JJA	2.77	(0.28, 5.40)	−0.18	(−0.34, −0.01)
	MAM	1.88	(−2.46, 6.37)	−0.24	(−0.51, 0.01)
	Annual	**2.04**	**(0.55, 3.62)**	***−0.21***	***(−0.47, 0.02)***
1951–1984	DJF	−2.54	(−5.31, 0.18)	−0.05	(−0.31, 0.23)
	SON	−2.14	(−4.46, 0.34)	**−0.26**	**(−0.48, −0.06)**
	JJA	**−4.95**	**(−7.68, −2.81)**	−0.07	(−0.24, 0.10)
	MAM	−5.12	(−9.33, −0.90)	−0.12	(−0.35, 0.11)
	Annual	**−3.72**	**(−5.14, −2.29)**	−0.12	(−0.23, −0.02)
1929–1950	DJF	2.60	(−2.67, 7.56)	0.16	(−0.40, 0.68)
	SON	**5.87**	**(1.96, 9.81)**	0.14	(−0.29, 0.55)
	JJA	**5.83**	**(2.35, 9.42)**	−0.01	(−0.23, 0.21)
	MAM	2.55	(−5.16, 9.95)	0.33	(−0.10, 0.81)
	Annual	**4.18**	**(1.81, 6.52)**	0.15	(−0.04, 0.34)

Note: Values significant at a level greater than 95% in bold. Values of annual trends significance in italic are calculated with seasonal Mann–Kendall; otherwise they are calculated with regular Mann–Kendall.

addition, it can be noticed that the maximum cloudiness peaks coincide with the minimum GHI dips (e.g., in late 1960s) and vice versa (1940s and 2010s). However, there is no statistically significant negative correlation between GHI duration and cloudiness in 1929–1950 and 1950–1985 periods. In fact, during 1929–1950 and 1951–1984

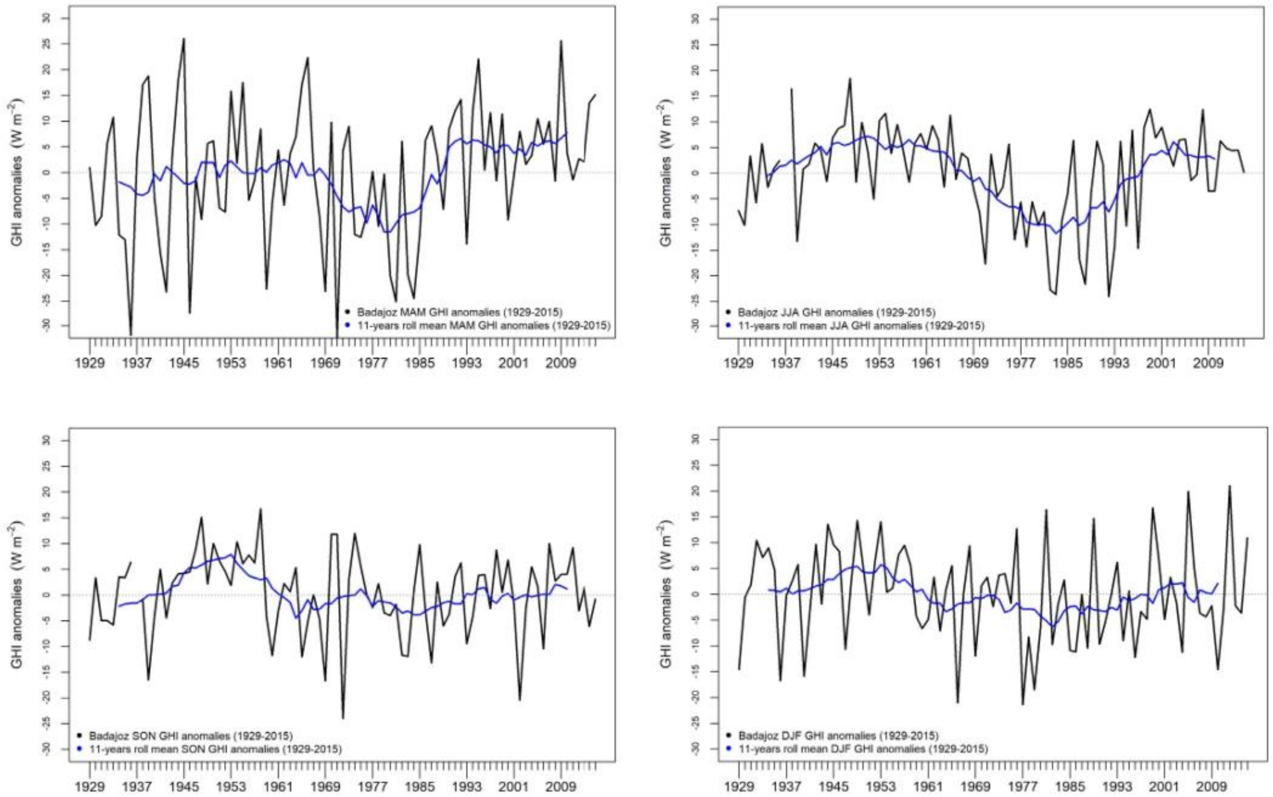

FIGURE 8 Averaged seasonal GHI anomalies series ($W{\cdot}m^{-2}$) in Badajoz during the 1929–2015 period, plotted together with 11-year running mean time series (blue line) [Colour figure can be viewed at wileyonlinelibrary.com]

