Global dimming and brightening: A review

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[1] There is increasing evidence that the amount of solar radiation incident at the Earth's surface is not stable over the years but undergoes significant decadal variations. Here I review the evidence for these changes, their magnitude, their possible causes, their representation in climate models, and their potential implications for climate change. The various studies analyzing long-term records of surface radiation measurements suggest a widespread decrease in surface solar radiation between the 1950s and 1980s (''global dimming''), with a partial recovery more recently at many locations (''brightening''). There are also some indications for an ''early brightening'' in the first part of the 20th century. These variations are in line with independent long-term observations of sunshine duration, diurnal temperature range, pan evaporation, and, more recently, satellite-derived estimates, which add credibility to the existence of these changes and their larger-scale significance. Current climate models, in general, tend to simulate these decadal variations to a much lesser degree. The origins of these variations are internal to the Earth's atmosphere and not externally forced by the Sun. Variations are not only found under cloudy but also under cloud-free atmospheres, indicative of an anthropogenic contribution through changes in aerosol emissions governed by economic developments and air pollution regulations. The relative importance of aerosols, clouds, and aerosol-cloud interactions may differ depending on region and pollution level. Highlighted are further potential implications of dimming and brightening for climate change, which may affect global warming, the components and intensity of the hydrological cycle, the carbon cycle, and the cryosphere among other climate elements.

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1. Introduction

[2] Solar radiation incident at the Earth's surface is the ultimate energy source for life on the planet, and largely determines the climatic conditions of our habitats. The amount of solar energy reaching the surface is a major component of the surface energy balance and governs a large number of diverse surface processes, such as evaporation and associated hydrological components, snow and glacier melt, plant photosynthesis and related terrestrial carbon uptake, as well as the diurnal and seasonal course of surface temperatures.

[3] It has also major practical implications, for example, for solar energy technologies and agricultural productivity. Changes in the amount of solar energy reaching the Earth's surface can therefore have profound environmental, societal and economic implications. These changes can be of natural origin, such as those induced by a major volcanic eruption on time scales of a few years, up to time scales of many millennia due to changes in the Earth orbital parameters. On the other hand, there is growing evidence that human interference with climate leads to alteration of solar radiation in polluted atmospheres.

[4] Solar energy reaches the Earth's surface either as direct beam from the Sun or in diffuse form after scattering in the atmosphere. The sum of the direct and diffuse radiation incident on the surface is known as global radiation (mostly among experimentalists), or surface solar radiation (among modelers), sometimes also as surface insolation or solar/shortwave irradiance. I will refer to it as surface solar radiation (SSR) in the following.

[5] Observational and modeling studies emerging in the past 2 decades suggest that SSR is not necessarily constant on decadal time scales, as often assumed for simplicity, but shows substantial decadal variations. Largely unnoticed over many years, this evidence recently gained a rapid growth of attention under the popular expressions ''global dimming'' and ''brightening,'' which refer to a decadal decrease and increase in SSR, respectively. While the term ''global'' in ''global dimming'' is often intuitively associated with a global scale of the phenomenon, this expression has been coined with the more technical ''global radiation dimming'' in mind, with ''global'' not necessarily referring to the spatial scale, but rather to the sum of diffuse and direct solar radiation (global radiation) (G. Stanhill, personal communication, 2008). Although this terminology is therefore somewhat ambiguous, it has reached by now such a broad recognition and dissemination that the community has

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decided to keep these terms [*Ohring et al.*, 2008; working group 1, workshop on global dimming and brightening at the Death Sea, Israel, Feb. 2008].

[6] In this review I address a number of "frequently asked questions" which are typically raised in the context of the global dimming and brightening issue. On the basis of the extended literature that is now available on the subject, I will start with a summary of the observational evidence of the phenomenon (section 2), then discuss its potential origins (section 3), its larger-scale significance (section 4), its representation in the current generation of climate models (section 5), its potential impact on the climate system (section 6), and finally its possible future evolution (section 7).

2. What is the Evidence for Global Dimming/Brightening?

2.1. Evidence From Direct Observations at the Surface

2.1.1. Available Data

[7] Monitoring of SSR (i.e., the electromagnetic radiation in wavelengths between 0.3 and 4.0 μm from the Sun and sky incident on a horizontal surface) started in the early 20th century at selected sites, as for example at the Stockholm site in 1923. More widespread measurements of this quantity with thermopile pyranometers were initiated in the International Geophysical Year (IGY, 1957/1958). Many of these historic measurements have been compiled in the Global Energy Balance Archive (GEBA) at ETH Zurich [*Ohmura et al.*, 1989; *Gilgen et al.*, 1998], and the World Radiation Data Center (WRDC) of the Main Geophysical Observatory in St. Petersburg maintained by A. Tsvetkov (Figure 1a). The accuracy of these historic SSR measurements has been estimated by *Gilgen et al.* [1998] 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. Consequently, in the late 1980s the necessity for a reference network of surface radiation measurements with improved and defined accuracy has been recognized. As a result, the Baseline Surface Radiation Network (BSRN) has been established [*Ohmura et al.*, 1998]. First BSRN sites, equipped with instruments of highest possible accuracy, became operational in the early 1990s. To date more than 30 anchor sites in different climate regimes provide data at high temporal resolution (minute data). Other radiation networks with comparable quality standards were established around the world in recent years: the Atmospheric Radiation Measurement (ARM) Program with several worldwide distributed sites [*Ackerman and Stokes*, 2003], the surface radiation (SURFAD) network maintained by the National Oceanic and Atmospheric Administration (NOAA) with seven sites within the United States [*Augustine et al.*, 2000], the NOAA Earth System Research Laboratory (ESRL) Network with five worldwide distributed remote sites [*Dutton et al.*, 2006], the Australian Network maintained by the Bureau of Meteorology (B. Forgan), and the Alpine Surface Radiation Budget network (ASRB) with seven sites in the Swiss Alps [*Philipona et al.*, 2004] (Figure 1b).

[8] The major focus in the following subsections is on SSR, as it is the most widely measured quantity of all surface radiative and energy components and largely determines the solar energy input to the surface, which has major implications for the energetics of the climate system. Knowledge on variations in diffuse and direct components, on the other hand, is important to diagnose the causes of global dimming and brightening and also, for example, to study the impacts on the biosphere and plant photosynthesis, and will be briefly summarized in a separate subsection.

[9] The estimates given on the magnitude of global dimming/brightening in the various studies discussed below are summarized in Tables 1 and 2 (surface based) and Table 3 (satellite derived). To facilitate comparison, they have been converted from the original literature into common units (W m^{-2} decade^{-1} for absolute changes and % decade^{-1} for relative changes). If either absolute or relative changes were not provided in the publications, they were inferred from the originally published changes and additional information on the absolute magnitude of SSR at the corresponding station or region under consideration. These inferred estimates are flagged with a "[b]" in Tables 1, 2, and 3.

[10] I start with a historic outline of the studies that estimated decadal SSR variations from radiation observations taken at the Earth's surface. It is these studies that brought the global dimming/brightening issue into focus.

2.1.2. Early Studies

[11] The earliest studies, which analyzed extended observational records of SSR, appeared in the late 1980s and early 1990s [*Ohmura and Lang*, 1989; *Russak*, 1990; *Dutton et al.*, 1991; *Stanhill and Moreshet*, 1992a, 1992b, 1994; *Liepert et al.*, 1994; *Abakumova et al.*, 1996]. These pioneering studies presented first evidence that solar radiation at the Earth's surface has not been constant over time as previously assumed, but showed significant decadal variations. Specifically, they pointed to an overall decline in SSR since the 1950s. *Ohmura and Lang* [1989] used 13 long-term records in Europe and found decreasing trends in SSR, at least at the interior continental sites, among them a decrease of 20% at the site in Zurich in a 20-year period between the late 1950s and the late 1970s. The overall change at the 13 sites shown in this study has later been quantified at -8 W m^{-2} between 1959 and 1988 (Table 1). *Russak* [1990] noted a decrease in SSR of 6.8% between 1955 and 1986 at the site Toravere in Estonia, and decreases from 11% to 12% in SSR between 1964 and 1986 at three sites in the Baltic region (Helsinki, Stockholm, Kaunas). *Dutton et al.* [1991] found a decrease in SSR at the South Pole between 1976 and 1987, which was particularly pronounced during the late summer season with a 15% reduction. *Stanhill and Moreshet* [1992a] estimated that SSR measured in the year 1958 was 9 W m^{-2} (5.3%) larger than in the year 1985 on the basis of 46 sites and an area weighting in an attempt to scale the estimates up to a global number. *Stanhill and Moreshet* [1994] used data from seven remote sites on different continents and largely differing climate regimes and found decreasing trends (six of them statistically significant), of 5.6 W m^{-2} decade^{-1} on average between the mid-1950s and late 1980s (3% per decade). *Liepert et al.* [1994] investigated SSR at eight sites in Germany and found an average decrease of 10% (15 W m^{-2}) over the period 1964–1990. *Abakumova et al.* [1996] determined a decreasing trend at the vast majority of 160 stations in the former Soviet Union between 1960 and 1987, with a

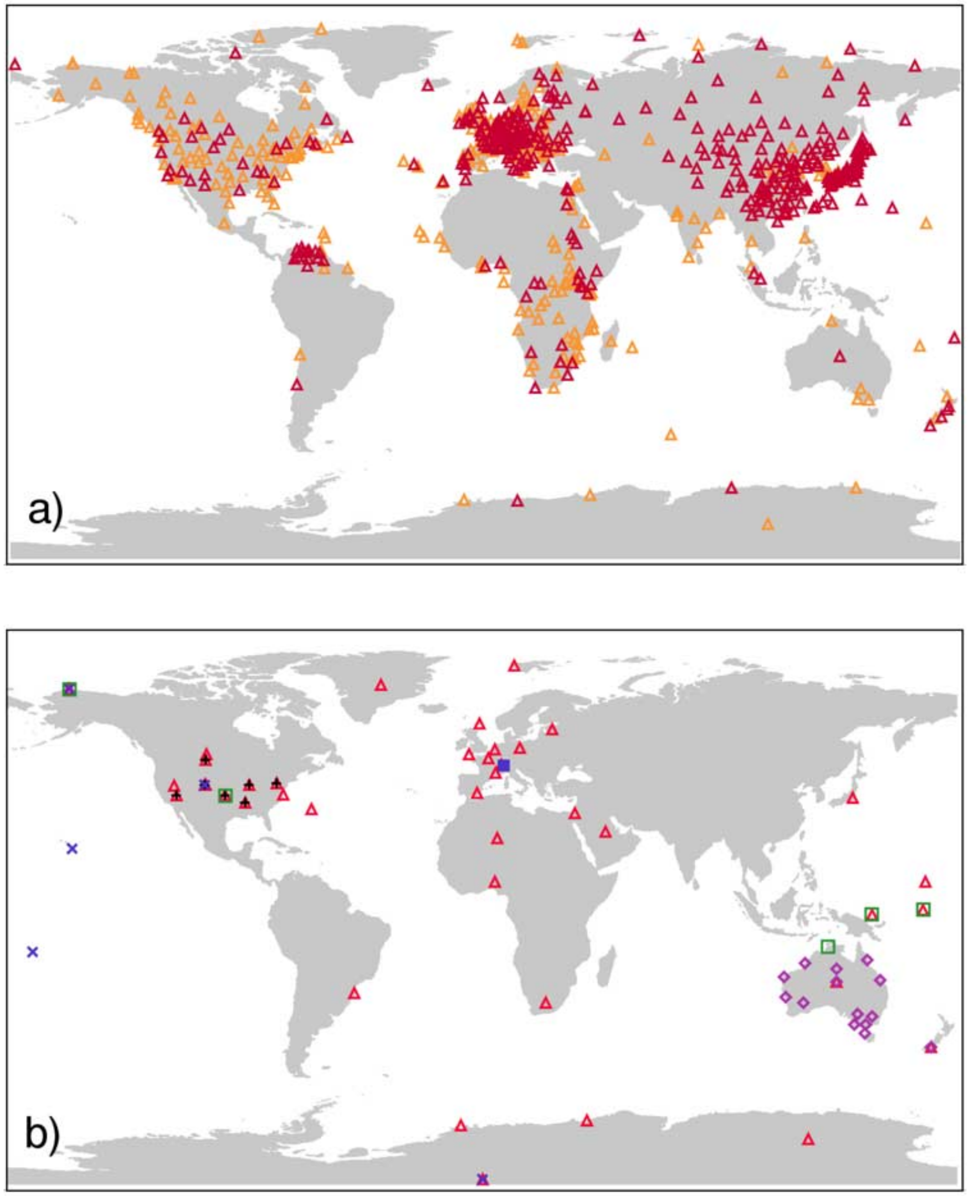

Figure 1. Global distribution of surface radiation networks: (a) historic GEBA/WRDC stations with more than 10 years (orange triangles) and 20 years of measurement records (red triangles), many of them going back to the 1960s, (b) modern high-accuracy stations with multiyear records: BSRN (38 sites worldwide, red triangles), ARM (5 sites worldwide, green squares), NOAA/SURFRAD (7 sites in the United States, black plus signs), NOAA/ESRL (5 sites worldwide, blue crosses), Australian Network (14 sites in Australia, purple diamonds), and the Alpine Surface Radiation Budget network (ASRB) (7 sites in the Swiss Alps, filled blue square).

statistically significant decrease of more than 2% at 60% of the sites (Table 1).

2.1.3. Regional Studies With Focus on the Period ~1960–1990 (Dimming Period)

[12] Various other studies followed up these early studies and confirmed SSR dimming in different parts of the world over a period of roughly 1960–1990. Probably one of the largest decadal decline of SSR measured at an individual site was noted by *Stanhill and Kalma* [1995] in Hong Kong, where SSR was reduced by as much as one third of its absolute amount (1.06% per year) between 1957 and 1992 (Table 1).

[13] Dimming has also been observed in Polar regions. SSR changes at 22 sites located in the Arctic Circle were investigated by *Stanhill* [1995]. He found a highly significant decrease in SSR of 3.6 W m^{-2} $decade^{-1}$ at these sites over the period 1950–1993. Similarly, *Stanhill and Cohen* [1997] found a significant reduction in SSR at 12 sites in Antarctica of 2.8 W m^{-2} $decade^{-1}$ from the late 1950s to the late 1980s.

Table 1. Estimated Linear Changes in Surface Solar Radiation Over the Period of Roughly 1960s to 1980s Based on Surface Observations[a]

Region	Reference	Number of Sites	Period	Absolute Trend ($W\ m^{-2}\ decade^{-1}$)	Relative Trend (% $decade^{-1}$)
		Global Focus			
Global land sites	*Gilgen et al.* [1998]	400	1960–1990	−3.5[b]	−2
Global land sites	*Stanhill and Cohen* [2001]	145	1958–1992	−5.1	−2.7
Global land sites	*Liepert* [2002]	295	1961–1990	−2.3	−1.3
Global urban sites	*Alpert et al.* [2005]	144	1964–1989	−4.1	−2.3[b]
Global rural sites	*Alpert et al.* [2005]	174	1964–1989	−1.6	−0.9[b]
Global remote sites	*Stanhill and Moreshet* [1994]	7	1953–1991	−4.8	−3.3
Global remote sites	*Dutton et al.* [2006]	5	1977–1990	decrease	decrease
		Europe			
Europe	*Ohmura and Lang* [1989]	13	1959–1988	−2.7	−2.0[b]
Europe	*Norris and Wild* [2007]	75	1971–1986	−3.1	−2.3[b]
Zurich (Switzerland)	*Ohmura and Lang* [1989]	1	1960–1980	−10	−7[b]
Baltic	*Russak* [1990]	3	1964–1986	−5.5[b]	−5
Toravere (Estonia)	*Russak* [1990]	1	1955–1986	−2.5[b]	−2.2
Germany	*Liepert et al.* [1994]	8	1964–1990	−6	−4
European part of FSU	*Abakumova et al.* [1996]	diverse	1960–1987	−2.5 to −8[b]	−2 to −6
Moscow	*Abakumova et al.* [1996]	1	1958–1993	−2.3	−2
Turkey	*Aksoy* [1997]	34[c]	1960–1994	−2[b,c]	−1[c]
Israel	*Stanhill and Ianetz* [1997]	2	1954–1994	−8.8	−5
Ireland	*Stanhill* [1998a]	8	1954–1995	−5.2	−5[b]
Iberian Peninsula	*Sanchez-Lorenzo et al.* [2007]	72[c]	1950–1980	−3[c]	−1.5[b,c]
Northern Europe	*Stjern et al.* [2009]	11	1955–2003	−4.3	−3.7
		North America			
United States	*Liepert* [2002]	43	1961–1990	−6	−3
Canada	*Cutforth and Judiesch* [2007]	7	1958–1999	−2.6[b]	−1.7
		Central America			
Wider Caribbean	J. C. Antuna et al. (submitted manuscript 2009)	30	1961–1990	−10	−4.5[b]
		Asia			
Hong Kong	*Stanhill and Kalma* [1995]	1	1958–1992	−18	−10.6
Former Soviet Union	*Abakumova et al.* [1996]	160	1960–1987	−1 to −8	−1 to −7
China	*Che et al.* [2005]	64	1961–2000	−4.5	−3[b]
China	*Liang and Xia* [2005]	42	1960–2000	−4.9[b]	−3.3
China	*Qian et al.* [2007]	85	1955–2000	−3.2	−2.1[b]
China	*Shi et al.* [2008]	84	1957–2000	−3.8[b]	−2.5
China	*Shi et al.* [2008]	84	1961–1989	−7[b]	−4.6
Japan	*Ohmura* [2006]	26	1961–1990	−8	−5[b]
Japan	*Norris and Wild* [2009]	86	1971–1989	−1.3	−0.8[b]
India	*Ramanathan et al.* [2005]	10	1966–1990	−2.9	−1.4[b]
		Africa			
Egypt (Cairo)	*Omran* [2000]	1	1968–1994	−13[b]	−6
South Africa/Namibia	*Power and Mills* [2005]	10	~1960–1990	−5.4	−2.2
Zimbabwe	*Wild et al.* [2005]	3	1965–2000	decrease	decrease
		Oceania			
New Zealand	*Liley* [2009]	4	1954–1990	−4.8[b]	−3
		Polar Regions			
South pole	*Dutton et al.* [1991]	1	1976–1987	decrease	decrease
Arctic	*Stanhill* [1995]	22	1950–1993	−3.6	−4[b]
Antarctica	*Stanhill and Cohen* [1997]	12	1957–1994	−2.8	−2.3[b]

[a]Originally published estimates converted into common units ($W\ m^{-2}\ decade^{-1}$ for absolute changes and % $decade^{-1}$ for relative changes). Studies within individual regions are ordered according to the year of publication.
[b]If not both absolute and relative changes were given in the publications, they were determined from the originally published values and additional information on the absolute magnitude of SSR at the station or region under consideration and flagged with "[b]".
[c]Derived from sunshine duration data.

