Advanced Review

Decadal changes in radiative fluxes at land and ocean surfaces and their relevance for global warming

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Anthropogenic interference with climate occurs primarily through modification of radiative fluxes in the climate system. Increasing releases of greenhouse gases into the atmosphere lead to an enhancement of thermal radiation from the atmosphere to the surface by presently about $2\,W\,m^{-2}$ per decade, thereby causing global warming. Yet not only thermal radiation undergoes substantial decadal changes at the Earth surface, but also incident solar radiation (SSR), often in line with changes in aerosol emissions. Land-based observations suggest widespread declines in SSR from 1950s to 1980s ('global dimming'), a partial recovery ('brightening') since mid-1980s, and indication for an 'early' brightening in 1930s and 1940s. No similar extended observational records are available over oceans. However, modeling studies, conceptual frameworks and available satellite-derived records point to the existence of decadal SSR variations also over oceans. SSR changes overall match with decadal variations in observed warming rates, suggesting that SSR variations may effectively modulate greenhouse gas-induced warming. Specifically, on the Northern Hemisphere, the lack of warming from 1950s to 1980s and its subsequent acceleration in the 1990s fits to the trend reversal from dimming to brightening and associated changes in air pollution levels. From the 1950s to 1980s no warming was also observed over Northern Hemispheric Oceans, in line with conceptual ideas that subtle aerosol changes in pristine ocean areas, effectively amplified by aerosol–cloud interactions, can substantially alter SSR, thereby modulating Sea Surface Temperatures. On the Southern Hemisphere, the absence of significant aerosol levels fits to the observed stable (greenhouse gas-induced) warming rates since the 1950s.

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INTRODUCTION

Radiative fluxes at the Earth surface are major determinants of ambient climate and provide the energy for a variety of vital climate processes. Variations in these fluxes therefore may play a crucial role in various environmental issues such as global warming, glacier retreat, water availability, and carbon budgeting.[1] On a more applied level, changes in the amount of solar radiation reaching the Earth surface may substantially affect agricultural production[2] and the rapidly growing market of solar power generation.[3]

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In the following, I will review the evidence for decadal changes in the radiative fluxes at the Earth surface, with emphasis on the downward fluxes of solar and thermal radiation. I assessed many of the related studies in the last (fifth) assessment report of the Intergovernmental Panel on Climate Change (IPCC AR5, Section 2.3)[4] and in earlier reviews on this subject.[1,5] In the present review, after introducing the underlying data, I will summarize some of the key findings and publications in the field, and emphasize new studies that appeared since the publication of IPCC AR5. The focus will be on changes over terrestrial surfaces, where most radiation sites are located and most of the recent analyses have been performed, but I will also discuss the evidence for changes over oceans. I will further discuss possible causes for these changes, and finish up by outlining potential resulting implications for global warming.

AVAILABLE DATA

Monitoring of radiation incident at the surface began in the early 20th century at selected locations, primarily focusing on surface solar radiation (SSR, also known as global or shortwave radiation). One of the longest records, available from Potsdam (Germany) since 1937, is illustrated in Figure 1. More widespread measurements of this quantity were initiated during the International Geophysical Year (IGY, 1957/1958). Many of these historic radiation measurements have been collected in the Global Energy Balance Archive (GEBA)[6] at ETH Zurich and in the World Radiation Data Centre (WRDC) of the Main Geophysical Observatory St. Petersburg. The accuracy of these historic measurements has been estimated in Gilgen et al.[6] at 2% on an annual basis. However, the quality of the measurements, performed predominantly under the auspices of the national weather services, is highly variable and not always well established.[6–9] Rigorous quality control is necessary to avoid spurious trends in these data and not all records are properly homogenized yet.[10] In addition, possible 'urbanization effects' in the SSR data may affect the trend magnitudes and their representativeness for larger scale areas,[11,12] even though this effect may not be as pronounced as claimed in some of the studies.[13,14]

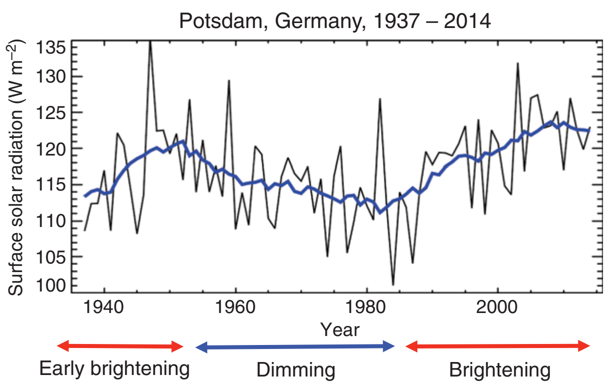

FIGURE 1 | Annual mean surface solar radiation (in W m^{-2}) as observed at Potsdam, Germany, from 1937 to 2014. Five year moving average in blue. Distinct phases of inclines (1930s–1940s, 'early brightening'), declines (1950s–1980s, 'dimming'), and renewed inclines (since 1980s, 'brightening') can be seen. Units W m^{-2}. In addition, a stabilization since around 2010 can be noted.

In the late 1980s, the necessity for a reference network of surface radiation measurements with improved and defined accuracy was recognized. As a result, the Baseline Surface Radiation Network (BSRN),[15,16] the Atmospheric Radiation Measurement Program (ARM),[17] and the US-based Surface Radiation Network (SURFRAD)[18] were established. These networks measure surface radiative fluxes at the highest possible accuracy with well-defined and calibrated state-of-the-art instrumentation at selected sites in various climate regimes. It is only with the establishment of these networks that the monitoring of the downward thermal radiation in addition to SSR was initiated at diverse sites. To date, more than 50 anchor sites in different climate regimes report their measurements to the World Radiation Monitoring Center (WRMC) hosted at the Alfred Wegener Institute in Bremerhaven[16] at high temporal resolution (1-min data) for both solar and thermal components.

Despite the increasing number of high accuracy surface radiation stations, large regions are insufficiently covered by direct surface radiation stations, such as vast areas of Africa, South America and the Maritime Continent, and particularly the entire ocean areas. Since the turn of the millennium, surface radiative fluxes are increasingly recorded on automated buoys.[19] The quality of these unmanned sites is, however, not well established and not at the level of the BSRN measurements. Records from buoys are typically still fairly short, covering a few years only and therefore cannot yet be used to infer decadal changes in radiative fluxes over oceans.

