



How strong are the links between global warming and surface solar radiation changes?

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Abstract

The aim of this study is to investigate the possible relationship between the recent global warming and the interdecadal changes in incoming surface solar radiation (SSR), known as global dimming and brightening (GDB). The analysis is done on a monthly and annual basis on a global scale for the 35-year period 1984–2018 using surface temperature data from the European Centre for Medium-Range Weather Forecasts (ECMWF) v5 (ERA5) reanalysis and SSR fluxes from the FORTH (Foundation for Research and Technology-Hellas) radiative transfer model (RTM). Our analysis shows that on a monthly basis, SSR is correlated with temperature more strongly over global land than ocean areas. According to the RTM calculations, the SSR increased (inducing brightening) over most land areas during 1984–1999, while this increase leveled-off (causing dimming) in the 2000s and strengthened again in the 2010s. These SSR fluctuations are found to affect the global warming rates. Specifically, during the dimming phase in the 2000s, the warming rates across land areas with intense anthropogenic pollution, like Europe and East Asia, slowed down, while during the brightening phases, in the 1980s, 1990s and 2010s, the warming rates were reinforced. Although the magnitude of GDB and the Earth's surface warming trends are not proportional, indicating that GDB is not the primary driver of the recent global warming, it seems that GDB can affect the warming rates, partly counterbalancing the dominant greenhouse warming during the dimming or accelerating the greenhouse-induced warming during the brightening phases of GDB.

Keywords Climate change · Global warming · Global dimming and brightening · Radiative transfer model · ERA5

1 Introduction

The temperature and the incoming surface solar radiation at the Earth's surface are two crucial parameters for climate and life on the Earth. They both significantly changed during the past decades, contributing to climate change (IPCC et al. 2021; Wild 2009). The increase in surface temperature over the last decades is mainly attributed to the increase in

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anthropogenic emissions of greenhouse gases, which trap the emitted thermal energy of the Earth (IPCC 2021). However, the Earth's emitted thermal radiation depends on the main energy source of the Earth, that is the incoming solar radiation, which penetrates the terrestrial atmosphere undergoing scattering and absorption by the atmospheric constituents and reaches the Earth's surface determining the available energy that is absorbed by the planet. It is well known that SSR experiences interdecadal changes with increasing or decreasing phases, a phenomenon known as Global Dimming and Brightening (GDB) (Stanhill and Cohen 2001; Wild et al. 2005; Wild 2009). It has been suggested (Hatzianastassiou et al. 2020; Ruckstuhl et al. 2008; Stamatis et al. 2023; Wild et al. 2021) that GDB is mainly caused by changes in clouds and aerosols, which are its main drivers. Such changes, e.g. in cloud reflectance, scattering aerosols or variations in the solar flux incident at the top of the atmosphere, modify the total amount of solar energy absorbed by the climate system leading to changes in surface temperature (Ramanathan et al. 2001; Wild et al. 2007; Wild 2009). Thus, the SSR fluctuations, namely GDB, have been linked with the recent anthropogenic global warming (Glantz et al. 2022; Ramanathan 2007; Ruckstuhl et al. 2008; Trenberth and Fasullo 2009; Stamatis et al. 2022, 2023; Wang and Dickinson 2013; Wild et al. 2007). Specifically, it has been proposed (Wild et al. 2007) that the solar dimming from the middle of the 20th century until the 1980s has concealed the evolving greenhouse warming, which has only become fully apparent on a global scale during the brightening that followed the 1980s. Nevertheless, it has been pointed out that the brightening has not substituted the greenhouse effect as the main cause of global warming (Glantz et al. 2022; Wang and Dickinson 2013; Wild et al. 2007; Wild 2009). Both GDB and global warming are climatic phenomena that have attracted a strong interest of the scientific community since a few decades. Indeed, numerous studies have delved into the nuanced behavior of GDB over the recent decades, revealing stabilizations of brightening or even a dimming during the 2000s (Hatzianastassiou et al. 2020; Sanchez-Lorenzo et al. 2015; Stamatis et al. 2022, 2023; Wild 2009) over many areas and a general brightening after 2010 (Dong et al. 2022; Stamatis et al. 2022, 2023; Wild et al. 2021; Wohland et al. 2020). On the other hand, in recent years, the concept of a "hiatus" in global warming has gathered scientific attention, referring to a perceived slowdown in the rate of surface temperature increase observed from the late 20th century to the first decade of the 21st century (England et al. 2015; Trenberth and Fasullo 2013). The hiatus debate underscores the complexity of the Earth-atmosphere climate system and the need for detailed analysis to discern short-term variations from the overarching warming trend due to the anthropogenic greenhouse effect. Recent investigations attempting to explain the hiatus have also focused on factors such as natural climate variability (Watanabe et al. 2014), ocean heat uptake (Liu et al. 2016a) slowdown in radiative forcing caused by anthropogenic aerosols or volcanic eruptions (Kaufmann 2011; Santer 2014; Solomon 2011), decreasing surface solar radiation (Kaufmann 2011), and the role of specific atmospheric and oceanic phenomena (Arora et al. 2016). Researchers studying the recent hiatus in global warming often explored the role of internal variability such as El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multi-decadal Oscillation (AMO), in influencing short-term temperature trends (Arora et al. 2016; Augustine and Capotondi 2022; Chtirkova et al. 2023; Loeb et al. 2018). While anthropogenic greenhouse gas emissions drive the centennial scale warming trend, internal variability and SSR trends (GDB) can lead to periods of slower or accelerated warming over shorter timeframes, e.g. over decadal scales (Gou et al. 2022). An example, concerning the role of GDB, was the

hypothesis of (Wild et al. 2007) that GDB can modulate the global warming rates, which was based on analyses of GDB and global warming from 1958 till 2002. After 2010 and following the period of the recent hiatus in the 2000s, the rates of warming continued the accelerating pace (Jenkins et al. 2022). Therefore, it is important to further expand the time period in order to test again the hypothesis under the evolving phases, including the more recent ones, of GDB and global warming. In the present work we attempt to do this by examining the interdecadal changes of SSR and surface temperature from the early 1980s through to 2018, i.e. over 35 years, in order to confirm the hypothesis that the Earth's land surface air temperature fluctuations are impacted by dimming and brightening, which may contribute and partly control the progressing warming of our planet.

