

Global dimming and brightening: An update beyond 2000

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[1] This study investigates recent variations in downwelling surface solar radiation inferred from a comprehensive set of ground-based observational records updated for the period 2000-2005. Surface radiation data beyond the year 2000 are particularly interesting as they provide independent and complementary information to the ambitious satellite programs which became operational with the beginning of the new millennium. The surface records suggest a continuation of the surface solar brightening beyond 2000 at numerous stations in Europe and the United States, as well as parts of east Asia (Korea). Surface solar radiation variations in Europe after 2000 are dominated by a large positive anomaly in the year 2003 with its unprecedented summer heat wave, exceeding 10 Wm^{-2} on an annual and 20 Wm^{-2} on a summer mean basis in central Europe. The brightening seen at sites in Antarctica during the 1990s, influenced by a recovery from the low atmospheric transparency after the Mount Pinatubo volcanic eruption in 1991, fades after 2000. The brightening tendency also seems to level off at sites in Japan. 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. Overall, the available data suggest continuation of the brightening beyond the year 2000 at numerous locations, yet less pronounced and coherent than during the 1990s, with more regions with no clear changes or declines. Therefore, globally, greenhouse warming after 2000 may be less modulated by surface solar variations than in prior decades.

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1. Introduction

[2] There is increasing evidence that solar radiation incident at the Earth's surface (also known as surface solar radiation, global radiation or insolation) has not been constant over time, but has undergone climatologically significant decadal variations. This is for example indicated in indirect data from sunshine duration recorders, which show substantial decadal changes since their initiation in the late 19th century [e.g., *Pallé and Butler*, 2002; *Stanhill and Cohen*, 2005; *Sanchez-Lorenzo et al.*, 2008].

[3] Direct surface radiation measurements started to become available on a widespread basis in the late 1950s, with the establishment of numerous radiation sites during the International Geophysical Year (IGY) 1957–1958. On the basis of these records, several studies pointed to a wide-

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spread decrease of surface solar radiation from the early 1960s up to the late 1980s ("global dimming" [Ohmura and Lang, 1989; Gilgen et al., 1998; Stanhill and Cohen, 2001; Liepert, 2002; Wild et al., 2004; Wild, 2009a, and references therein]). Only data prior to 1990 were available at the time these studies were completed. More recent studies used data records updated for the 1990s and suggested, that the decline in surface solar radiation faded during the 1980s, and leveled off or even reversed toward an increase during the 1990s ("brightening" [Wild et al., 2005, 2007, 2008; Gilgen et al., 2009]). The present study investigates how surface solar radiation further evolved into the new millennium, on the basis of newly updated surface observational records. The years after 2000 are particularly interesting, as this marks the start of an era with new ambitious satellite programs such as CERES (Clouds and the Earth's Radiant Energy System [Wielicki et al., 1996]) and GERB (Geostationary Earth Radiation Budget [Harries et al., 2005]). These satellite programs provide a wealth of new information on top of atmosphere (TOA) radiative fluxes as well as retrievals of aerosol and cloud properties. This is in contrast to the 1990s when only very limited and discontinuous broadband satellite observations of TOA radiative fluxes were made. CERES started to provide continuous measurements of the TOA fluxes of unprecedented accuracy from the polar orbiting satellite platform TERRA in December 1999, and from the satellite platform

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AQUA in 2002 [Loeb et al., 2007a, 2007b]. The GERB program provides high temporal resolution measurements of the TOA radiative fluxes from the geostationary Meteosat satellites since 2002 [Harries et al., 2005]. In light of the unprecedented information provided by these new satellite programs since the turn of the millennium, it is interesting to see what the complementary surface measurements can tell us over the same period. It is also of interest to see how the recent changes in surface observations relate to the changes in alternative planetary albedo estimates by Earthshine measurements, which also became operational with the turn of the millennium [Pallé et al., 2004]. Further, the Aerosol Comparisons Between Observations and Models (AEROCOM) project has one of its main focuses on hindcast simulations covering the years after 2000. This project aims at assessing the aerosol distribution as simulated in global atmospheric transport models [Schulz et al., 2006; Kinne et al., 2006; Chin et al., 2007]. Surface radiation observations are envisaged to be used as a major diagnostics in this project. Surface radiation observations beyond 2000 may also be useful for the evaluation of new reanalyses such as Global and Regional Earth-System Monitoring Using Satellite and In Situ Data (GEMS), and of updated surface radiation budgets derived from satellite observations [Hatzianastassiou et al., 2005; Pinker et al., 2005] as well as global climate model simulations [Wild, 2009b].