Satellite-derived fluxes can provide a near global picture, going back to the early 1980s at most.[20–22] As the surface fluxes cannot be directly measured from satellites, they have to be inferred from measurable top-of-atmosphere signals using in addition empirical or physical models to remove atmospheric perturbations. Satellite-inferred surface fluxes may also suffer from potential inhomogeneities due to changes in satellites, viewing geometries, inaccurate positioning, or sensor degradation, particularly in the earlier records.[23]

To enlarge the limited number of direct SSR observations in space and back in time, more widely measured meteorological quantities have been proposed as proxies for SSR changes. SSR changes thus have been inferred from observed changes in sunshine duration, diurnal temperature range (DTR), or pan evaporation. There is increasing evidence that sunshine duration records are not only able to capture variations in cloudiness, but may also contain signals from varying concentrations of atmospheric aerosols,[24–27] and thus may incorporate particularly valuable information on the causes of long-term SSR variations.

VARIATIONS OF SOLAR RADIATION OVER LAND SURFACES

Variations in the Second Half of the 20th Century

The first pioneering studies pointing to decadal variations in observational SSR records appeared in the early 1990s covering the period from the 1950s, where widespread direct measurements of SSR began, up to the late 1980s.[6,28–30] These studies, as well as a number of others as reviewed in Wild,[1] noted a general decrease of SSR at widespread land-based locations over this period. This phenomenon has become popularly known as 'global dimming.'[2] Follow-up studies using SSR records updated to the 2000s found, however, a trend reversal and partial recovery at many of these sites since the 1980s (see also Figure 1 as an illustrative example; Ref 1 and references therein). The term 'brightening' was thereby coined to emphasize that the widespread decline in SSR and associated global dimming no longer continued after the 1980s.[31] Particularly in industrialized areas, the majority of the sites showed some recovery from prior dimming, or at least a leveling off, between the 1980s and 2000. The brightening has been somewhat less coherent than the preceding dimming, with trend reversals at widespread locations, but still some regions with continued decrease, such as in India.[1,32]

Since AR5, new evidence for brightening based on direct observations has been documented at 13 sites in Spain for the period 1985–2010.[33] At the same time, diffuse radiation measured at these sites has overall decreased, indicative of a reduction of clouds and/or aerosols in Spain over this period. Brightening over the period 1988 to 2012 has also been noted at four high-elevation sites on the island of Maui, Hawaii during the dry season (May–October), whereas trends in the wet season were not significant.[34] Further since AR5, the various studies that noted a strong dimming in China since the 1960s and a leveling off since the 1990s have been assessed in the study of Wang and Yang.[35] In a regionally related study by You et al.,[36] substantial overall dimming of SSR, with a slight recovery during the 1990s has also been recently documented at sites in the Tibetan plateau over the period 1960–2009.

Evidence for SSR dimming/brightening comes also from related, more widely measured meteorological variables which have been used as proxies to infer decadal SSR changes in areas poorly covered by direct radiation measurements. For example, decadal variations in pan evaporation and sunshine duration measurements provide independent indication for dimming and subsequent brightening in various regions of the globe, such as in Europe, China, the Former Soviet Union, South America, New Zealand, and on Pacific islands.[1,37–43] Since my assessment in IPCC AR5, a number of studies analyzing changes in sunshine duration records have provided evidence for dimming and brightening in formerly unexplored areas of the globe: The occurrence of dimming and subsequent brightening phases has been identified in the Gulf region, based on 29 stations in Iran with sunshine duration records over the period 1961–2009,[44] and on the Bahrain International Airport over the period 1968–2010.[45] Using 104 sunshine duration records in Italy, Manara et al.[46] noted a distinct brightening from the 1980s onward, whereas the prior dimming phase was more evident in southern than in northern Italy. The recently published extended sunshine duration record from the Izana Atmospheric Observatory on Teneriffe also indicates substantial dimming from the 1950s to the 1990s, and subsequent brightening on the Canary Islands.[47] The various studies using sunshine duration records to document dimming since the 1950s and a stabilization in the 1990s in China were recently compiled by Wang and Yang.[35] Sunshine duration records have in addition been used to document brightening in the Taklimakan Desert over the period 1980–2009.[48] Attempts have further been made to derive quantitative changes in energy fluxes from the observed changes in sunshine duration, as demonstrated, e.g., with sunshine duration records in Switzerland,[49] Spain,[50] and the Canary Islands.[47]

The widely available data on the DTR (difference between daily maximum and minimum temperature) were shown to contain information on decadal changes in SSR, as they allow to disentangle the solar and thermal surface radiative heating.[44,51–55]

Because SSR is only present during daytime, it affects the daily maximum temperature more than daily minimum temperature, the latter being mainly determined by the thermal radiative exchanges. DTR observations over global land surfaces display overall a distinct decrease from the 1950s to 1980s, caused by increasing daily minimum temperatures and declining daily maximum temperatures, the latter may reflecting SSR dimming[52] (cf. Figure 2). However, since the mid-1980s, DTR no longer declined, but stabilized, in line with the transition from dimming to brightening where daily maximum temperatures were no longer attenuated by the dimming.[52] This distinct signature in the global terrestrial DTR evolution may provide additional indication for a large-scale dimension of the dimming/brightening phenomenon. Since AR5, Wang and Dickinson[55] further investigated this issue in detail and showed that the variability of DTR is consistent with the variability of SSR records from GEBA at timescales from monthly to decadal.

Significant areas of the globe remain uncovered even when proxy estimates are considered in addition to the direct measurements of SSR, which hampers a true global assessment. Satellite-derived products, however, can provide a near global picture. Such estimates are available since the early 1980s.[20–22] Available satellite-derived products qualitatively agree on a brightening from the mid-1980s to 2000 averaged globally and over oceans, on the order of 2–3 W m^{-2} per decade,[1,20–22] and also suggest a brightening over the area covered by the geostationary satellite Meteosat.[57] Averaged over global land, however, trends are positive or negative during this period depending on the respective satellite product.[1]

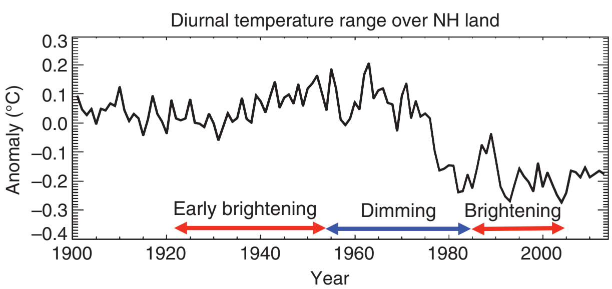

FIGURE 2 | Annual mean anomalies of diurnal temperature range averaged over Northern Hemispheric land surfaces, from 1900 to 2013. Variations of diurnal temperature range may provide a useful proxy for variations in surface solar radiation over extended temporal and spatial scales. Data source: CRU TS3.22.[56] Anomalies are shown with respect to 1961–1990 mean. Units °C. Updated from Wild[1] to 2013.