2 Data and methodology

2.1 Data

In this study, globally distributed monthly mean SSR fluxes computed with the FORTH-RTM, and temperature data, namely monthly mean temperature at 2 m (T_{mean}), and the corresponding average values of the maximum daily temperature at 2 m (T_{max}), the minimum daily temperature at 2 m (T_{min}), and the difference $T_{\text{max}} - T_{\text{min}}$, which is the diurnal temperature range (DTR), from the extensively used ERA5 reanalysis were used over the study period of 1984–2018. The detailed FORTH spectral radiative transfer model, which is described and thoroughly evaluated by (Hatzianastassiou et al. 2020; Stamatis et al. 2023), discriminates the atmosphere into clear and cloudy (low-, mid-, and high-level cloud covered) fractions. It solves a set of monochromatic radiative transfer equations using the modified Delta Eddington method and considers the cloud and aerosol scattering and absorption, Rayleigh scattering, molecular absorption in the ultraviolet, visible and near-infrared spectral ranges of solar radiation, and surface albedo. The model runs on a monthly basis with a $0.5^\circ \times 0.625^\circ$ latitude $\times$ longitude resolution and estimates SSR (in Wm^{-2}) at the corresponding temporal and spatial resolutions. The utilized detailed daytime-only cloud input data (cloud amount, cloud optical depth, and cloud-top pressure for liquid and ice phases) resulted from the synergy of two satellite products, the CLARA-A2 (CM-SAF Cloud, Albedo And Surface Radiation dataset from AVHRR data—second edition) (Karlsson et al. 2020) and ISCCP-H (International Satellite Cloud Climatology Project-H series) (Young et al. 2018). The aerosol optical depth, single scattering albedo, asymmetry parameter, ozone concentration, surface albedo and specific humidity were computed from data taken from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) Reanalysis as described by (Gelaro et al. 2017; Korras-Carraca et al. 2021). ERA5 (Hersbach et al. 2020) is the fifth generation of atmospheric reanalysis produced at the European Centre for Medium-Range Weather Forecasts (ECMWF) and currently covers the period from 1940 to the present. It should be noted that although ERA5, MERRA-2 and CLARA provide data up to the present, the current study period is confined by the temporal coverage of ISCCP-H, which is 1984–2018. ERA5 provides hourly estimates of various atmospheric and land surface quantities as well as ocean wave data at a horizontal resolution of $0.25^\circ \times 0.25^\circ$ latitude $\times$ longitude resolution. The original ERA5 temperature data used in this study are publicly available (Hersbach et al. 2020) and were regridded onto the $0.5^\circ \times 0.625^\circ$

horizontal resolution of the FORTH-RTM SSR fluxes. Furthermore, to validate the calculated FORTH-RTM SSR and GDB, ground-truth SSR measurements were utilized from the GEBA (Global Energy Balance Archive; Wild et al. 2017) network and BSRN (Baseline Surface Radiation Network; Driemel et al. 2018).

2.2 Methodology

First, the Pearson correlation coefficients (r), along with their statistical significance at 95% confidence level, quantifying the correlation between the monthly timeseries of the deseasonalized SSR and temperature (T_{mean} , T_{max} , T_{min} , DTR) anomalies, were computed for each grid cell on a global scale for the entire time period (1984–2018). The deseasonalized monthly anomalies refer to the entire study period (1984–2018) and were calculated by subtracting the average value of all corresponding months within the entire time period from the current monthly value. Then, the timeseries of the annual mean anomalies of SSR and temperatures, computed with respect to the entire study period, were produced. Next, the low-pass Savitzky–Golay (SG, Schafer 2011) filter, was applied to the annual mean timeseries with a window size of 10 years, in order to reveal possible long-term relations between SSR and surface temperatures on global, hemispherical, land and ocean scale as well as during the boreal cold (November to April) and warm (May to October) periods of the year. Note that the SG filter relies on polynomial-based local least-squares fitting of the data and is a widely used technique for noisy data derivative computations and data smoothing. Also, the non-parametric robust Sen's slope and the Mann–Kendall test are applied to determine the annual changes and their significance at the 95% confidence level. The annual change is given in $\text{Wm}^{-2}\text{decade}^{-1}$ or $^{\circ}\text{Cdecade}^{-1}$. Along with the value of change, also the uncertainty of this change was calculated using the lower and upper bound of the confidence interval of the slope, which we multiplied by the length of the time period to provide inside brackets next to the value of change the lower and upper limits of the change (i.e. change [low change, high change]). In a further step, the per decade changes of monthly deseasonalized SSR and temperature anomalies were computed at each grid cell utilizing the Sen's slope, while the Mann–Kendall test was applied to estimate their significance at the 95% and 70% confidence level. This analysis has been performed for 3 time-periods and 18 land regions. The 18 land regions (study sub-regions, Fig. S1) of the globe were selected, covering almost all continents. The selection of these areas was made based on the criterion that they define specific continental entities and also have roughly coherent patterns of GDB. Over these sub-regions the decadal changes of either SSR and temperatures were calculated for 3 different time periods that are characterized, according to the station measurements-based literature (Stamatis et al. 2023; Wild 2009), by brightening (1984–1999), weak brightening (2000–2009) and brightening (2010–2018). Then, the calculated changes were spatially averaged for each sub-region and sub-period. Moreover, we calculated the standard deviation of these spatial averages along with the percentage number of grid-cells having statistically significant trends at the 95% and 70% confidence level. This regional analysis aims to examine to what extent the warming of the planet is accelerating during solar brightening or decelerating during solar dimming on a specific regional basis, over a certain region. This is important information, given the regional patterns in both GDB (Hatzianastassiou et al. 2020; Norris and Wild 2009; Ohmura 2009; Stamatis et al. 2023; Wild 2012) and planetary warming (Cheshmehzangi 2020; Hansen et al. 2006; IPCC et al. 2021, 2022; Semenov et

al. 2010). To effectively test the hypothesis that brightening allows surface warming due to anthropogenic greenhouse effect to fully occur, or better reinforces it, while dimming slows down the rate of warming, we examined to what extent this relationship between GDB and surface temperature (T_{mean}) is observed over the selected 18 world areas where and when we have brightening and dimming. Thus, for each of the 18 regions and each of the three time periods, namely for 54 cases, we searched for the cases in which the solar brightening coexists with surface warming, as well as the dimming coexists with weak warming. Besides, to increase the reliability of our results, we used a threshold to identify in which cases there were strong positive trends both in SSR and temperature and also in which cases there were dimming or weak brightening along with weak warming. Thus, if the % per decade SSR/temperature change is larger in absolute terms than that of the global land average change during 1984–2018 (i.e., 1.4% and 0.1% per decade for SSR and temperature, respectively), then the change is considered as strong and it is noticed with bold, otherwise it is considered as no strong. In the following, the methodology of FORTH-RTM SSR and GDB validation against ground truth is presented, as described in detail by Stamatis et al. 2023.

3 Results and discussion

3.1 FORTH-RTM SSR and GDB evaluation

Initially, to confirm the reliability of our model, the FORTH-RTM SSR and GDB (trends of SSR) were validated against ground-truth measurements of GEBA and BSRN networks. Overall, on a monthly basis, the r values for the FORTH-RTM calculated time-series and the corresponding observational time-series from GEBA and BSRN are satisfactory, being equal to 0.97 and 0.94 for SSR fluxes or 0.75 and 0.71 for deseasonalized SSR anomalies. The FORTH-RTM has an overall small positive bias in the absolute SSR magnitudes, of 4.50 Wm^{-2} , or 2.7%, against the larger network of 1091 GEBA stations. Additionally, the model's SSR bias over the fewer 64 BSRN sites is equivalent to -2.50 Wm^{-2} , or -1.3%. Furthermore, the RMSE values for GEBA and BSRN, which are 20.90 Wm^{-2} (12.8%) and 29.01 Wm^{-2} (15.4%), respectively, are likewise good. Following this assessment, which demonstrated the FORTH-RTM SSR's good performance, the signs of the slopes of deseasonalized SSR anomalies for every station were calculated, and these were compared to the corresponding signs of slopes calculated using FORTH-RTM deseasonalized SSR anomalies for the pixels that included the stations. The purpose of this comparison was to determine whether or not the FORTH-RTM GDB sign agrees with that of the stations' GDB sign. Agreement is found for the majority of stations that have statistically significant trends in Europe, India, and East Asia. There is an overall agreement of 80% (or 90% for statistically significant trends) over GEBA sites and 65% (or 88% for statistically significant trends) when compared to the fewer BSRN stations. It should be mentioned that we carried out a similar comparison study (results not shown here) to ensure the FORTH-RTM's reliability for both the full time period and decadal sub-periods. This is a crucial step, because in the sections that follow, we will examine the GDB in decadal sub-periods. According to this study, the FORTH-RTM GDB's agreement with GEBA stations in terms of the sign of the trends during the 1980s, 90s, 00s, and 10s is pretty good, equal to 71%, 62%, 67%, and 73%, respectively. Furthermore, the FORTH-GDB exhibits agreement of 64%, 72%, and 68% over BSRN sites for the 90's,

00's, and 10's, respectively, demonstrating the good representation of the FORTH-RTM GDB phases once more.