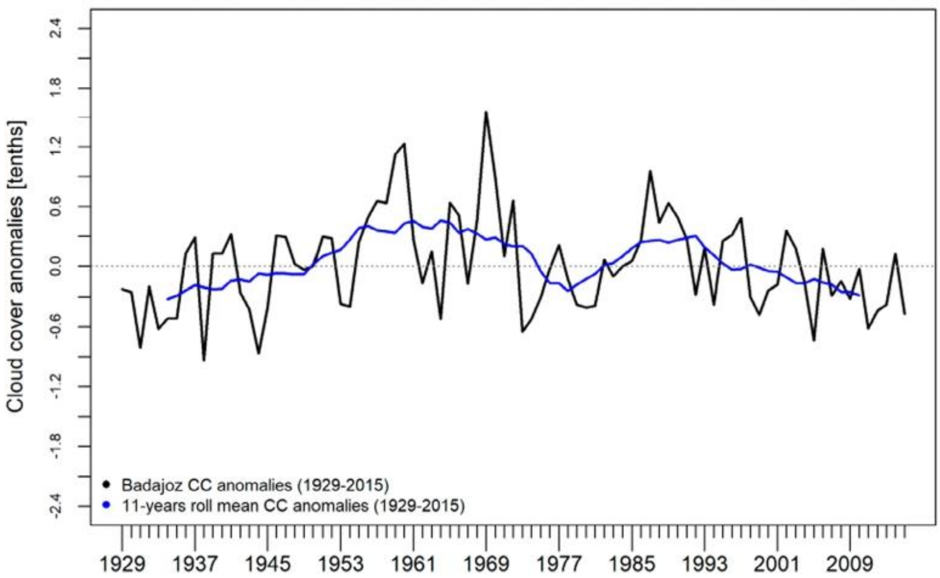

FIGURE 9 Averaged annual CC anomalies series (tenths) in Badajoz during the 1929–2015 period, plotted together with an 11-year running mean time series (blue line) [Colour figure can be viewed at wileyonlinelibrary.com]

both variables appear to develop similarly, which is contrary to what would be expected. Therefore, it would be possible to assume that the variation in GHI anomalies in Badajoz could be also modulated by decadal variations in other atmospheric variables like the atmospheric aerosol load.

Figure 10 presents the CC anomalies series in Badajoz during the 1929–2015 period in spring, summer, autumn and winter. Despite the fact that every season time series appearing to be similar to the annual CC anomalies series, autumn and winter series present a higher