[4] In the present paper we restrict ourselves to the information contained in surface records, updated to include data beyond 2000. The present paper thus aims at providing a reference on the available surface observations for the above mentioned and related projects.

2. Data

[5] For the present study we made an effort to bring together updates from as many surface radiation records as possible that extend beyond the year 2000. The data are taken from the major sources available on surface solar radiation measurements: the Global Energy Balance Archive (GEBA) at ETH Zurich [Ohmura et al., 1989; Gilgen et al., 1998] status July 2008, the World Radiation Data Centre (WRDC) of the Main Geophysical Observatory in St. Petersburg maintained by Dr. A. Tsvetkov, the Baseline Surface Radiation Network (BSRN) [Ohmura et al., 1998] at the Alfred Wegener Institute in Bremerhaven, the Surface Radiation (SURFRAD) network operated in the United States by the National Oceanic and Atmospheric Administration (NOAA) [Augustine et al., 2000], the Earth System Research Laboratory (ESRL) network of NOAA [Dutton et al., 2006], the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) program [Ackerman and Stokes, 2003], and the radiation database of the Swiss Meteorological Institute.

[6] While for a few stations an update until 2007 was possible (mainly the Swiss stations), many series could be updated to 2005 (GEBA/WRDC, SURFRAD, BSRN). In the present study we include therefore only stations with records up to at least 2005. Accordingly, we will focus on the period 2000–2005 with comparisons to the preceding decades. The limited record lengths will not allow for rigorous trend analyses at the individual sites. Rather, we

aim at detecting common characteristics at a large number of sites.

3. Change in Surface Solar Radiation Beyond 2000

3.1. Europe

[7] Most data on surface solar radiation for the post-2000 period are found in the European region. For Europe we brought together updated information from 133 stations extending to 2005 from the GEBA/WRDC and the Swiss Meteorological Institute. We grouped them into different regions: Germany (7 sites), Austria/Switzerland (19 sites), France (23 sites), Benelux (10 sites), UK/Ireland (19 sites), Scandinavia (21 sites), Spain/Portugal (11 sites), and eastern Europe (23 sites).

[8] For each region, we determined annual time series by averaging over complete records of the individual sites. At each individual site, we allowed for up to 3 missing months per year which were replaced by the corresponding months of the sites' climatology, thus retaining in the worst case at least 75% of the information on the variation in an individual year. These time series are shown in Figure 1, starting from 1985 to 2005. The mid-1980s are considered as average turning point in the transition from dimming to brightening at many sites in Europe [Wild et al., 2005]. We also visually separated the time series at the year 2000. This separation has no particular physical reasoning and is therefore to some extent arbitrary, but is motivated by the new data availability and the ambitious complementary remote sensing projects initiated around this time, as outlined in the introduction. The time series with the highest absolute values stems from the Iberian sites, the one with the lowest values from Scandinavia, as expected from their latitudinal location. All series show a general increase over the entire period, with a particularly pronounced upward tendency since 2000. The linear changes over the 1985-2005 period are 0.46 $Wm^{-2}a^{-1}$ for Germany, 0.37 $Wm^{-2}a^{-1}$ for Austria/ Switzerland, 0.36 $Wm^{-2}a^{-1}$ for France, 0.42 $Wm^{-2}a^{-1}$ for Benelux, 0.03 Wm⁻²a⁻¹ for United Kingdom/Ireland, 0.16 Wm⁻²a⁻¹ for Scandinavia, 0.49 Wm⁻²a⁻¹ for Spain/ Portugal, and 0.23 $Wm^{-2}a^{-1}$ for Eastern Euorope; all of them except for United Kingdom/Ireland being larger than the 1σ uncertainty estimates. In addition to these changes in individual regions, a Pan-European time series, constructed as average over the different regional time series, is shown in Figure 1. This series shows a linear increase of 0.20 $\text{Wm}^{-2}a^{-1}$ (1.5% per decade) over the period 1985–1999 (1 σ uncertainty estimate 0.17 Wm⁻²a⁻¹) and of 1.33 Wm⁻²a⁻¹ over the period 2000–2005 (1 σ uncertainty estimate 0.92 $\text{Wm}^{-2}\text{a}^{-1}$). It is evident that the latter period is strongly affected by the year 2003 with the record warm summer in central Europe [Schär et al., 2004]. The linear change over the entire 1985-2005 period amounts to 0.33 $\text{Wm}^{-2}\text{a}^{-1}$ (2.5% per decade, 1σ uncertainty 0.11 Wm⁻²a⁻¹), or 0.24 Wm⁻²a⁻¹ (1.8% per decade, 1σ uncertainty 0.10 $\text{Wm}^{-2}\text{a}^{-1}$) if we exclude the anomalous year 2003 from the analysis.