Variations Further Back in Time

The records of direct SSR observations extending farthest back in time in Europe are Stockholm (Sweden, since 1923), Wageningen (Netherlands, since 1928), Davos (Switzerland, since 1936), Potsdam (Germany, since 1937, see Figure 1), and Locarno (Switzerland, since 1940). These sites indicate increasing SSR in their early parts of the records during the 1930s and 1940s,[1,58] also known as ‘early brightening’ (cf. Figure 1).

As the number of direct observations is very limited in the first half of the 20th century, proxy information becomes even more important to get an idea of the SSR variations during this period. Using sunshine duration records as a proxy for SSR variations Sanchez-Lorenzo et al.[39] found indication for an early brightening at the beginning of their record consisting of 79 sites in Western Europe covering the period 1938–2004, thus confirming the limited evidence for an early brightening in Europe from direct observation with a spatially denser network. Based on 11 stations with extended homogeneous sunshine duration records in Switzerland covering the entire 20th century in Switzerland, Sanchez-Lorenzo and Wild[49] found no indication for relevant SSR changes between the 1900s and the 1930s, but a subsequent strong and brief increase in the 1940s.

Since AR5, more evidence for a widespread ‘early brightening’ has been provided in the literature. Manara et al.[46] found some indication of an early brightening in Italy in the beginning of their sunshine duration record starting in 1936, although data availability is low from this period. An overall increasing SSR over the first half of the 20th century can also be noted in a recent extension of the Potsdam SSR record (shown in Figure 1) further back in time by Stanhill and Ahiman,[59] inferred from sunshine duration measurements performed in Potsdam since 1893. Sunshine recorders also suggest a brightening between the 1930s and the early 1950s on the Canary Islands at the Izana station,[47] thus extending the area with documented early brightening into the North Atlantic. Atmospheric clear sky transmission calculated from the longest stationary pyrheliometer record, located at the Physikalisch-Meteorologisches Observatorium Davos (PMOD) covering the years 1909 to 2010, show an indication for an early brightening up to 1930 in the direct clear sky solar radiation, but not thereafter.[60] No significant changes in direct clear sky solar radiation were found in the pyrheliometer record from Madrid between 1911 and 1928, except for a strong signature of the Katmai volcanic eruption in 1912/1913.[61]

Thus, since AR5 more indications for a widespread early brightening in the 1930s and 1940s under all sky conditions emerged from sunshine duration measurements, while the limited pyrheliometer measurements provide no indications for an increased clear sky transmission in this period.

I argued in a previous publication[1] that the extended DTR records may be able to provide useful additional information on large-scale SSR variations back to the early 20th century. Figure 2 (updated from Ref 1) displays the evolution of DTR averaged over Northern Hemispheric land surfaces over the entire 20th century. A decline in DTR, caused by a decrease in daily maximum and increase in daily minimum temperatures, and thus indicative for SSR dimming, is primarily seen between the 1950s and 1980s. Before the 1950s, no evidence for a decline can be seen, and thus also no evidence for an SSR dimming, which would reduce DTR due to the preferential attenuation of daily maximum temperatures. Rather a slight increase in DTR can be seen in Figure 2 in the 1930s and 1940s, caused by a somewhat stronger increase in daily maximum than minimum temperatures, and thus indicative of an 'early brightening.' Therefore, the early brightening may have affected not only Europe, but also hemispheric scales.[1]

While we can try to stretch our knowledge on SSR variations inferred from related historic meteorological measurement at most back to the late 19th century,[62,63] no information on SSR variations is available from before the instrumental period. Promising attempts are currently under way to reconstruct SSR variations from the information contained in tree rings. Dorado Liñán et al.[64] identified SSR as the main driver of $\delta^{13}C$ changes in tree-rings in northeast Spain, and demonstrated the potential of this method to reconstruct SSR changes over the past 600 years. Similarly, Stine and Huybers[65] proposed tree ring densities as means for the reconstruction of historic SSR changes, based on their notion that arctic tree ring densities can act as recorders of variations in light availability.

Recent Variations Since 2000

Updates on the SSR evolution beyond the year 2000 show mixed tendencies. Overall, the direct observations suggest that brightening is less distinct after 2000 than in the 1990s. Brightening continued beyond 2000 at sites in Europe and the United States, but leveled off at Japanese sites, and shows some indications for a renewed dimming in China after a phase of stabilization during the 1990s, while dimming persists throughout in India.[5,66,67] The sunshine recorders in Iran and Bahrain indicate also a trend reversal into a renewed dimming in the Gulf region after 2000.[44,45] Recent updates of 56 homogenized European SSR records from GEBA to 2012 show a continuation of the brightening over Europe over the first decade of the new millennium, with a tendency toward stabilization in the most recent years,[68] as also seen in the Potsdam record in Figure 1. Extensions of satellite-derived SSR beyond 2000 in two products indicate globally tendencies toward an overall renewed dimming for the first years after 2000.[22,69,70] However, the most up-to-date satellite-derived SSR product (surface CERES-EBAF[71]), does not indicate a globally significant trend over the period 2001–2012.[70] Over the area covered by the geostationary Meteosat satellites (Meteosat disk), Posselt et al.[57] inferred in an extension of the SSR record of the Satellite Application Facility on Climate Monitoring (CM SAF) a statistically significant positive trend of +3.4 $W\,m^{-2}$ per decade over the period 1994–2010, and a trend of +4.4 $W\,m^{-2}$ per decade for Europe. Also the Northern Hemispheric land mean DTR record in Figure 2, which I updated to 2013 for the present review using the CRU TS3.22 dataset,[56] does not show obvious indication for a large-scale SSR dimming in the early 2000s. Dimming would reduce DTR due to the stronger attenuation of daily maximum than minimum temperatures, yet DTR appears to be fairly stable so far since 2000, in contrast to the strong DTR decline in the dimming phase between the 1950s and 1980s[1] (Figure 2).

Causes of the Variations

The decadal variations in SSR as described above cannot be explained by changes in the luminosity of the Sun, because these are at least an order of magnitude smaller[72] and uncorrelated. The observed SSR variations therefore have to originate from alterations internal to the climate system that affect the transparency of the atmosphere for solar radiation. This transparency depends on the presence of clouds, aerosols, and radiatively active gases, as discussed briefly in the following.

Role of Radiatively Active Gases

From the radiatively active gases in the atmosphere, water vapor has the largest potential to modify solar radiation. However, various studies suggest that changes in water vapor as observed are not able to explain the magnitude of the observed SSR trends.[1,57,73,74] Changes in concentration of other radiatively active atmospheric gases on SSR were shown to have similar (ozone) or smaller effects (NO_2, H_2O, CH_4, and CO_2) as water vapor.[73] The changes in radiatively active gases therefore may only play a minor role in the explanation of the observed changes in SSR.[74] This points to aerosol and clouds as the remaining major suspects at the origin of the decadal SSR variations.