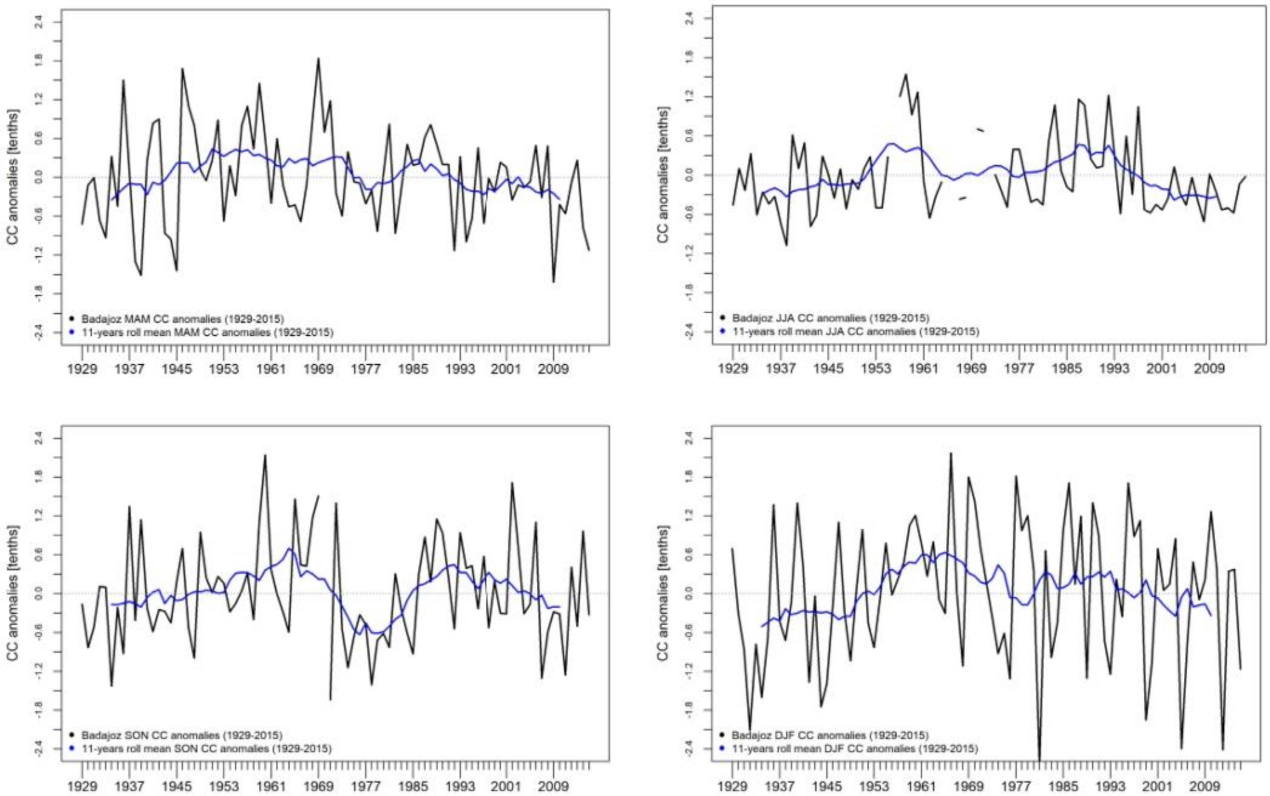

FIGURE 10 Averaged seasonal CC anomalies series (tenths) in Badajoz during the 1929–2015 period, plotted together with 11-year running mean time series (blue line) [Colour figure can be viewed at wileyonlinelibrary.com]

interannual variability than spring and summer series. Winter series shows the highest (1966) and the lowest (1981) anomalies due to that variability. These peaks are coincident with the lowest and highest peaks in winter GHI anomalies series. This negative correlation can be observed in the rest of seasons. Furthermore, focusing on the linear trends, during 1985–2015, all seasons (except winter) exhibit negative linear trends of around −0.2 tenths per decade but without a 95% significance (Table 1). However, this agrees with the brightening in seasonal GHI time series since 1985. No significance is found in linear trends either during 1929–1950 or 1951–1984 periods.

To test the hypothesis that the variation in GHI anomalies in Badajoz can be also linked to changes in aerosol load, GHI series under cloud-free conditions have been checked. Figure 11 shows the time series of averaged GHI fraction under cloud-free conditions (less than 1 tenth) in summer during 1929–2015. We explore the results for summer, as this season presents the minimum CC, and consequently maximum number cases of clear-sky conditions, in this part of Spain (Sanchez-Lorenzo et al., 2009; Sanchez-Romero et al., 2016).

Figure 11 displays a stable behaviour of GHI fraction around 0.73 with no significant trend along the whole period. However, we highlight a statistically significant decrease between 1950 and 1984 of −0.5%·decade^{-1}, followed by an increase of 0.3%·decade^{-1} during 1985–2015. These results are in line with the evolution of GHI for all sky conditions (Figure 7), so the variability of aerosol load possibly plays an important role in the long-term decadal evolution of solar radiation in Badajoz as in other regions of the Iberian Peninsula (Antón et al., 2017).

These results might be associated with the black carbon emissions in Europe since the 1950s (Lamarque et al., 2010; McConnell et al., 2007; Novakov et al., 2003). Equally, some authors have suggested that changes in mineral particles originating from northern Africa may also have a significant role in the dimming/brightening of Spain (Sanchez-Romero et al., 2016) and Italy (Manara et al., 2016). It is worth mentioning that the consequences of the volcanic aerosols emitted by the El Chichón (1982) and, especially Pinatubo (1991), are not clearly visible in the GHI records in Badajoz in disagreement with other relevant volcanic eruptions which produced a clear signal over solar radiation data or SD records in Spain (Antón et al., 2014; Obregón et al., 2020; Sanchez-Lorenzo et al., 2009). Further research is needed in this area including more stations from other regions of

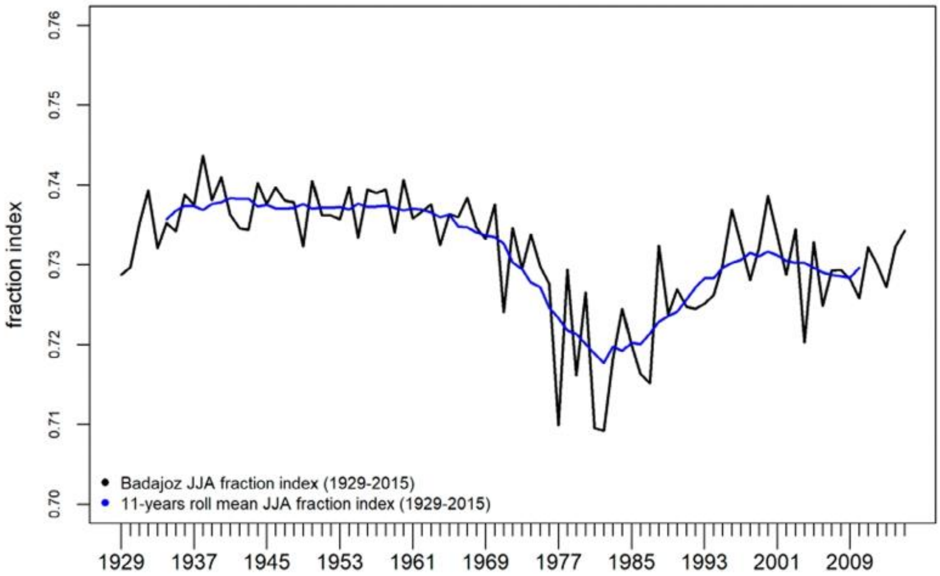

FIGURE 11 Average GHI fraction for cloud-free conditions in summer during the 1929–2015 period in Badajoz, plotted together with an 11-year running mean time series (blue line) [Colour figure can be viewed at wileyonlinelibrary.com]

Europe in order to smooth the noise and to extract only the physical signal. Overall, our results also emphasize the potential of GHI and cloud cover data to achieve information of the aerosol load in the atmosphere (Sanchez-Romero et al., 2014; Wandji Nyamsi et al., 2020). This is a vital issue due to the lack of reliable information about its variation before the satellite era.