[9] Figure 2 shows in more detail data from all available sites in the focal period 2000–2005 within the individual European regions noted above. The time series are shown here in form of annual mean anomalies with respect to their



Figure 1. Evolution of annual mean surface solar from 1985 to 2005 as measured in various regions in Europe. Regions include Switzerland/Austria (AT/CH), Germany (DE), France (FR), Belgium/ Netherlands (BE/NL), United Kingdom (UK), Scandinavia, and Spain/Portugal (ES/PT). A Pan-European time series is determined as average over the regional time series (in red). The updated focal period 2000–2005 is visually separated from the preceding 1985–2000 period. Units are given in Wm⁻².

2000-2005 mean. Linear changes are added in Figures 1 and 2, but should merely be understood as "tendencies" rather than "trends" in a statistical sense, as the determination of trends and confidence intervals is not appropriate over the limited number of years in the 2000-2005 period. A common feature of most regions is the above mentioned strong peak in surface solar radiation in 2003. Figures 1 and 2 show that the excessive insolation during summer 2003 associated with the exceptional heat wave had a discernible influence on the annual total insolation in most regions. This is further quantified in Table 1, which compares the annual mean insolation in 2003 with an annual climatology composed of the neighboring years 2000-2005. Similarly, in Table 2 the summer (June-July-August mean) insolation in 2003 is compared with a summer climatology of the neighboring years 2000-2005. The strongest insolation peaks in 2003 are found in Germany, Switzerland/Austria, and in the Benelux, with annual anomalies of 17, 14, and 15 Wm^{-2} , respectively (Figures 2a, 2b, and 2d and Table 1). Focusing only on summer 2003, where the heat wave was confined, the insolation anomalies in Germany, Switzerland/ Austria, and in the Benelux reach as much as 31, 26 and 23 Wm⁻², respectively (Table 2). A distinct maximum in 2003 is also evident in eastern Europe, with a positive anomaly of 11 Wm^{-2} in the annual mean and 23 Wm^{-2} in the summer mean (Figure 2h and Tables 1 and 2). This

suggests that extended regions in central Europe received over the entire summer 2003 more than 20 Wm^{-2} excess solar input at the surface. This represents a major additional energy input to the Earth surface that has induced significant changes in the surface energy balance with associated record high surface temperatures [cf. Schär et al., 2004]. The only regions in Figure 2 with no distinct maximum in 2003 are Scandinavia and the Iberian Peninsula (Figures 2f and 2g and Tables 1 and 2). They lie outside the area primarily affected by the 2003 heat wave [cf. Schär et al., 2004, Figure 1]. Stations in France show substantial positive anomalies in 2003 at locations in central and northern France, but no similar evidence at locations in Southwestern France outside the core region of the 2003 central European heat wave (Figure 2c). A simple average over all European regions gives an excess in solar radiation of 8 Wm^{-2} in the annual and 16 Wm⁻² in the 2003 summer mean (cf. Pan-European time series in Figure 1 and Tables 1 and 2). Note that the reference climatology used here, composed of the 5 years 2000–2005 without 2003, is somewhat higher than a climatology determined over a longer period because of the continuous brightening (e.g., 2 Wm^{-2} higher than the 1985-2005 climatology, Figure 1). Compared to a longer reference period the European 2003 anomaly would therefore be accordingly higher. Note further that this excessive insolation in summer 2003 has not been a global phenom-

Figure 2. Evolution of annual mean surface solar radiation at various sites in different European regions from 2000 to 2005. (a) Germany, (b) Switzerland/Austria, (c) France, (d) Belgium/Netherlands, (e) United Kingdom, (f) Scandinavia, (g) Spain/Portugal, and (h) eastern Europe. Individual time series are shown as annual deviations (anomalies) from their 2000-2005 mean. Units are given in Wm⁻².