[14] Several studies focused on SSR variations in the eastern Mediterranean region. *Aksoy* [1997] determined a decrease at 34 sites in Turkey of 3.4% over the period 1960–1994, however not from direct SSR observations, but derived from sunshine duration measurements. *Stanhill and Ianetz* [1997] determined a decline of as much as 20% (8.8 $W\ m^{-2}\ decade^{-1}$) at two sites in Israel (Bet Dagan, Jerusalem) between 1954 and 1994. *Omran* [2000] noted a decreasing trend in SSR at three sites in Egypt, with a decrease of 6% $decade^{-1}$ between 1968 and 1994 at the longest time series from Cairo (derived from *Omran* [2000, Figure 8]) (Table 1).

Table 2. Estimated Linear Changes in Surface Solar Radiation Over the Period of Roughly 1980s to 2000s Based on Surface Observations[a]

Region	Reference	Number of Sites	Period	Absolute Trend ($W\ m^{-2}\ decade^{-1}$)	Relative Trend (% $decade^{-1}$)
Global Focus					
Global land sites (GEBA)	*Wild et al.* [2008]	352	1986–2000	2.2	1.2[b]
Global remote sites (BSRN)	*Wild et al.* [2005]	8	1992–2002	6.6[c]	3.6[b,c]
Global remote sites (NOAA/ESRL)	*Dutton et al.* [2006]	5	1990–2000	increase	increase
Global remote sites (BSRN)	*Wild et al.* [2009]	17	1992–2005	5.1[c]	2.8[b,c]
North America					
Continental United States	*Long et al.* [2009]	7	1995–2007	8	4.4[b]
Oregon	*Riihimaki et al.* [2009]	3	1980–2007	2 to 3	1 to 2
Europe					
Europe	*Norris and Wild* [2007]	75	1987–2002	1.4	1[b]
Europe	*Wild et al.* [2009]	133	1985–2005	3.3 (2.4[d])	2.5 (1.8[d])
Iberian Peninsula	*Sanchez-Lorenzo et al.* [2007]	72[e]	1980–2000	4[e]	2.2[b,e]
Iberian Peninsula	*Wild et al.* [2009]	11	1985–2005	4.9	2.6[b]
France	*Wild et al.* [2009]	23	1985–2005	3.6	2.4[b]
Switzerland	*Ruckstuhl et al.* [2008]	25	1981–2005	2.6 (1.6[d])	2[b] (1.2[b,d])
Switzerland/Austria	*Wild et al.* [2009]	19	1985–2005	3.7	2.6[b]
North Germany	*Ruckstuhl et al.* [2008]	8	1981–2005	3.3 (2.4[d])	3[b] (2.2[b,d])
Germany	*Wild et al.* [2009]	7	1985–2005	4.6	3.8[b]
Eastern Europe	*Wild et al.* [2009]	23	1985–2005	2.3	1.7[b]
Toravere (Estonia)	*Russak* [2009]	1	1990–2007	increase	increase
Moscow	*Abakumova et al.* [2008]	1	1985–2006	increase	increase
Benelux	*Wild et al.* [2009]	10	1985–2005	4.2	3.7[b]
Great Britain	*Ohmura* [2009]	7	1990–2005	5	4.7[b]
Northern Europe	*Stjern et al.* [2009]	11	1983–2003	2.2[b]	2.1
Scandinavia	*Wild et al.* [2009]	21	1985–2005	1.6	1.6[b]
Asia					
India	*Padma Kumari et al.* [2007]	12	1984–2001	−8.6	−4
Japan	*Ohmura* [2006]	26	1990–2002	8	5[b]
Japan	*Wild et al.* [2009]	13	1990–2000	7.7	5[b]
Japan	*Norris and Wild* [2009]	86	1990–2002	8.9	5.5[b]
China	*Shi et al.* [2008]	84	1990–2000	2.7[b]	1.8
China	*Norris and Wild* [2009]	23	1990–2002	4.0	2.7[b]
China	*Wild et al.* [2009]	12	1990–2000	5.0	3.3
China	*Wild et al.* [2009]	12	2000–2005	−4.2	−2.8[b]
Oceania					
Australia	*Wild et al.* [2005]	14	1994–2003	increase	increase
New Zealand	*Liley* [2009]	4	1990–2008	0.5[b]	0.3
Antarctica					
South pole	*Wild et al.* [2009]	1	1992–2004	4.1	3.1[b]
Georg von Neumayer station	*Wild et al.* [2009]	1	1993–2005	13.4	10.7[b]

[a]Originally published estimates converted into common units ($W\ m^{-2}\ decade^{-1}$ for absolute changes and % $decade^{-1}$ for relative changes). Studies within individual regions are ordered according to the year of publication.
[b]If not both absolute and relative changes were given in the publications, they were determined from the originally published values and additional information on the absolute magnitude of SSR at the station or region under consideration and flagged with "[b]".
[c]Enhanced by Pinatubo influence at beginning of records.
[d]Without year 2003.
[e]Derived from sunshine duration data.

[15] *Power and Mills* [2005] analyzed data from eight sites in South Africa and two sites in Namibia covering roughly the 1960 to 1990 period. They found decreasing SSR at eight of these sites (six statistically significant) and no station with a statistically significant increase, and determined a mean decrease of 2.2% per decade (5.4 $W\ m^{-2}\ decade^{-1}$).

[16] In China, *Li et al.* [1995] noted decreasing SSR between 1976 and 1990 on the basis of 55 sites. A number of studies with focus on China followed. *Liang and Xia* [2005] found decreasing trends in SSR in China between 1961 and 2000 at 38 out of 42 sites, at 3.3% $decade^{-1}$ (~5 $W\ m^{-2}\ decade^{-1}$). Similarly, *Che et al.* [2005] found an overall decreasing trend at 64 sites in China over the period 1961–2000 of 4.5 $W\ m^{-2}\ decade^{-1}$, while *Qian et al.* [2007] determined an average decrease of 3.1 $W\ m^{-2}\ decade^{-1}$ in SSR between 1955 and 2000 at 85 sites in China. *Shi et al.* [2008] performed rigorous quality tests on the Chinese data before estimating the trends. Out of 84 stations, suspect data were found at 35 sites. On the basis of data that passed the quality tests they still found a decreasing trend of 2.5% $decade^{-1}$ (~3.8 $W\ m^{-2}\ decade^{-1}$) between 1955 and 2000, with a more pronounced dimming of 4.6% $decade^{-1}$ (~7 $W\ m^{-2}\ decade^{-1}$) for the period 1961–1989 (Table 1).

Table 3. Estimated Linear Changes in Surface Solar Radiation Over the Period of Roughly 1980s to 2000s in Satellite-Derived Products[a]

Region	Reference	Period	Absolute Trend ($W m^{-2}$ $decade^{-1}$)	Relative Trend (% $decade^{-1}$)
Global	*Pinker et al.* [2005]	1983–2001	1.6	0.9[b]
Global land	*Pinker et al.* [2005]	1983–2001	−0.5	−0.3[b]
Global ocean	*Pinker et al.* [2005]	1983–2001	2.4	1.3[b]
Global	*Hatzianastassiou et al.* [2005]	1984–2000	2.4	1.3[b]
Global land	*Hatzianastassiou et al.* [2005][c]	1984–2000	1.8	1.0[b]
Global ocean	*Hatzianastassiou et al.* [2005][c]	1984–2000	2.7	1.5[b]
Global	N. Hatzianastassiou et al. (submitted manuscript, 2009)	1984–2001	3.5	1.9[b]
Global land	N. Hatzianastassiou et al. (submitted manuscript, 2009)	1984–2001	3.7	2.1[b]
Global ocean	N. Hatzianastassiou et al. (submitted manuscript, 2009)	1984–2001	3.6	2.0[b]
Global	*Hinkelman et al.* [2009]	1991–1999	3.2	1.8[b]
Global	*Hinkelman et al.* [2009]	1983–2004	0.25	0.1[b]

[a]Units $W m^{-2}$ $decade^{-1}$ for absolute changes and % $decade^{-1}$ for relative changes.
[b]If not both absolute and relative changes were given in the publications, they were determined from the originally published values and additional information on the absolute magnitude of SSR at the station or region under consideration and flagged with "[b]".
[c]Personal communication, based on data set described in reference.

[17] A pronounced dimming of 1.7% $decade^{-1}$ was also noted at seven sites in the Canadian Prairie [*Cutforth and Judiesch*, 2007]. One of the few studies reporting no evidence for a decrease at a larger number of sites over the period ~1960–1990 is based on data from Australia [*Stanhill and Kalma*, 1994]. However, in these data any trends were filtered out, as the solar radiation data were corrected back to a modeled climatology, since there was no on-site calibration (B. Forgan, Bureau of Meteorology, Melbourne, personal communication, 2005). Indication for dimming over the period ~1960–1990 also on the Southern Hemisphere was noted by *Liley* [2009] at four sites in New Zealand. J. C. Antuna et al. (Observed solar dimming in the Wider Caribbean, submitted to *Journal of Geophysical Research*, 2009) used data from 30 sites in the wider Caribbean between 1960 and 1990 and noted a decrease at 20 of them (Table 1).

2.1.4. Globally Oriented Studies With Focus on the Period 1960–1990 (Dimming Period)

[18] All the aforementioned studies focused on specific regions or on a limited number of stations. An attempt to analyze a comprehensive data set of worldwide distributed sites was made by *Gilgen et al.* [1998]. They made use of the numerous records collected in GEBA and sampled them onto a global 2.5° × 2.5° grid. They found that SSR decreased significantly in large regions of Africa, Asia, North America, and Europe, at 2% per decade on average from the late 1950s up to 1990. Significant positive trends were observed only in four very small regions. In another study with a global perspective, *Liepert* [2002] used 252 long-term records from GEBA as well as 43 time series contained in the United States National Solar Radiation Database [*Maxwell et al.*, 1995]. *Liepert* [2002] estimated a decline of SSR at these worldwide distributed sites of 7 $W m^{-2}$, or 4%, on average over the period 1961–1990. *Liepert* [2002] further noted a decline of 18 $W m^{-2}$, or 10% at the U.S. sites from the National Solar Radiation Database, which provides a combination of measured and modeled SSR (Table 1).

[19] *Stanhill and Cohen* [2001] stated in their comprehensive review of the "evidence for a widespread and significant reduction in global radiation," that SSR has been reduced worldwide by 2.7% $decade^{-1}$ (5.1 $W m^{-2}$ $decade^{-1}$) on the basis of data for the years 1958, 1965, 1975, and 1992. In this review they coined the expression "global dimming" to describe the phenomenon of the widespread decrease of SSR. *Alpert et al.* [2005] analyzed worldwide trends in the GEBA data with respect to the population density and proposed an "urbanization effect" in the SSR data. They argued that the decline at highly populated sites is much larger (4.1 $W m^{-2}$ $decade^{-1}$) than at sites in less populated areas (1.6 $W m^{-2}$ $decade^{-1}$). Although differences between urban and nonurban sites were noted before, *Alpert et al.* [2005] argued, on the basis of these differences, that the global extent of dimming was minor because of the small areal extent of highly populated areas (see section 4).

2.1.5. Studies Including Data Beyond 1990 (Brightening Period)

[20] All the above studies pointing to a decline of SSR in large parts of the globe were restricted to observational data up to about 1990. More recent data were hardly available to these studies, since for example GEBA was not updated further at the time these studies were completed. In the early 2000s an effort has been made at ETH Zurich to update GEBA with data covering the 1990s, with the help of the WRDC and other sources. Furthermore, in the early 1990s, a number of radiation sites were established and equipped with comprehensive state of the art instrumentation. These well maintained sites are organized in networks such as BSRN, ARM, NOAA/SURFRAD, NOAA/ESRL and ASRB as outlined at the beginning of section 2.1. Data from these networks, together with the GEBA and WRDC archives allowed an evaluation of the period beyond 1990 up to the millennium. A first assessment was presented by *Wild et al.* [2005]. They showed that the reported decreases in SSR over large parts of the global land surfaces were no longer found in many of the updated records covering the 1990s. Instead, they noted increases in SSR since the mid-1980s at widespread locations. These increases were particularly evident at the majority of 300 sites in Europe and 45 sites in Japan contained in GEBA/WRDC, at the U.S. sites from SURFRAD and the majority of the sites in Australia. Also, the worldwide distributed BSRN sites with data records in the 1990s showed an increase of 6.6 $W m^{-2}$ $decade^{-1}$ on average between 1992 and 2002 [*Wild et al.*, 2005] (Table 2). Even in China a slight recovery from the strong SSR dimming in prior decades was found during the 1990s. A continuation of the dimming was only evident at a

limited number of sites in India, Zimbabwe, Chile and Venezuela, and at a minority of the European sites. *Wild et al.* [2005], therefore, coined the term ''brightening'' to emphasize that ''global dimming'' has largely vanished after the mid-1980s.

[21] *Wild et al.* [2008] estimated the brightening over land surfaces at 2.0 W m^{-2} $decade^{-1}$ on the basis of 365 updated sites in GEBA over the period 1986–2000 (Table 2). The stronger increase on the order of 6 W m^{-2} $decade^{-1}$ between 1992 and 2002 obtained at the BSRN sites was partly due the recovery from the volcanic eruption of Mount Pinatubo in 1991. The evidence for widespread increases in SSR at globally distributed sites in GEBA since the mid-1980s was further emphasized in the works of *Ohmura* [2006, 2009] and *Gilgen et al.* [2009]. *Dutton et al.* [2006] examined five remote sites from the NOAA/ESRL network with high measurement accuracy. These globally distributed and well-maintained sites provide data since 1977. In line with the above studies, they found evidence for a decrease in SSR at these sites from the beginning of the records up to 1987, and an increase thereafter.

[22] A growing number of studies appear in the literature, which include data up to the millennium and focus on specific regions in more detail. They generally support the picture of a widespread brightening since the mid-1980s portrayed in the above studies. Several of these studies discuss the brightening in Europe in more detail. *Norris and Wild* [2007] determined a Pan European time series based on 75 stations from GEBA, and estimated a linear decline of 3.1 W m^{-2} $decade^{-1}$ for the ''dimming'' period 1971–1986, but an increase of 1.4 W m^{-2} $decade^{-1}$ for the ''brightening'' period 1987–2002. M. Chiacchio and M. Wild (Long-term seasonal variations of surface solar radiation in Europe, submitted to *Journal of Geophysical Research*, 2009) pointed out that the brightening in Europe is particularly pronounced in the spring and summer seasons, while there is no evidence for a brightening in the other seasons. *Ruckstuhl et al.* [2008] determined an annual average increase of 2.6 W m^{-2} $decade^{-1}$ and 3.3 W m^{-2} $decade^{-1}$ at 25 sites in Switzerland and eight sites in Germany, respectively, between 1981 and 2005. This increase reduced to 1.6 W m^{-2} $decade^{-1}$ and 2.4 W m^{-2} $decade^{-1}$, respectively, when the year 2003 with its anomalous summer heat wave in Central Europe [*Schär et al.*, 2004] was excluded from their analysis. Focusing on eleven sites in northern Europe, *Stjern et al.* [2009] noted an overall linear downward trend of 18% over the period 1955–2003, however with a partial recovery of 4.4% over the period 1983–2003, which fits well to the trends discovered in the more globally focused studies. An evident trend reversal from dimming to brightening in the late 1980s was also noted by *Russak* [2009] at the long-term (1955–2007) monitoring site Toravere in Estonia, and by *Abakumova et al.* [2008] in the 50-year time series from Moscow State University (1958–2007) (Table 2).

[23] *Long et al.* [2009] examined recent SSR variations in the United States. They found an average increase in SSR of about 10 W m^{-2} $decade^{-1}$ over the continental United States between 1995 and 2007 on the basis of seven sites from the SURFRAD network and the ARM Climate Research Central Facility. *Riihimaki et al.* [2009] determined a continuous brightening at three sites in Oregon, at 1 to 2% $decade^{-1}$ (2 to 3 W m^{-2} $decade^{-1}$) over the period 1980–2007 (Table 2).

[24] In China, *Liang and Xia* [2005], *Che et al.* [2005], *Qian et al.* [2007], and *Shi et al.* [2008] all stated that the decreasing trends since the 1960s no longer persist in the 1990s, and that ''conditions have improved in the last decade'' of the 20th century [*Che et al.*, 2005], in line with the findings by *Wild et al.* [2005]. *Shi et al.* [2008], *Norris and Wild* [2009], and *Wild et al.* [2009] quantified this partial recovery in China over the 1990s, at 1.7%, 2.7%, and 3.4% per decade, respectively. A partial recovery from prior dimming has also been noted by *Liley* [2009] at four sites with long-term records on the Southern Hemisphere in New Zealand.

[25] On the other hand, in India, ongoing dimming was noted by *Padma Kumari et al.* [2007], in line with *Wild et al.* [2005]. They included 12 sites in India from 1984 to 2001 in their study, and found a decrease in SSR at all sites, ranging from 1.7 to 14.4 W m^{-2} $decade^{-1}$, with an average decrease of 8.6 W m^{-2} $decade^{-1}$. No evidence for a change in the dimming trend was also found in a time series constructed from seven sites in the Canadian Prairie covering the period 1951–2005 [*Cutforth and Judiesch*, 2007], and at two sites in Zimbabwe [*Wild et al.*, 2005].

[26] The most recent update, based on worldwide data records from GEBA, WRDC, and BSRN updated beyond the year 2000, is discussed by *Wild et al.* [2009]. Overall, they noted a less distinct and coherent brightening after 2000 compared to the 1990s. They found continuous brightening beyond 2000 at numerous stations in Europe and in the United States as well as in parts of east Asia. However, brightening seems to level off at sites in Japan and Antarctica after 2000. In China there is some indication for a renewed dimming, after the stabilization in the 1990s. A continuation of the long-lasting dimming is also noted at the sites in India [*Wild et al.*, 2009]. The most recent analysis of the records from the worldwide distributed BSRN sites updated to 2005 gave a mean increase of 5 W m^{-2} $decade^{-1}$ over the 1992–2005 period, still to some extent influenced by the Pinatubo effects in the early parts of the records [*Wild et al.*, 2009] (Table 2).

2.1.6. Dimming and Brightening in the First Half of the 20th Century

[27] Only very few time series of direct observations of SSR extend back into the first half of the 20th century [e.g., *De Bruin et al.*, 1995; *Gilgen et al.*, 1998; *Ohmura*, 2006]. These historic data suggest that SSR at these sites increased during the 1930s and 1940s, at 5 W m^{-2} $decade^{-1}$ on average, before it peaked around the late 1940s/early 1950s, and then started to decrease [*Ohmura*, 2006]. The increase in SSR in the first part of the century at these selected sites is also known as ''early brightening.'' This might suggest that ''global dimming'' was mainly confined to the second half of the 20th century, at least according to the limited number of sites with records extending back into the first half of the 20th century. Additional evidence for this ''early brightening'' comes from analyses of diurnal temperature range and sunshine duration (see section 2.3).