5 | CONCLUSIONS

It is worthy to mention that in the framework of this study our research team has recovered and digitized 22 years of SD records in Badajoz (1929–1950), completing one of the earliest SD series at the Iberian Peninsula. Additionally, 27 years of CC observations have also been recovered (1929–1955). The recovery of these two series has allowed the reconstruction of GHI values for all-sky and cloud-free conditions since 1929 in Badajoz.

The reconstructed GHI series in Badajoz is homogeneous during the whole 1928–2015 period, and there is clear evidence of the three periods related to the solar radiation reaching the surface in the Iberian Peninsula: the early brightening during the second quarter of 20th century, the dimming from 1950s to midd-1980, and the brightening form midd-1980 to nowadays. Thus, it was found a positive trend (+4.2 $W \cdot m^{-2} \cdot decade^{-1}$) during 1929–1950, followed by a negative trend (−3.7 $W \cdot m^{-2} \cdot decade^{-1}$) until the mid-1980s, both trends statistically significant. The seasonal trend analysis for these two periods indicated that the summer is the main season responsible for explaining the behaviour of the annual trend, reporting a strong positive (negative) trend during 1929–1950 period (1951–1984 period). Finally, a statistically significant brightening (+2.0 $W \cdot m^{-2} \cdot decade^{-1}$) appears since 1985–2015.

The CC series has also been digitized for the common period and can be considered as homogeneous. It is observed an anticorrelation with GHI records but not shown statistically significant trends, although after 1985 the CC series exhibits a negative trend which could partially explain the GHI increase between 1985 and 2015. Nevertheless, the GHI evolution could be also affected by other factors such as atmospheric aerosols. The pattern of the GHI series under cloud-free conditions supports the hypothesis that the evolution of GHI records in Badajoz from the 1930s to 2015 might be related to decadal changes in atmospheric aerosol load.

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3.4. Artículo 4.

Título: Analysis of sunshine duration and cloud cover trends in Lisbon for the period 1890-2018.

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Aspectos destacables del artículo:

Este trabajo, en la línea de los anteriores, se centra en la digitalización de los registros diarios y mensuales de insolación en Lisboa (Portugal) durante el período de 1890 a 1940. Así, se pretende ampliar las series de datos disponibles de esta variable en la Península Ibérica, permitiendo así un análisis detallado de su variabilidad a lo largo de más de un siglo. La serie de datos resultante, que abarca desde 1890 hasta 2018, se posiciona como la más antigua en Portugal y la segunda en la Península Ibérica, proporcionando una visión única de la evolución de la insolación en la región. Además de la digitalización de los registros de insolación, también se digitalizan los datos de cobertura nubosa registrados en la estación.

La serie de insolación en Lisboa muestra una tendencia negativa estadísticamente significativa desde finales del siglo XIX hasta principios del siglo XX, lo cual es coherente con un período de disminución (*early dimming*) en la radiación solar en la superficie informado en otras partes del mundo. Sin embargo, durante el período de 1910 a 1950, no se observan tendencias discernibles en la insolación. Esta aparente estabilidad puede deberse a una serie de factores, como cambios en la cobertura de nubes, variaciones estacionales y otros fenómenos atmosféricos que puedan interactuar y compensarse entre sí. Las décadas posteriores, desde los años 1950 hasta los 1980 y luego de los 1980 hasta los 2010, presentan dos tendencias significativas y en direcciones opuestas. Los fenómenos de *dimming* y *brightening* se reflejan en estas tendencias, lo que indica cambios significativos en la radiación solar que alcanza la superficie. Esta variabilidad puede atribuirse a fenómenos climáticos globales o a modificaciones en la composición atmosférica, como la presencia de aerosoles y gases de efecto invernadero.

Los datos de cobertura de nubes añaden una información muy valiosa a las tendencias de insolación observadas. Así, la serie anual de dicha variable presenta un aumento desde 1890 hasta la década de 1980, seguido de una disminución hasta 2018. Este patrón sugiere cambios en la evolución nubosa en la región y su posible relación con la radiación solar que alcanza la superficie.

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

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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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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 Português 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

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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	°/o
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

