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Key Points:

- The Potsdam solar radiation record, one of the world's longest and best maintained measurement series, is a key witness of the dimming and brightening phenomenon
- For the first time, we investigate dimming and brightening tendencies in this prominent record not only under "all-sky" but also under "clear-sky" conditions
- Dimming and brightening is evident also under cloud-free conditions, pointing to a human influence through aerosol pollutants as major cause of these variations

Supporting Information:

- Supporting Information S1

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Evidence for Clear-Sky Dimming and Brightening in Central Europe

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Abstract For the explanation of the observed decadal variations in surface solar radiation (known as dimming and brightening), the relative importance of clouds and the cloud-free atmosphere (particularly aerosols) is currently disputed. Here, we investigate this issue using daily data from the prominent long-term observational radiation record at Potsdam, Germany, over the 71-year period 1947–2017. We identify cloud-free days based on synop cloud observations as well as on days with maximum atmospheric transmission. Irrespective of the cloud-screening method, strong dimming and brightening tendencies in the atmospheric transmission are evident not only under all-sky but also of similar magnitude under clear-sky conditions, causing multidecadal variations in surface solar radiation on the order of 10 Wm^{-2}. This points to the cloud-free atmosphere as a main responsible for dimming and brightening in central Europe and suggests that these variations are anthropogenically forced rather than of natural origin, with aerosol pollutants as likely major drivers.

Plain Language Summary The amount of sunlight received at the Earth's surface undergoes substantial variations on decadal timescales, known as "dimming and brightening." These variations have fundamental implications for a variety of key environmental issues as well as for solar power generation, agriculture, and human health. However, the causes of these variations are still insufficiently established and currently disputed. Particularly debated is whether these variations are man-made through air pollution (and associated blocking of sunlight by aerosols), or rather a result of natural variations in the climate system (through the modulation of sunlight by clouds). Here, we investigate this issue based on one of the longest and best maintained records of sunlight measured at Potsdam, Germany. We filter out the effects of clouds on solar radiation in this prominent record, to be able to study the variations in sunlight both under cloudy and cloud-free conditions. Our analysis shows that strong decadal variations (dimming and brightening) not only appear when clouds are considered but also remain evident under cloud-free conditions when cloud effects are eliminated. This implies that aerosol pollutants play a crucial role in these variations and points to a discernible human influence on the vital level of sunlight required for sustainable living conditions.

1. Introduction

Numerous studies analyzing observational records of surface solar radiation (SSR) measured at widespread observation sites indicate that the level of SSR is not just stable over time, but rather undergoes substantial multidecadal variations (e.g., Wang et al., 2012; Wild, 2009, 2016, and references therein). In the late 1980s and 1990s, first evidence for a gradual decline in SSR has been found at many observation sites since the 1950s (Ohmura & Lang, 1989; Stanhill & Moreshet, 1992), a phenomenon that has been later on become popularly known under the term "global dimming" (Stanhill & Cohen, 2001). In the early 2000s, it has been recognized that this decline in SSR did no longer persist but recovered at many of the observation sites during the 1980s, which has been coined "brightening" (Wild et al., 2005). SSR trends since the mid-1980s have also been noted in satellite-derived products (e.g., Hatzianastassiou et al., 2005; Pfeifroth et al., 2018; Pinker et al., 2005; Posselt et al., 2014; Sanchez-Lorenzo et al., 2017).

Since the availability of sunlight is vital for any ecosystem and the existence of life in general, decadal variations in SSR have important implications for a variety of key environmental processes as well as for numerous practical applications, such as solar power generation, agricultural production, and human health.

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Despite this, the causes of these variations are still not well established and currently debated. It is evident that the changes cannot stem from changes in the intensity of the sun itself, as variations in the solar radiation incident at the Top of Atmosphere (TOA) (Willson & Mordvinov, 2003) are more than an order of magnitude smaller than the variations in SSR and are not correlated (Aparicio et al., 2020). The SSR variations therefore have to be due to changes within the climate system, namely in the transparency of the atmosphere for solar radiation. It has been argued that variations in aerosol loadings due to varying air pollution may have caused these variations, since the transition from dimming to brightening temporally coincided with changes in air pollution levels and associated changes in aerosol emission and optical depth (Kudo et al., 2012; Nyamsi et al., 2020; Ruckstuhl & Norris, 2009; Streets et al., 2006; Turnock et al., 2015; Wang et al., 2012; Wild et al., 2005). Similarly to the SSR, these emissions also show a distinct trend reversal during the 1980s particularly in industrialized countries, associated with the implementation of air pollution regulations and the breakdown of the former Soviet Union (e.g., Stern, 2006; Streets et al., 2006; Wild, 2009). Other studies also pointed to changes in cloud characteristics as important contributors to dimming and/or brightening (e.g., Augustine & Dutton, 2013; Kumari & Goswami, 2010; Liepert, 1997; Liley, 2009; Mateos et al., 2014; Pfeifroth et al., 2018).