[28] The essential features discussed in the previous sections are illustrated in Figure 2. Figure 2 depicts the time series of Stockholm, which is the longest available SSR record in GEBA, reaching back to 1923. An increase in

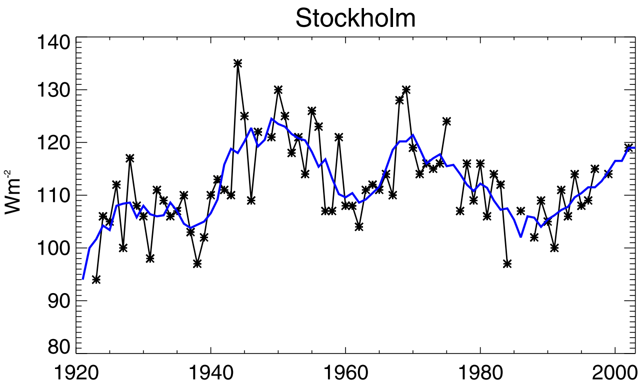

Figure 2. Annual mean surface solar radiation as observed at Stockholm, the longest observational record available form GEBA (since 1923). Five year moving average shown in blue. Units are W m^{-2}.

the 1930s and 1940s (''early brightening''), a gradual decrease from the 1950s to the 1980s (''dimming''), and the partial recovery in recent decades (''brightening'') are clearly visible in the Stockholm time series.

2.1.7. Decadal Changes in Clear-Sky, Diffuse, and Direct Solar Radiation

[29] Far less studies have investigated the decadal changes in SSR specifically under cloud-free conditions, and the partitioning between direct and diffuse radiation. These more specialized analyses can provide additional insight into the origins of observed dimming and brightening (see section 3).

[30] The determination of cloud-free conditions in SSR records requires a high temporal resolution (hourly data or higher) together with additional information on cloudiness, sunshine duration or diffuse/direct radiation to infer clear-sky episodes. *Liepert* [1997] used hourly SSR data together with sunshine duration data and synoptic cloud observations from two sites in Germany. No significant trend in the SSR under cloud-free episodes was found at either site between 1964 and 1990. *Wild et al.* [2005] used the high temporal resolution data from the BSRN network together with a clear-sky detection algorithm developed by *Long and Ackerman* [2000] to construct multiannual clear-sky records at the BSRN sites. They found increases in these clear-sky records between 1992 and 2002 at all eight sites considered, on average by 6.7 W m^{-2} decade^{-1}. In a recent update, *Wild et al.* [2009] found increases in clear-sky SSR at 15 out of 17 BSRN sites over the period 1992–2005, on average by 4.9 W m^{-2} decade^{-1}, similar to the all-sky trends in Table 2. *Ruckstuhl et al.* [2008] used a method based on sunshine duration measurements to separate cloud-free from cloudy conditions. They found increases in the clear-sky SSR determined this way, between 1981 and 2005 of 0.81 W m^{-2} decade^{-1} and 1.49 W m^{-2} decade^{-1} at 25 sites in Switzerland and eight sites in Germany, respectively.

[31] *Norris and Wild* [2007, 2009] developed a method to eliminate effects of cloud cover changes from the historic monthly time series in GEBA. The resulting time series give some indication of clear-sky changes, although they still potentially contain signals of changes in cloud optical properties, which are not completely eliminated by this method. These cloud cover–corrected time series show downward tendencies before the mid-1980s in Europe and China, and upward tendencies thereafter in Europe, China and Japan. Clear-sky changes in China have also been determined by *Liu et al.* [2004a] and *Qian et al.* [2007], which showed a downward trend from the 1960s to the 1990s and a partial recovery thereafter, in line with the changes noted under all-sky conditions. At sites in the United States, *Long et al.* [2009] found increasing tendencies in SSR under cloud-free conditions for the period 1995–2007, similarly to the ones under all-sky conditions in Table 2.

[32] Investigations on variations in the radiative transfer through the cloud-free atmosphere were also carried out in conjunction with atmospheric transmission measurements, where the direct solar beam at the surface measured with pyrheliometers is related to the solar beam incident at the top of atmosphere. Specifically, the zenith transmittance is the ratio of the direct solar radiation measured at the Earth's surface under cloudless skies to the zenith solar irradiance at the top of atmosphere. Long-term changes in this quantity were studied, e.g., by *Roosen and Angione* [1984], *Dutton et al.* [1985], *Russak* [1990, 2009], *Abakumova et al.* [1996, 2008], *Wild et al.* [2005], *Ohmura* [2006, 2009], and *Ohvril et al.* [2009] at a number of sites in Europe, Russia, Japan, California, Hawaii and Chile. Apart from strong signatures of major volcanic eruptions such as El Chichon and Pinatubo, they also found generally decreasing tendencies in atmospheric clear-sky transmission before the mid-1980s and a partial recovery thereafter at the European and Japanese sites.

[33] Overall, the available analyses of decadal changes in solar irradiances under cloud-free atmospheres draw a picture similar to the more numerous studies performed under all-sky conditions discussed in previous paragraphs, with predominately decreasing tendencies before the mid-1980s and increasing tendencies since. This suggests that the dimming and brightening phenomenon is not only a characteristics of cloudy atmospheres, but also evident under cloudless skies at many locations.

[34] Of further interest is the partitioning of the total SSR into its diffuse and direct components. This is, for example, relevant for plant photosynthesis, since diffuse radiation can penetrate deeper into the vegetation canopy than direct radiation (see section 6.4). An increase in the diffuse fraction of SSR can be expected in areas with strong dimming owing to increased cloudiness and/or aerosol loads, as these factors tend to enhance scattering in the atmosphere. Far less information on long-term diffuse and direct measurements is available compared to total solar flux (SSR) measurements. Overall, the limited information gives a picture that is less coherent than with the total all-sky and clear-sky fluxes, particularly for the diffuse component, while the direct component typically follows the changes in the total flux (SSR). *Liepert* [1997] and *Liepert and Kukla* [1997] found decreases in diffuse radiation at the German sites Hamburg under clear and cloudy conditions, and Hohenpeissenberg only under cloudy conditions between 1964 and 1990. *Power* [2003] pointed to the absence of spatial homogeneity in diffuse trends at 13 German sites. *Russak* [2009] identified at the Toravere site in Estonia a decrease in direct radiation up to the mid-1980s and an

increase thereafter, similar to the all-sky fluxes at the same site. On the other hand, the diffuse radiation at this site shows weaker, but opposite changes. An increase in diffuse radiation under clear-sky condition in Moscow between 1955 and 1993 was noted by *Abakumova et al.* [1996], while direct solar radiation declined. Since the mid-1980s, SSR and direct radiation increased again at this site, whereas the diffuse fraction decreased [*Abakumova et al.*, 2008], as might be expected under brightening conditions with less scattering. Reductions in direct solar radiation were also inferred from sunshine duration measurements at two sites in Israel and Ireland between 1967 and 1995 by *Stanhill* [1998b]. At the Egypt sites, *Omran* [2000] found, in contrast to the global and direct radiation, no decrease in diffuse radiation between the 1970s and 1990s. Declines in SSR at the sites in southern Africa were associated with declines in direct radiation, but no clear overall trend in the diffuse radiation [*Power and Mills*, 2005]. This still implies that the diffuse fraction of SSR overall has increased at these sites. The studies focusing on China [e.g., *Liang and Xia*, 2005; *Che et al.*, 2005; *Shi et al.*, 2008] point to a strong decrease in direct solar radiation similarly to the total radiation (SSR), and to a complex pattern in diffuse radiation with a tendency for a slight increase since the 1960s in some of the studies. This would imply an overall increase in the diffuse fraction also at the Chinese sites. *Qian et al.* [2007] showed a steady increase in diffuse radiation over China specifically under cloud-free conditions, which suggests that the lack of increase in all-sky diffuse radiation found in other studies might be due to the concurrent decrease in cloudiness (see section 3).

[35] Overall, the limited analyses of extended time series of diffuse and direct measurement are in broad agreement with the expectation of a decrease of the direct radiation and increase in diffuse radiation (or at least the diffuse fraction) under conditions of SSR dimming, and vice versa during brightening. There are, however, exceptions which need further investigation. For example, *Long et al.* [2009], observed an increase in diffuse radiation and diffuse fraction at the U.S. sites from 1995 to 2007, despite the clear-sky and all-sky brightening mentioned above.

2.1.8. Summary on Evidence From Direct Observations

[36] To sum up, the vast majority of the literature focusing on the period ~1960–1990 reports predominant downward trends in SSR in the various regions under investigation (see Table 1). Increases have been noted at a minority of sites in several of these regions, but there is no single study reporting a coherent region with an increase in SSR over the ~1960–1990 period. On the other hand, when it comes to the more recent years, the situation is reversed, and it is difficult to find studies that show a decrease in SSR (Table 2). The picture is somewhat less coherent, with trend reversals and increases at widespread locations, but also some regions with continued decrease (e.g., India). At many sites, the more recent brightening has not fully compensated for prior dimming, and SSR levels around 2000 are still lower than in the 1960s [*Wild et al.*, 2007]. There remain a number of methodological issues related to dimming/brightening studies based on surface observations, concerning data quality, analysis, coverage, and representativeness as discussed below.

2.1.8.1. Data Quality

[37] In general, the accuracy of historic radiation measurements is not well established and often unknown as noted above. Quality assessment procedures were applied in some of the analyses as, e.g., described by *Gilgen et al.* [1998], *Dutton et al.* [2006], and *Shi et al.* [2008]. In addition, the recent reversal of the downward tendencies at many sites adds credibility to the measured variations because most radiometers typically lose sensitivity with time, and unless properly postcalibrated, can indicate spurious downward, but not upward trends. The more recently established radiation networks (e.g., BSRN, ARM, SURFRAD, ESRL, and ASRB, see section 2.1.1) provide high-quality radiation data with known accuracy since the early 1990s.

2.1.8.2. Data Analysis

[38] The establishment of significant changes at individual sites by a rigorous trend analysis is often not possible given the combination of the amount of data, scatter in the data, and autocorrelation in the data, as well as lack of statistical independence of the fit residuals. Yet, the preponderance of similar results based on a large number of records analyzed in various independent studies with different methods gives support to the existence of nonspurious decadal changes in SSR. Note also that linear regressions as used in most of the above studies and also in Tables 1 and 2 for simplicity may not always be an appropriate statistical model to describe the temporal changes in the data. Higher-order statistical models, for example, may provide a more adequate description of the temporal evolution in SSR, particularly if the period considered includes both dimming and brightening phases [see, e.g., *Gilgen et al.*, 1998, 2009; *Dutton et al.*, 2006; *Makowski et al.*, 2009].

2.1.8.3. Data Coverage and Representativeness

[39] Despite the impressive number of studies cited above, the literature does not cover the entire terrestrial surfaces, as can be deduced from Figure 1 and Tables 1 and 2. There are large gaps in direct observations over vast areas of Africa, South America and the Maritime Continent. And, of course, ocean surfaces are almost entirely unrepresented in the surface observations, except for a few sites on small islands. For the more recent decades, satellite-derived estimates may be able to close these gaps (see next section). Further, proxy information on decadal changes in SSR inferred from a number of other measurement quantities may be used to extend records spatially and temporally (see section 2.3). In any attempt to scale up information from point observation, the representativeness of the individual sites for their larger-scale settings becomes critical. *Dutton et al.* [2006] provided a framework to estimates a site's spatial representativeness by using spatial cross correlation with satellite-derived global estimates of SSR. Also, possible "urbanization effects" in the SSR data [*Alpert et al.*, 2005] may have to be taken into account (section 4).

2.2. Evidence From Satellite-Derived Products

[40] Since the surface radiation sites are too sparse to cover the entire globe, spaceborne sensors with their wide footprints offer an attractive alternative approach to determine large-scale SSR variations. They can provide a far better spatial coverage than the surface networks, which is

particularly valuable over ocean and remote land areas. However, satellites can only measure the fraction of solar radiation that is reflected back to space (i.e., back to the satellite sensor) and therefore cannot determine SSR directly. Various methods have been developed to derive SSR from these satellite measurements [see, e.g., *Pinker et al.*, 1995, and references therein; *Zhang et al.*, 2004; *Hatzianastassiou et al.*, 2005]. They use either empirical relationships between the top of atmosphere (TOA) reflectances and the surface fluxes, or physical radiation models together with information on the atmospheric structure (typically from reanalyses) and cloud characteristics (typically from satellite-derived products such as the International Satellite Cloud Climatology Project ISCCP) [*Rossow and Duenas*, 2004]. However, useful satellite information has become only available since the early 1980s. Therefore, satellite-derived SSR cannot be determined for the "dimming period" up to the 1980s and can therefore only cover the more recent "brightening period."

[41] Several groups attempted to estimate decadal changes in satellite-derived SSR over this period. *Pinker et al.* [2005] derived SSR using the University of Maryland version of the Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget algorithm [*Pinker and Laszlo*, 1992] and ISCCP D1 satellite data as input. They estimated a global mean linear increase in SSR of 1.6 W m^{-2} $decade^{-1}$ over the period 1983–2001 (Table 3). This increase is a combination of a decrease until about 1990, followed by a sustained increase. *Hatzianastassiou et al.* [2005] determined monthly mean SSR for the period 1984–2000 using a physical radiative transfer code as described by *Hatzianastassiou et al.* [2004] together with the ISCCP D2 satellite data for cloud characteristics, NCEP/NCCAR data for water vapor, TIROS Operational Vertical Sounder (TOVS) data for ozone, as well as aerosol characteristics derived from the Global Aerosol Data Set (GADS) [*Koepke et al.*, 1997]. *Hatzianastassiou et al.* [2005] determined a linear increase of 2.4 W m^{-2} $decade^{-1}$ over the similar period 1984–2000 (Table 3), again composed of a decrease in the early part of the record and reversal to an increase around 1990. N. Hatzianastassiou et al. (Two-decadal trends of aerosol optical thickness and direct radiative effect on surface solar radiation and their role in global dimming and brightening, submitted to *Journal of Geophysical Research*, 2009) used a similar setup with a refined radiation scheme and more realistic aerosol characteristics from TOMS (Total Ozone Mapping Spectrometer) as input. They estimated a slightly higher increase in SSR of 3.5 W m^{-2} $decade^{-1}$ over the 18-year period 1984–2001. *Hinkelman et al.* [2009] analyzed SSR variations as estimated in the NASA/GEWEX Surface Radiation Budget (SRB) [*Gupta et al.*, 2006]. They noted substantial decadal variations with a decrease between July 1983 and July 1991 of 2.5 W m^{-2} $decade^{-1}$, an increase of 3.2 W m^{-2} $decade^{-1}$ between July 1991 and October 1999, both in qualitative agreement with the other satellite-based studies, and a renewed decrease between October 1999 and June 2004 of 5.3 W m^{-2} $decade^{-1}$. The overall linear regression over the entire period under investigation (1983–2004), which may not be a particularly appropriate model in this case, shows an insignificant trend of 0.25 W m^{-2} $decade^{-1}$ (Table 3). The renewed decrease in the latest years lies outside the investigation period of the other satellite-based studies and contributed to the lower linear change compared to these estimates. It is also to some extend in line with the notion of a slowdown of the brightening after 2000 in the surface observations by *Wild et al.* [2009].

[42] The reliability of the satellite-derived SSR trends depends, apart from the accuracy of the physical or empirical radiative transfer algorithms, on the accuracy of the observational input data used in the computations. Yet the satellite instruments that provide much of this input since the early 1980s were designed for weather applications which do not require the same level of accuracy as climate monitoring. Particularly, the realistic inclusion of temporally varying cloud and aerosol effects without contamination by satellite-measurement artifacts remains a challenge. For example, the substantial decadal changes in the extended cloud cover records from ISCCP, used as input in all above mentioned satellite-derived SSR products, are controversial and may be spurious, presumably owing to changes in the satellite viewing angles [e.g., *Evan et al.*, 2007]. *Hinkelman et al.* [2009] argue that these spurious trends in the ISCCP cloud cover did not affect the NASA/GEWEX SRB trends considerably, even so the qualitative evolution of the derived global mean SSR mirrors the ISCCP trends. The uncertainties in representing aerosol effects in satellite-derived SSR may further contribute, among other factors, to some of the disagreement between surface and satellite-derived trends. *Pinker et al.* [2005], with no explicit inclusion of aerosols, found an increase in SSR only over oceans, but not over land. On the other hand, an increase in SSR over both land and sea is found in the satellite-derived SSR data sets described by *Hatzianastassiou et al.* [2005, also submitted manuscript, 2009], which consider an explicit treatment of aerosols in their calculations (N. Hatzianastassiou, personal communication, 2008; Table 3). The different satellite-derived products are therefore not yet fully consistent in terms of trends in SSR. A more in-depth comparison of various satellite-derived products is currently undertaken in the GEWEX Radiative Flux Assessment (RFA) project (available at http://eosweb.larc.nasa.gov/GEWEX-RFA/).

2.3. Evidence From Indirect Sources

[43] A number of independent measurement quantities can provide to some extent information on decadal variations in SSR. Among them are sunshine duration, diurnal temperature range, pan evaporation, and planetary albedo observations. They may be useful as proxies to fill the substantial spatial and temporal gaps that exist in the surface radiation networks, and allow for consistency checks among the various implied SSR trends. As outlined below, these quantities provide additional evidence for the existence of large-scale decadal variations in SSR.

2.3.1. Planetary Albedo

[44] Changes in planetary albedo govern the net (total) absorption of solar energy in the climate system and therefore may provide a first-order estimate of the changes in SSR. A limitation is that planetary albedo changes are only indicative of those SSR changes caused by changes in scattering back to space, but not of those due to changes in

the absorption within the atmosphere. Unlike SSR, the planetary albedo is a quantity that can be directly measured from spaceborn platforms. However, satellite-based broadband shortwave observations (i.e., measurements covering the full spectral range of solar radiation, and not only selected channels at discrete wavelengths as typically on board of weather satellites) were largely discontinuous before 2000. Covering the entire planet, they were only available during the Earth Radiation Budget Experiment (ERBE) [*Barkstrom et al.*, 1990] between 1985 and 1990, and during the Scanner for Radiation Budget (ScaRaB) experiment for eleven months in 1994/1995 and five months in 1998/1999. Therefore, we have no complete information on the variations of the global mean planetary albedo from broadband satellite observations even in the satellite era of the 1980s and 1990s. The only continuous broadband satellite record in this period was the coarse resolution nonscanner instrument onboard of the ERBS satellite covering the lower latitudes, which was in operation from the mid-1980s to the end of the 1990s. These data allowed an analysis of the decadal variations in planetary albedo over the tropics. *Wielicki et al.* [2002] and *Wong et al.* [2006] noted not only a very strong peak in solar reflectance in the years following the volcanic eruption of Mount Pinatubo, but also a generally decreasing solar reflectance in the tropical latitude belt between 20°N and 20°S over the period 1985–1999. This by itself would favor an increase of SSR and fits to the concept of a brightening during the 1990s. With the turn of the millennium, new ambitious satellite programs, such as Clouds and the Earth's Radiant Energy System (CERES) [*Wielicki et al.*, 1996] or Geostationary Earth Radiation Budget (GERB) [*Harries et al.*, 2005] started to become operational. These programs provide a wealth of new information on top of atmosphere (TOA) radiative fluxes as well as aerosol and cloud properties. First analyses indicate no distinct changes in global mean planetary albedo after 2000 [*Loeb et al.*, 2007].