Figure 2

Table 1. Annual Mean Surface Solar Radiation in the Year 2003for Different Regions in Europe Compared to Climatological MeanConditions^a

Region	Annual Climatology	Year 2003	Year 2003 Anomaly
Scandinavia	103	102	-1
United Kingdom and Ireland	105	112	7
Belgium and Netherlands	117	132	15
Germany	121	138	17
Switzerland and Austria	145	159	14
Eastern Europe	137	149	12
France	151	160	9
Spain and Portugal	184	178	-6
Average	133	141	8

^aDetermined as average over the period 2000-2005 without the year 2003. Regions ordered from north to south. Units are given in Wm⁻².

enon. It has been favored by the quasi-stationary behavior of the planetary wave in that particular summer, which caused anomalously high insolation over Europe, while unusually low insolation over east Asia (cf. the low insolation in 2003 at Korean and Japanese sites in Figures 10 and 11) [*Ogi et al.*, 2005].

[10] Yet, even after excluding the year 2003 data, all European regions still show a general increase over the period 2000–2005. This is illustrated at a number of French and German sites in Figure 3, where the increase remains evident also after eliminating the year 2003 data from the analysis (cf. Figures 3a and 3b). A similar behavior can be seen in the other European regions (not shown).

[11] There is evidence that atmospheric aerosol concentrations and emissions, after decades of decrease, stabilized in Europe since 2000 [Ruckstuhl et al., 2008; D. G. Streets et al. Discerning human and natural signatures in regional aerosol trends, 1980-2006: Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition, submitted to Journal of Geophysical Research, 2009]. Thus the increase in insolation in Europe since 2000 seems not be due to a reduction in aerosol optical depth, which may have played a role during the 1990s [Wild et al., 2005; Streets et al., 2006; Norris and Wild, 2007], in addition to potential changes in cloud optical properties. This indicates that decreases in cloudiness or cloud albedo may have enabled the continuation of the increase in surface solar radiation over Europe beyond 2000 despite the stabilization of the aerosol concentrations. We found evidence for this hypothesis by studying records of sunshine duration measurements, which are directly affected by changes in cloudiness. These records are compiled at the World Radiation Data Centre in St. Petersburg. An average over the sunshine duration measurements at the 10 Benelux Sites given in Figure 2d shows a similar percentage change over the 2000-2005 time period as the average surface solar radiation at the same sites (Figure 4). This gives support for the above mentioned hypothesis that decreases in cloudiness, rather than aerosol reductions, could have maintained the continued increase in surface solar radiation over Europe beyond 2000.

3.2. North America

[12] A detailed discussion of the recent tendencies in the continental United States is given by *Long et al.* [2009]. Here we give a general overview over this region for

completeness. Unfortunately, continuous solar radiation records extending over several decades up to present are scarce in the United States. They are mainly restricted to the NOAA/ESRL sites Boulder and Barrow with accurate measurements since the 1970s [Dutton et al., 2006] and three sites in Oregon since 1980 [Riihimaki et al., 2009]. More widespread accurate monitoring of surface radiation in the United States started in the 1990s with the establishment of the ARM, SURFRAD, and BSRN programs. We show annual means at the American ARM, SURFRAD, and BSRN sites in Figure 5. Most of the sites started to become operational in the mid to late 1990s. Shown are the total lengths of observed records as to date available from the BSRN database. We also determined linear changes over both the full record length as well as the focal period 2000-2005. Over both periods, six out of seven sites show an increase, and only one site (Rock Springs, located in the NE continental United States) a decrease. The average increase over the 2000–2005 period is 0.6 $Wm^{-2}a^{-1}$, similar to the full record tendency of 0.5 $Wm^{-2}a^{-1}$. In contrast to the WRDC/GEBA type data, which are available in the form of daily or monthly means, the ARM, SURFRAD, and BSRN data have a much higher temporal resolution (minute data). This high temporal resolution allows the determination of clear-sky insolation estimates, using the cloud detection algorithm of Long and Ackerman [2000]. From these estimates we built yearly clear-sky fluxes (see Wild et al. [2006] for details), and show the related time series in Figure 6. As with the all-sky time series, the clear-sky time series also indicate increasing tendencies, with all sites showing a linear increase over both the total available records and the period 2000-2005 (all but one site above the 1σ uncertainty level). The change over the period 2000-2005 averaged over all sites is $0.6 \text{ Wm}^{-2}a^{-1}$ and therefore very similar to the changes under all-sky conditions noted above. This suggests that not only the all sky, but also clearsky insolation over the United States has recently been increasing. This is a similar finding to that by Wild et al. [2005], where worldwide distributed BSRN sites showed overall a similar increase in all-sky and clear-sky insolation during the 1990s (see also section 3.8). This may indicate that the aerosol optical depth has recently been decreasing in the United States, in line with evidence from satellite observations [Chylek et al., 2007]. It is also in line with an average decrease in aerosol optical depth of 6% determined at