A separation of the observed SSR changes measured under cloudy and cloud-free conditions can give an indication on the relative importance of clouds and the (direct) aerosol effects in the context of dimming and brightening. Only a few studies investigated this in long-term radiation records from specific regions, for example, from Italy (Manara et al., 2016), China (Yang et al., 2019), India (Kumari & Goswami, 2010), Japan (Kudo et al., 2012; Tanaka et al., 2016) as well as from a site in Cuba (Antuna-Marrero et al., 2019) and Greece (Kazadzis et al., 2018). Furthermore, a few studies have looked into clear-sky trends in related sunshine duration data (Founda et al., 2014; Sanchez-Lorenzo et al., 2009).

Here, we investigate this further with a focus on central Europe, based on the prominent data record of one of the longest and best maintained operational radiation monitoring stations at Potsdam, Germany. This iconic SSR time-series has been widely used in the literature as illustration for the dimming and brightening phenomenon (e.g., Behrens, 2013; Ohmura, 2009; Ohmura & Lang, 1989; Stanhill & Ahiman, 2014; Wild, 2016). Despite the prominent stature of this radiation record, an assessment of the contribution of clouds and the cloud-free atmosphere to its remarkable variations has to date been lacking and will be pursued in the following.

2. Data and Methods

Measurements of SSR and diffuse solar radiation started in Potsdam in 1937 (Behrens, 2013), thus covering by now more than 80 years. Monthly mean SSR data from Potsdam are available from the Global Energy Balance Archive (GEBA) located at the first author's institute (Wild et al., 2017). Daily data since 1947 are available directly from the German Weather Service (DWD). Since we require for our clear-sky assessment daily SSR data, our study period extends over 71 years from 1947 to 2017, the final year with complete observations available at the time this analysis has been performed.

From 1937 up to 1967, Moll-Gorczynski-pyranometers were used to measure SSR and diffuse radiation (Behrens, 2013). In 1968, these instruments were replaced by Sonntag-pyranometers, and by Kipp & Zonen CM 11 pyranometers in 1997. While the uncertainty of the Moll-Gorczynski-pyranometer is not well established, the uncertainty of the Sonntag-pyranometer is close to the uncertainty of a secondary standard pyranometer such as the CM11 from Kipp & Zonen operational since 1997 at Potsdam. For the latter, an uncertainty of 2% for daily totals has been reported. In addition to the instrumental uncertainty, the stability and thus the calibration of the radiometers is essential. Calibrations were conducted monthly from 1947 until 2003 (then every second year) using well-calibrated reference sensors participating in numerous international pyrheliometer comparisons and hence traceable to the various pyrheliometer scales. Thus, the traceability of the observations to the used pyrheliometer scales is also an important issue for such long-term series. The traceability of the whole Potsdam series to the World Radiometric Reference was realized during the homogenization of the series described in detail in Behrens (2013). Radiation data collected in the ground network of DWD undergo a general quality control as described in Becker and Behrens (2012).

The Potsdam radiation observatory is located in a semirural area with quite intensive agriculture, but also large areas covered by forests and lakes and a fairly low population density. The location can be considered as typical for central Europe (Northern France, Germany). We also made an effort to objectively quantify the representativeness of the Potsdam SSR record for its larger scale surroundings. Thereby, we used the satellite-derived SSR data set SARAH from Satellite Application Facility on Climate Monitoring (CM-SAF), which is available on a 0.05° grid from 1983 to 2017 (Pfeifroth et al., 2019). We correlated the CM-SAF SSR annual mean time-series of the gridbox at the Potsdam location with the corresponding time-series from all other gridboxes in Europe (Figure S1). Figure S1 shows that SSR time-series over a large domain in central Europe highly correlate with the time-series at the Potsdam location. This indicates that the Potsdam SSR record can be considered representative for a substantial area in central Europe.