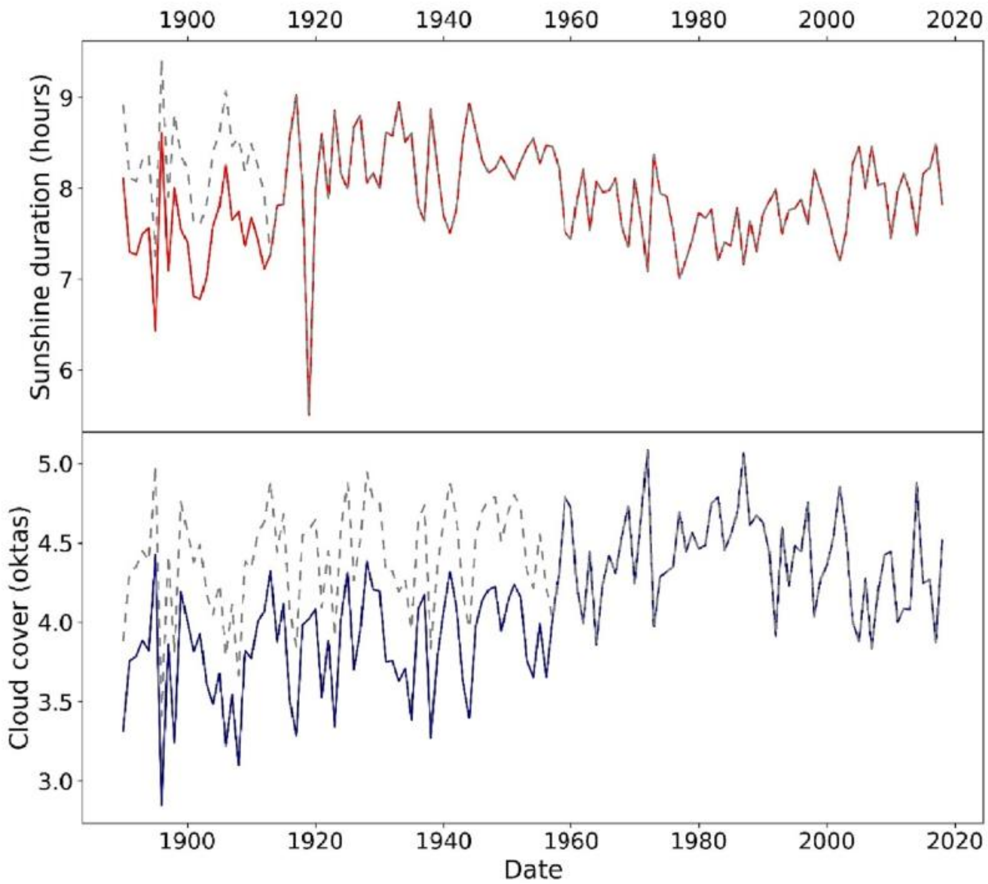

Fig. 2. Time evolution of annual series of sunshine duration (SD, top panel) and cloud cover (CC, bottom panel) in Lisbon for the period 1890–2018 before (continuous lines) and after (dashed lines) correcting for inhomogeneities.

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 $\pm$ 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

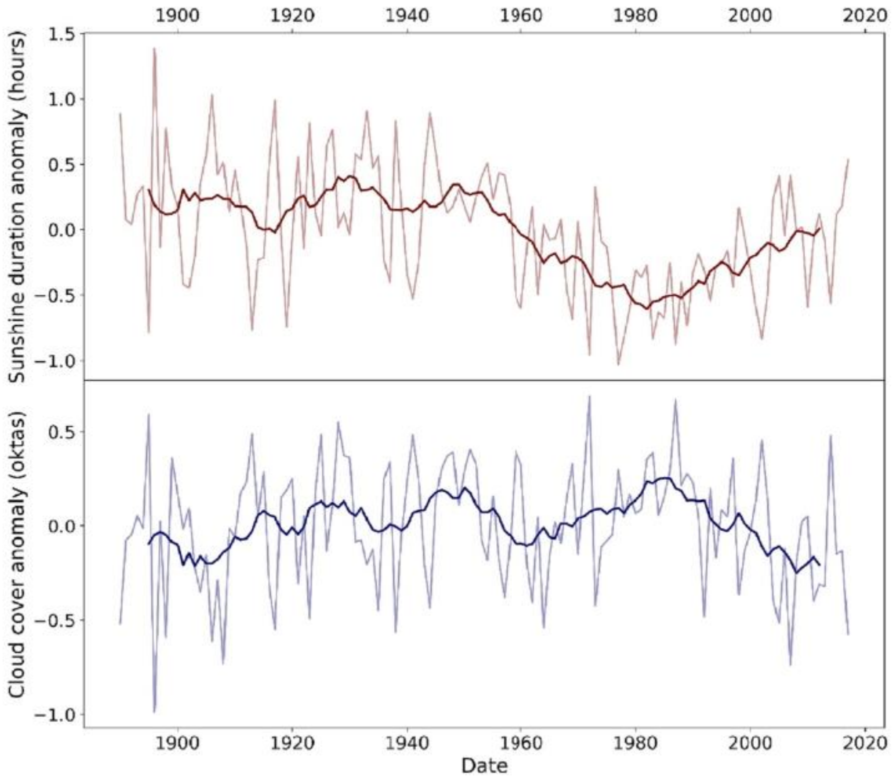

Fig. 3. Time evolution of homogenized and deseasonalized annual anomalies of SD (red thin line, top panel) and CC (blue thin line, bottom panel) in Lisbon for the period 1890–2017. Thick lines represent 11-year running averages. (For interpretation of the references to colour in this figure legend, the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