Role of Clouds and Aerosols

Changes in cloud amount and cloud optical properties can substantially alter SSR. But also aerosols can attenuate SSR, by scattering and absorbing solar radiation (direct effect), or indirectly by cloud mediated effects, through their ability to act as Cloud Condensation Nuclei (CCNs), thereby increasing cloud reflectivity and lifetime (first and second indirect effects; e.g., Refs 75,76). Both direct and indirect aerosol effects act toward reducing SSR with increasing aerosol levels. The relative importance of clouds, aerosol as well as their interactions for the explanation of the observed SSR variations have been widely disputed, but this issue is far from being settled. Cloud cover changes effectively modulate SSR on an interannual basis, but their contribution to the detected longer-term (multidecadal) SSR trends is not always obvious. While cloud cover changes were found to explain the multidecadal trends in some areas such as New Zealand[41] or Alaska,[77] this is not always the case particularly in relatively polluted regions.[1,38,78–80]

In recent decades, at various locations, SSR changes have not only been observed under all sky conditions, but also under clear skies, pointing to a prominent role of atmospheric aerosols (Ref 1 for a review). Anthropogenic air pollution has lead to substantial changes in atmospheric aerosol levels over past decades.[81–83] Particularly, anthropogenic emissions, such as sulfur and black carbon, increased from the 1950s to the 1980s, but decreased thereafter on the Northern Hemisphere.[81] This decrease is attributed to the implementation of air quality measures in industrialized countries as well as to major economic crises (breakdown of communist system in Eastern Europe and Russia in late 1980s, Asia financial crisis in 1990s). These emission histories fit with the observed dimming/brightening tendencies and suggest that anthropogenic air pollution may play a significant role in the explanation of decadal SSR variations.[82]

Since AR5, additional arguments for both aerosol and clouds as major contributors to the SSR variations were provided in the literature. An assessment of the abovementioned studies focusing on the early part of the 20th century suggests that all sky and clear sky tendencies from reconstructions and atmospheric transmission measurements, respectively, are not overly consistent, indicative of a prominent role of clouds for the explanation of the 'early brightening.' Based on an analysis of sunshine duration records at five stations in different climate regimes, Stanhill and Achiman[84] recently emphasized the importance of changes in cloud cover rather than anthropogenic aerosols for the explanation of the SSR variations. The decline in SSR in Bergen, Norway, in the 1970s and 1980s has been related to increased frequencies of storms and associated cloudiness, whereas the increasing SSR at this site since 1990 is not accompanied by decreasing cloudiness, yet by a decrease in aerosol optical depth (AOD) from 0.15 to 0.10.[85] The strong brightening at the high elevation sites in Hawaii during the dry season has also been related to changes in cloudiness rather than changes in aerosol burden.[34] Mateos et al.[86] estimated that for the strong brightening over the Iberian Peninsula between 2003 and 2012 three fourths of the SSR trend is explained by clouds, while one fourth is related to aerosol changes. An assessment of SSR trends in the CM-SAF satellite-derived product shows a good agreement compared to surface observations over Europe for the 11-year period 1994–2005 considered as homogeneous.[10] The fact that the SSR retrieval algorithm in the CM-SAF product does not consider time varying aerosols suggests that changes in cloudiness alone may be able to explain the changes in SSR over this 11-year period. Thus, for comparatively short periods on the order of one decade these new studies emphasize a dominant role of clouds. However, on a longer period of 30 years (1980 to 2010) Nabat et al.[87] suggested that aerosol changes can explain around 80% of the brightening over Europe, based on simulations with a regional aerosol climate model driven with reanalysis data, with the direct aerosol effect dominating the magnitude of the simulated brightening. From long-term records of direct solar radiation at a high altitude site in the Tatra Mountains (Poland) away from local sources, increases in AOD from 1964 to 1983 and subsequent declines from 1984–2003 were inferred, that fit to the SSR dimming and brightening, respectively.[88] Dimming and brightening has also been consistently detected at the Izana station on the Canary Islands both under all sky and clear sky conditions, indicative of aerosol as a major contributor.[47] The recent strong brightening seen in all sky and clear sky US records between 1995 and 2010[67,89] has been associated with decreasing aerosol burdens, particularly in the Eastern United

States,[90] even though this association is confounded by an observed increase in clear sky diffuse SSR over the same period. A possible explanation for the latter might be an increase in high level cirrus clouds due to increasing air traffic over the United States.[90] Increasing anthropogenic aerosol loading is also regarded as the most plausible explanation for China's multidecadal dimming in a recent assessment of the comprehensive literature by Wang and Yang.[35] Persad et al.[91] suggested in a modeling study with the Geophysical Fluid Dynamics Laboratory's atmospheric general circulation models, that trends in aerosol absorption may drive a large portion of East Asian clear-sky solar dimming since the 1960s. Another modeling study based on the ECHAM-HAM model emphasized the importance of aerosols for SSR dimming in China and suggests that the simulated aerosol-induced SSR dimming over China fits well to the observed trends from GEBA.[92] Kudo et al.[80] suggested that brightening in Japan has been caused by changes in aerosol optical properties rather than by cloud effects, based on 14 sites with long term records of direct and diffuse radiation that indicate decreasing and increasing trends in inferred AOD and single scattering albedo, respectively, yet no trend in cloud effects. Updates on global sulfur emissions beyond 2000 indicate a renewed increase of total global sulfur emissions after the year 2000, because the rapidly growing emissions in Asia increasingly outweigh the decreasing emissions in the western world.[82] This fits to the lack of a clear overall brightening signal and indications for renewed dimming in China after 2000.[66]

Overall, the majority of the studies since AR5 thus appear to support the general picture that since the mid-20th century aerosol effects dominate on the longer (multidecadal) timescales, whereas cloud effects become more relevant on shorter decadal/subdecadal timescale. However, regional deviations do occur, and the smaller the station sample, the more also circulation-induced changes in cloudiness may come into play. Clouds appear to have also played a significant role in the 'early brightening' in the first half of the 20th century with lower aerosol emissions. Generally, the relative importance of clouds versus aerosols for the explanation of the decadal SSR variations appears to have shifted toward aerosols during the course of the 20th century. This is also for example reflected in a long-term sunshine duration record in Athens covering the period 1897–2011, where sunshine duration until the mid-20th century is strongly related to cloudiness, whereas after the mid-20th century it agrees with emission variations.[93] This is also similarly seen in the extended sunshine duration records in Switzerland,[49] where cloud cover changes appear to explain the major part of the decadal variability from 1885 to the 1970s, whereas from the 1970s to present sunshine duration and cloud cover trends diverge, indicative of a more prominent role of aerosol in recent decades.[49]