3.2 Correlation between SSR and surface temperature

In order to examine and quantify the theoretically established dependence of surface temperature on SSR, the two parameters were correlated all over the globe, on a monthly basis, and the 35-year study period (1984–2018). In general, SSR is positively correlated with surface temperature (yellowish and reddish colors), as expected, over most areas of the globe. Figure 1a shows that T_{mean} is more strongly correlated with SSR over land areas such as Europe, much of Asia, especially its southern parts, and South America, as well as over western North America and eastern southern Africa, where values reach 0.70. On the other hand, however, a negative correlation appears mainly over the polar regions and the Sahara with the maximum negative value being -0.62. While, theoretically, a positive correlation (i.e., more solar radiation leading to higher temperatures) is generally expected, local and regional factors, such as changing surface albedo or changes in temperature advection through changes in atmospheric circulation, can influence the distribution of heat within a region and introduce complexities. For instance, regions with high and increasing surface reflectivity (albedo), such as areas covered by snow, ice, or deserts, may experience lower temperatures due to the decrease of the surface absorbed solar radiation. The dependence of surface temperature on SSR is expected to be stronger for T_{max} , since the temperature daily maximum values, occurring around noon, are largely determined by the surface incoming solar radiation, especially in cloudless skies (Wild 2009). Indeed, this is confirmed in Fig. 1b, which shows larger correlation coefficients between SSR and T_{max} than between SSR and T_{mean} . Now, the regions that already had high correlation coefficients with T_{mean} show even higher coefficients with T_{max} , with values reaching 0.78, again being larger over land than over ocean. Yet still a slight negative correlation remains over the polar regions and the Sahara. The r values between SSR and T_{min} generally remain the lowest in Fig. 1, which has to do with the fact that the daily minimum temperature, practically occurring during the night, is determined by the emitted thermal radiation by the Earth's surface and the associated longwave radiative cooling and not by solar radiation (Campbell and VonderHaar 1997; Makowski et al. 2008; Wild et al. 2007). The strongest correlation is found between SSR and DTR, but this is valid over land, whereas over the oceans the corresponding r values are either smaller in magnitude when positive or larger in magnitude when negative, i.e. they are worse than r values for the SSR and T_{max} and the SSR and T_{min} pairs. This can be expected, since the sea surface temperature and the temperature near over the sea change much less over the course of a day than over land. Hence, the correlation coefficients between SSR and DTR range between -0.84 and 0.88, reaching larger values for positive correlation over land and negative correlation over ocean. This confirms that DTR is a good proxy of the interannual change of SSR over land, as it is expected, since the subtraction of T_{min} from T_{max} , minimizes the thermal effects in the DTR records (Wild et al. 2007; Wild 2009). The stronger negative correlation between SSR and DTR over oceans should be attributed either to the larger thermal inertia of oceans compared to land as well as to the different meteorological conditions that prevail over them. The larger thermal inertia of oceans means that they respond more slowly to changes in solar radiation, as the heat absorbed during the day is released more gradually over time. Besides, evaporation from the ocean surface absorbs a significant amount of solar

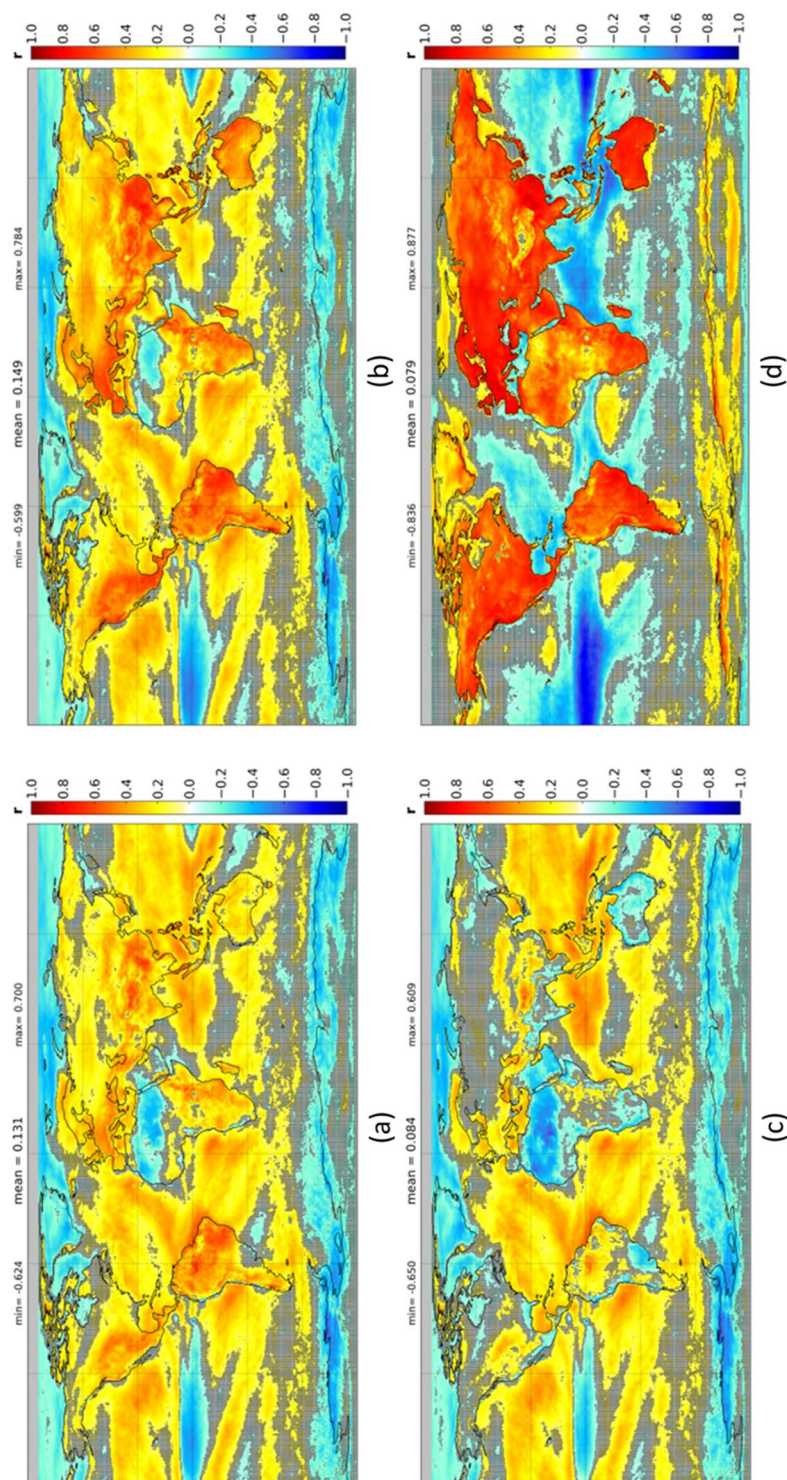


Fig. 1 The global distribution of correlation coefficients (r) between monthly deseasonalized anomalies of FORTH-RTM SSR and ERA5 temperatures (T_{mean} -a, T_{max} -b, T_{min} -c, DTR-d) during 1984-2018. Positive correlation is depicted in yellow and red while negative correlation in blue colors. The statistically no significant r values at the 95% confidence level are denoted with black x symbols

energy, leading to cooling. This latent heat flux can act as a buffer, dampening the direct impact of solar radiation on surface temperature over oceans (Hastenrath 1991). There is a noticeable strong anticorrelation between SSR and surface temperatures (T_{mean} , T_{max} , T_{min} and DTR) over the tropical oceans, which is even more evident for DTR (Fig. 1d). This can be explained by the intricate interplay of factors unique to tropical climates. The combination of high convective cloud activity, which limits the solar radiation impact, and the thermal dynamics associated with elevated temperatures and enhanced latent heat release can contribute to an anticorrelation between SSR and temperatures. Furthermore, the influence of phenomena like El Niño and the trade winds introduce additional complexities, altering atmospheric circulation patterns and intensifying the estimated negative correlation between solar radiation and DTR in tropical regions (Hastenrath 1991).