We applied two different ways to identify and compose cloud-free records from the daily Potsdam radiation data. An obvious approach is to use synop cloud information to identify cloud-free days. This approach has been used for the determination of clear-sky solar radiation trends in several studies, for example, by Yang et al. (2019) and Manara et al. (2016). The synop cloud observations have been carried out in Potsdam with a 3-hourly frequency (hourly since August 29, 1977). The synop cloud information is, however, only available in form of daily means for the whole investigation period, as provided by DWD. The common units of cloud fraction in the synoptic records are octas. An issue is then to define a threshold for cloud fraction which can be considered as approximately clear sky. A rigorous use of zero cloud fraction as threshold for cloud-free conditions often reduces the size of the remaining data set overly much for analyses of cloud-free situations, so that as a compromise in the literature higher thresholds are usually applied (Manara et al., 2016; Yang et al., 2019). These studies also indicated that the relaxation of the threshold (up to 1 or 2 octas) has no significant influence on the derived radiation trends. In the present study, we request the cloud fraction to be no more than 1 octa to consider a day as cloud free. Our own sensitivity studies confirm the previous findings that the results are not overly sensitive to the exact definition of the threshold.

Rather than inferring trends from the absolute magnitudes of the SSR of cloud-free days, we normalized the daily mean SSR measured at Potsdam with the collocated daily mean TOA insolation, to obtain daily mean solar atmospheric transmissions, that is, the ratio between surface and collocated TOA insolation, also known as clear-sky index (Yang et al., 2019). This avoids the risk of spurious trends in the clear-sky time-series, in case the occurrence of cloud-free days is systematically shifted within the course of the year and thus the associated TOA insolation may systematically change over the study period. Further, we constructed cloud-free transmission time-series first for each season of the year by averaging for each year all transmission values of days that pass the clear-sky threshold in the respective season. Annual clear-sky transmission series were then obtained by averaging over the four seasonal clear-sky transmission series. Thereby, we ensured that specific seasons could not be overrepresented or underrepresented in the annual records due to a higher or lower number of cloud-free days, respectively. We applied this seasonal separation also successfully in an earlier study (Yang et al., 2019).

Alternatively, clear-sky conditions may be inferred directly from the radiative fluxes themselves, to avoid the use of the somewhat subjectively determined cloud synop observations by human observers. To do so, we determined for each season of each year the day with maximum transmission, as the best approximation of a cloud-free day of the respective year and season. This implies that there must be at least one cloud-free day within each season of a year, which seems a reasonable assumption. This allowed then to construct for each season a time-series with the seasonal maximum transmission days (thus for each of the four seasons a record with 71 entries consisting of the seasonal maximum transmission days over the 71 years of data 1947–2017). Annual series of daily maximum transmission were then obtained again by averaging over the four seasonal maximum transmission series, thereby ensuring that all seasons are represented in the annual series.

3. Results

As a starting point in Figure 1 (upper panel), we display the annual mean SSR as measured at Potsdam during our study period from 1947 to 2017. The record shows remarkable decadal variations, with a decline in SSR until the 1980s, and a recovery thereafter, illustrating the dimming and brightening phenomenon. These long-term variations are on the order of 10% of the absolute magnitude of the SSR measured at Potsdam (118 Wm^{-2} long-term annual mean 1947–2017). Figure 1 (middle panel) displays the horizontal