However, clouds and aerosols may not be seen as entirely independent influential factors, but can also be intrinsically linked through aerosol–cloud interactions. I have proposed a conceptual framework, suggesting that aerosol-induced dimming and brightening trends may be amplified or dampened by aerosol–cloud interactions depending on the prevailing pollution levels.[1,5] In pristine regions, small changes in CCNs can have a much bigger impact on cloud characteristics than in polluted environments,[94,95] because clouds show a non-linear (logarithmic) sensitivity to CCNs.[96] Additional CCNs due to air pollution in pristine regions may therefore be particularly effective in increasing the formation, lifetime and albedo of clouds, which all act toward a reduction of SSR through enhanced cloud shading. Thus, aerosol–cloud interactions in pristine environments may cause a strong amplification of dimming (brightening) trends induced by small increases (decreases) in aerosols. This implies that dimming/brightening could be substantial even in areas far away from pollution sources, such as over ocean and remote land areas, where subtle changes in background aerosol levels induced by long-range transports can effectively alter SSR through cloud modifications.[1,5] This concept is supported for example by the notion of Parungo et al.[97] that total cloud amount over oceans overall increased during the dimming period (1952–1981) by 1.5 % according to synoptic observations compiled in the Comprehensive Ocean–Atmosphere Dataset (COADS), with a largest increase over Northern Hemispheric midlatitude oceans, where continental anthropogenic emissions are largest.

In polluted regions, however, cloud microphysics effects tend to saturate with logarithmic sensitivity to CCNs, whereas the direct extinction of SSR by aerosols becomes more relevant, which increases proportionally to the aerosol loadings. Absorbing pollution layers further heat and stabilize the atmosphere, and attenuate SSR and related surface evaporation. This generally leads to a suppression of convective cloud formation, and dissolves clouds in layers heated by absorbing aerosol. The associated reduced cloud shading may partly counteract the aerosol-induced reduction of SSR in heavily polluted areas. Thus, in contrast to pristine areas, aerosol–cloud interactions may tend to dampen dimming/brightening trends induced by direct aerosol effects.[1,5] This concept may help to explain for example the seemingly counterintuitive notion of observed declines in both cloud amount and SSR in China in the second half of the 20th century,[38] where the SSR declines due to massive aerosol increases may have been partially dampened by suppressed cloud formation.

VARIATIONS IN SOLAR RADIATION OVER OCEAN SURFACES

Unlike over land, no long-term monitoring radiation sites exist in maritime environments, which could give direct evidence for possible multidecadal SSR variations over oceans. Also, extended measurements of other related climate variables, which are useful proxies for SSR variations over terrestrial surfaces as outlined above, are largely absent over oceans. The only observed variable with comprehensive spatial and temporal coverage in maritime areas which may incorporate a signature of SSR variations is sea-surface temperature (SST) as discussed further below. Thus, with respect to multidecadal variations of radiation at ocean surfaces, we have to rely on a combination of conceptual ideas, limited *in situ* observations, modeling results, and for the more recent decades satellite-derived products.

In this respect, there is some evidence for distinct aerosol trends also in remote locations far away from the pollution sources that match with dimming/brightening, based for example on black carbon and non-sea-salt sulfur in ice cores in Greenland,[98] and *in situ* observations in the Canadian Arctic.[99] Declines in AOD over the world oceans since the early 1990s inferred from satellites may be indicative of a reduction in the global background aerosol level in recent decades,[100] and were consistently found in different satellite-derived products[101] as well as in an analysis which discarded the effect of volcanic aerosols on these trends.[102] Atmospheric transport modeling studies further point to a large-scale distribution of anthropogenic aerosol pollutants over the entire Northern Hemisphere,[103] thus also affecting the ocean areas. Based on simulations with a climate model with sophisticated interactive aerosol treatment (ECHAM-HAM), Dallafior et al.[104] showed that anthropogenic aerosol plumes can reach from their source regions on the continents far out into the oceans, causing significant changes in AOD also in remote oceanic regions. Averaged over entire ocean surfaces, they noted an overall simulated SSR dimming due to anthropogenic aerosol of $-3.2\ \mathrm{W\,m^{-2}}$ between the 1870s and the 1990s, with a much larger decline over the Northern Hemispheric ($-6\ \mathrm{W\,m^{-2}}$) than over the Southern Hemispheric oceans ($-1.4\ \mathrm{W\,m^{-2}}$), in line with hemispheric asymmetry in emission histories. They further note a significant aerosol-induced brightening over Northern midlatitude oceans in the last two decades of the 20th century in their simulations, which matches the decreasing emissions in developed countries located predominantly in these latitudes. A substantial impact of anthropogenic aerosols on SSR changes has also been inferred by Booth et al.[105] over the North Atlantic in a modeling study based on the HadGEM2 Earth System model. In their simulations, SSR declined by about $-4\ \mathrm{W\,m^{-2}}$ since preindustrial times over the North Atlantic, with aerosol–cloud interactions (indirect aerosol effects) responsible for 80% of the SSR changes.

Thus, there are indications from *in situ* observations, remote sensing and modeling efforts that anthropogenic aerosol can be transported over long distances into remote areas and far out in the oceans. The potential for a modification of SSR by aerosols and their interactions with clouds is thus given also over ocean areas, where a subtle change in aerosols in these pristine areas may modify cloud amount and reflectance and thus alter SSR according to the conceptual framework outlined above.[1,5] This potential has been further evidenced by Goren and Rosenfeld[106] who used continuous geostationary satellite observations to show that ship emissions can induce transitions from broken to closed marine stratocumulus cells over large areas. They argued that anthropogenic aerosols transported from continents may explain the formation of large closed cell areas over the oceans that are presently not recognized as originated by aerosol perturbation. They further estimated that the added radiative forcing from the closed cells, depending on latitude and season, could exceed $100\ \mathrm{W\,m^{-2}}$ mainly due to the enlarged cloud cover in the closed stratocumulus cells. This mechanism may thereby have also the potential to effectively amplify the impact of subtle long-term aerosol changes on SSR over the oceans. Parungo et al.[97] further evidenced that variations in ocean cloudiness appear to be in accord with the temporal trend and geographic distribution of SO_2 emissions. This was based on their notion of an increase in total cloud amount in synoptic oceanic cloud observations during the dimming period 1952–1981, which was twice as large over Northern than Southern Hemispheric oceans, with a maximum increase in altocumulus and altostratus clouds over Northern Hemispheric midlatitude oceans.