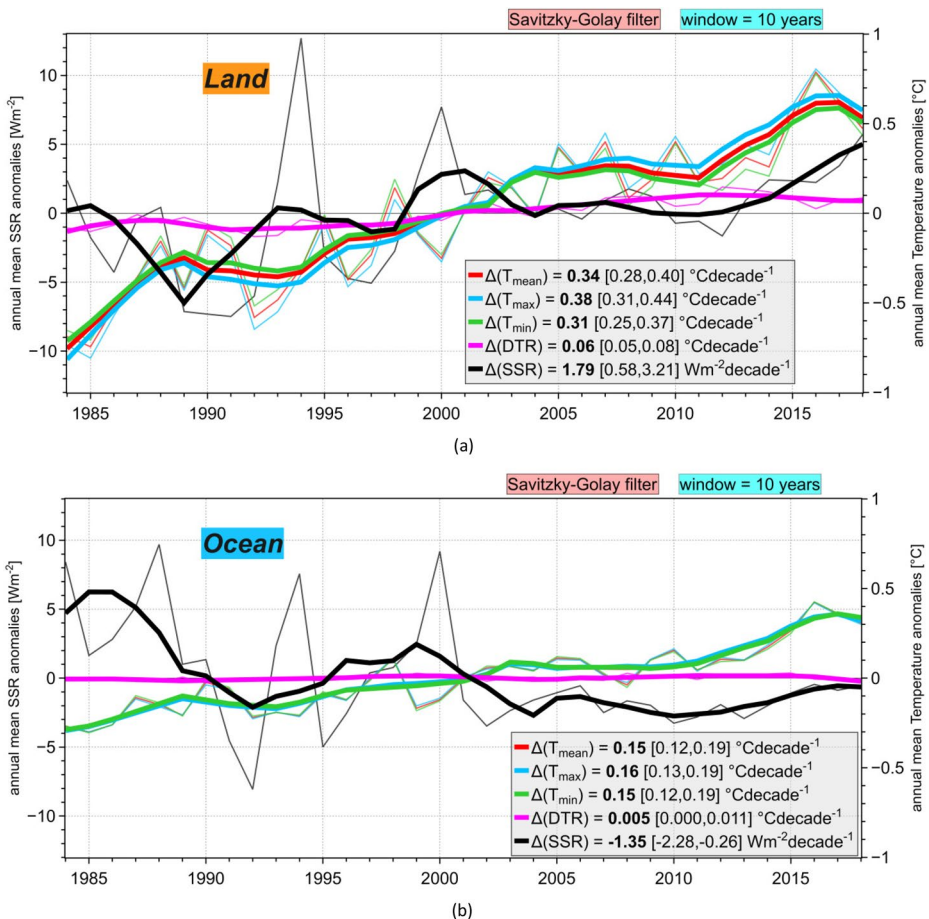


Fig. 2 Timeseries of annual anomalies of globally averaged SSR (with black) and ERA5 Earth surface temperatures (T_{mean} -red, T_{max} -blue, T_{min} -green, DTR-purple) during 1984–2018. Results are given separately over global land (a) and ocean (b) areas. The thick lines represent the Savitzky-Golay filtered data with the window size of 10 years. Anomalies are computed with respect to the entire study period 1984–2018, while inside the legend the associated per decade linear trends are shown and specifically with bold the statistically significant trends at the 95% confidence level

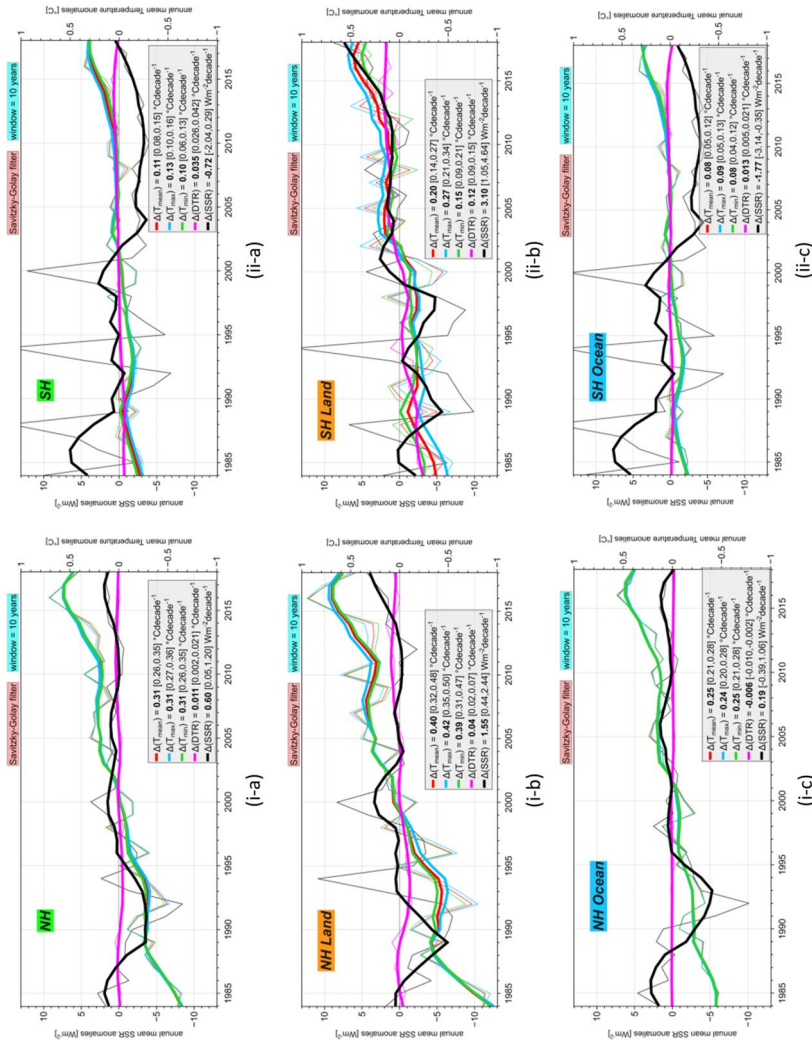


Fig. 3 Anomalies of spatially averaged timeseries over North Hemisphere (NH-i) and South Hemisphere (SH-ii) for FORTH-RTM SSR (with black) and ERA5 temperatures (T_{mean} -red, T_{max} -blue, T_{min} -green, DTR-purple) over the entire hemisphere (a), over land (b) and over ocean (c). The thick lines represent the Savitzky-Golay filtered data with the window size of 10 years. Note that the reference period for the anomalies is the entire study period 1984-2018, while the linear per decade trends are displayed inside the legend, and the statistically significant trends at 95% confidence level are indicated in bold