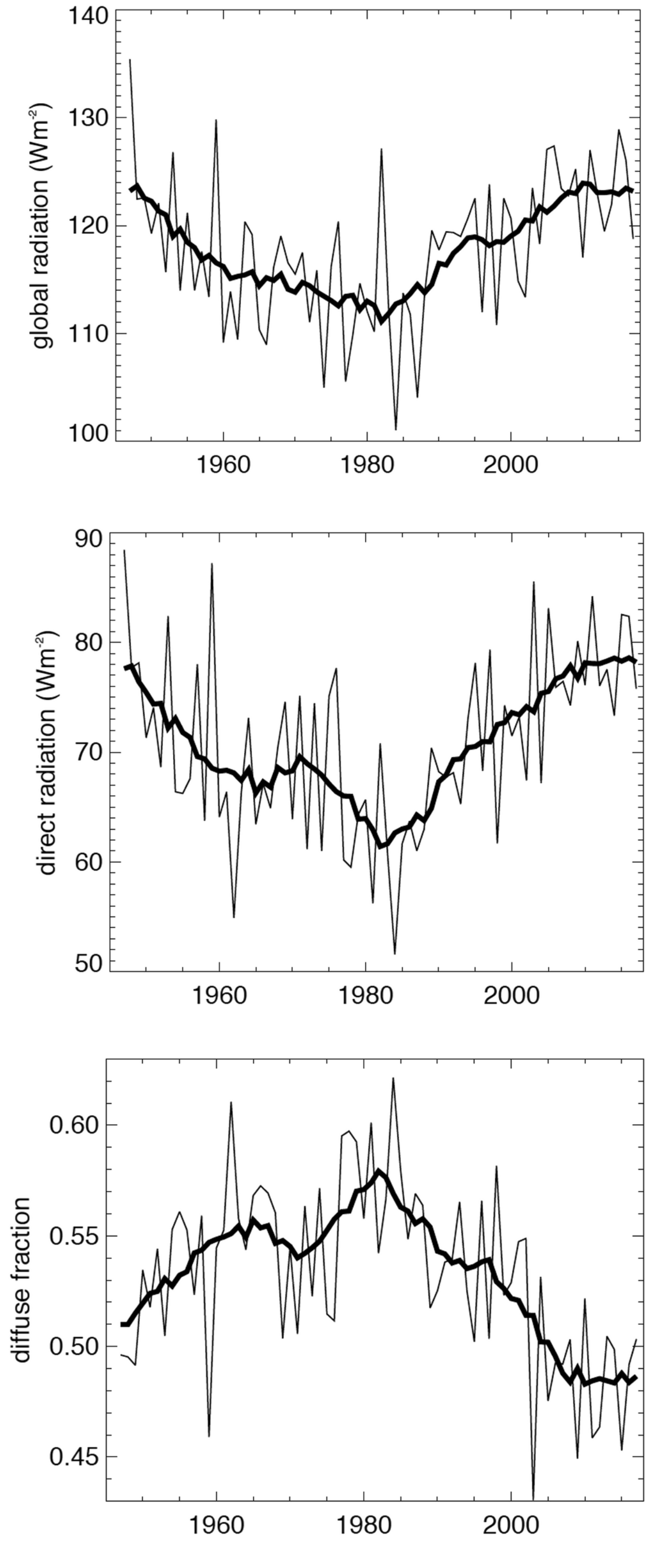

Figure 1. Observed annual mean surface solar radiation (SSR, also known as global radiation) (upper panel; units Wm^{-2}), direct horizontal component (middle panel, determined as difference between observed SSR and diffuse solar radiation; units Wm^{-2}), and diffuse fraction (lower panel, ratio between diffuse radiation and SSR, dimensionless units) as measured at Potsdam between 1947 and 2017 (thin lines). Five-year running means are shown for all time-series (thick lines).

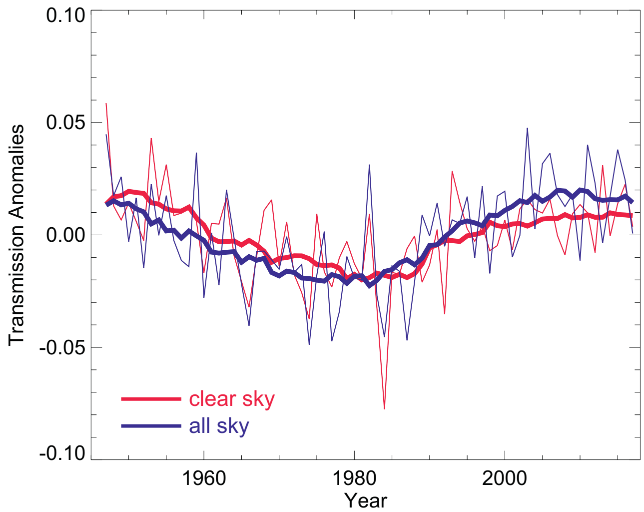

Figure 2. Annual anomalies of maximum atmospheric solar transmission ("clear sky," thin red lines) and mean atmospheric transmission ("all sky," thin blue lines) measured at Potsdam from 1947 to 2017. Anomalies calculated with respect to the long-term mean (1947–2017 average). In addition, 5-year running means are shown for both time-series (thick lines). Units are dimensionless.