 Table 2. As in Table 1 but for Summer (June-July-August)

 Mean^a

Region	Summer Climatology	Summer 2003	Summer 2003 Anomaly
Scandinavia	192	194	2
United Kingdom and Ireland	178	188	10
Belgium and Netherlands	202	224	23
Germany	206	237	31
Switzerland and Austria	225	251	26
Eastern Europe	227	250	23
France	247	262	15
Spain and Portugal	279	282	3
Average	220	236	16
^a Pagions ordered from port	h to south Units	250	in Wm ⁻²

"Regions ordered from north to south. Units are given in Wm⁻².



Figure 3. Effect of year 2003 on the linear changes over the period 2000-2005, illustrated with a number of French and German sites. (a) Changes including the year 2003, and (b) changes after omitting the year 2003 data. Units are given in Wm⁻².

the SURFRAD sites over the period considered [Augustine et al., 2008; Long et al., 2009].

[13] Though using data from these same United States sites, but for the period 1996–2007, *Long et al.* [2009] find only a limited relationship between aerosol optical depth anomalies and the clear-sky downwelling solar anomalies which suggests that AOD changes alone may not be the cause of the surface solar changes, but rather other factors occurring under the definition of "clear sky" may also contribute. Further investigation is therefore necessary to elucidate the origins of recent changes of clear-sky surface solar radiation in the United States.

3.3. Central America

[14] Only few stations are available with data from recent years in central America (Figure 7). While the 1990s show no clear changes or rather a slight tendency for a brightening at these sites, the data indicate a transition into a dimming during the 2000–2005 period. In several decades before 1990 the region of the greater Caribbean showed predominantly a dimming as discussed in more detail by J. C. Antuna et al. (Observed solar dimming in the wider Caribbean, submitted to *Journal of Geophysical Research*, 2009).

3.4. Antarctica

[15] As with the United States sites, data with high temporal resolution are available for sites in Antarctica up to 2005. These include two sites from BSRN, South Pole and Georg von Neumayer. Time series of the complete BSRN records are shown again together with linear changes over both the complete records and the period 2000-2005 (Figure 8 (top)). As with the United States sites, the high temporal resolution of the BSRN data allowed us to construct clear-sky annual estimates, on the basis of the Long and Ackerman [2000] algorithm (Figure 8 (bottom)). The linear changes given in Figure 8 indicate that the data records show an increase in clear-sky insolation over the total period, but no longer over the more recent part of the record (2000-2005). This applies for both stations in the clear-sky records, and for the Georg von Neumayer time series also in the all-sky record. The all-sky record of South

Pole shows a continuous brightening also in the more recent years. Thus, the insolation increase at the Antarctic sites noted by *Wild et al.* [2005] over the 1990s seems to have leveled off in more recent years, at least under cloud free conditions. This is in line with evidence that the increase in clear-sky insolation in the early part of the Antarctic BSRN records has been strongly influenced by the recovery from low atmospheric transmission after the volcanic eruption of Mount Pinatubo in 1991 (C. N. Long et al., manuscript in preparation, 2009). This influence is no longer present in the 2000–2005 data.