3.3 The long-term changes of SSR and temperature over land and oceans and their relationship

In the next step, we investigated if there is a correlation between the long-term changes of SSR, namely the GDB, and the Earth's surface temperatures, but on a global average scale and annual basis and the results are shown in Fig. 2. Different temporal changing patterns are observed between the time series of both SSR and temperatures over land and ocean as it is shown in detail in Table S1. More specifically, over land (Fig. 2a), in parallel to the brightening ($0.58 [-5.74, 5.71] \text{ Wm}^{-2}\text{decade}^{-1}$) occurring from 1984 to 1999 there is a corresponding accelerated rate of land warming, with the changes of T_{mean} , T_{max} and T_{min} being equal to $0.37 [0.12, 0.63]$, $0.37 [0.11, 0.68]$ and $0.35 [0.11, 0.63] \text{ }^{\circ}\text{Cdecade}^{-1}$, respectively. On the contrary, when the brightening over land ceased during 2000–2009 and GDB shifted to a slight dimming ($-0.02 [-3.56, 2.35] \text{ Wm}^{-2}\text{decade}^{-1}$), the land warming slowed down, actually at least halved to $0.19 [-0.45, 0.65]$, $0.26 [-0.38, 0.74]$ and $0.11 [-0.32, 0.65] \text{ }^{\circ}\text{Cdecade}^{-1}$ for T_{mean} , T_{max} and T_{min} , respectively, corresponding to the so-called recent hiatus (Douville et al. 2015; Gou et al. 2022; Xie and Kosaka 2017; Yan et al. 2016; Yang et al. 2023). This behavior is remarkable as similar findings were observed in the 1950–1980 dimming (Wang and Dickinson 2013; Wild et al. 2007) which preceded the brightening starting in the early 1980s. Following the 2000's slight dimming and recent hiatus, in the absence of dimming during the 2010s, the SSR increased producing a brightening of $7.47 [4.93, 11.18] \text{ Wm}^{-2}\text{decade}^{-1}$ (note that this high value is associated with the negative 2012 anomaly of -1.65 Wm^{-2} and the large 2017 and 2018 anomalies both 3.44 Wm^{-2} and 5.72 Wm^{-2} , respectively), while the land warming continued its accelerating pace, with the T_{mean} increasing by $0.45 [-0.29, 1.22] \text{ }^{\circ}\text{Cdecade}^{-1}$. Thus, our findings reinforce the hypothesis that a solar dimming is accompanied by a decelerated warming of global land areas, while the brightening is associated with an accelerated global warming. It should be noted that in contrast to the clear increase in temperatures (T_{mean} , T_{max} , T_{min}) over the entire 35-year study period, the DTR does not show a noticeable change, but only a small increase equal to $0.06 [0.05, 0.08] \text{ }^{\circ}\text{Cdecade}^{-1}$, which is qualitatively consistent with the overall increase of SSR ($1.79 [0.58, 3.21] \text{ Wm}^{-2}\text{decade}^{-1}$) over the entire study period of 1984–2018. Furthermore, the interdecadal changes of DTR, which are clearly smaller than those of the other surface temperature variables, do not seem to be in line with the phases of GDB. On the other hand, the interdecadal changes show a bit different behavior over oceans. The temperature appears to have undergone a much smaller increase compared to over land, $0.54 [0.43, 0.66]$ versus $1.19 [0.97, 1.39] \text{ }^{\circ}\text{C}$, respectively for the entire time period 1984–2018, while it appears to be increasing continuously ($0.15 [0.12, 0.19] \text{ }^{\circ}\text{Cdecade}^{-1}$ for T_{mean} , T_{max} , T_{min} and $0.005 [0.0002, 0.01] \text{ }^{\circ}\text{Cdecade}^{-1}$ for DTR) despite the decreasing SSR during the study period. Note that although during the 2000s the dimming is stronger over the oceans than land areas ($-0.35 [-7.19, 3.04]$ versus $-0.02 [-3.56, 2.35] \text{ Wm}^{-2}\text{decade}^{-1}$), the decelerated rate of the warming, in comparison to the rate of the 1990s, is more apparent over the land than the ocean (maybe also related to the higher heat capacity and associated inertia of the oceans), indicating a stronger link of GDB with the global warming rate over land areas than over oceans.

The same analysis was performed for the Northern and Southern Hemispheres, both over land and oceans (Fig. 3). The warming is larger for the NH than SH, being equal to $0.31 [0.26, 0.35]$ and $0.11 [0.08, 0.15] \text{ }^{\circ}\text{Cdecade}^{-1}$, respectively. In addition, this warming is