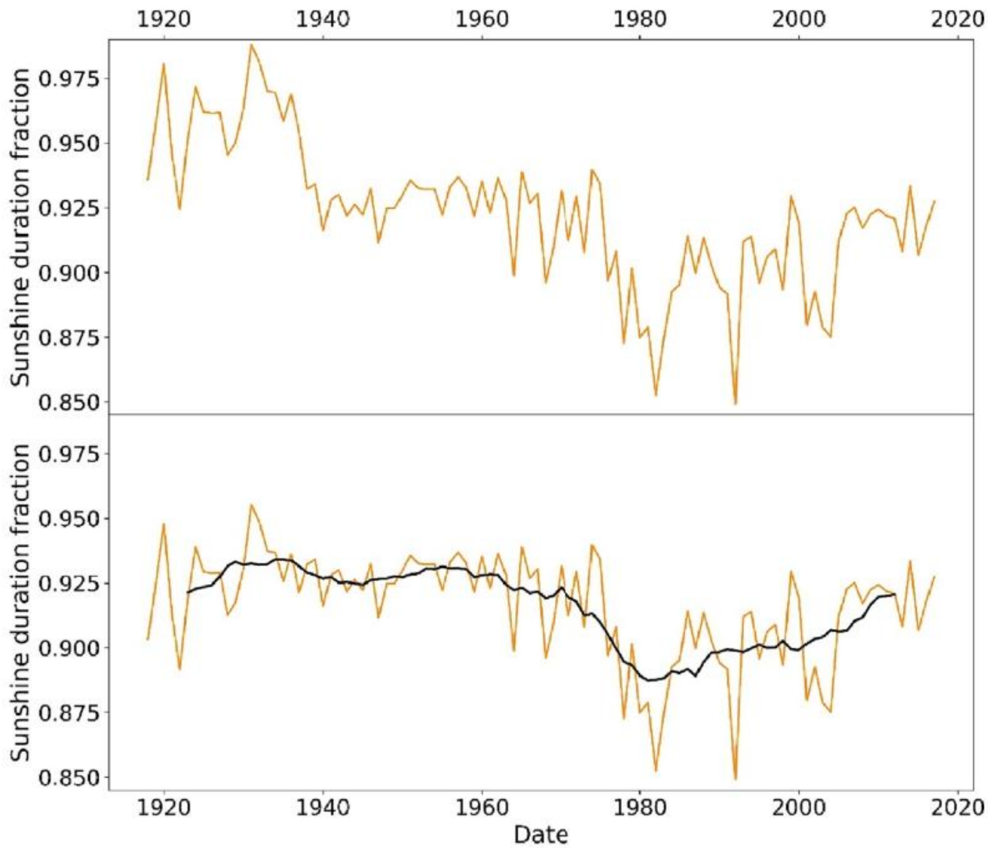

Fig. 4. Time series of raw (top panel) and homogenized (bottom panel) cloudless SD fraction in Lisbon for the period 1918–2017. The thick black line represents 11-year running averages.