[45] An alternative approach to determine changes in the planetary albedo is the Earthshine method [*Palle et al.*, 2004]. Thereby, changes in the sunlight reflected from the Earth onto the dark side of the moon are monitored as an indication of changes in planetary albedo. Continuous Earthshine measurements were initiated in 1999 [*Palle et al.*, 2003]. *Palle et al.* [2004] correlated the Earthshine data with the International Satellite Cloud Climatology Project (ISCCP) [*Rossow and Duenas*, 2004] cloud cover data to reconstruct the Earth reflectance between 1985 and 2000. They estimated thereby a reduction in planetary albedo on the order of 6 W m^{-2} over the reconstruction period, in line with the surface-based evidence for a "brightening" over this period [*Wild et al.*, 2005] and other independent surface and satellite-based estimates [*Palle et al.*, 2005]. On limitations in the ISCCP cloud cover data see section 2.2. For the more recent years 2000–2004, controversial results were reported with indications for an increase in Earth reflectance estimated from the Earthshine data on one hand [*Palle et al.*, 2004], and a decrease estimated from CERES data on the other hand [*Wielicki et al.*, 2005]. This apparent discrepancy was recently reconciled by a reanalysis of the Earthshine data on one side, and a recalibration of the CERES data on the other side, resulting in a more constant and therefore more consistent planetary albedo in both approaches for the post 2000 period [*Palle et al.*, 2009]. The near constant planetary albedo over the post 2000 period is in broad agreement with the lack of evidence for substantial changes overall after 2000 in the surface SSR records [*Wild et al.*, 2009].

2.3.2. Diurnal Temperature Range

[46] The diurnal temperature range (DTR), i.e., the difference between daily maximum and minimum temperature 2 m above the surface, has a good prospect to serve as a proxy for SSR. This is due to the fact that the DTR allows the separation of solar and thermal radiative influences which affect the DTR in different ways [e.g., *Bristow and Campbell*, 1984]. Since the solar flux is obviously only present during daylight, it affects the daily maximum temperature more than daily minimum temperature. The nighttime minimum temperature, on the other hand, is mainly governed by the thermal radiative exchanges. After subtraction of the minimum temperature from the maximum temperature as done in the DTR, thermal effects are to considerable extent eliminated from the records. This leaves the solar influences as a major forcing factor of DTR. This is particularly true when integrated over larger areas, where advective influences become less important, which also affect DTR locally [*Wild et al.*, 2007; *Makowski et al.*, 2009]. Indeed, several studies demonstrated a high correlation of observed records of surface solar radiation and DTR [e.g., *Bristow and Campbell*, 1984; *Roderick and Farquhar*, 2002; *Liu et al.*, 2004a; *Makowski et al.*, 2009]. *Liu et al.* [2004a] determined a correlation of 0.88 between annual mean DTR and SSR based on 85 radiation sites in China. Similarly, *Makowski et al.* [2009] obtained a correlation of 0.89 based on 31 pairs of annual DTR and SSR records of at least 35 years in Europe. *Roderick and Farquhar* [2002] found quantitatively consistent trends between SSR and DTR over the former Soviet Union, using the relation between solar transmission and DTR developed by *Bristow and Campbell* [1984]. The sensitivity of the DTR to changes in radiative forcings has also been highlighted by *Travis et al.* [2002], who noted an increase in DTR in the United States from 11 to 14 September 2001, when aircrafts were grounded and associated contrails reduced.

[47] Compared to direct SSR measurements, DTR is measured globally with a network of much higher density and further back in time. Therefore, if proven to be a useful proxy for SSR, DTR records can help to fill the gaps in the temporal and spatial distribution of SSR observations. Using the gridded global maximum and minimum surface temperature data set provided by the Climate Research Unit (CRU) of the University of East Anglia [*Mitchell and Jones*, 2005], *Wild et al.* [2007] noted significant decadal changes in the evolution of DTR over global land surfaces. They comprise a substantial decrease from the late 1950s to the 1980s, and a remarkable transition to a levelling off from the mid-1980s to 2000, indicative of a major change in the large-scale radiative forcing. *Wild et al.* [2007] pointed out that this fits well to the concurrent SSR dimming and brightening evidenced from the surface radiation observations. This further suggests that dimming and brightening has indeed a larger-scale dimension, since it is also reflected in the DTR evolution over global land surfaces with its much denser and more representative global network. Similar decadal variations in DTR, with several decades

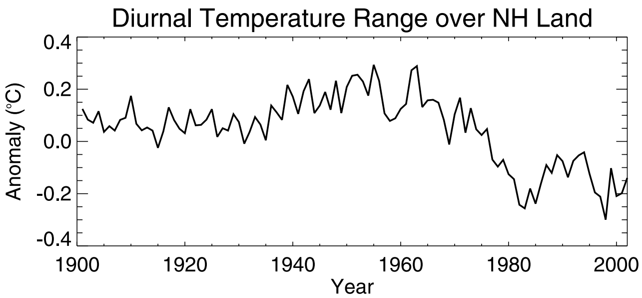

Figure 3. Annual mean diurnal temperature range averaged over Northern Hemispheric land surfaces, from 1900 to 2002. Variations of diurnal temperature range may provide a useful proxy for variations in surface solar radiation. Data from Climate Research Unit (CRU) [*Mitchell and Jones*, 2005]. Anomalies are shown with respect to 1961–1990 mean. Units are °C.

of decline up to the 1980s and a partial recovery afterward, were also found on more regional scales in China by *Liu et al.* [2004a] on the basis of 305 weather stations recording DTR from 1955 to 2000 and in Europe by *Makowski et al.* [2008] on the basis of about 200 stations with long-term DTR records covering the period 1950–2005. These changes match well with the overall evolution of SSR observed in these regions (section 2.1).

[48] The close correlation between DTR and SSR changes may also allow a reconstruction of SSR trends back to the first part of the 20th century, when radiation measurements were lacking, but DTR observations were already abundant. This is at least feasible for the Northern Hemisphere with much more historic temperature records than for the Southern Hemisphere (P. Jones, personal communication, 2008). Figure 3 depicts the annual mean DTR evolution over Northern Hemisphere land surfaces over the 20th century determined here from the CRU data set. Figure 3 not only suggests a downward tendency in DTR predominantly between the 1950s and 1980s and a leveling off thereafter as discussed above, but also a slight upward tendency in the 1930 and 1940s. This gives, on the one hand, support for two episodes of "brightening," one at the end of the 20th century, and a second one in the 1930s and 1940s ("early brightening," see section 2.1). On the other hand it implies that "global dimming" was essentially a phenomenon confined to about a 30–40-year period in the second half of the 20th century.

2.3.3. Sunshine Duration

[49] Sunshine duration is defined as the total amount of time the disk of the Sun is above the horizon and not obscured by cloud, fog or haze. Sunshine recorders are of the oldest and most robust types of radiation measurements. They measure the time over a day during which SSR is of sufficient intensity to exceed a certain threshold and activate the recorder. Measurements of sunshine duration (SD) started on a widespread basis in the late 19th century. SD variations in various regions have been analyzed in numerous studies, as for example summarized by *Sanchez-Lorenzo et al.* [2007]. A global-oriented analysis on SD variations, however, is to date still lacking. SD may serve as useful proxy for SSR, as pointed out, for example, by *Stanhill and Cohen* [2005] on the basis of a correlation of annual SSR and sunshine duration data in the United States. *Sanchez-Lorenzo et al.* [2007], using 72 SD records on the Iberian Peninsula, noted a decrease in SD from the 1950s to the early 1980s, followed by a positive trend up to the end of the 20th century. This matches the "dimming" and the subsequent "brightening" described in section 2.1. *Sanchez-Lorenzo et al.* [2008] went on to estimate SD over the entire western Europe including 79 sites for the period 1938 to 2004. They found a very similar SD evolution with a decrease since the 1950s until the early 1980s, followed by a subsequent recovery during the last two decades of the 20th century, in line with the studies investigating SSR changes over Europe [e.g., *Norris and Wild*, 2007; *Stjern et al.*, 2009; *Philipona et al.*, 2009; Chiacchio and Wild, submitted manuscript, 2009]. A similar characteristics can be noted in the 50-year SD record from the Moscow State University (1958–2007) shown by *Abakumova et al.* [2008], with decreasing SD until the mid-1980s and a recovery thereafter, thereby reflecting the concurrent decadal SSR changes measured at the same site. *Stanhill and Cohen* [2005] investigated SD variations in the United States between 1891 and 1987, and noted considerable decadal variations, but no significant linear trend when determined over the entire 20th century. They found this result to be in conflict with the reports on declining SSR in the United States in the second part of the 20th century. On the other hand, as they note, SSR in the U.S. National Solar Radiation Database [*Maxwell et al.*, 1995] is based at least partly on a model derived from a limited number of reliable measurements which may add uncertainties. Further, from their Figure 3, a linear trend in their SD time series restricted to the period 1960 to 1990 would also have a negative sign, thereby reducing the discrepancies, while the positive linear trend in SD in the early decades of the 20th century would agree with the "early brightening" concept outlined above. In a more recent study, *Stanhill and Cohen* [2008] derived proxy relationships from SD measurements in Japan between 1890 and 2002 to study century-scale changes in solar forcing at the Earth's surface. They estimated a linear trend of 0.8 W m^{-2} decade^{-1} over the 20th century, with particularly strong increase from about 1910 to 1940, and 1980 to 2000, and a decrease in between [*Stanhill and Cohen*, 2008, Figure 6]. Thus, their findings fit well to the general picture portrayed in this review, with an "early brightening" in the first part of the 20th century, a dimming after the midcentury and the brightening in more recent decades as outlined in section 2.1 and in the DTR section above. Evidence for a decrease of SD from the 1950s to 1990 and a recovery thereafter was also found on the Southern Hemisphere at the majority of 207 sites in New Zealand and on South Pacific Islands [*Liley*, 2009].

[50] *Kaiser and Qian* [2002] noted downward trends in SD in China over a period from about 1954 to 1990, despite the decrease of cloud amount over the same time [*Kaiser*, 2000]. They attributed the decrease in SD to the massive increase in anthropogenic aerosol loadings over China, which outweighed the decrease in cloud amount. Whether SD measurements are also capable of detecting more subtle changes in aerosol that may have contributed to the decadal dimming and brightening (see section 3) still remains to be shown. A method to eliminate linear cloud cover influences in SD records is proposed by *Sanchez-*

Lorenzo et al. [2009], which may help to make changes due to aerosol and cloud optical properties in SD records more evident.

2.3.4. Pan Evaporation

[51] SSR is a major driver of evaporation in energy-limited environments. Potential evaporation is therefore highly correlated with SSR and may be considered as another useful proxy [e.g., *Ohmura and Lang*, 1989]. Evaporation out of open pans of water (''pan evaporation'') is a robust and widely used measurement to estimate potential evaporation. *Peterson et al.* [1995] noted that worldwide distributed pan evaporation records covering a period of about 1960 to 1990 showed a steady decrease over large parts of the terrestrial surfaces. Since then numerous other studies noted a similar behavior in various regions of the world [see, e.g., *Roderick et al.*, 2007, and references therein]. *Roderick and Farquhar* [2002] pointed out that this decrease in pan evaporation is consistent with decreases in SSR noted over the same period in the various studies discussed in section 2.1. The consistent changes in the fully independent data sets of SSR and pan evaporation give further indication that the ''dimming'' in the period 1960 to 1990 has been real and not a pure measurement artifact. This evidence is not jeopardized by the controversial discussion in the literature whether the pan evaporation trends are indicative of a similar or even opposing trend in actual evaporation [e.g., *Brutsaert and Parlange*, 1998; *Brutsaert*, 2006].

[52] On a more regional scale, results presented by *Liu et al.* [2004b] and *Qian et al.* [2007] show that SSR and pan evaporation in China underwent very similar decadal changes, with decreasing tendencies in both quantities between the 1960s and 1990, and a common partial recovery during the following 1990s. The pan measurements therefore also provide independent evidence for some recovery in SSR in China during the 1990s after strong dimming over several decades. *Roderick and Farquhar* [2004] point out that the decline of pan evaporation is not just limited to the Northern Hemisphere, but also found of similar magnitude in Australia. Some of the changes there, however, have been attributed to decreases in wind speed in addition to decreasing radiative energy [*Roderick et al.*, 2007]. Also, *Cohen et al.* [2002] noted at the site of Bet Dagan, Israel, that increases in wind speed and vapor pressure deficit outweighed the effect of decreasing SSR on the long-term changes of pan evaporation measured there. Interpretation of pan evaporation changes as indicator of SSR changes at individual sites therefore requires careful analyses.

2.3.5. Summary of Evidence From Proxy Measurements

[53] A number of valuable proxy parameters for the decadal changes in SSR have been put forward in the literature. Multidecadal records of sunshine duration, pan evaporation and DTR measurements as well as planetary albedo estimates, despite their individual drawbacks, may allow an extension of the spatial and temporal information on the evolution of SSR. Overall, these proxies provide independent and reasonably consistent additional evidence for the existence of large-scale decadal variations in SSR. Specifically, the dimming of SSR from the 1950s to the 1980s obtained additional support from worldwide observations of concurrent declines in sunshine duration, pan evaporation and DTR. The recent brightening in the last decades of the 20th century is backed up by the estimates of changes in planetary albedo, DTR and to some extent also by pan evaporation and sunshine duration data. Finally, the early brightening in the 1930s and 1940s gets some support from corresponding changes in DTR and sunshine duration observations in the early part of the 20th century. Thus, the indirect evidence from these proxies allows us to put the estimated changes in SSR on a more solid basis and points to their significant impact on climate.

3. How Can We Explain Global Dimming/Brightening?

[54] Basically, changes in SSR can either be caused by external (extraterrestrial) changes in the amount of solar radiation incident on the planet at the top of atmosphere, or by internal changes (within the climate system) in the transparency of the atmosphere which modify the solar beam on its way to the Earth's surface.

[55] Extraterrestrial changes depend on the Earth's orbital parameters and the solar output. Changes in the atmospheric transparency can be due to (1) changes in cloud characteristics, namely, cloud cover and cloud optical properties, (2) changes in radiatively active gases in the atmosphere, particularly water vapor, which is a strong absorber of solar radiation, and (3) changes in the mass and optical properties of aerosols, which scatter and/or absorb solar radiation depending on their physical and chemical composition. These potential causes are discussed in more detail in the following.

[56] Earth orbital parameters vary substantially on geological time scales of 10,000 to 100,000 years and may be able to explain the ice age cycles. On the decadal time scales considered here, they are, however, negligibly small. Variations in the solar output were directly measured by various satellite missions since the early 1980s. They show a periodic signal related to the 11-year sunspot cycle with an amplitude of about ± 1 W m^{-2}. Attempts have been made to put together the records from the different satellites to obtain a composite time series starting in 1979 [*Fröhlich and Lean*, 1998; *Willson and Mordvinov*, 2003]. *Fröhlich and Lean* [1998] determined an almost negligible linear trend of -0.009% per decade, while *Willson and Mordvinov* [2003] estimated a slight increase in solar output of 0.047% per decade. The larger of these two estimates is equivalent to a global average increase of 0.17 W m^{-2} decade^{-1} in energy input to the climate system due to the variable emission from the Sun. These estimates are at least an order of magnitude smaller than the changes detected from surface observations of SSR. Extraterrestrial influences can thus be neglected in the interpretation of the observed variations in SSR. The phenomenon of global dimming and brightening is consequently a pure result of changes and processes that take place within the climate system, particularly in the atmosphere.

[57] From the gaseous constituents in the atmosphere, water vapor has the largest potential to modify solar radiation. However, sensitivity studies with radiative transfer models indicate that considerable changes in water vapor would be necessary to explain the observed SSR trends. For

example, a 10% increase in atmospheric water vapor content would decrease SSR by less than 0.5%, corresponding to less than 1 W m^{-2} on a global mean basis [*Wild*, 1997]. The estimated increase in atmospheric column water vapor over the past decades as given by IPCC AR4 is around 5% per 1°C warming. Taking a 0.8°C warming over land between 1960 and 2000 [*Wild et al.*, 2007], this would imply an increase in column water vapor of 4% over this period, corresponding to a decrease of SSR of less than 0.5 W m^{-2}, or, in a first-order linear approximation, no more than 0.1 W m^{-2} $decade^{-1}$. This is again at least an order of magnitude smaller than the changes discussed in section 2. Therefore, atmospheric water vapor can also be excluded as a major contributor to the observed decadal changes in SSR. Effects of changes in the concentration of various atmospheric gases on SSR between preindustrial and present day were estimated in *Kvalevag and Myhre* [2007]. They estimated a total decrease in SSR due to the changes in atmospheric concentrations of NO_2, H_2O, CH_4, and CO_2 at 0.31 W m^{-2} globally, with the largest individual contributors being water vapor with −0.29 W m^{-2} and stratospheric ozone with +0.33 W m^{-2}. The water vapor contribution is in line with the estimate derived above. The changes in radiatively active gases from preindustrial to present-day atmospheric concentrations have therefore, at least globally, a minor effect on the changes in SSR.

[58] This leaves clouds and aerosols as the most likely candidates for the explanation of the global dimming and brightening phenomenon. These two candidates may not be completely independent, as cloud and aerosols can interact in various ways [e.g., *Ramanathan et al.*, 2001a]. Nevertheless I first summarize the arguments for clouds and aerosols in separate paragraphs and then synthesize in the last paragraph.

3.1. Evidence for Clouds as Contributor to Global Dimming and Brightening

[59] Cloud information over the majority of the 20th century is restricted to synoptic observations carried out by human eye inspection of the sky. Accordingly, uncertainties in historic cloud observations are substantial. Nevertheless, a number of studies attempted to infer changes, mainly in cloud amount, from these data sets [see *Intergovernmental Panel on Climate Change* (*IPCC*), 2007, and references therein]. These studies suggested an increase over many continental regions including the United States, the former Soviet Union, western Europe, midlatitude Canada, and Australia over the second half of the 20th century, but also some decreases over China, Italy and Central Europe. These studies therefore are in broad agreement with the observed decrease in SSR and DTR over the major part of this period.