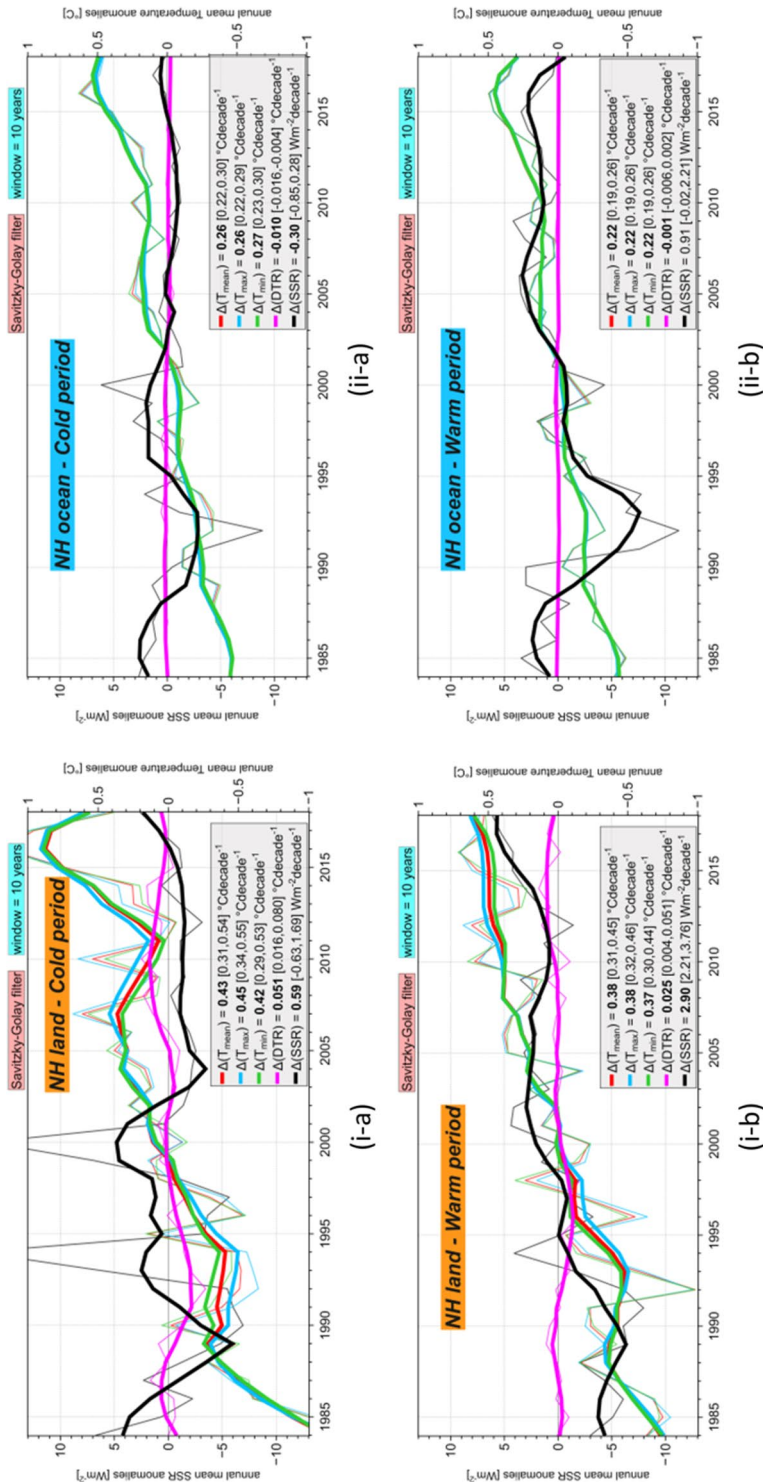


Fig. 4 Anomalies of spatially averaged timeseries over Northern Hemisphere's land (i) and ocean (ii) for FORTH-RTM SSR (with black) and ERA5 temperatures (T_{mean} -red, T_{max} -blue, T_{min} -green, DTR-purple) during the boreal cold (a November-April) and warm (b May-October) period for 1984–2018. The thick lines represent the Savitzky-Golay filtered data with the window size of 10 years. Anomalies are computed with respect to the entire study period 1984–2018, while inside the legend the associated per decade linear trends are shown and specifically with bold the statistically significant trends at the 95% confidence level

stronger over land than oceans in both hemispheres with the largest rate of warming occurring over land in the NH ($0.40 [0.32, 0.48] ^\circ\text{Cdecade}^{-1}$). With respect to the GDB, the NH experienced a brightening equal to $0.60 [0.05, 1.20] \text{ Wm}^{-2}\text{decade}^{-1}$ during the study period, which arose mainly from land, while the SH underwent a dimming that mainly occurs over the oceans. Moreover, Fig. 3 reveals that during the 2000s the warming rate slowed down with respect to the period 1984–99 on the NH, which is not evident on the SH, although the 2000s dimming seems to be stronger on the SH. This is rather expected since during the 2000s dimming over land, the decelerated rate of the warming is more apparent than over the ocean as Fig. 2 shows, and the NH contains much more land areas than the SH. Also, the stronger dimming in the 2000s over NH land leads to a clearer slowdown of the warming rate than over SH land, which experiences a weak dimming, while oceans show an almost steadily increasing warming despite the GDB phases.

Moreover, the timeseries of the annual SSR and temperature anomalies are also investigated for the Northern Hemisphere separately for the warm (May to October) and the cold (November to April) periods of the year, both over land and ocean (Fig. 4). Similarly to our previous findings, the rate of global warming seems to slow down during the dimming of 2000s over land over both periods, this being more apparent during the cold (with stronger dimming ($-2.30 [-12.17, 1.91] \text{ Wm}^{-2}\text{decade}^{-1}$)) than the warm (with weak brightening ($0.09 [-3.74, 4.02] \text{ Wm}^{-2}\text{decade}^{-1}$)) period of the year (respective values equal to $0.32 [-0.19, 0.86]$ and $0.35 [-0.45, 0.89] ^\circ\text{Cdecade}^{-1}$), while over oceans, in both cold and warm periods the surface temperature over oceans are steadily increasing despite the solar dimming occurring (more during the cold than the warm period) in both periods.

Even though Wild (2016) found an imprint of the 1950s to 1970s dimming on the sea surface temperature changes as provided by the Hadley Centre particularly over the NH oceans, such an imprint is not found in the results of this subsection referring to the period 1984–2018 and obtained using the interdecadal changes of the ERA5 surface temperature over oceans and the FORTH-RTM SSR and its changes (GDB). Probably this is due to the shorter time period and the smaller magnitude of dimming in the 2000s than in 1950–1970 s. Therefore, in the rest of our work, we will examine in detail the trends of surface temperature and SSR only over land areas of the globe, where there is also more confidence of the FORTH-RTM SSR and GDB than over oceans.

3.4 The relationship between the changes of SSR and surface temperature over various land areas

According to our analysis based on the FORTH-RTM, the SSR experienced a brightening phase over most land regions of the Earth from 1984 to 1999, followed by both dimming and brightening phases in different regions during the 2000s. Also, since 2010, the brightening has occurred over all selected areas of this study, while in the 3 time periods the GDB magnitude is different from one region to another. These findings point to the complex nature of the GDB phenomenon. In order to simplify this study, 18 land areas of the planet were selected (shown in Fig. S1) and the study period of GDB was divided into 3 phases/periods. Thus, the long-term changes of SSR and surface temperature (surface-air temperature, T_{mean}), and their interrelationship, were studied for a total of 54 (18×3) cases, for which the trends of SSR and temperatures were investigated and intercompared (cf. Fig. 5). It should be noted, that for completeness, along with the spatial averages of the long-term

changes shown in Fig. 5, there are also their associated standard deviations in Fig. S2 and the percentage number of grid-cells that have statistically significant trends at the 95% and 70% confidence level in Fig. S3 and S4, respectively. We initially notice that during 1984–1999 a brightening occurred in most land areas of the Earth, except for Australia, Africa, and in particular the polar regions and especially Antarctica. At the same time, the temperature practically rose all over the globe except for Antarctica, showing that the global warming, wherever it occurred along with solar dimming, was not driven by GDB such as over Africa and the Arctic during 1984–1999. Yet, the absence of surface warming of Antarctica can be partly attributed to the strong dimming in this area. After 2000 and till 2009, in many land areas the brightening is offset, and a dimming is observed in some areas such as the largest part of Europe and the southern and East Asia. During this decade, the warming continues and even strengthens, as expected from the evolving anthropogenic greenhouse effect, but in some areas, there is a stabilization of the warming rate or even a reversal to cooling, such as in Europe, the Middle East, North America and Greenland. It is interesting to note that in most of them, namely Europe, the Middle East and North America, a solar dimming took place in the 2000s, which may have contributed to their surface cooling. Besides, the reversal from dimming to brightening over a significant part of Antarctica may be associated with the remarkable warming over these parts of Antarctica in the 2000s, opposite to the cooling there before 2000, also indicating the existence of a strong relationship between SSR and T_{mean} . During the 2010s, brightening prevails in all the selected areas, which reversed the dimming occurring in the previous decade over many regions, such as Europe, India and Southeast Asia. The rates of warming in 2010s were generally higher than the rates in the previous sub-periods, except for E. USA, where surface cooling occurred, and Sahara and Arctic, where the warming rates were negligible despite the brightening occurring there. Also, during this decade (2010s) it is interesting to note that the strong brightening was associated with strong warming rates in many areas of the planet, such as Europe, India, Southeast Asia and Australia.