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

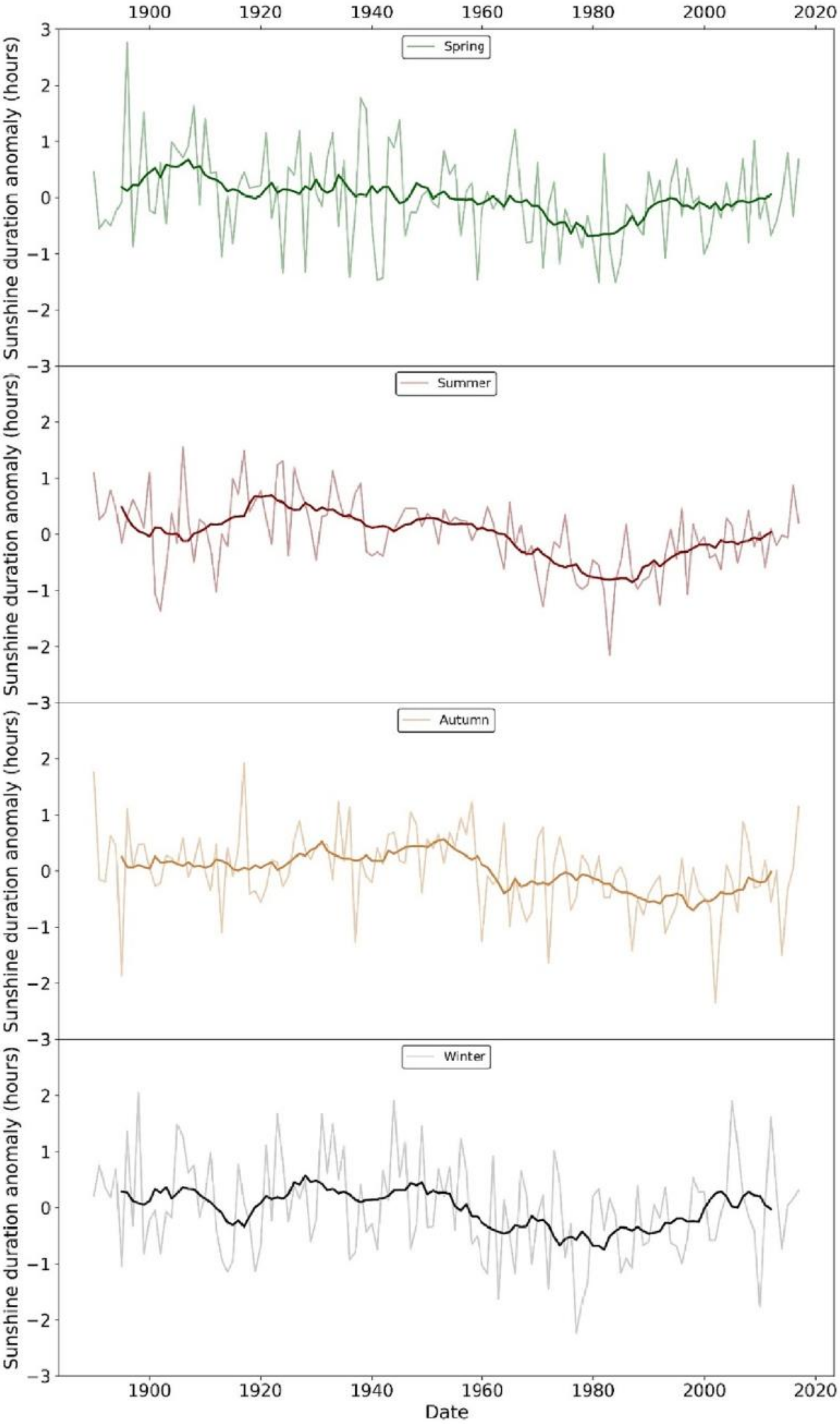

Fig. 5. Time evolution of seasonal anomalies of SD (thin lines) in Lisbon for the period 1890–2017. Thick lines represent 11-year running averages.

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

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Appendix A. Supplementary data

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

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4. Discusión

Esta sección analiza de forma conjunta los resultados generales obtenidos en los cuatro artículos publicados que componen esta tesis. La Tabla 1 muestra las tendencias de radiación solar e insolación en los observatorios de Coímbra (Artículo 2), Badajoz (Artículo 3) y Lisboa (Artículo 4) en cada uno de los periodos comunes desde finales del siglo XIX hasta principios del siglo XXI, así como las tendencias de nubosidad en dichos periodos. Además, la Tabla 1 también recoge el promedio de las tendencias obtenidas a partir de datos de piranómetros y de las observaciones de satélite (SARAH-2 and CLARA-A2) en 12 localizaciones de la Península Ibérica (Artículo 1).

Respecto a la insolación y radiación solar, se distinguen claramente los cuatro periodos conocidos. En primer lugar, destaca un periodo de *early dimming* entre 1890s y 1910s, con tendencias negativas en Lisboa (no significativa) y Coímbra (significativa), coincidiendo con otros estudios en la Península Ibérica (Antón et al., 2017; Aparicio et al., 2019; Bravo-Paredes et al., 2019). Posteriormente, entre 1910s y mitad del siglo XX, se aprecia un aumento significativo de la radiación solar en Badajoz, lo cual podemos asociar al *early brightening* también observado en otros estudios (Ohmura, 2007, Ohmura, 2009, Sanchez-Romero et al., 2014, Stanhill et al., 2014, Stanhill et al., 2018). Por el contrario, en las dos localidades portuguesas analizadas no se observa ese aumento, aunque la tendencia negativa del periodo anterior desaparece. A partir de 1950s y hasta 1980s, al igual que se observa en otras regiones (Román et al., 2014, Sanchez-Lorenzo et al., 2013, Wild 2016), se registra de nuevo un descenso significativo de la radiación solar e insolación (*dimming*) tanto en Lisboa como en Badajoz. Finalmente, desde la década de 1980 hasta la actualidad se observa claramente el fenómeno de *brightening*, con tendencias positivas significativas en Lisboa y

Badajoz. Este aumento de la radiación solar coincide con lo analizado en otras zonas de Europa y a nivel global (Pallé y Butler, 2002, Sanchez-Lorenzo y Wild, 2012). Además, dicho *brightening* queda también patente al analizar los datos de piranómetros y observaciones satelitales en 12 estaciones de la Península Ibérica, mostrado tendencias positivas estadísticamente significativas. No obstante, se observa que las tendencias promedio determinadas con las dos series de observaciones satelitales son notablemente inferiores a la tendencia calculada con los piranómetros. Esta discrepancia, que aparece fundamentalmente cuando se analizan los datos registrados en verano, puede atribuirse al uso de promedios climatológicos de aerosol atmosféricos en los modelos de estimación de los satélites. Así, estos modelos no recogerían la notable disminución de la carga de aerosol en la Península Ibérica desde finales del siglo XX, la cual produce el fuerte incremento de los valores de radiación solar en superficie registrados por los piranómetros.

Tabla 1. Tendencias de radiación solar (W/m^2 por década), insolación (horas por década) y nubosidad (décimas/octas por década) desde finales del siglo XIX hasta principios del siglo XXI en Lisboa, Coímbra, Badajoz y Península Ibérica (promedio de 12 estaciones). Las tendencias vienen dadas con sus respectivas incertidumbres (intervalo de confianza en Badajoz, ± desviación estándar en Lisboa, ± 2·desviación estándar en Coímbra y Península Ibérica). Las tendencias significativas al 95% aparecen marcadas en negrita.