direct solar radiation, determined as difference between the observed SSR and diffuse solar radiation. Multidecadal dimming and brightening tendencies are apparent as well, but more pronounced in amplitude than in the SSR, both in absolute and relative terms (exceeding 20%). In Figure 1 (lower panel), the annual mean diffuse fraction measured at Potsdam over the same period is shown (ratio between the measured diffuse solar radiation and SSR). A clear overall increase until the mid-1980s can be seen, synchronous with the dimming of SSR, and turnover to a decline thereafter, while SSR is recovering. This illustrates the shift toward more diffuse radiation at the expense of less direct radiation with stronger dimming, and vice versa during subsequent brightening, as can be expected from an atmosphere with decreasing and increasing transparency, respectively. Further, a stabilization in recent years can be noted in all components in Figure 1. Such a stabilization has been noted not only in Potsdam but also in numerous other SSR records in Europe (Manara et al., 2016; Sanchez-Lorenzo et al., 2015; Wild, 2016).

We then constructed annual series of daily maximum atmospheric transmission as described in Section 2, as a simple approximation of a "clear-sky" transmission time-series. The average transmission over the entire period 1947–2017 is 0.73 (standard deviation 0.02), that is, 73% of the incoming radiation at the TOA over Potsdam reaches the ground in the long-term mean during these approximate clear-sky conditions. We then compared this series with the annual mean atmospheric transmission time-series at Potsdam, obtained by a simple averaging over all daily mean transmission data in each year, which can be considered as an "all-sky" transmission series including all types of weather and cloud conditions. The long-term annual average of this mean transmission time-series is, as expected, considerably lower due to the inclusion of cloudy days, at 0.40 (standard deviation 0.02), indicating that on average under all-sky conditions, 40% of the solar radiation incident at the TOA over Potsdam reaches the ground. Annual anomalies of both maximum ("clear-sky") and mean ("all-sky") transmission time-series have then been calculated as deviations from their above-mentioned long-term means (average over the 1947–2017 period) (Figure 2). Figure 2 shows that dimming and subsequent brightening tendencies are seen not only in the mean transmission time-series ("all sky," shown in blue) but similarly also in the maximum transmission time-series ("clear sky," shown in red). This suggests that dimming and brightening not only occurred when clouds are considered but also under cloud-free conditions when cloud effects are absent. The multidecadal variations in atmospheric transmission shown in Figure 2 are on the order of 4% of the TOA insolation, corresponding in absolute terms to a magnitude on the order of 10 Wm^{-2} (annual TOA insolation at Potsdam 274 Wm^{-2}), in line with Figure 1. Averages over subsequent 10-year periods for the maximum ("clear-sky") and mean ("all-sky") transmission time-series can be found in Table 1. Differences between the decades with the highest and lowest values are 0.040 and 0.038 in the maximum ("clear-sky") and mean ("all-sky") transmission time-series, respectively, suggesting that when cloud effects are minimized, the amplitude of the decadal variations in atmospheric transmission remains similar. Also noteworthy is the leveling off in both maximum and mean transmission series in recent years.

In an alternative approach, we also selected cloud-free days based on synop information on cloud fraction (see Section 2). Here, we used a threshold of 1 octa to discern (near-) clear-sky conditions (see Section 2).

Table 1
Decadal Means of Maximum Transmission ("Clear Sky") and Mean Transmission ("All Sky") Over Distinct 10-Year Periods as Measured at Potsdam

	1947–1956	1957–1966	1967–1976	1977–1986	1987–1996	1997–2006	2007–2016
Maximum transmission ("clear sky")	0.754	0.732	0.727	0.714	0.732	0.740	0.743
Mean transmission ("all sky")	0.415	0.394	0.389	0.382	0.399	0.417	0.420

Note. Units are dimensionless.