From the above discussion, it appears thus plausible to expect aerosol-induced multidecadal variations in SSR not only over land, but also over ocean areas. As stated earlier, unlike over land, we lack the direct observational SSR records to underpin this hypothesis. Only since the 1980s, satellite-derived records of SSR over ocean areas are available. Although SSR trends inferred from satellites have well-known limitations, we can expect their reliability to be higher over oceans than over land for two reasons: (1) the direct aerosol effects, which are difficult to infer from space, become less important over oceans than over land, and (2) aerosol-induced changes in cloud properties which are considered particularly important over remote areas according to the above frameworks, are from satellites easier to identify over oceans than over land due to the darker and more homogeneous background albedo of the ocean surface. Accordingly, also the overall SSR trends of different historic satellite derived products (going back to the early 1980s) are more consistent over oceans than over land.[1] They estimate an increase of SSR over oceans of +2.4 W m^{-2} per decade (1983–2001)[20] or +2.7 W m^{-2} per decade (1984–2000),[21] thus suggesting a brightening also over the oceans during this period. This would fit to the general picture of an overall reduction of aerosol emissions and background aerosol levels over oceans during this period and their effective amplification of SSR changes through aerosol–cloud interactions as outlined above.

CHANGES IN THERMAL RADIATION

Thermal radiation, also known as long-wave, terrestrial, or far-infrared radiation is sensitive to changes in atmospheric greenhouse gases, temperatures, and humidity.[107] The downward thermal radiation at the Earth surface is a particularly interesting quantity in the discussion of anthropogenic climate change, as it is most directly affected by the increasing release of greenhouse gases into the atmosphere. Increasing levels of atmospheric greenhouse gases enhance the flux of thermal radiation from the atmosphere to the Earth's surface, thereby causing global warming.[108] Compared to SSR, downward thermal radiation is measured at far fewer sites, and not as far back in time. Downward thermal radiation observations have become available only since the early 1990s at a limited number of worldwide distributed sites from the BSRN network. As an illustration, the evolution of the annual downward thermal radiation measured since 1994 at the BSRN site located at the South Pole is shown in Figure 3. From the 12 earliest BSRN records, Wild et al.[109] determined an overall increase of +2.6 W m^{-2} per decade over the 1990s, in line with model projections and the expectations of an increasing greenhouse effect. Wang and Liang[110] estimated an increase in downward thermal radiation of +2.2 W m^{-2} per decade over the period 1973–2008 from globally available terrestrial observations of temperature, humidity and cloud fraction using empirical relations. Prata,[111] combining observed temperature and humidity profiles from the worldwide radiosonde stations with radiative transfer calculations, estimated a slightly lower increase of +1.7 W m^{-2} per decade for clear sky conditions over the earlier period 1964–1990. Philipona et al.[112] and Wacker et al.[113] noted increasing downward thermal fluxes in the records of the Swiss Alpine Surface Radiation Budget (ASRB) network since the mid-1990s. For mainland Europe, Philipona et al.[114] inferred an increase of downward thermal radiation of +2.4 to +2.7 W m^{-2} per decade for the period 1981–2005. For the present review, I revisited the longest records of downward thermal radiation currently available from BSRN. From 25 records covering altogether 353 years (including, e.g., the South Pole record displayed in Figure 3), I obtained an overall mean increase in downward thermal radiation of +2.0 W m^{-2} per decade since the early 1990s. Three quarter of these BSRN sites showed increasing trends (19 sites in total, 9 of them significant), while one quarter showed negative trends (6 sites, 3 significant). This change in downward thermal radiation quantitatively agrees very well with the respective change calculated by the latest generation of global climate models used in IPCC AR5. In their simulations, including all known relevant climate forcings ('all forcings experiments') the global mean

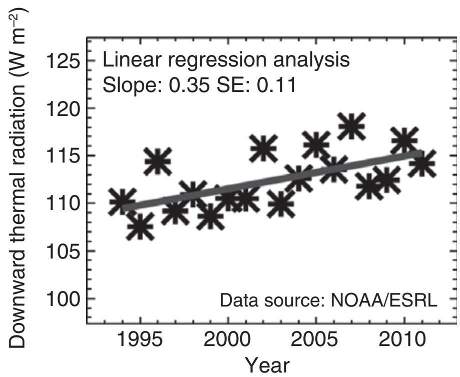

FIGURE 3 | Annual downward thermal radiation at the surface measured at the BSRN site South Pole. A linear regression analysis has been applied. As at the majority of the BSRN sites, an increase can be seen since the initiation of the BSRN network starting from the early 1990s. Units W m^{-2}.

downward thermal radiation shows a very similar increase of around +2 $W\,m^{-2}$ per decade over the same period. Thus, the limited observational evidence on downward thermal radiation changes matches well with our understanding of the functioning of the greenhouse effect and its representation in climate models. Based on these considerations I argue here that the flux of downward thermal radiation at the Earth's surface is presently enhanced by around +2 $W\,m^{-2}$ per decade globally as a consequence of anthropogenic releases of greenhouse gases into the atmosphere. This corresponds to the rate of energy increase at the Earth's surface due to the enhanced greenhouse effect that is causing global warming.

IMPLICATIONS FOR GLOBAL WARMING

The changing solar and thermal radiative fluxes reaching the ground may have a profound impact on various aspects of global change (see Ref 1 for an overview). With the limited space available here I have to restrict the focus to one particular aspect, namely their potential impact on global warming.

I pointed out in a paper in 2007[52] that the period with a lack of warming over global terrestrial surfaces between the 1950s and 1980s coincided with the phase of declining SSR, which may have largely offset the additional energy obtained at the Earth surface from the greenhouse-gas induced increase in downward thermal radiation over this period. Since the 1980s, with the transition from dimming to brightening, the increasing downward thermal radiation (as evidenced in the section above) may have no longer been compensated by SSR declines, in line with the observed rapid warming.[52]

The hypothesis that SSR variations could have contributed to these multidecadal variations in the warming rates got further support from the separate analysis of trends in daily maximum and minimum temperatures, and the notion that the lack of warming between the 1950s and 1980s over global land surfaces has primarily been due to a slight decrease in daily maximum temperature, whereas the daily minimum temperature showed an increase over the same period.[52] This fits to the hypothesis that the warming was suppressed by SSR dimming, as SSR obviously affects the daily maximum temperature much more than daily minimum temperature. I estimated that SSR dimming has dampened the greenhouse-gas induced temperature rise on the order of 60–70% between 1958 and 1985.[52] More recently Wang and Dickinson[55] estimated that SSR caused a reduction of more than 0.2°C in mean temperature during May–October from the 1940s through the 1970s, and a reduction of nearly 0.2°C in mean air temperature during November to April from the 1960s through the 1970s. Since the cease of SSR dimming in the 1980s, the temperature rise has been more forced by thermal (greenhouse-induced) radiation, as reflected in daily minimum and maximum temperatures increasing at similar rates and a near-constant DTR evolution as a consequence[52,55] (cf. Figure 2).