Observatorio	Variable Climática	*Early dimming*	*Early brightening*	*Dimming*	*Brightening*
Lisboa (1890-2018)		1890-1915	1915-1953	1953-1982	1982-2017
	Insolación (h/déc)	-0.17 ± 0.09	-0.02 ± 0.05	**-0.28 ± 0.07**	**+0.20 ± 0.05**
	Nubosidad (octas/déc)	+0.10 ± 0.08	+0.07 ± 0.04	+0.09 ± 0.06	**-0.16 ± 0.05**
Coímbra (1891-1950)		1891-1913	1913-1950	-------------	-------------
	Insolación (h/déc)	**-0.51 ± 0.32**	-0.08 ± 0.13	-------------	-------------

	Nubosidad (déci-mas/déc)	+0.01 ± 0.27	**+0.25 ± 0.12**	-------------	-------------
Badajoz (1929-2015)		-------------	1929-1950	1951-1984	1985-2015
	Radiación solar (W/m^2·déc)	-------------	**+4.18 (1.81,6.52)**	**-3.72 (-5.14,-2.29)**	**+2.04 (0.55,3.62)**
	Nubosidad (déci-mas/déc)	-------------	+0.15 (-0.04, 0.34)	-0.12 (-0.23,-0.02)	**-0.21 (-0.47, 0.02)**
Península Ibérica (Piranómetros)		-------------	-----------	-------------	1985-2015
	Radiación solar (W/m^2·déc)	-------------	-------------	-------------	**+4.4 ±1.3**
Península Ibérica (SARAH-2)		-------------	-----------	-------------	1985-2015
	Radiación solar (W/m^2·déc)	-------------	-------------	-------------	**+1.5 ±1.1**
Península Ibérica (CLARA-A2)		-------------	-----------	-------------	1985-2015
	Radiación solar (W/m^2·déc)	-------------	-------------	-------------	**+1.9 ±1.2**

Respecto a la cobertura nubosa a lo largo de cada uno de los periodos, se puede apreciar en la Tabla 1 la evolución de la misma en las tres localidades de estudio. Durante el *early dimming*, no existe tendencia en la nubosidad en Coímbra, mientras que en Lisboa se aprecia una tendencia positiva, aunque no significativa. Posteriormente, hay un aumento de la nubosidad en los tres observatorios (únicamente significativa en Coímbra), lo cual puede explicar que el fenómeno *early brightening* no se observe en Lisboa y Coímbra. De la misma forma, no se registran tendencias significativas a lo largo del periodo de *dimming*. Finalmente, para el último periodo (*brightening*) se obtiene un descenso significativo de la nubosidad, que explicaría parcialmente el notable aumento de la radiación solar en Lisboa y Badajoz.

Los resultados mostrados en la Tabla 1 pone de manifiesto que no existe una correlación directa generalizada en las estaciones de estudio entre los descensos de nubosidad y los aumentos de la radiación solar en superficie, y viceversa. Por tanto, se intuye que otros factores, como los aerosoles atmosféricos, deben tener una fuerte influencia en la variabilidad de la radiación solar registrada en superficie. En este contexto, para cada emplazamiento de estudio se determinaron las tendencias en verano de la insolación y radiación solar en casos de días despejados, mostrando efectivamente este efecto, en línea con los resultados reportados por otros trabajos (Antón et al., 2017, Antón et al., 2014, Obregón et al., 2020, Sanchez-Romero et al., 2016).

5. Conclusiones

Las principales conclusiones que se pueden extraer de esta tesis doctoral son:

- La recuperación de datos meteorólogos de fuentes documentales antiguas es una labor necesaria para completar las series de medidas que proporcionan los servicios meteorológicos. Así, en esta tesis se han digitalizado datos de insolación y nubosidad desde finales del siglo XIX en Coímbra y Lisboa, y desde el primer cuarto del siglo XX en Badajoz, generando algunas de las series más largas de estas variables en España y Portugal.
- El análisis de las series mencionadas ha permitido evaluar los fenómenos de *early dimming* (1890-1920), *ealry brightenig* (1920-1950), *global dimming* (1950-1980) y *brightening* (1980-2020) en cada uno de los tres emplazamientos.
- El análisis de las tendencias de las medidas de insolación (Coímbra y Lisboa) y de la radiación solar reconstruida (Badajoz) para casos despejados de nubes permite evaluar el impacto de la variabilidad de los aerosoles atmosféricos en dichas tendencias.
- Las tendencias de la radiación solar en superficie determinadas a partir observaciones satélites en la Península Ibérica muestran una evidente subestimación de las tendencias obtenidas mediante datos de piranómetros, principalmente en verano. Estas discrepancias pueden estar relacionadas con el fuerte descenso en la carga de aerosol sobre la Península Ibérica desde finales del siglo XX, el cual no se recoge en los modelos de estimación de los satélites.

Conclusions

The main conclusions that can be drawn from this doctoral thesis are:

- The recovery of meteorological data from ancient documentary sources is a necessary task to complete the measurement series provided by meteorological services. In this thesis, insolation and cloudiness data have been digitized from the late 19th century in Coimbra and Lisbon and from the first quarter of the 20th century in Badajoz, generating some of the longest series for these variables in Spain and Portugal.
- The analysis of the mentioned series has allowed the evaluation of the phenomena of early dimming (1890-1920), early brightening (1920-1950), global dimming (1950-1980), and brightening (1980-2020) at each of the three locations.
- The analysis of trends in insolation measurements (Coimbra and Lisbon) and reconstructed solar radiation (Badajoz) for clear-sky conditions allows evaluating the impact of aerosol variability on these trends.
- Trends in surface solar radiation determined from satellite observations in the Iberian Peninsula show a clear underestimation compared to trends obtained from pyranometer data, especially in summer. These discrepancies may be related to the significant decrease in aerosol load over the Iberian Peninsula since the late 20th century, which is not captured in satellite estimation models.

6. Referencias

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