[60] A systematic analysis of the changes in cloudiness at the sites of the historic pyranometer networks has, however, not yet been conducted on a worldwide basis, but only for selected sites or regions. For example, changes in SSR records in the European winter season could be traced back to changes in NAO and associated changes in cloudiness (Chiacchio and Wild, submitted manuscript, 2009). *Liepert* [1997] found that SSR decreased substantially with overcast conditions (8% per decade), but not so under cloud-free conditions between 1953 and 1990 at two sites in Germany, Hohenpeissenberg, and Hamburg, thus pointing to increasing cloud optical thickness as a major cause for the decline in SSR observed over this period. For the United States, *Liepert* [2002] suggested that increasing cloud optical thickness and a shift from cloud-free to more cloudy skies were the major contributors (−18 W m^{-2}) to the decline in SSR estimated between 1960 and 1990 and dominated the direct aerosol effect (−8 W m^{-2}). M. Chiacchio et al. (Climate shifts in decadal variations of surface solar radiation in Alaska, submitted to *Journal of Geophysical Research*, 2009) argue that the decadal changes in SSR in Alaska were predominantly caused by changes in cloud amount associated with a shift in the Pacific Decadal Oscillation and changes in the Pacific North American circulation pattern. *Liley* [2009] pointed out that the dimming and brightening observed in New Zealand is unlikely related to the direct aerosol effect, since aerosol optical depth measurements showed too little aerosol to explain the changes. On the basis of sunshine duration measurements he argued that increasing and decreasing cloudiness could have caused dimming and brightening at the New Zealand sites.

[61] On the other hand, concurrent decreases in both cloudiness and SSR has been noted over China between 1954 and 1994 [*Kaiser*, 2000; *Qian et al.*, 2006, 2007] and in Europe from 1971 to 1986 on an annual basis [*Norris and Wild*, 2007]. This seemingly counterintuitive behavior needs further discussion (see section 3.2).

[62] Additional information on cloud characteristics became available with the advent of the satellite era in the early 1980s. Data from various weather satellites have been processed within the International Satellite Cloud Climatology Project (ISCCP) [*Rossow and Schiffer*, 1999] and an extended time series of global mean cloud amount has been compiled [*Rossow and Duenas*, 2004]. This record shows an increase in cloud amount from the beginning of the record in 1983 to the late 1980s and then a decrease until 2000. This would fit well to the dimming/brightening transition at the end of the 1980s. However, as mentioned in previous sections, the credibility of the trends in this satellite record has been heavily disputed, and evidence has been presented that they are possibly spurious [*Evan et al.*, 2007].

3.2. Evidence for Aerosols as Contributor to Global Dimming and Brightening

[63] Atmospheric aerosols can directly modify SSR by scattering and/or absorbing solar radiation in the atmosphere depending on their composition (direct aerosol effect). In addition, aerosols can modify SSR indirectly, through their ability to act as Cloud Condensation Nuclei (CCN), thereby altering cloud optical properties and lifetime (first and second indirect aerosol effect) [e.g., *Ramanathan et al.*, 2001a]. Further, absorbing aerosols in heavily polluted regions heat and stabilize the atmosphere, which may inhibit cloud formation or dissolve existing clouds (semi-direct effect). In general, all the above effects act toward reducing SSR with increasing aerosol levels in the atmosphere.

[64] *Stanhill and Moreshet* [1992a] first pointed to a possible connection between the decreasing SSR trends they found between 1958 and 1985 and changes in aerosols. They stated that "one indication that the major cause of the dimming is an increased industrial and urban production of

aerosols, is the latitudinal variation in insolation changes, which corresponds to that of pollution sources.'' They substantiated their argument in the work by *Stanhill and Cohen* [2001], where they overlaid their latitudinal estimates of SSR changes between 1960 and 1990 with latitudinal fossil fuel emission estimates for the same period. A similar latitudinal dependence with a distinct common peak in SSR decrease and emission increase can be seen around 35°N [*Stanhill and Cohen*, 2001, Figure 2]. This corresponds to the latitude of maximum industrial activity and population.

[65] *Stanhill and Moreshet* [1992b] give a striking example of the potential of anthropogenic aerosols to reduce SSR using data from Bet Dagan, Israel. This SSR time series showed a decline of as much as 58 W m^{-2} between 1958 and 1985 without any obvious changes in cloud cover, and a high correlation with the increasing number of motor vehicles on nearby highways. *Alpert et al.* [2005]and *Alpert and Kishcha* [2008] found a particularly strong dimming at sites in GEBA in highly populated urbanized areas, further pointing to an influence of pollution and associated aerosol effects on SSR.

[66] As further discussed in section 4, there is also evidence that anthropogenic aerosols have the potential to modify SSR on a large-scale basis. While for clouds at least some information on decadal changes over the 20th century is contained in the synoptic observations, no similar direct information is available on historic changes in aerosol loads in the atmosphere. Hypotheses of an impact of aerosols on the historic SSR trends during the dimming phase of the 1960s to 1980s are therefore difficult to verify in a strict sense and have to rely to some extent on (plausible) speculations and indirect evidence, such as given by *Stanhill and Cohen* [2001].

[67] The aerosol influence on the more recent transition phase from dimming to brightening and the subsequent brightening is better documented. *Wild et al.* [2005] examined SSR at worldwide distributed BSRN stations and found brightening tendencies during the 1990s not only under all-sky conditions, but also in cloud-free conditions. This indicates that aerosol changes may have contributed to the recent brightening. *Streets et al.* [2006] noted a qualitative agreement between changes in the anthropogenic emissions of sulphur and black carbon and the widespread transition from dimming to brightening found by *Wild et al.* [2005] in various regions around the world. The historic emission inventories suggest that global sulfur emissions peaked in late 1980s, and decreased thereafter [*Stern*, 2006; *Streets et al.*, 2006]. The decline in the emissions of sulphur and black carbon was particularly strong in large areas of the industrialized world over the period 1980–2000, after increases in previous decades [*Streets et al.*, 2006], in line with the changes noted in the SSR records. This reversal in the emission trends is likely related, on one hand, to the air pollution legislations that have started to become effective in many developed nations in the 1980s. On the other hand, economic crises also led to reduced emissions in eastern Europe and the former Soviet Union from the late 1980s onward, and in Asia in the 1990s [*Streets et al.*, 2009]. These developments may also be the cause of the reduction of the aerosol optical depth over the world oceans since 1990 as inferred from satellite data by *Mishchenko et al.* [2007]. The early part of this aerosol optical depth record (1983–1990) rather suggests an increase. This trend reversal in aerosol optical depth over the oceans, possibly indicative of changes in the background aerosol levels, fits the general picture of a widespread transition from dimming to brightening.

[68] N. Hatzianastassiou et al. (submitted manuscript, 2009) estimated worldwide changes in the aerosol direct radiative effect on SSR from 1984 to 2001 based on TOMS aerosol optical depth data and their calculations as described in section 2.3. They determined a decrease in the aerosol direct radiative effect in the northern tropical and subtropical latitudes, with aerosols being responsible for almost 100% of the SSR brightening over large areas extending from the Arabian Sea through North Africa and the tropical Atlantic Ocean, characterized by transport of African dust. A decrease in the aerosol direct radiative effect has also been determined in northern middle-to-high latitudes. In contrast, significant increases in the aerosol direct radiative effect on SSR were noted in areas like east Asia (China) or the southern Amazonian basin, with increasing emissions of anthropogenic aerosols and biomass burning activities (N. Hatzianastassiou et al., submitted manuscript, 2009).

[69] An increasing number of studies suggest that changes in aerosol concentrations have contributed to the observed dimming and subsequent brightening also on more regional scales around the globe. In Europe and Japan, long-term records of clear-sky atmospheric transmission measurements at several sites show consistent downward trends from the 1950s to the 1980s and a partial recovery thereafter, indicative of aerosol changes [*Wild et al.*, 2005; *Ohmura*, 2006; *Ohvril et al.*, 2009]. *Ohmura* [2009] used these transmission measurements to infer a contribution of roughly 50% from the direct aerosol effect to the SSR dimming and brightening observed at these sites. Using long-term sunshine duration data of the Iberian Peninsula, *Sanchez-Lorenzo et al.* [2009] found the characteristic dimming and subsequent brightening not only in the total records, but similarly also in records that only contained sunshine duration data of cloud-free days, pointing to changes in aerosol radiative effects. *Ruckstuhl et al.* [2008] analyzed aerosol optical depth measurements taken at six sites in Switzerland and northern Germany between 1986 and 2005. They found decreases in aerosol optical depth of up to 60% over this period, which has lead to the significant increase in solar radiation under cloud-free condition observed between 1981 and 2005 in Switzerland and northern Germany. They further argued that the direct aerosol effect had a five times larger impact on SSR changes than cloud effects at these sites. *Vautard et al.* [2009] inferred substantial reductions in haze, mist and fog over Europe over the past 30 years from multidecadal data on horizontal visibility, which are spatially and temporally correlated with trends in sulfur dioxide emissions, and which may have favored SSR brightening in Europe.

[70] *Norris and Wild* [2007] made an attempt to remove the effects of cloud cover changes on the all-sky SSR trends observed in the dense network of European radiation sites in GEBA. They used synoptic and satellite observations of cloud amounts and an empirical relation between cloud

amount and surface radiative forcing to estimate the impact of changing cloud cover on the SSR trends. Their results suggest that the dimming and brightening over Europe becomes even more pronounced after the effects of changes in cloud amounts were removed. Thus, cloud cover changes rather counteracted than enhanced the observed dimming and brightening trends over Europe. This indicates that aerosol effects and/or changes in cloud optical properties (possibly related to the aerosol changes) may have caused the observed changes in SSR over Europe [*Norris and Wild*, 2007]. *Norris and Wild* [2009] applied the same method also to the east Asian data in GEBA, and estimated that cloud cover changes made negligible contributions to the SSR decline in China before the 1990s, and that the strong SSR increase in Japan during the 1990s can only partly be explained by cloud cover changes. This points to aerosols as major modulator of SSR in Southeast Asia.

[71] Particularly strong evidence for aerosol effects on SSR with increasing air pollution in China between the 1960s and the 1990s were also noted in various other studies [e.g., *Liang and Xia*, 2005; *Che et al.*, 2005; *Xia et al.*, 2006; *Qian et al.*, 2007; *Shi et al.*, 2008]. The partial recovery in SSR in China during the 1990s is in line with some reductions in fossil fuel emissions [*Streets et al.*, 2001]. Also, *Qian et al.* [2007], based on *Novakov et al.* [2003], pointed out that the single scattering albedo (i.e., fraction of extinction due to scattering) of aerosols over China has been fairly stable from the 1950s to the 1980s, but then increased significantly after 1983. This implies less absorptive aerosols and consequently more SSR at the surface from the mid-1980s onward over China, in line with the available surface observations. This also suggests that changes of fuel utilization, and thus of aerosol composition and of associated single scattering albedo, may have contributed the changes in SSR.

[72] There is also strong evidence that aerosols are a major factor for the ongoing dimming observed over the Indian subcontinent. Pollution clouds, known as Atmospheric Brown Clouds (ABC) [*Ramanathan et al.*, 2005], prevail over the Indian subcontinent in the dry season and strongly reduce SSR [*Ramanathan et al.*, 2005; *Padma Kumari et al.*, 2007]. Measurements carried out during Indian Ocean Experiment (INDOEX) [*Ramanathan et al.*, 2001b] revealed that the Atmospheric Brown Clouds can spread over vast areas of the Indian Ocean and reduce seasonal mean SSR over the entire North Indian Ocean by 14 W m^{-2}. Modeling studies, which specifically incorporate the aerosol forcing observed during the INDOEX campaign, are able to quantitatively reproduce the strong reduction in SSR observed in GEBA [*Ramanathan et al.*, 2005] (see also section 5).

[73] Extended records of direct measurements of atmospheric aerosol concentrations are scarce. In the Canadian Arctic, atmospheric concentrations of sulfate and black carbon aerosols are monitored since 1989. An evaluation of these records showed a substantial decrease of 29% in sulfate aerosols and 60% in black carbon aerosols between 1989 and 2002 [*Sharma et al.*, 2004], again in line with the brightening seen in the pyranometer networks over the same period. Backward trajectory calculations suggest that this decrease in ‘Arctic haze’ is caused by the reduced advection of emissions from Europe and the former Soviet Union.

[74] Sulfur trapped in ice cores in Greenland is indicative of the presence of sulfate aerosols downwind of the United States and Canada [*McConnell et al.*, 2007]. These data show an increase of sulfur in Greenland ice cores from the 1940s to 1980s and a decrease thereafter, in line with northern American emission inventories. They further show a decrease in sulfur around the 1930s, which fits to the postulated “early brightening.” Interestingly, this sulfur record from the Greenland ice core mirrors the tendencies found in the Northern Hemispheric DTR records as well as in the long-term radiation records over the 20th century (see Figure 3).

[75] Apart from the aerosols of anthropogenic origin, aerosols from natural sources could potentially also influence SSR variations. Among them are mineral dust, biogenic emissions, sea salt, Dimethyl Sulfide (DMS) and volcanic sulfur aerosols. *Streets et al.* [2009] estimated that natural contributions to aerosol optical depth over the period 1980 to 2006 showed no significant trends (<1% year^{-1}), except for a small increase in Europe and a small decrease in South America and Southeast Asia. These estimates were obtained using the comprehensive Goddard Chemistry Aerosol Radiation and Transport model (GOCART) [*Chin et al.*, 2000] extended in time by trends in emissions of man-made and natural sources. This suggests that anthropogenic aerosol indeed play a dominant role in the decadal variations of aerosol optical depth and associated SSR changes in many areas of the globe.

[76] Volcanic aerosols have a particularly large influence on SSR for a few years after the major volcanic eruptions such as El Chichon (1982) and Pinatubo (1991). This is evident in the long-term atmospheric transmission records, where these eruptions induce strong spikes in the time series [e.g., *Wild et al.*, 2005; *Ohvril et al.*, 2009]. They are also clearly seen as temporal minima in some of the satellite-derived time series of global average SSR [*Hatzianastassiou et al.*, 2005, also submitted manuscript, 2009; *Pinker et al.*, 2005; *Hinkelman et al.*, 2009]. However, the imprint of volcanic eruptions on SSR fades after a few years and cannot alter longer-term trends.

3.3. A Conceptual Framework on the Role of Aerosols and Clouds in Dimming/Brightening

[77] As outlined above, the origin of SSR dimming and brightening comes from variations in the transparency of the atmosphere, with changing cloud and aerosol characteristics as dominant factors. Although closely interlinked through various ways of aerosol-cloud interactions, aerosols and clouds may be of different importance for SSR variations in different regions of the world, as estimated, e.g., by N. Hatzianastassiou et al. (submitted manuscript, 2009).

[78] Particularly, aerosols may affect clouds in different ways depending on the levels of pollution. For a given aerosol type, clouds have a logarithmic sensitivity to CCN [e.g., *Kaufman et al.*, 2005]. This means that small changes in CCNs potentially have a much bigger impact on cloud characteristics in pristine than in polluted environments [*Koren et al.*, 2008; *Rosenfeld et al.*, 2008]. Cloud microphysics effects thus saturate at some level of pollution. On the other hand, the overall absorption of solar radiation by

aerosols increases steadily and linearly with aerosol loading and aerosol optical depth. This suggests that cloud microphysics effects, such as the first and second indirect effect, come more into play in relatively pristine regions, while the direct and semidirect aerosol effects play the major role in highly polluted areas.

[79] In pristine areas, additional CCNs will strongly increase the formation, lifetime and the albedo of clouds [*Kaufman et al.*, 2005]. All these effects work toward a reduction of SSR through enhanced cloud shading. Therefore, when aerosols are added in relatively pristine environments, associated aerosol-cloud interactions will enhance surface cloud radiative forcing and thereby enhance dimming (and correspondingly enhance brightening if CCNs are removed). Thus, aerosol-cloud interactions cause in these situations an amplification of dimming and brightening trends.

[80] In highly polluted areas, on the other hand, cloud formation is suppressed, since absorbing aerosol layers heat and stabilize the atmosphere, while the reduced SSR due to the high pollution reduces the available energy for the surface evaporation which fuels convective clouds. Both stabilization and reduction of surface evaporation lead to a suppression of cloud formation. Therefore, if clouds cannot form in the first place, obviously cloud microphysics effects cannot apply. This may have happened in China, which would explain why the strong increase in pollution from the 1960s to the 1990s led to both reduced SSR and cloud amounts at the same time. Therefore, in highly polluted areas, aerosol-cloud interaction will tend to dampen the dimming and brightening trends induced by the direct aerosol effect. The reduced (increased) surface cloud forcing associated with increased (reduced) aerosols therefore causes under these conditions an attenuation of dimming and brightening trends.

[81] *Rosenfeld et al.* [2008] further suggested that adding CCNs in pristine conditions can invigorate convective clouds and enhance precipitation. This applies up to a certain level of pollution, where suppression of cloud formation through radiation starts to become dominant. While the radiative forcing of the invigorated convective clouds is uncertain, and possibly positive owing to associated cirrus cloud formation, this is another example of how aerosol-cloud interactions can alter with changing pollution levels.

[82] Observational support for these concepts as given by *Rosenfeld et al.* [2008] may also come from *Bell et al.* [2008]. They found that the weekly cycle of aerosols from air pollution in the southeastern United States is associated with a weekday maximum and weekend minimum in the intensity of afternoon convective precipitation. This weekly cycle emerged only in the late 1980s and strengthened through the 1990s, when aerosol levels decreased to the range where microphysical effects invigorate convection.

[83] Further observational and modeling studies are necessary to determine to what extent these concepts can explain the relative impact of the indirect, semidirect and direct aerosol effects on decadal SSR variations in different areas of the globe. The physical basis underlying these concepts can provide an explanation why, depending on the region (and the pollution level therein), different processes may dominate dimming and brightening.