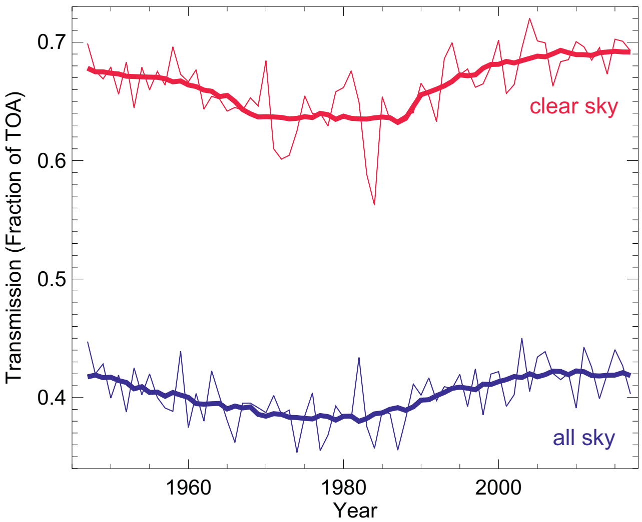

Figure 3. Annual atmospheric solar transmission averaged over days with synop cloud fraction of no more than 1 octa ("clear sky," thin red lines) as well as mean atmospheric transmission averaged over all cloud fractions ("all sky," thin blue lines) measured at Potsdam from 1947 to 2017. In addition, 5-year running means are shown for both time-series (thick lines). Units are dimensionless.

We again determined solar transmissions for each day identified as cloud free within the four seasons, rather than taking the absolute SSR fluxes. The numbers of cloud-free days identified on average in the different seasons were as follows: spring 6.5 days, summer 4.8 days, autumn 5.7 days, and winter 4.4 days. We then constructed again annual mean cloud-free transmission time-series from the seasonal time-series as described in Section 2. This time-series is shown in Figure 3 in red, this time in terms of absolute transmission values rather than anomalies, to illustrate the effect of reducing the cloud influence on the atmospheric transmission. In addition, the annual mean "all-sky" transmission series is shown in Figure 3 in blue, which corresponds to the one shown in Figure 2, but now also in absolute amounts. Figure 3 illustrates, that eliminating days with significant cloudiness as expected leads to a substantial increase in the level of solar atmospheric transmission, from on average 0.41 to 0.67. The average clear-sky transmission over the entire period 1947–2017 shown in Figure 3 is somewhat lower than the clear-sky transmission inferred from the maximum transmission criterion discussed before. While by definition in the maximum transmission method only the day with maximum transmission within a season is considered, in the synop cloud-based method all daily transmission values within a season with cloud estimates not exceeding 1 octa are taken into account. The lower absolute magnitude might partially be due to some remaining cloud contamination not captured by the human observer, missed by the observation frequency or tolerated by the threshold of 1 octa.

In addition, Figure 3 also shows that dimming and brightening tendencies of similar magnitude than in the all-sky records remain when only transmissions from nearly cloud-free days are considered. Thus, irrespective of the chosen criterion for the identification of cloud-free days (based on days with maximum transmission within a season or human-observed cloud fraction), multidecadal variations remain in the composed clear-sky records, which are not overly different from the all-sky records. This demonstrates that indeed decadal variations exist also under cloud-free conditions and do not seem to be an artifact of the clear-sky identification criterion.

4. Discussion and Conclusions

In the present study, we analyzed decadal changes in one of the worlds' longest and best maintained surface radiation records observed at the Potsdam observatory not only under all-sky but for the first time also specifically under quasi clear-sky conditions. We used two different criteria to identify cloud-free conditions, on the one hand based on days with maximum atmospheric transmission (ratio between the insolation incident at the surface and the TOA) within a season, on the other hand based on the information on cloud fraction from synop observations. We deliberately used simple robust approaches, which are particularly suited for the analysis of long-term historical radiation records. Both approaches have specific weaknesses. Although not very likely, the day with the maximum transmission within a season could still not be entirely cloud free (in case there would be no cloud-free day within an entire season). This would cause some spuriously low spikes in the clear-sky time-series. On the other hand, synop cloud observations, performed by human observers, are to some extent subjective and only taken at distinct times over a day. However, irrespective of the method to determine the cloud-free days, we found that the dimming and brightening tendencies do not disappear in the observational record once the influence of clouds is minimized. This suggests that indeed also the cloud-free atmosphere seems to undergo relevant multidecadal variations in its transparency for solar radiation and thus seems to play a major role in the explanation of the decadal dimming and brightening trends prominently visible in central Europe.

Variations in the transmission of the cloud-free atmosphere can basically be caused by variations in aerosol burdens and composition or by changes in the radiatively active gases. With respect to the latter, the largest potential has water vapor. However, numerous studies showed that changes in water vapor cannot nearly modify the solar transmission in the atmosphere to the extent as observed in the dimming/brightening phenomenon (Mateos et al., 2013; Posselt et al., 2014; Vaquero-Martinez et al., 2020; Wild, 2009; Yang et al., 2019). This leaves variations in aerosol radiative effects as the primary cause for the decadal variations in the cloud-free atmospheric transmission. Varying background atmospheric aerosol levels may be very effective in constraining the maximum possible transmission under cloud-free conditions and thereby governing its multidecadal variations. This may also be the reason that with a limited sample of clear days per year, multidecadal variations as shown in Figures 2 and 3 can be effectively captured.