Global climate models do neither reproduce the substantial decline in DTR shown in Figure 2 nor its distinct trend reversal in the 1980s, despite the inclusion of all known natural and anthropogenic forcings over the 20th century in so called historic 'all forcings' simulations.[115] Climate models further tend to underestimate the suppression of warming through dimming between the 1950s and 1980s over global land surfaces in the simulations, and simulate a stronger warming than observed during this period.[115] However, for the more recent decades the models underestimate the rate of global warming, indicative of a lack of brightening.[115] Indeed, climate models appear to underestimate SSR dimming and brightening when compared to the direct surface observations in the historic 'all forcings' simulations.[116–118] This still applies for the climate models used in the latest (fifth) assessment of the Intergovernmental Panel on Climate Change (IPCC-AR5).[118] Potential explanations for these model deficiencies include the substantial uncertainties in historic emission inventories and associated aerosol burdens in the atmosphere, which may not consider the full extent of decadal variations, the inadequate parameterization of the direct and indirect aerosol forcings in the models as well as a general underestimation of the unforced natural variability.[1,116–118]

I further pointed out in an earlier publication that the pronounced lack of warming from the 1950s to the 1980s and subsequent rapid warming until 2000 was most prominently seen on the Northern Hemisphere, whereas, in contrast, on the Southern Hemisphere a steady gradual warming was observed throughout these years[5]. This is illustrated in Figure 4, where I extended the Northern and Southern Hemispheric temperature records shown in Ref 5 up to 2014 for the present study, based on the latest dataset from the Climate Research Unit of the University of East Anglia (HadCRUT4). The same general picture remains: On the Northern Hemisphere, largely differing temperature trends appear between the dimming period 1950s to 1980s on the one hand, which shows overall a slight cooling, and

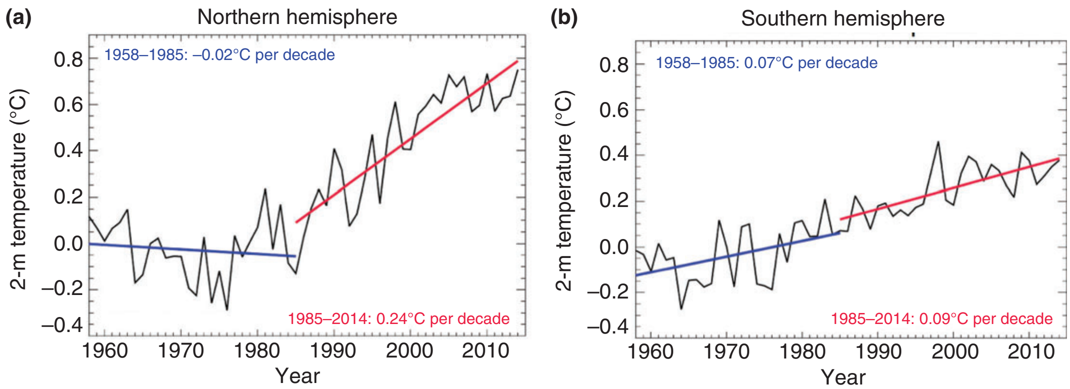

FIGURE 4 | Annual 2-meter temperature anomalies observed on the (a) Northern and (b) Southern Hemispheres. Observations from HadCRUT4, anomalies with respect to 1960–1990. Linear trends over the dimming phase (1950s–1980s) in blue, over the brightening phase (1980s–2000s) in red. On the polluted Northern Hemisphere, no warming is observed during dimming with strong aerosol increase whereas rapid warming is observed during subsequent brightening with aerosol decrease. On the more pristine Southern Hemisphere, with greenhouse-gases as sole major anthropogenic forcing, observed warming is similar during both periods. Updated from Wild.[5] Units °C.

the subsequent brightening period from the 1980s onward on the other hand with a substantial overall warming (Figure 4(a), updated from Ref 5). In contrast, on the Southern Hemisphere, warming rates in the 1950s–1980s period and in the more recent 1980s–present period are remarkably similar (Figure 4(b), updated from Ref 5). This fits well to the asymmetric hemispheric evolution of anthropogenic air pollution which strongly increased from the 1950s to the 1980s and declined thereafter on the Northern Hemisphere, while pollution levels on the Southern Hemisphere were an order of magnitude lower and steadily increased with no trend reversal.[5,81] This again points to a possible large-scale influence of aerosol-induced SSR dimming and brightening on global warming.

Climate models, however, do not fully reproduce these characteristic differences in interhemispheric warming rates either.[5] On the Northern Hemisphere with substantial aerosol loadings, the average warming simulated by the models in 20th century ‘all forcings’ experiments is too strong during dimming, and too weak during subsequent brightening as noted above for the global scale. This points again to a potentially insufficient representation of the processes causing dimming/ brightening in the models to adequately dampen and enhance greenhouse warming, respectively. In contrast, on the Southern Hemisphere, where aerosol pollution is much smaller and greenhouse-gas forcing dominates, the models perform very well, with warming rates close to observed.[5] Thus climate models adequately reproduce decadal warming trends when greenhouse gases act as the sole major anthropogenic forcing as on the Southern Hemisphere, but reveal deficiencies when in addition strong decadal aerosol variations come into play, as on the Northern Hemisphere.[5]

The widely debated slowdown of global warming in the early twenty-first century (‘hiatus’) that can also be noted in Figure 4 may be interpreted as a reflection of the transition from a period with prevailing brightening in the 1990s into a period with no clear overall SSR trends in the 2000s.[66] In contrast to the 1990s, in the 2000s warming thus may have no longer been enhanced by SSR brightening,[55] but also, if anything, only weakly suppressed by a potential renewed SSR dimming. However, a variety of other plausible factors are in discussion.[4]

Interestingly enough, the lack of warming during the dimming period from the 1950s to the 1980s on the Northern Hemisphere was even somewhat more pronounced over oceans than over land areas (slight cooling of –0.08°C per decade over oceans between 1958 and 1985, compared to a slight warming over land of +0.05°C per decade over the same period (Figure 5). For the analysis presented in Figure 5, I used the CRUTEM4 dataset over land and the HadSST3 dataset over oceans. Even though anthropogenic air pollution sources are located over land, according to the conceptual frameworks outlined above, the subtle changes in background aerosol levels over the relatively pristine oceans could have amplified SSR dimming through effective cloud-aerosol interactions, which may enhance the formation, lifetime, and albedo of clouds. During the dimming period, such SSR declines may have compensated the increasing downward thermal radiation from the greenhouse effect also over oceans, and may have suppressed the corresponding rise in SSTs accordingly. During the brightening period, where