4. How "Global" is Global Dimming/Brightening?

[84] This question has recently been disputed [e.g., *Alpert et al.*, 2005; *Alpert and Kishcha*, 2008; *Stanhill and Cohen*, 2009; *Liley*, 2009; *Karnieli et al.*, 2009]. Obviously, local variations of SSR can be expected when nearby heavy pollution sources change in strength. However, is there also evidence for dimming and brightening away from strong local emitters, in support of a larger-scale dimension of dimming and brightening? First evidence for this was provided by *Stanhill and Moreshet* [1992b], who found a decline in SSR also at worldwide distributed sites remote from surface pollution sources between the 1950s and 1990. Similarly, *Stanhill and Cohen* [1997] found dimming from 1957 to 1994 in the pristine region of Antarctica. This fits well to the concepts outlined in section 3.3 that pristine areas are particularly susceptible to small aerosol changes in terms of their effects on SSR, through amplifying effects. Numerous other studies are found in the literature in support of a nonlocal dimension of dimming/brightening. For example, decadal variations in SSR with dimming and brightening tendencies are found in the high-accuracy NOAA/ESRL network with five worldwide distributed radiation sites in remote locations [*Dutton et al.*, 2006]. Brightening tendencies were found under clear-sky and all-sky conditions by *Wild et al.* [2005, 2009] at worldwide distributed BSRN stations despite the absence of nearby pollution sources at most of these sites. *Russak* [1990, 2009] and *Ohvril et al.* [2009] noted substantial decadal changes in the atmospheric clear-sky transparency at the rural site Toravere, Estonia, undisturbed by local anthropogenic pollution sources. The decrease in atmospheric clear-sky transparency from the late 1950s to the mid-1980s and the more recent recovery document the importance of aerosol background variations also in rural areas. Evidence that anthropogenic pollution sources may not only influence local aerosol concentrations, but also large-scale background aerosol levels, is not only found at remote surface radiation sites, but also in a number of satellite and modeling studies. *Mishchenko et al.* [2007] inferred aerosol optical depth record variations over the world oceans from AVHRR satellite data for the period 1981 to 2005. Their global ocean mean aerosol optical depth record indicates, apart from a strong peak after the Mount Pinatubo eruption, a decline over the 1990s, which is in line with estimates of declining anthropogenic pollution over this period [*Streets et al.*, 2006; *Stern*, 2006] and indicative of a modulation of remote aerosol background levels by anthropogenic pollution. Large-scale aerosol optical depth changes, which are also evident in zonal averages over the globe, can also be seen in the MODIS data [*Kishcha et al.*, 2007] and further point to nonlocal impact of the aerosol changes. Modeling studies with global atmospheric chemistry transport models within the Aerosol Model Intercomparison (AEROCOM) [*Kinne et al.*, 2006; *Schulz et al.*, 2006] and Hemispheric Transport of Air Pollutions (HTAP) [*Economic Commission for Europe*, 2007] projects suggest that anthropogenic aerosols can undergo substantial long-range and interconti-

nental transports [*Chin et al.*, 2007]. For example, they showed that a considerable fraction of global aerosol mass can be found in polar regions, where anthropogenic emissions are almost absent [*Textor et al.*, 2007]. Modeling results further suggest that in four large receptor areas (North America, Europe, east Asia, and south Asia) more than 30% of the sulfate aerosol column load originates from areas outside the receptor areas [*Economic Commission for Europe*, 2007]. Back trajectory calculations by *Sharma et al.* [2004] show that Arctic haze pollution measured at a remote site in the Canadian Arctic is caused by anthropogenic emissions from Europe and the former Soviet Union. Also, the measurements of black carbon, vanillic acid, and non sea-salt sulfur in ice cores in Greenland originating from boreal forest fires and industrial activities particularly in northern America document the long-range transport of aerosols [*McConnell et al.*, 2007].

[85] To sum up, the various surface and satellite-based observational studies, aerosol transport modeling studies as well as the concepts of cloud-aerosol interactions suggest that anthropogenic air pollution and associated aerosol loads can be hemispherically dispersed, alter background aerosol levels, and thus affect remote regions, where cloud formation and modification is particularly sensitive to subtle changes in aerosols. Therefore, anthropogenic emissions have the potential to induce large-scale dimming and brightening, so that significant effects can be expected not only in areas with strong emitters, but also in relatively pristine areas through amplifying aerosol-cloud interactions. The most accurate radiation data support the existence of decadal dimming and brightening also at sites in remote locations. A large-scale change in decadal surface radiative forcings is also evident in the SSR proxy records which allow a better global coverage, particularly in the DTR evolution over global land surfaces (section 2.3 and Figure 3) [*Wild et al.*, 2007]. Also, recent satellite-derived estimates of SSR, which include an explicit treatment of temporally varying aerosols show global land mean changes in line with surface-based estimates. This applies at least for the "brightening" period, where such a comparison is feasible [*Wild et al.*, 2008; N. Hatzianastassiou et al., submitted manuscript, 2009]. This does not rule out the possible existence of an urbanisation effect in some of the larger-scale estimates of decadal SSR changes based on surface observations, as pointed out by *Alpert et al.* [2005] and *Alpert and Kishcha* [2008]. This requires further careful analysis and quantification. Population densities as used by *Alpert et al.* [2005] and *Alpert and Kishcha* [2008] as proxies for the effects of local pollutants on SSR can give a first indication, but have their limitations [*Stanhill and Cohen*, 2009]. For example, they do not depend on changes in air pollution regulations, and can neither account for changes in background aerosol loads, nor for the higher sensitivity of cloud microphysics to pollution changes in relatively pristine areas. Also, the quality of the sites used for a quantification of local versus nonlocal effects has to be rigorously assessed. Often, the maintenance at sites in remote locations is poor. Once well established and shown to be significant, a correction for local effects may be applied, similarly to the much better known urbanisation effect in temperature time series. A conservative assumption for now is that the larger-scale estimates based on surface data without considerations of urbanisation effects may pose an upper limit on decadal changes in the SSR, particularly during the "dimming period" (Table 1).

5. How Do Current Climate Models Simulate Global Dimming/Brightening?

[86] Global Climate Models (GCMs) are the most powerful tools currently available to investigate the effect of anthropogenic activities on the climate system, and to project the future evolution of Earth's climate. A large number of studies have investigated the ability of the GCMs to reproduce the decadal changes in standard observations like temperature or precipitation. Fewer studies have focused on the ability of the models to simulate the variations in SSR as discussed in the present review.

[87] *Liepert et al.* [2004] performed two equilibrium simulations with the ECHAM4 model of the Max Planck Institute for Meteorology, Hamburg, representing once present-day and once preindustrial aerosol and greenhouse gas conditions. They noted that the simulated reduction in SSR between preindustrial and present-day conditions was, at 5.2 W m^{-2}, smaller than the 7 W m^{-2} change over the 30-year period 1960–1990 inferred by *Liepert* [2002] from surface observations. *Nazarenko and Menon* [2005] analyzed transient simulations from 1960 to 2002 with and without anthropogenic aerosols performed with the NASA Goddard Institute for Space Studies (GISS) GCM. In the simulation which considers anthropogenic aerosols, they found a linear decrease in SSR of 0.21 W m^{-2} $decade^{-1}$ over the period considered, with a reversal of the dimming to a brightening after 1990, in qualitative agreement with observational evidence. In absolute terms, the simulated changes were an order of magnitude smaller than the ones reported in the observational studies (section 2). Similar results were found in a study with the Hadley Center Global Environmental Model (HadGEM1) by *Bodas-Salcedo et al.* [2008], who obtained a dimming which is far less than the estimates derived from surface observations.

[88] *Romanou et al.* [2007] investigated SSR over the 20th century as simulated by nine models taking part in the fourth IPCC assessment report [*IPCC*, 2007]. They showed that these models simulate a reduction in SSR over the entire 20th century of 1–4 W m^{-2}. This is still below the estimates reported in the literature from surface observations for the 1960 to 1990 period. They further show in single forcing simulations with the GISS-ER GCM, that the simulated dimming signal is predominantly caused by aerosol effects in the model. They found that the models without inclusion of indirect aerosol effects simulate the smallest dimming.

[89] At ETH Zurich, in collaboration with the Max Planck Institute for Meteorology, Hamburg, SSR fluxes as simulated in a special version of the ECHAM GCM were analyzed [*Wild*, 2008]. This model version includes an interactive microphysical formulation of all major global aerosol components, with prognostic treatment of their composition, size distribution, and mixing state (ECHAM5-HAM) [*Stier et al.*, 2005]. With this model version, transient experiments have been performed, using historic inventories of aerosol and aerosol precursor emissions [*Stier et al.*, 2006]. The model simulates a general

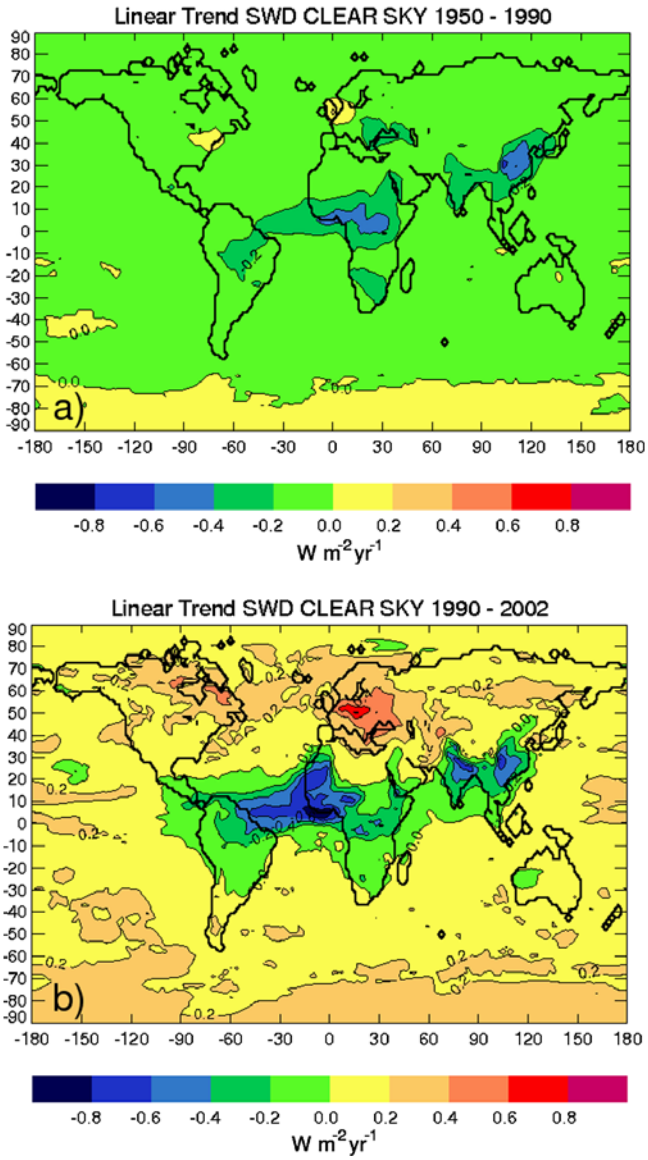

Figure 4. Simulated linear trends in surface solar radiation under cloud-free conditions for the (a) "global dimming" period 1950–1990 and (b) "brightening" period 1990–2002. Simulations done with the aerosol-climate modeling system ECHAM5 HAM [*Stier et al.*, 2005, 2006]. Units are W m^{-2} a^{-1}.

decrease in clear-sky surface solar radiation from the 1950s to the 1980s (Figure 4a) and a more recent recovery over large parts of the globe (Figure 4b). This is in qualitative agreement with the observational evidence discussed in section 2 in broad regions of the extratropics as well as in India. Not captured in the simulation is the slight recovery observed in China during the 1990s. In Figure 5, the simulated clear-sky SSR evolution is averaged over high, middle, and low latitudes, respectively, for the period 1950–2000. While most of the extratropics show a reversal from dimming to brightening during the 1980s in this particular model simulation, dimming persists up to the present day in many low-latitude areas (Figures 4 and 5). This latitudinal dependence has been favored by a transition from increasing to decreasing sulfur and black carbon emissions in industrialized countries since the 1980s [*Streets et al.*, 2006], which are mostly located in the extratropics. Some of the developing countries in the low latitudes, on the other hand, have seen ongoing increases in aerosol emissions, contributing to the continuing dimming in these areas [*Wild*, 2008]. There are too few reliable long-term observations in the tropics to verify this latitudinal dependence of dimming and brightening, and it has been argued that the increase in tropical emissions, dominated by biomass burning, might be unrealistically high in the emission history data set used in this model (M. Schultz, personal communication, 2007). Still, the latitudinal dependence of dimming/brightening gets some support from satellite analyses by *Kishcha et al.* [2007] based on recent aerosol optical depth data from the Moderate Resolution Imaging Spectroradiometer (MODIS). Their analyses suggest a decline in aerosol optical depth over much of the globe, except for the tropics where in contrast a slight increase prevails.

[90] *Ruckstuhl and Norris* [2009] assessed the ability of IPCC-AR4 models to reproduce the observed trends in SSR in Europe under cloud-free conditions as derived from a combination of satellite cloud observations, synoptic cloud reports, and SSR measurements [*Ruckstuhl et al.*, 2008; *Norris and Wild*, 2007]. They noted large discrepancies in sign and magnitude between modeled and observed "dimming" and "brightening" trends (up to 4.5 W m^{-2} decade^{-1} for Europe). They attributed the differences in the model simulation primarily to differences in the estimated aerosol burden and emission histories used in the IPCC-AR4 models. They also stated that decadal clear-sky dimming and brightening over Europe simulated by the IPCC-AR4 models, on average, is smaller than indicated by the observational evidence.

[91] Overall, the available studies suggest that GCMs simulate smaller decadal changes in SSR than what has been inferred from surface observations during the 20th century. This becomes also evident in a comparison of the evolution of the Diurnal Temperature Range (DTR) over Northern Hemisphere land surfaces [*Wild*, 2009] (Figure 6). As discussed in section 2.3, decadal changes in DTR may serve as a proxy for SSR dimming and brightening. The IPCC AR4 models (Figure 6, left) simulate a much lower decadal variation in DTR over the 20th century than observed in the CRU data set (Figure 6, right), indicative of a lack of decadal variation in SSR [*Wild*, 2009]. This is further illustrated in Figure 7, where the longest SSR time series available in GEBA from Stockholm (see section 2.1, Figure 2) is compared with the SSR as simulated at the nearest grid point in 18 GCMs from the IPCC AR4 "all forcings" 20th century simulations [*Wild*, 2009]. Figure 7 indicates that decadal variations of SSR at the simulated Stockholm grid point are much lower than observed. Specifically, the standard deviation of the observed annual mean time series Stockholm lies, with 8.4 W m^{-2}, outside the range of variations at the corresponding grid points in 18 GCMs, which range from 3.7 W m^{-2} to 8.1 W m^{-2}.

[92] The discrepancies between simulated and observed decadal changes in SSR could have several origins. A number of studies pointed to the large uncertainties in the historic emission inventories and associated aerosol burdens

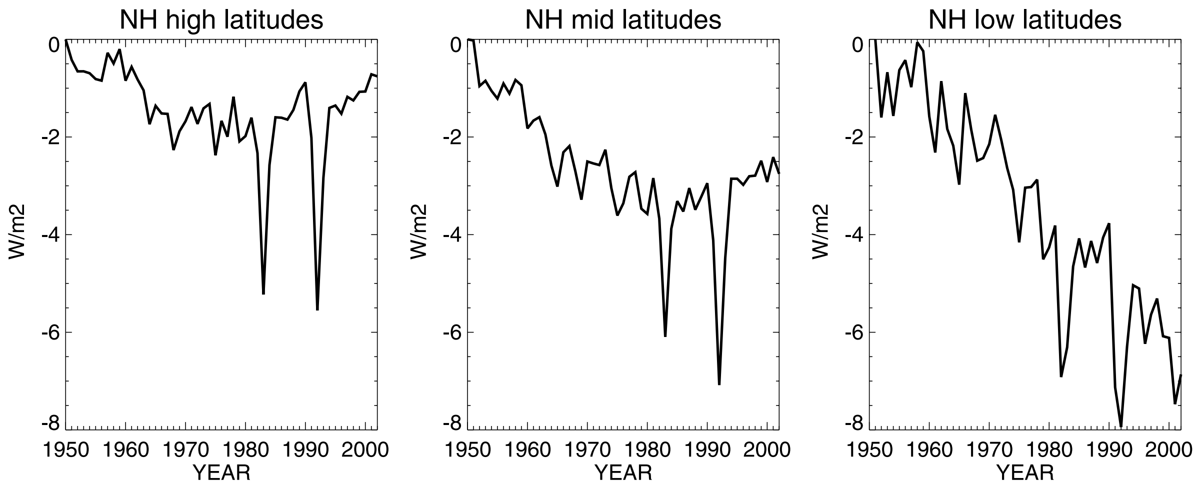

Figure 5. Simulated annual clear-sky surface solar radiation anomalies over the period 1950–2000 in different latitude belts of the Northern Hemisphere: High latitudes (60°N–90°N), middle latitudes (30°N–60°N), and low latitudes (0°–30°N). Simulations done with the aerosol-climate modeling system ECHAM5 HAM [*Stier et al.*, 2005, 2006]. Reference value is 1950. Units are W m^{-2}.

in the atmosphere [e.g., *Ruckstuhl and Norris*, 2009; *Wild*, 2009], which may not consider the full extent of decadal variations.

[93] When the aerosol forcing is well established, then observed and simulated SSR changes can reach better agreement. This is for example shown by *Ramanathan et al.* [2005] for the case of India. They obtained an excellent agreement for the dimming over India, determined at 4.2 W m^{-2} decade^{-1} in their study based on GEBA data, and 3.7 W m^{-2} decade^{-1} in their global simulation between 1960 and 2000. This model simulation used in addition to greenhouse gas and sulfate forcings, specifically prescribed forcings to account for the effects of atmospheric brown clouds as determined from observations during INDOEX [*Ramanathan et al.*, 2001b].

[94] Also, indirect effects, which were only included in a minority of the IPCC-AR4 models [*IPCC*, 2007, Table 10.2], can amplify aerosol-induced SSR dimming and brightening effects, at least in relatively pristine environments (see section 3.3). Further, the "urbanisation effect" [*Alpert et al.*, 2005; *Alpert and Kishcha*, 2008] in the observational SSR data needs better quantification and correction, although this effect alone may not be able to reconcile model-calculated and observed trends (see section 4). Further work is required to nail down the causes of the discrepancies between model-simulated and observed changes in SSR. The inability of the models to simulate the full extent of decadal SSR variations may lead to problems in the adequate simulation of other climate variables as outlined in the section 6.

6. What is the Impact of Global Dimming/Brightening on the Climate System and Climate Change?

[95] SSR takes a prominent role in the climate system as it states a major energy exchange at the interface between the atmospheric component on the one hand, and land,

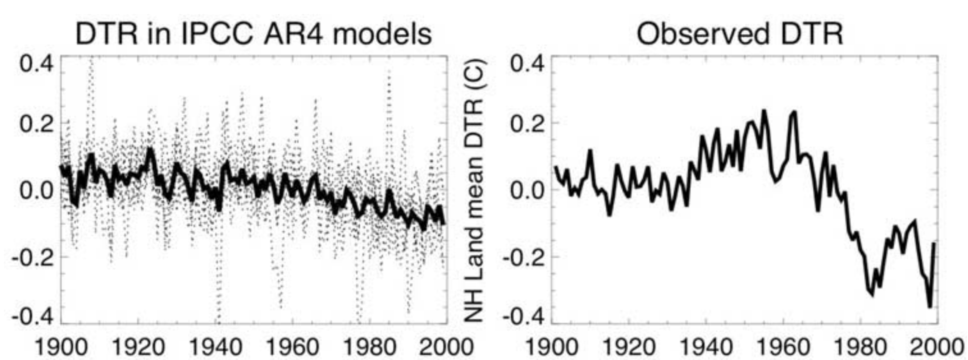

Figure 6. Annual averaged diurnal temperature range (DTR) anomalies over Northern Hemisphere land surfaces over the entire 20th century, as simulated by 8 GCMs in "all forcings" 20th century experiments (left) performed for the fourth IPCC assessment report and (right) as observed. Multimodel mean given as thick black lines. Individual model realizations shown as dashed lines. Reference period for anomalies is the entire 20th century. Observations from the CRU data set [*Mitchell and Jones*, 2005]. Units are °C [from *Wild*, 2009].