Varying aerosol levels have further a particularly strong influence on the direct component of the solar irradiance. Therefore, we also performed a similar clear-sky transmission analysis for the daily mean horizontal direct radiation, inferred from the difference between the observed daily mean SSR and diffuse solar radiation (Figure S2). According to Figure S2, the transmission of the horizontal direct radiation under cloud-free conditions (identified based on the synop cloud criterion) shows particularly pronounced multidecadal dimming and brightening tendencies, with an amplitude of 26%. This further points to aerosols as major drivers of the multidecadal dimming and brightening tendencies.

A prominent role of aerosols has been advocated in the dimming and brightening discussions for many years. The similar temporal evolution with increasing aerosol burdens from the 1950s to 1980s due to increasing air pollution during dimming in Europe, as well as their subsequent reductions since the 1980s with the implementation of effective air pollution control measures during brightening, has made a connection between aerosol pollutants and dimming and brightening plausible. Yet the direct observational evidence for this hypothesis has been very limited so far. Our study provides thus direct observational support that changing aerosol burdens were indeed able to substantially modify SSR on decadal timescales, as demonstrated here with the famous time-series of Potsdam. Our results are also in line with measurements of aerosol optical depth (AOD) taken since 1986 at the Meteorological Observatory Lindenberg of the DWD (Weller & Gericke, 2005). This observatory, located 80 km to the east of Potsdam, is in a rural setting and its AOD record may be representative of the evolution of the background atmospheric aerosol concentration in the greater Potsdam region. AOD measured in Lindenberg overall gradually decreased from 1986 until around 2005 by 60% and stabilized thereafter (Ruckstuhl et al., 2008). This is in line with the clear-sky brightening since the mid-1980s and the stabilization in recent years evidenced in Figures 2 and 3. The overall reduction and subsequent stabilization of the AOD at low levels has been attributed to the successful implementation of air pollution mitigation measures and their saturation in recent years (Turnock et al., 2016, and references therein).

To quantify the effect of a reduction of AOD of 60% in Potsdam on clear-sky SSR and associated clear-sky atmospheric transmission, we performed calculations with the library for radiative transfer libRadtran 2.0 (Emde et al., 2016). Molecular absorption was parameterized with the LOWTRAN band model, as adopted from the SBDART code (Ricchiazzi et al., 1998). We did the calculations from sunrise to sunset for four distinct days in the course of the year (21 March, 21 June, 21 September, and 21 December) using the US-Standard atmosphere and holding all atmospheric constituents constant. The calculations yielded a pronounced dependency of the change in SSR due to a decrease of 60% in AOD on the solar zenith angle (Figure S3). When integrating over the 4 days we obtained an average increase of daily mean clear-sky global radiation of 8.75% due to the 60% decrease in AOD. This increase is of similar magnitude as the observed increase in clear-sky atmospheric transmission from 0.64 to 0.69 shown in Figure 3, which corresponds to an increase of 8%. This makes a link between the changes in aerosol levels and clear-sky atmospheric transmission also quantitatively plausible.

Our findings rule out arguments that the substantial decadal variations seen in the Potsdam record could be merely induced by internal (natural) modes of variations of the climate system and associated variations in cloudiness. The results presented in this study rather point to human-induced aerosol modifications as origins of these variations. Our study thus does not contradict previous studies that used the observed decadal changes of (all-sky) SSR to constrain the historic aerosol forcing (e.g., Cherian et al., 2014; Storelvmo et al., 2016).

We can hypothesize, that if the stabilization at low pollution and AOD levels in recent years and the concurrent high clear-sky transmission seen in Figures 2 and 3 are sustainable, then the influence of aerosols on

SSR variations may become less prominent in the future than it has been in the past, and prospective SSR variations might be more governed by changes in cloud characteristics instead. Therefore, the continuation of careful monitoring of these quantities is imperative for our understanding and prediction of the variations in solar energy levels, which are so vital for sustainable living conditions on our planet.

Data Availability Statement

The data used in this study are available from the German Weather Service DWD (https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/daily/kl/historical/).

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