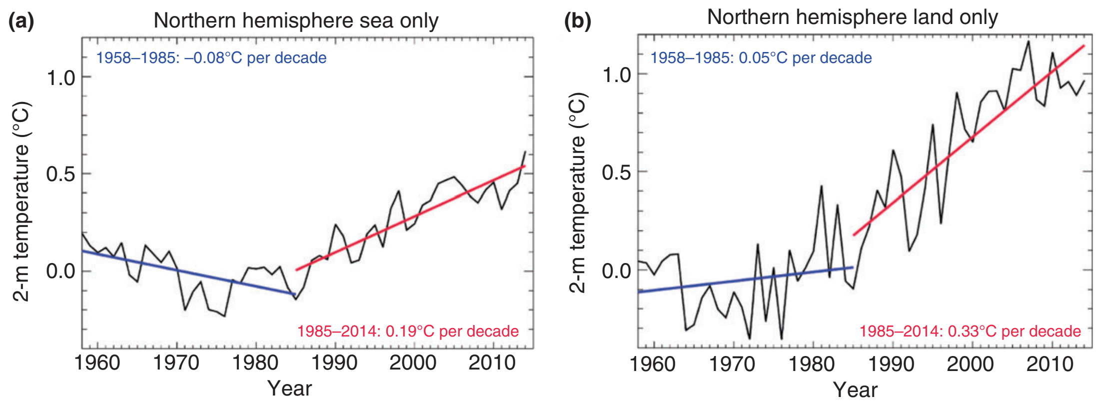

FIGURE 5 | Annual 2-m temperature anomalies observed over (a) Northern Hemispheric oceans and (b) Northern Hemispheric land surfaces. Observations from CRUTEM4 (land) and HADSST3 (oceans), anomalies with respect to 1960–1990. Linear trends over the dimming phase (1950s–1980s) in blue, over the brightening phase (1980s–2000s) in red. Units °C.

both solar and thermal downward radiation acted toward increasing the surface heat content, warming over land was found to be more rapid than over oceans in Figure 5. Despite the plausible existence of brightening also over oceans as outlined earlier on, the land surfaces with lower heat capacity may have responded more rapidly to the trend reversal in SSR than the oceans with higher thermal inertia.

This does not rule out, however, the possibility that the multidecadal variations in SSTs could also be merely a reflection of the oceans' internal variability, known as, e.g., the Atlantic Multidecadal Oscillation (AMO), or the Pacific Decadal Oscillation (PDO).[119] Unforced natural decadal variations in the atmosphere/ocean system could have induced changes in cloudiness and thereby contributed to the changes in SSR and SSTs.[120] The similar temporal variations of the AMO, PDO, and the dimming/brightening phenomenon hamper the attribution of the SST changes to either of these causes. However, the similarity in these variations may also be interpreted as an indication for a possible casual link between dimming/brightening and AMO/PDO.[5] Based on the extensive set of climate model simulations used in IPCC-AR5, Allen et al.[121] suggested that anthropogenic aerosols may be able to modify SSTs by influencing the PDO trends, thereby altering the extension of the Tropical belt. The hypothesis that anthropogenic aerosol-induced changes in SSR may be able to effectively alter SSTs is also supported by the modeling study of Booth et al.,[105] who noted in their simulations that aerosol induced changes in SSR were able to explain a large fraction of the multidecadal variations of SSTs in the North Atlantic during the 20th century. Thus, there is a potential that dimming and brightening induced by anthropogenic aerosols and their cloud-mediated effects could have forced decadal variations in SSTs to a considerable extent.

It remains a challenge for future research to disentangle possible cause–effect relationships between dimming/brightening, atmosphere/ocean variability and multidecadal SST changes.

CONCLUSIONS

Radiative energy available at the Earth surface drives a variety of essential climate processes, and any change in its amount has the potential to significantly alter the state of Earth's climate and environment. From greenhouse theory, we expect a gradual increase in downward thermal radiation received at the Earth surface. The limited observational evidence supports such an increase on the order of +2 $W\,m^{-2}$ per decade over recent years, in line with simulated changes in this quantity in state of the art climate models. However, observations indicate not only changes in the downward thermal fluxes, but even more so in their solar counterparts, whose records have a much wider spatial and temporal coverage. These records suggest multidecadal variations in SSR at widespread land-based observation sites. Specifically, declining tendencies in SSR between the 1950s and 1980s have been found at most of the measurement sites ('dimming'), with a partial recovery at many of the sites thereafter ('brightening'). With the additional information from more widely measured meteorological quantities which can serve as proxies for SSR (primarily sunshine duration and DTR), more evidence for a widespread extent of these variations has been provided, as well as additional indications for an overall increasing tendency in SSR in the first part of the 20th century ('early brightening'). It is well established that these SSR variations are not caused by variations in the output of the sun itself, but rather by variations in the transparency of the atmosphere for solar radiation. It is still debated, however, to what extent the two major modulators of the atmospheric transparency, i.e., aerosol and clouds, contribute to the SSR variations. The balance of evidence suggests that on longer (multidecadal) timescales aerosol changes dominate, whereas on shorter (decadal to subdecadal) timescales cloud effects dominate. More evidence is further provided for an increasing influence of aerosols during the course of the 20th century. However, aerosol and clouds may also interact, and these interactions were hypothesized to have the potential to amplify and dampen SSR trends in pristine and polluted areas, respectively. The multidecadal changes in the observed rates of global warming, their hemispheric asymmetries, as well as the evolution of DTR over land surfaces do match with our conceptual understanding of how SSR changes may modulate the greenhouse-induced global warming.

No direct observational records are available over ocean surfaces. Nevertheless, based on the presented conceptual ideas of SSR trends amplified by aerosol–cloud interactions over the pristine oceans, modeling approaches as well as the available satellite-derived records it appears plausible that also over oceans significant decadal changes in SSR occur. The coinciding multidecadal variations in SSTs and global aerosol emissions may be seen as a smoking gun, yet it is currently an open debate to what extent these SST variations are forced by aerosol-induced changes in SSR, effectively amplified by aerosol–cloud interactions, or are merely a result of unforced natural variations in the coupled ocean atmosphere system. Resolving this question could state a major step toward a better understanding of multidecadal climate change.

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