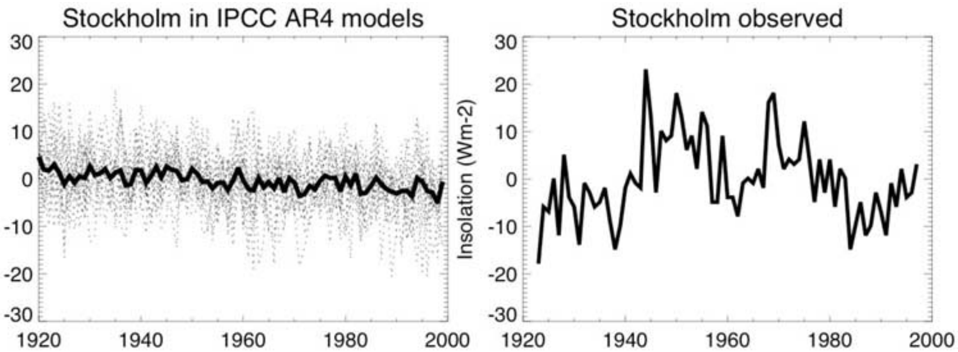

Figure 7. Annual mean surface solar radiation (right) as observed at the long-term monitoring station Stockholm and (left) as represented at the respective grid points in 18 GCMs used in the IPPCC fourth assessment report. Shown are anomalies with respect to the 1923–1999 mean. Units are W m^{-2} [from *Wild*, 2009].

biosphere, cryosphere and ocean components on the other hand. Variations in SSR have, therefore, the potential to significantly impact the climate system. Not many studies so far have specifically addressed this issue. Therefore, some of the aspects presented below are, at this stage, hypotheses which will require further investigation. Still they may give an idea of the potential of dimming and brightening to affect diverse aspects of the climate system.

6.1. Impact on Surface Temperature and Global Warming

[96] SSR governs to a considerable degree the temperature evolution at the Earth's surface. This is obvious in the everyday experience of the temperature variations over the daily and seasonal cycles which largely follow the strength of SSR. In terms of anthropogenic climate change, decadal changes in the strength of SSR are most relevant. Numerous studies suggest that aerosol increase (and associated SSR dimming) may counteract global warming [e.g., *Charlson et al.*, 1992]. Observed reductions of SSR were suggested to be responsible for the absence of a significant temperature rise between the 1950s and the 1980s in various parts of the world, such as in the Arctic [*Stanhill*, 1995], in China [e.g., *Li et al.*, 1995; *Qian and Giorgi*, 2000], in the United States [*Liepert*, 2002], and India [*Menon et al.*, 2002; *Ramanathan et al.*, 2005]. *Ramanathan et al.* [2005] suggested that the dimming induced by the atmospheric brown clouds over the Indian subcontinent has masked 50% of the surface warming due to the global increase in greenhouse gases.

[97] On the basis of the CRU temperature data set, *Wild et al.* [2007] pointed out that the suppression of global warming through SSR dimming over the global land surfaces only lasted into the 1980s. Thereafter, the vanishing dimming no longer masked the greenhouse effect, enabling the much stronger temperature rise in recent decades (+0.38°C $decade^{-1}$ over land since mid-1980s). *Ruckstuhl et al.* [2008] and *Philipona et al.* [2009] came to similar conclusions for the area of Europe, where brightening due to the substantial reduction in aerosol optical depth (up to 60% since 1986 at six remote locations in Europe) may have significantly contributed to the recent rapid warming in this region. *Vautard et al.* [2009] estimated, that reduced haze, mist and fog conditions in Europe could have contributed on average to about 10–20% of Europe's recent daytime warming and to about 50% of eastern European warming.

[98] The IPCC AR4 models do not seem to fully account for these observed decadal modulations of global warming through SSR dimming and brightening [*Wild*, 2009] (Figure 8). They underestimate the suppression of warming through SSR dimming between the 1950s and 1980s over global land surfaces, and give a higher rate of temperature rise than observed. On the other hand, for the more recent decades the models underestimate the rate of global warming, indicative of a lack of brightening [*Wild*, 2009]. *Wild et al.* [2007] provided evidence for a strong impact of dimming and brightening on global warming, based on analyses of decadal changes in observed daily maximum and minimum temperatures and related DTR (see section 2.2). They found a slight decrease in the daily maximum temperatures over the "dimming" period from the 1960s to the 1980s, which is in line with the reduction of SSR over this period. Daily minimum temperatures, on the other hand, have been increasing over the same period, causing a decline in the DTR. This behavior is to a much lesser extent found in the IPCC-AR4 models [*Wild*, 2009]. Cooling trends mainly due to a decrease in the daily maximum temperature were also observed in parts of China during the period with strong dimming [*Li et al.*, 1995; *Qian and Giorgi*, 2000]. In contrast, since the mid-1980s, observed minimum and maximum temperatures at global land surfaces increase at a very similar pace [*Wild et al.*, 2007]. This is indicative of a major change in the surface radiative forcing regime, where the maximum temperature rise is no longer suppressed as in previous decades, due to the transition from dimming to brightening.

[99] The evolution of observed 2-m temperature averaged over global land surfaces during the 20th century is shown in Figure 9 (adapted from *Wild et al.* [2007]). It depicts the well-known temperature curve with a rapid rise in the first half of the 20th century, then a 30–40-year period with little changes, and finally a rapid rise since the 1980s. This temperature evolution fits very well to the "early brightening-dimming-brightening" sequence inferred from the observational SSR records, and further points to the crucial role that decadal SSR variations may play in modulating global warming.

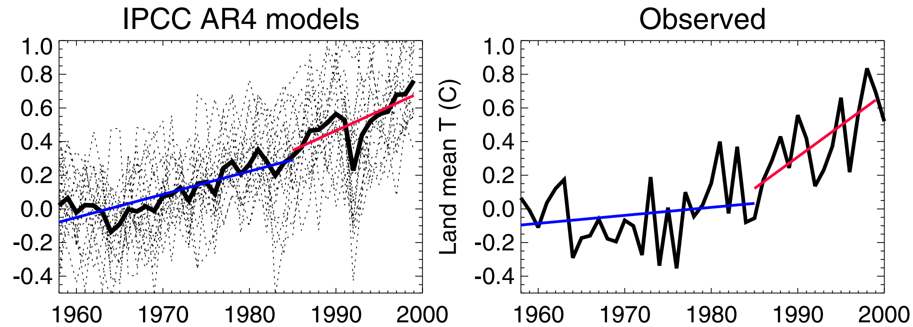

Figure 8. Annual mean temperature anomalies over land surfaces from 1958 to 1999, (left) as simulated by 18 GCMs in all forcings 20th century experiments performed for the fourth IPCC assessment report and (right) as observed. Multimodel mean given as thick black lines. Individual model realizations shown as dashed lines. Linear regressions for the periods 1958–1985 in blue and 1985–1999 in red. Observations from the CRU data set [*Mitchell and Jones*, 2005]. Reference period for anomalies is the entire 20th century. Units are °C [from *Wild*, 2009].

[100] Note, however, that I do not claim here that SSR changes can explain global warming over the 20th century. Recent brightening cannot supersede the greenhouse effect as the main cause of global warming, since land surface temperatures overall increased by 0.8°C from 1960 to 2000, even though solar brightening did not fully outweigh prior dimming within this period [*Wild et al.*, 2007]. Without greenhouse warming, global land temperatures should have decreased more during the dimming period than increased during the subsequent brightening period, since dimming overall has likely been more pronounced than the subsequent brightening, and SSR levels around 2000 were generally not as high as in the 1960s [*Wild et al.*, 2007]. Such a behavior is not seen in the observed global land temperature record (Figure 9). Therefore, a gradual increase in greenhouse warming superimposed by strong decadal modulations induced by dimming and brightening is required to explain the evolution of global warming during the 20th century. For a discussion of potential future effects of dimming and brightening see section 7.

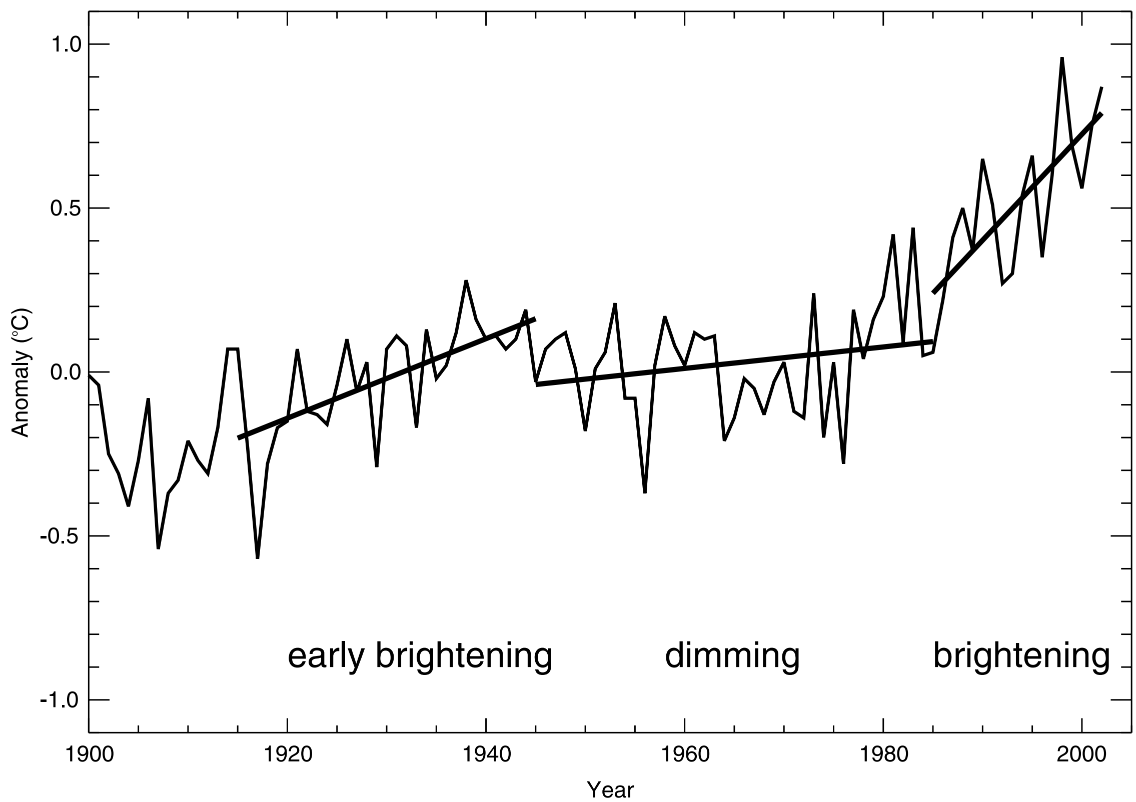

Figure 9. Observed 2-m temperature anomalies over global land surfaces during the 20th century. There is indication for a suppression of greenhouse-induced warming through "global dimming" between the 1950s and 1980s, and an enhancement through "brightening" between the 1920s and 1940s as well as from the 1980s onward. Anomalies with respect to the 20th century average. Units are °C. Adapted from *Wild et al.* [2007].

[101] Note also that surface temperature may only effectively respond to changes in SSR, if these changes are caused by processes which alter the total amount of solar energy absorbed in the climate system (such as through scattering aerosols, cloud reflectance or variations in the solar flux incident at the top of atmosphere) [*Ramanathan et al.*, 2001a; *Wong et al.*, 2006; *Wild et al.*, 2007]. If, however, the SSR changes are merely caused by a redistribution of solar absorption between atmosphere and surface with little effect on the total amount absorbed in the climate system (such as through changing absorbing aerosols), the SSR-induced temperature change at the surface would be largely suppressed by an opposed temperature change in the energetically tightly coupled troposphere. Anthropogenic emission inventories suggest that both scattering sulfur and absorbing black carbon aerosols underwent large decadal changes, with decreasing tendencies since the 1980s after decades of increase [*Stern*, 2006; *Streets et al.*, 2006] (see section 3.2). Changes in scattering sulfur aerosols are thereby estimated to be the largest individual contributor to the associated decadal changes in aerosol optical depth [*Streets et al.*, 2009]. This suggests that the SSR variations are to a considerable degree caused by changes in scattering processes which are particularly effective in modifying surface temperature, but in addition also by absorbing processes with less or opposing impact on surface temperature.

[102] These absorbing processes may also help to reconcile an apparent contradiction between the magnitude of SSR changes (surface radiative forcing) and tropopause radiative forcings, as, e.g., presented by the *IPCC* [2007], which are much smaller. If the changes in SSR would be entirely due to scattering processes, changes in the surface fluxes should be identical to changes in tropopause fluxes. A change in the absorptive capacity of the atmosphere, which alters the surface fluxes much more than the tropopause fluxes can reconcile the apparent discrepancies in surface and tropopause forcing estimates.

6.2. Impact on Components and Intensity of the Hydrological Cycle

[103] Radiative energy available at the Earth's surface is the principal driver of the hydrological cycle [e.g., *Ramanathan et al.*, 2001a]. Variations in the SSR induce changes in the surface net radiation (the sum of the solar and thermal energy exchanges at the Earth's surface), and thereby alter the energy available for evaporation, which equals precipitation in the global annual mean. Surface net radiation therefore governs the intensity of the global hydrological cycle [e.g., *Ohmura and Wild*, 2002], i.e., the rates of precipitation and evaporation.

[104] *Roeckner et al.* [1999] performed transient climate change scenario experiments with the climate model ECHAM4 and found that the intensity of the global hydrological cycle becomes weaker in a warmer climate if both direct and indirect aerosol effects are included in addition to the greenhouse gases. They attributed this to the reduction of SSR through aerosols, which is balanced by reduced turbulent transfer of both sensible and latent heat (the energy equivalent of evaporation) from the surface to the atmosphere.

[105] *Liepert et al.* [2004] carried out equilibrium experiments with a climate model with greenhouse gas and aerosol concentrations representative for preindustrial (mid-1880s) and present-day (mid-1980s) conditions, respectively. They found a slight spin down of the hydrological cycle in the model under mid-1980s conditions, related to a concurrent decrease in SSR of 3.8 W m^{-2} and surface net radiation of 1.9 W m^{-2} globally. This reduction of available energy at the surface led then to a decrease in evaporation, and globally averaged to the same reduction in precipitation.

[106] *Wild et al.* [2004] inferred from observations, that surface net radiation may have decreased by 5–8 W m^{-2} over the 30-year period 1960–1990 over land surfaces, since the decrease in SSR outweighed the greenhouse-induced increase in downwelling thermal radiation over this period. They further suggested that this reduction in available energy may have reduced surface evaporation over this period accordingly. This is in line with *Peterson et al.* [1995] and *Roderick and Farquhar* [2002], who pointed to worldwide declines in evaporation from pans (see section 2.3), even though the relationship between pan and actual evaporation is not necessarily direct [*Brutsaert and Parlange*, 1998; *Brutsaert*, 2006].

[107] The above studies, suggesting a deceleration of the hydrological cycle with dimming of SSR, were at the time of their publication opposing conventional wisdom that the intensity of the hydrological cycle has to increase in a warming climate. However, the evaluations of 20th century precipitation records indeed indicate that the hydrological cycle, at least over land surfaces, has decelerated over the period of about 1950–1990 [see *IPCC*, 2007, Figure 3.12], when dimming prevailed.

[108] On the other hand, there is evidence for a more recent recovery and acceleration of the hydrological cycle over global land surfaces during the 1990s, with increasing land precipitation after the decreasing tendencies in earlier decades [see, e.g., *IPCC*, 2007, Figure 3.12]. *Wild* [2008] and *Wild et al.* [2008] estimated that surface net radiation over land has increased by about 2 W m^{-2} decade^{-1} between 1986 and 2000, after several decades with no evidence for an increase. They attributed this increase to a combination of SSR brightening with more transparent atmospheres, and an increased flux of downward thermal radiation, due to enhanced levels of greenhouse gases. They further showed that the increase in surface net radiation is quantitatively consistent with the observed substantial increase in land precipitation (3.5 mm y^{-1} between 1986 and 2000) and the associated intensification of the land-based hydrological cycle. This recent intensification is not seen to its full extent in the current generation of GCMs (Figure 10). Figure 10 (left) shows the observed evolution of global land precipitation over the 15-year period 1986–2000 as discussed by *Wild et al.* [2008]. Here I show in addition the same quantity as simulated by 18 GCMs in the 20th century "all forcings" experiments carried out for the IPCC-AR4 (Figure 10, right). None of the 18 models shows an increase as large as the observations suggest. This is in line with several studies suggesting that climate models driven by estimated historical forcings simulate smaller increases in precipitation than observed [*Zhang et al.*, 2007; *Wentz et al.*, 2007; *Allan and Soden*, 2007]. *Wild et al.* [2008] pointed

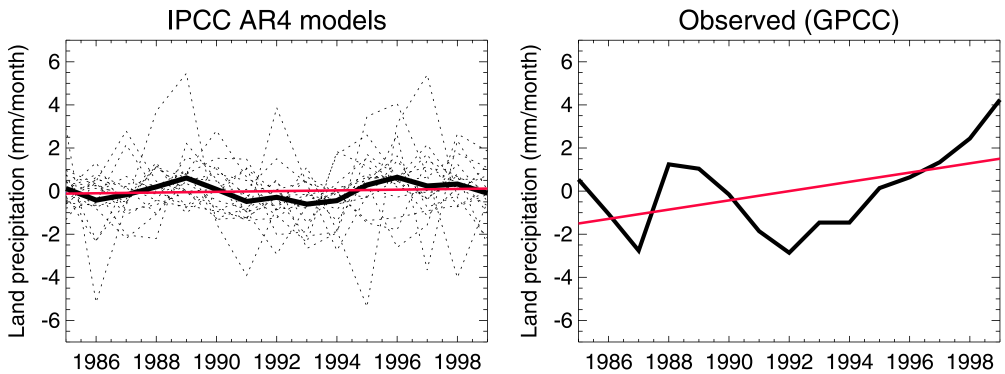

Figure 10. Annual mean precipitation anomalies over global land surfaces from 1985 to 1999, (left) as calculated in 18 state of the art GCMs used in the IPCC fourth assessment report and (right) as observed. Observations compiled at the Global Precipitation Climatology Center of the German Meteorological Service [*Grieser and Beck*, 2006]. Reference period 1985–1999. Units are mm month^{-1}.

out that the recent brightening effect, which is not fully reproduced in these simulations (see section 5), could account for some of these discrepancies.