As it was shown, it is challenging to analyze the simultaneous change of SSR and surface temperature over all selected world sub-regions and during the three subperiods. Therefore, in order to effectively test the hypothesis that brightening allows surface warming due to the anthropogenic greenhouse effect to fully occur, while dimming slows down the rate of warming, it was examined if it is common to observe this notable link between GDB and surface temperature (T_{mean}) over the selected 18 world areas where and when we have brightening and dimming. Thus, for each one of the 18 regions and each of the three time periods, namely for 54 cases, we searched for the cases in which the solar brightening (red-dish colors in Fig. 5) coexists with surface warming (yellow and red colors, Fig. 5), as well as the dimming (bluish colors, Fig. 5) coexists with weak warming (light yellow colors in Fig. 5). Our analysis revealed that in 89% of the cases (48/54) this happens, indicating the existence of a potential relation between SSR and the rates of change of temperature. Moreover, during the selected 3 time-periods, it was found that there are 31/54 cases (or 57%) which satisfy the criterion of the co-existence of strong brightening along with strong warming and dimming or weak brightening along with weak warming. In a further step, in order to examine the validity of the hypothesis on a more rigorous basis, we examined if the hypothesis (that dimming slows down the rate of warming, while brightening accelerates it) is valid continuously, i.e. in all 3 time-periods, over a region, in other words, we searched for areas where there is a strong connection between the GDB and global warm-

ing during the entire 35-year study period. It is found that the areas where this happens are Europe, East Asia, East China, the Middle East, the Mediterranean and Australia. It should be noted that these are either areas with intense anthropogenic activity and pollution (such as Europe and East Asia (Di Antonio et al. 2023; Yoon et al. 2011) or with frequent export of desert dust (such as the Mediterranean and the Middle East (Gavrouzou et al. 2021; Gkikas et al. 2013). On the other hand, in all other regions the hypothesis does not seem to be valid for all 3 periods (continuously). For example, over South America and Mexico, in one period (2000s) the brightening may have kept pace with the warming, but in the next period (2010s) with a weaker brightening, a stronger warming was observed. It is well known that aerosols, through scattering and absorption in the atmosphere, depending on their type and loading, cool or heat the atmosphere and the surface of the area over which they occur (Korras-Carraca et al. 2021; Krishnan and Ramanathan 2002; Storelvmo et al. 2016). As Wild (2009) pointed out, SSR changes, i.e. GDB, can have a larger and more pronounced impact on land surface temperatures only, when these changes are caused by processes which alter the solar absorption by the entire Earth-atmosphere system (such as through scattering aerosols, cloud reflectance or variations in the solar flux incident at the top of atmosphere). Otherwise, if the SSR changes are caused by a redistribution of solar absorption between atmosphere and surface with little effect on the total amount absorbed by the Earth-atmosphere system (such as through changing absorbing aerosols), the effect of SSR changes on surface temperatures is not expected to be clearly detectable. Indeed, according to our results, in regions with high loads of scattering aerosols, changes in the concentration of scattering aerosols could induce the phases of GDB, simultaneously affecting the solar absorption by the Earth-atmosphere system and consequently the land surface temperatures. This seems to happen above the world sub-regions where GDB is strongly connected to surface warming, namely over Europe, East Asia, East China, the Middle East and the Mediterranean. Note that according to our trend analysis of the input data (not shown here), Europe, East Asia, Mediterranean and the Middle East underwent noticeable changes of scattering AOD and cloud amount during the 3 sub-periods, which are in line, as expected, with the FORTH-RTM GDB phases there. Also, over Australia, changes in cloud amount seem to be more consistent with the FORTH-RTM GDB phases there during the 3 sub-periods, with scattering AOD contributing only to the brightening during the 2010s. Nevertheless, our results show that the strong connection between GDB and warming exists only in specific regions of the planet and for the global mean land, while not being a general phenomenon on regional scales. Indeed, the relationship between solar radiation and temperature is complex and therefore it cannot be assumed to exist across all areas and atmospheric conditions (Barbaro et al. 2013; Wild 2009; Zhang et al. 2010). Moreover, apart from the good qualitative agreement found in the specific 6 sub-regions we mentioned, for areas with at least two brightening phases, e.g. Australia, Siberia, the Middle East and South America, the magnitude of the surface temperature changes in these two brightening periods is not exactly proportional to the magnitude of the brightening. The above-mentioned findings of our analysis confirm that the general main factor that regulates the recent, beyond 1980, rapid global warming is not GDB, but the anthropogenic greenhouse effect. However, GDB should always be accounted for, since ignoring it could lead to an underestimation/overestimation of the true magnitude of the observed greenhouse warming in the dimming/brightening phases.

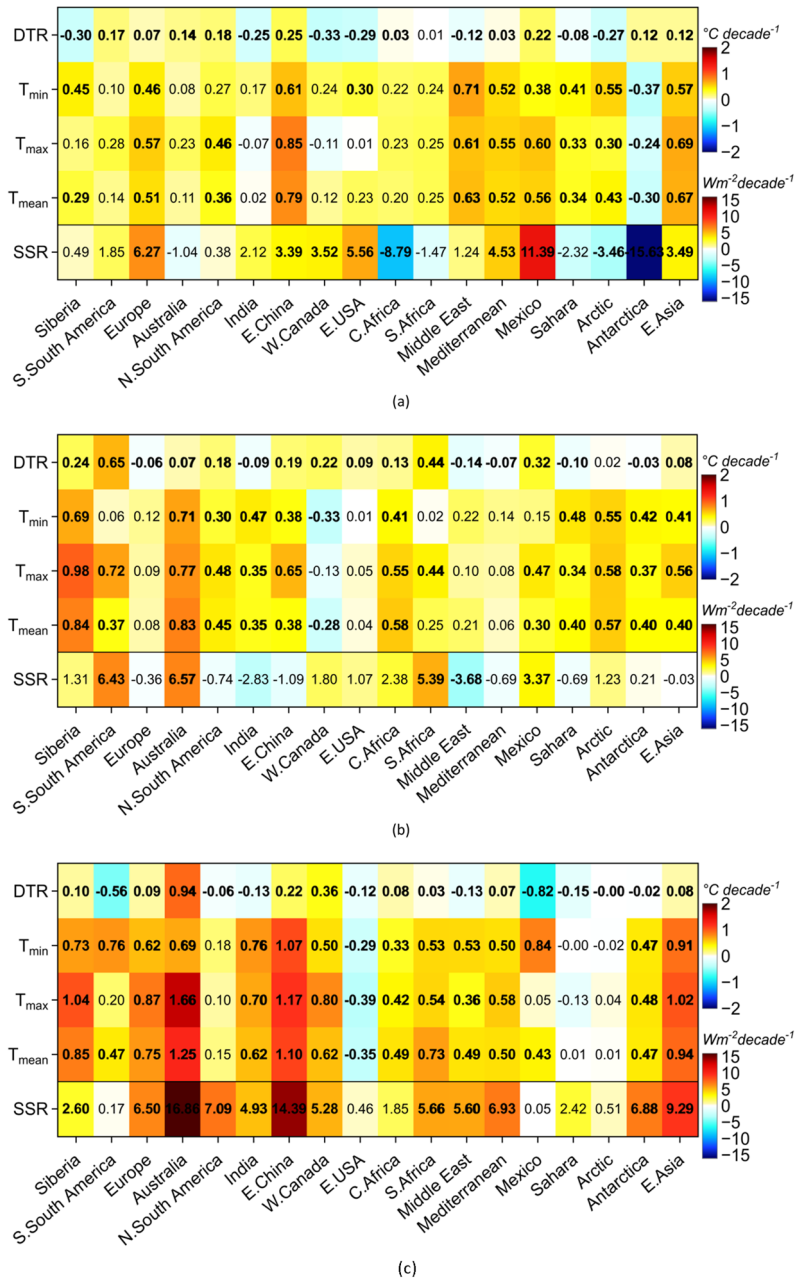


Fig. 5 Spatially averaged values of the decadal changes in T_{mean} , T_{max} , T_{min} , DTR as well as SSR over 18 world land areas (Fig. S1) for three periods: 1984–1999 (a) and 2000–2009 (b) and 2010–2018 (c). Green and blue colors indicate decreasing trends, while yellow and red colors indicate increasing trends. Trend values in bold denote that their percentage per decade changes are larger than the global land average of long-term changes

After the study of the relationship between the changes in T_{mean} (global warming) and SSR (GDB) that was found to exist in certain regions of the planet, our study also focused on a similar analysis, but for T_{max} and T_{min} , in order to distinguish between the effects of surface solar and thermal radiation on global warming, also emphasizing the comparison between them, considering that the daily course of temperature is affected differently by solar and thermal radiation. Indeed, it is very well known that T_{max} , occurring around mid-day, is largely determined by the incoming solar flux at the surface (SSR), while T_{min} at nighttime is mainly driven by the surface net longwave radiation and the associated surface radiative cooling, which is significantly affected by the ability of the atmosphere to absorb and reemit thermal radiation downwards to the surface. The anthropogenic greenhouse effect, by inducing global warming, also contributes to the observed increase of the daily T_{min} and T_{max} . Besides, T_{max} is greatly affected by the GDB. In order to explore if the T_{max} changes are more associated with the GDB or the anthropogenic greenhouse effect, we compared the magnitudes of the changes of both T_{min} and T_{max} . The stronger increase of T_{max} (affected by both GDB and anthropogenic greenhouse effect) than T_{min} (affected mainly by the greenhouse effect), such as in Europe and Mexico during 1984–1999 (Fig. 5a), could be attributed to the solar brightening. On the other hand, the weaker increase of T_{max} compared to that of T_{min} , such as in Europe and India in the 2000s (Fig. 5b), could be attributed to the global dimming. We found that in 65% of the cases (35/54), the GDB has a decisive impact on the changes of T_{max} along with the impact of greenhouse warming. These findings suggest that, as expected, the solar brightening played an important role in the observed increase of the maximum temperature. It is notable, for example, that over Europe and East Asia T_{max} is increasing with the lowest rate over the time of dominant solar dimming of the 2000s. This low surface warming rate supports the idea that solar dimming had a noticeable impact on the daily maximum surface temperature, i.e. caused its decrease, throughout the 2000s. However, in the other 19/54 cases the previous pattern (larger increase in T_{max} during brightening and smaller increase in T_{max} during dimming compared to T_{min}) is not observed, as in Australia and the Middle East during 1984–1999 and in East China in the 2000s. On the other hand, as expected, T_{min} is weakly related to the solar dimming of the 2000s over Europe, East Asia, India, the Middle East, Sahara and N. South America, exhibiting an increase, which is suggestive of a rising greenhouse forcing (Padma Kumar et al. 2007; Scherrer and Begert 2019; Wild 2009). In general, it is found that over all sub-regions the changes of T_{min} are weakly related to GDB, sometimes exhibiting different signs (Fig. 5b). Finally, changes in the diurnal temperature range (DTR, difference between T_{max} and T_{min}), were also investigated. According to ERA5, the DTR trends over the period 1984–2018 in most regions are smaller than the changes in T_{mean} , T_{max} and T_{min} , which is in line with Fig. 2 and the literature (Wild 2009). Negative trends in DTR are often associated with large increasing trends in T_{min} , while positive trends in DTR are typically linked with large increasing trends in T_{max} . However, even if SSR is strongly correlated with DTR over land, as also shown in Fig. 1d, it does not always mean that brightening leads to an increase in DTR. Changes in SSR and DTR with the same sign can occur if the brightening is strong enough and the T_{max} increases a lot and more than the T_{min} , which increases itself due to the greenhouse effect. This happened in many cases, e.g. in Europe, East Asia and East China in the 1984–1999 and 2010s and was suggested also by other studies (Makowski et al. 2009; Wild et al. 2007). However, there are also cases, such as Siberia and the Middle East during 1984–1999 and South America and Mexico in the 2010s, where weak brightening and

corresponding increase in $T_{\max}$ is accompanied by a stronger increase in $T_{\min}$, resulting in a reduction of DTR. Also, it should be noted that inconsistencies between the increases/decreases of SSR and $T_{\max}$ or DTR can exist due to the fact that other parameters affecting the maximum and minimum temperatures, such as atmospheric circulation (warm/cold advection), synoptic conditions, nighttime clouds and surface reflectivity, while inaccuracies in the calculated SSR trends could also induce inconsistencies.

3.5 Limitations of this study

One of the advantages of our study is that it examines the existence of a relationship between GDB and global warming rates at a global scale and on a long-term climatological basis. Although the evaluation of our model against reference surface station networks is satisfactory and the results of our analysis largely agree with other studies, this study is not based on direct observations, but uses (compares) RTM simulated SSR fluxes and reanalysis temperature data. The FORTH-RTM SSR fluxes, and the associated GDB (SSR trends), are derived from input data for which uncertainties have been identified, particularly for clouds (Feng and Wang 2021) and aerosols (Feng and Wang 2019). Despite the identified agreement between the sign of FORTH-RTM GDB and the corresponding one from the surface stations, there are still some necessary improvements as noted in Sect. 3.1. Additionally, another factor that could introduce uncertainties in the results of our analysis is that the model uses day-time only clouds, which is appropriate since during night-time there is no solar radiation, to estimate SSR changes and this might induce uncertainties when these SSR changes are compared with T_{mean} , which is affected by both day- and night-time clouds. Moreover, we lack strong confidence on the FORTH-RTM SSR and GDB over oceans, since a validation there is practically impossible, which restricts the confidence of our findings over land areas. Certainly, with future improvements in model input and reanalysis data, the uncertainty in the identified relationship between SSR changes and warming rates is expected to be further reduced.

4 Summary

The role of solar dimming and brightening (decadal changes in SSR) in relation to the recent global warming was examined in the present study. According to our findings, the estimated GDB phases are in line with the decadal variations of T_{mean} as well as $T_{\max}$, $T_{\min}$, and DTR over certain land areas of the globe with significant anthropogenic pollution, such as Europe and East Asia, as well as over global land. The interdecadal phases of GDB seem to complementarily modify and differentiate the rates of warming primarily caused by the monotonically increasing concentration of greenhouse gases. More specifically, since the mid-1980s, when solar brightening took place, the global land mean temperature response, originally driven by the evolving anthropogenic greenhouse effect, was rapid warming, which was decelerated or even stopped in the 2000s when solar dimming occurred and partly masked the anthropogenic greenhouse global warming. Then, during the transition from dimming to a renewed brightening in the 2010s, the greenhouse warming was no longer masked and the warming rates increased again. This relationship between GDB, namely the rates of change of SSR, and the Earth's surface temperature during the 35-year period 1984–2018 is

in line with the conclusions drawn by (Wild et al. 2007) for the decades from 1950 to 2000. Moreover, it is found that the inter-annual SSR variation also plays a role to the year-to-year changes of the Earth's surface temperature, although of course these are also driven by other factors, e.g. anthropogenic greenhouse gases warming, volcanic eruptions or ENSO (Gou et al. 2022; Santer 2014; Solomon 2011; Watanabe et al. 2014). The GDB was found to largely drive and to be more strongly related to $T_{\max}$ and secondarily to the mean surface-air temperature and the daily temperature range. The derived conclusions are more valid over the global land than ocean areas and apply to a considerable degree on the global scale. Also, in many regions where strong brightening occurred, $T_{\max}$ increased more than $T_{\min}$ (which increased primarily due to greenhouse warming), leading to an increase of DTR, confirming that GDB plays an important role in the $T_{\max}$ and DTR changes. However, the rates of brightening before and after the 2000s' dimming are not associated with proportional surface warming rates, confirming the complexity of the straight connection between SSR and surface temperature changes as well as the importance of the anthropogenic greenhouse effect as the main factor of the ongoing global warming.

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Data availability The ERA5 data used in this study can be freely downloaded at <https://Cds.Climate.Copernicus.Eu/Cdsapp#!/Dataset/Reanalysis-Era5-Single-Levels?Tab=overview>.

Code availability Not applicable.

Declarations

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