[109] An intensification of the terrestrial hydrological cycle in the brightening period is further supported by the evidence for a recent increase in terrestrial evapotranspiration found by K. Wang et al. (Increase in global terrestrial evaporation from 1982 to 2002, submitted to *Proceedings of the National Academy of Sciences of the United States of America*, 2009). They determined evapotranspiration at 265 radiation sites (mostly from GEBA) over the period 1982–2002 using a semiempirical model together with observational information on SSR, surface air temperature, diurnal temperature range, relative humidity and a vegetation index from satellite data. They estimated an increase in evapotranspiration at 77% of the sites, and found the increasing SSR to be the most important factor determining the long-term increase in evapotranspiration. *Teuling et al.* [2009] pointed out that evaporation changes are linked to SSR changes particularly in energy-limited environments such as central Europe. They find that in such environments evaporation trends derived from weighing lysimeters and river basin water budgets closely follow the dimming and brightening of SSR.

[110] Land precipitation seems to have increased not only in recent decades, but also over the period 1930 to 1950 [*IPCC*, 2007, Figure 3.12], which would fit well to the general picture of an "early brightening" and increasing energy availability at the surface for evaporation during this time. Overall, this implies that decadal variations in SSR, combined with increasing downwelling thermal radiation, indeed had a discernible impact on the variations of the hydrological cycle over the 20th century [*Wild*, 2008].

[111] The imprint of SSR dimming and brightening may also be visible in long-term observations of soil moisture as suggested by *Robock et al.* [2005]. A 45-year record of soil moisture measurements in the Ukraine covering the period 1958 to 2002 showed an increase in soil moisture in the first half of the record, followed by a slight decrease in the latter half [*Robock et al.*, 2005]. These changes could not be explained by changes in precipitation alone. Rather, they suggested that SSR dimming caused a decrease in surface evaporation up to the 1980s, which led to increasing soil moisture. Sensitivity experiments with a stand-alone land surface scheme and imposed changes in SSR at different rates supported these findings [*Robock and Li*, 2006].

[112] It has also been proposed that the dimming due to the Northern Hemispheric air pollution may have been a factor that caused the severe Sahelian droughts and famines during the 1970s and 1980s [*Rotstayn and Lohmann*, 2002]. They carried out equilibrium simulations with a climate model with sulfur aerosol emissions representative for preindustrial and year 1985 conditions, respectively, and found significant changes in precipitation patterns, particularly a southward shift of tropical rainfall, in broad agreement with observed trends. The sea surface temperature cooling produced by the dimming in the Northern Hemisphere results in less evaporation and drier air, which is advected into the Sahelian region. It is interesting to note here that in the 1990s, when Northern Hemispheric aerosol forcing reduced and dimming vanished, precipitation in the Sahel began to recover. It can be speculated that the transition from dimming to brightening may have helped to restore vital precipitation in the Sahel [*Wild*, 2008].

[113] Also monsoon systems may be affected by the dimming. *Ramanathan et al.* [2005] suggested in their simulation that, over India, dimming due to air pollution (atmospheric brown cloud) leads to a weakening of the monsoon and associated increased droughts over India. On the other hand, *Menon et al.* [2002] found with another model that increased absorbing aerosol loadings should enhance precipitation over India and increase summer floods in south China.

[114] Cleary, more work is required for a better understanding of the interactions between dimming/brightening and the various aspects of the hydrological cycle. The above studies, however, demonstrate the potential sensitivity of the hydrological cycle to changes in the surface radiative forcings induced by SSR dimming and brightening.

6.3. Impact on the Cryosphere (Glaciers and Snow Cover)

[115] SSR is a major energy source for the melt processes in snow and ice. A potential consequence of the solar dimming/brightening phenomenon can be seen in the behavior of mountain glaciers in Switzerland. Between 1973

and 1985, no significant changes in glacier area were found (1%). However, between 1985 and 2000 glacier area extent in Switzerland has reduced by 18% [*Paul et al.*, 2004]. This fits to the decadal SSR changes, in the sense that the greenhouse effect was masked by solar dimming up to the 1980s so that no major changes in glacier area extent could occur in this period. As soon as the dimming disappeared in the mid-1980s, glaciers started to retreat [*Ohmura et al.*, 2007; *Wild*, 2008]. Similar effects are also evident with other European glaciers [*Ohmura et al.*, 2007].

[116] It is also interesting to note here that Northern Hemisphere snow cover extent, according to IPCC 2007 (Figure SPM 3) underwent no major changes between the 1930s and 1980s, but then sharply declined from the 1980s to 2000 (on the order of 3 million km^2) [*Brown*, 2000]. One could speculate that the transition from dimming to brightening may have favored the rapid decline in Northern Hemisphere snow cover since the late 1980s.

[117] On a more regional scale, *Marty* [2008] found a significant step-like decrease in snow days in Switzerland at the end of the 1980s. He attributed this regime shift to influences in large-scale flow patterns and the concurrent transition from dimming to brightening.

6.4. Impact on the Terrestrial Biosphere and Carbon Cycle

[118] SSR, or more specifically, its Photosynthetic Active Range (PAR, 0.4 to 0.69 μm) is the primary driver of plant photosynthesis and thereby influences the carbon uptake of the biosphere and the carbon cycle. However, it is not only the total amount of SSR or PAR incident at the surface that matters in this context, but particularly also its partitioning into direct and diffuse radiation. Diffuse light penetrates deeper into the canopy and is thereby readily available to more leaves. Canopy photosynthesis, and associated net primary production, i.e., the carbon uptake in plants determined as difference between photosynthesis and plant respiration, therefore tends to increase with an increase in the fraction of diffuse light. This 'fertilization effect' has for example become evident after the volcanic eruption of Mount Pinatubo, where a substantial slowdown of the increase in atmospheric CO_2 concentration occurred [*Jones and Cox*, 2001]. This has at least partly been attributed to the increase in diffuse light with increased aerosol scattering, and the associated efficiency increase in photosynthesis [*Farquhar and Roderick*, 2003]. Dimming/brightening effects, generally associated with increasing/decreasing aerosol loads and cloudiness, and related increase/decrease in diffuse light may therefore need to be included in considerations on potential changes in carbon Net Ecosystem Exchange (NEE). In addition to the net primary production, NEE also accounts for the soil respirations and thus determines the net carbon exchange of entire ecosystems. NEE is also the quantity that ultimately determines whether the terrestrial biosphere is a source or sink of carbon. *Gu et al.* [2003] noted for example that the increased diffuse light after the Pinatubo eruption and the associated increase in canopy photosynthesis resulted in a sink of CO_2 in a hardwood forest.

[119] *Mercado et al.* [2009] reconstructed global variations in diffuse, direct, and total downward PAR over the entire 20th century, on the basis of radiative transfer calculations driven with estimates on past changes in aerosols and clouds. They then forced a global soil and vegetation model with these radiation fields and additional observations on temperature and precipitation changes to estimate NEE changes over the 20th century. In these simulations, a quarter of the accumulated land carbon sink over the 20th century could be attributed to changes in diffuse radiation effects on photosynthesis. These effects were particularly strong during the dimming phase from the 1950s to the 1980s with increasing diffuse radiation. *Mercado et al.* [2009] suggested that global dimming and brightening contributed to an increase and decrease in the land carbon sink, respectively. Thus, the effect of increasing (decreasing) diffuse fraction of radiation during the dimming (brightening) seems to have overcompensated the effect of decreasing (increasing) total radiative energy on NEE. This is in line with the above mentioned evidence after the Mount Pinatubo eruption, which may be seen as a short-term analogon for global dimming.

[120] Knowledge on decadal variations not only in total downward radiation, but also in its direct and diffuse components, is therefore essential for the understanding and projections of changes in the carbon cycle and vegetation growth.

7. What is the Future of Global Dimming/Brightening and Related Climate Impacts?

[121] To the extent that decadal variations in SSR are caused by anthropogenic air pollution, dimming and brightening will depend on future anthropogenic emissions of aerosols and aerosol precursors. These emissions may change substantially in the future in response to economic growth, energy consumption and air pollution regulations. Associated projections depend on various socioeconomic factors and are accordingly afflicted with considerable uncertainties. In a sensitivity study, *Brasseur and Roeckner* [2005] explored the impact of a hypothetical complete removal of the total amount of anthropogenic sulfate aerosols currently present in the atmosphere. On the basis of GCM simulations, they estimate that this "sudden brightening" would lead to an increase in global mean surface air temperature of 0.8 K and 3%, respectively, within less than a decade. The evolution of dimming and brightening in the simulation with the ECHAM5 HAM [*Stier et al.*, 2006] discussed in section 5 is extended in Figure 11 up to 2020. Shown is again the simulated SSR evolution under clear-sky conditions for Northern Hemisphere high-, middle-, and low-latitude belts as in Figure 5. In the Northern Hemisphere midlatitudes, after a partial recovery in the 1980s and 1990s from the prior dimming, a renewed dimming is projected after the year 2000. The renewed dimming is a consequence of the emission scenario which assumes that increasing emissions in Southeast Asia increasingly outweigh the decreasing emissions in the western world [see *Stier et al.*, 2006]. First indications of this may also be seen in the recent updates of surface radiation records, which indicate, for example a renewed dimming in China after 2000 [*Wild et al.*, 2009]. A renewed dimming in China would not be completely surprising, since for example coal consumption in China has doubled between 2002 and 2007 (data available from U.S. Energy Information

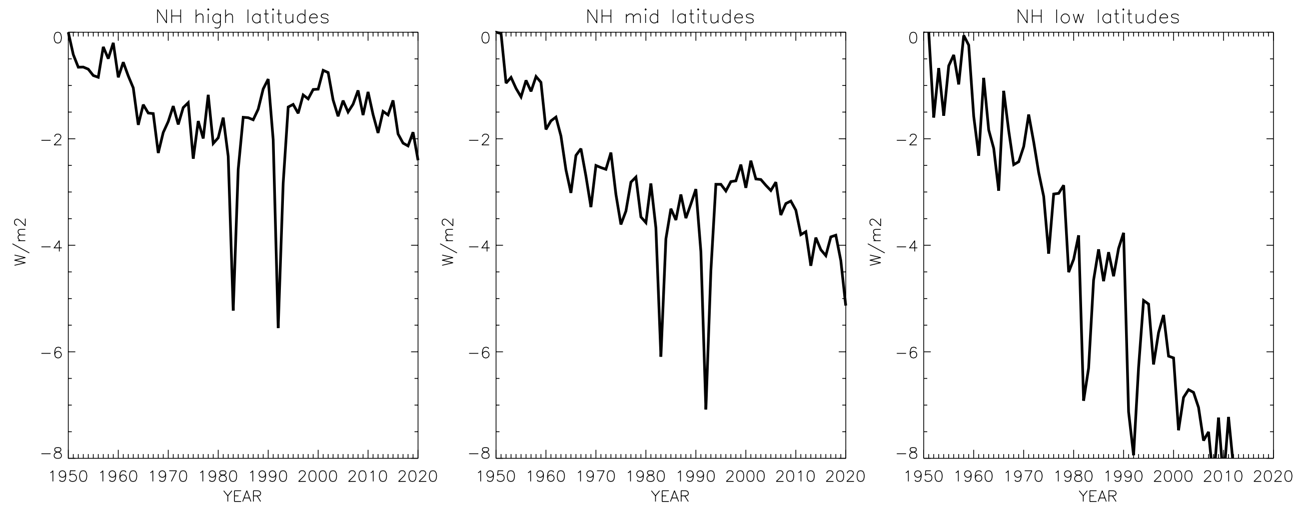

Figure 11. Simulated annual clear-sky surface solar radiation anomalies over the period 1950–2020 in different latitude belts of the Northern Hemisphere: High latitudes (60°N–90°N), middle latitudes (30°N–60°N), and low latitudes (0°–30°N). Simulations done with the aerosol-climate modeling system ECHAM5 HAM [*Stier et al.*, 2005, 2006]. Reference value is 1950. Units are W m^{-2}.

Administration http://www.eia.doe.gov/emeu/international/coalconsumption.html). On the other hand, not much further brightening might be expected in western industrialized countries, since aerosol levels stabilized since about 2000 at low values [*Philipona et al.*, 2009; *Streets et al.*, 2009; *Kishcha et al.*, 2009]. In low latitudes, the scenarios assume ongoing uncontrolled increases in emissions in developing nations and therefore a continued dimming. The possibility of a return into an overall dimming in the near future can therefore not be excluded, which may also have implications for predictions of global warming on shorter time scales. However, it is clear that also in developing countries as well as in east Asia and India air pollution regulations will become inevitable at some stage to prevent dramatic health problems. Therefore, in the longer run a turn into brightening can be expected also in these countries. At this stage it will be imperative that greenhouse gas concentrations in the atmosphere will be stabilized to compensate and mitigate unwanted effects of future brightening phases.

8. Concluding Remarks

[122] In the previous sections the increasing evidence for substantial decadal changes in the amount of solar radiation reaching the Earth's surface ("global dimming/brightening") was highlighted. These changes have not only become evident in direct measurements of surface solar radiation (SSR), but also in a number of related quantities (e.g., diurnal temperature range, sunshine duration, pan evaporation, planetary albedo, anthropogenic emission inventories, ice core records) as well as satellite-derived estimates. These additional quantities can help to close temporal and spatial gaps in our knowledge on SSR variations. The sum of these different data sets portrays a reasonably consistent picture of a widespread dimming of SSR between the 1950s and 1980s and a more recent trend reversal toward a brightening in some of the areas. There are also indications for an early brightening in the 1930s and 1940s. These variations left a remarkable imprint on the 20th century temperature records (see Figure 9).

[123] The decadal changes in SSR found in the dimming/brightening literature are at first sight often unrealistically large from a radiative forcing viewpoint, as, e.g., presented by *IPCC* [2007]. Therein, radiative forcings altering solar radiation between preindustrial (year 1750) and present day are on the order of minus 1–2 W m^{-2} on a global average, while some of the surface-based estimates show similar or larger changes already within a decade (Tables 1–3). Indeed, under the assumption of a climate sensitivity of 0.5–1°C per W m^{-2} radiative forcing as suggested by current climate models, a change of several W m^{-2} $decade^{-1}$ as inferred from surface observations would imply enormous decadal variations in surface temperature which are not observed. However, one should be aware that the radiative forcing concept as used in the IPCC reports applies to changes at the tropopause, which cannot be directly compared to changes at the surface. Scattering and absorbing processes in the atmosphere are additive with respect to their effects on SSR at the surface, but may be opposed at the tropopause. Scattering aerosols enhance the reflectance of solar radiation back to space and reduce the solar flux to the surface. Absorbing aerosols also reduce the solar flux to the surface, but at the same time may reduce the reflectance back to space, opposed to the effects from scattering aerosols at the tropopause. Therefore, surface changes can expected to be larger than tropopause changes, and consequently are also not necessarily representative for (tropopause) radiative forcing estimates (this would only be valid in a purely scattering atmosphere). SSR change estimates based on surface observations should therefore not be used to challenge the IPCC radiative forcings [*Liepert et al.*, 2007], even if these SSR changes would be free of biases from upscaling the surface point observations to global numbers.

[124] Nevertheless, accurate knowledge of the magnitude and origins of SSR variations is essential for our understanding of decadal changes in various elements of the

climate system as evidenced in this review, such as in the components of the hydrological cycle, diurnal temperature range, terrestrial carbon uptake, surface processes, glaciers and snow cover extent. These changes cannot be understood from information on tropopause or top of atmosphere changes alone, as, e.g., seen from satellites.

[125] The assessment of the magnitude of these SSR variations faces a number of challenges. One is related to data quality. Surface radiation networks with well-calibrated instrumentation and quality standards as those defined in BSRN [*Ohmura et al.*, 1998] need to be maintained on a long-term basis and if possible expanded into underrepresented regions (see Figure 1b). Historic radiation data have to undergo more rigorous quality checking and homogenization/gap filling where possible. Some of the measurement quantities that have been identified as useful proxies to complement the historic SSR data need to be consigned to centralized storage and undergo quality assessment to facilitate global-oriented evaluations (e.g., sunshine duration, pan evaporation).

[126] A further challenge is related to the representativeness of data. Information on SSR changes only becomes climatologically relevant if applicable to a larger-scale area. This requires upscaling methods and assessments of the representativeness of individual sites for their larger-scale setting. *Dutton et al.* [2006] provide a framework which allows such an assessment based on spatial cross correlations with satellite-derived estimates. This methodology may also provide a strategy for surface network planning to optimize coverage over an extended area, as it allows us to estimate the relative contribution of additional sites in obtaining larger-scale estimates. Urbanisation effects need to be more rigorously assessed in the data sets. Population densities as an indicator for local pollution at the sites can give a hint, but have their limitations [*Alpert et al.*, 2005; *Alpert and Kishcha*, 2008; *Stanhill and Cohen*, 2009]. Atmospheric transport models or fully interactive climate models together with latest satellite diagnostics from newly established satellite programs such as the A-Train [*Anderson et al.*, 2005] may be able to quantify the urbanisation effect on SSR on a more physical basis. Satellite-derived estimates of SSR with their larger-scale representativeness will become increasingly important with the wealth of information from the new satellite programs, but require stable long-term monitoring and funding sources.

[127] The origin of dimming/brightening has shown to be internal to the climate system and not externally forced by the Sun. The main causes appear to be changes in cloud and aerosol characteristics and abundance, which may or may not be microphysically linked. Evidence for an anthropogenic contribution through emission changes and associated modification of atmospheric aerosol loads has been presented. The relative importance of aerosols, clouds and aerosol-cloud interactions as contributors to dimming and brightening may not be uniform over the globe but varies from region to region. A conceptual framework has been outlined which may help to understand how these different factors affect SSR depending on pollution levels. This framework may be useful as guidance for further observational and modeling studies aiming at elucidating the origins of dimming and brightening in more detail.

[128] A better understanding of the magnitude and origins of SSR changes can also provide a basis for climate model improvement and will ultimately help to reconcile the current discrepancies between observed and model-calculated decadal variations in SSR and related quantities (e.g., DTR, hydrological components). Improved knowledge on SSR variations over the 20th century will also put additional constraints on GCM simulations and thereby contribute to the reduction of the uncertainties in future climate projections.

[129] Impact studies related to dimming and brightening have only just started to be carried out. The different hypotheses on possible implications for various aspects of climate change, such as the hydrological changes, snow cover and glacier retreat, global warming or terrestrial carbon uptake, call for better quantification and modeling studies.

[130] Although emphasis in this review paper was placed on the variations in surface solar radiation, it is essential to keep focused on all (solar and thermal) components of the Earth radiation balance, both from a surface as well as from a top of atmosphere (satellite) perspective. Only such a complete picture will allow us to fully quantify and understand the anthropogenic and natural perturbations of the radiation balance, which are at the basis of global climate change. Long-term monitoring of solar and thermal fluxes with known accuracy from both surface and space is therefore of utmost importance over the coming decades to provide the observational basis for our understanding of climate change.

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