3.5. China and Mongolia

[16] The Chinese sites underwent a strong dimming over the period 1960 to 1990 as evidenced in numerous studies [e.g., *Liu et al.*, 2004; *Liang and Xia*, 2005; *Xia et al.*, 2006; *Qian et al.*, 2007]. In the 1990s, the downward trend leveled off or even turned sign at the majority of the sites [*Wild et*



Figure 4. Evolution of sunshine duration and surface solar radiation in Belgium/Netherlands during the focal period 2000–2005 (shown as average over the sites used in Figure 2d). Time series are shown as percentage deviation from their respective 2000–2005 mean. Units are given in %.



Figure 5. Evolution of annual mean surface solar radiation at seven sites in the United States, based on data contained in the ARM/SURFRAD/BSRN networks. Shown are the total length of records as currently available in the BSRN archive from these sites, which started to become operational in the 1990s. Linear changes are determined over the entire record length and the focal period 2000–2005. Standard errors (1 σ uncertainty estimates) are only determined for the longer (total) records. Units are given in Wm⁻².



Figure 6. As in Figure 5 but for cloud-free conditions as determined using the *Long and Ackerman* [2000] clear-sky detection algorithm. Units are given in Wm^{-2} .



Figure 7. Evolution of annual mean surface solar from 1990 to 2005 as measured at sites in central America. The updated focal period 2000-2005 is visually separated from the preceding 1990-2000 period. Units are given in Wm⁻².

al., 2005; *Qian et al.*, 2007]. We were able to get data updates to 2005 from 12 sites in China and Mongolia (Figure 9). The mean linear change over the 1990s is, at +0.5 Wm⁻²a⁻¹ (+3.3% per decade) positive and above the 1σ uncertainty estimate (0.3 Wm⁻²a⁻¹). There is some

indication for a renewed dimming in the post-2000 data, with an average decline of 0.4 $Wm^{-2}a^{-1}$. While 9 out of the 12 sites showed an increase in surface solar radiation over the 1990s, after 2000 only 3 out of the 12 sites show an increase and 9 a decrease. These sites suggest to some



Figure 8. Evolution of annual mean surface solar radiation at the Antarctic BSRN stations Georg von Neumayer and South Pole. The total length of records as currently available from these sites, which became BSRN sites in the early 1990s, are shown. Linear changes are determined over the entire record lengths and the focal period 2000–2005. Standard errors (1 σ uncertainty estimates) are only determined for the longer (total) records. (top) All-sky time series, and (bottom) clear-sky time series determined using the *Long and Ackerman* [2000] algorithm. Units are given in Wm⁻².

China and Mongolia



Figure 9. Evolution of annual mean surface solar radiation from 1990 to 2005 as measured at various sites in China and Mongolia. The updated focal period 2000-2005 is visually separated from the preceding 1990–2000 period. Units are given in Wm⁻².

extent that the phase of stabilization or even brightening during the 1990s may no longer continue into the millennium. We investigated also the sunshine duration at the Chinese sites, obtained again from the WRDC, and found that sunshine duration also shows a decreasing tendency after 2000 (not shown). This might suggest an increased cloudiness at these sites, in line with the decline in surface solar radiation. Also, anthropogenic sulfur emissions have increased rapidly again after 2000 [*Streets et al.*, 2008, Figure 6], whereas they had been decreasing in the late 1990s [*Streets et al.*, 2001]. This may be a sign of the rebound in the east Asian economy after the Asian economic crisis in the 1990s. The emission data are thus in line with the noted tendency for an increase in surface solar radiation before and a decrease after 2000 in China. However, only



Figure 10. Evolution of annual mean surface solar radiation from 1990 to 2005 as measured at sites in Korea. The updated focal period 2000-2005 is visually separated from the preceding 1990-2000 period. Units are given in Wm⁻².



Figure 11. Evolution of annual mean surface solar radiation from 1990 to 2005 as measured at various sites in Japan. The updated focal period 2000-2005 is visually separated from the preceding 1990-2000 period. Units are given in Wm⁻².

longer-term records will allow for more definitive conclusions on these relations.

3.6. Korea and Japan

[17] The four sites from Korea with data available up to 2005 show, in contrast to the Chinese and Mongolian sites, a continuous increase in surface solar radiation from 1990 to 2005 (Figure 10). There is no evidence for a change in this tendency in recent years.

[18] Japanese sites with updates up to 2005 are shown in Figure 11. The mean composed of time series from 13 stations suggest that, after a substantial increase in the 1990s $(0.77 \text{ Wm}^{-2}\text{a}^{-1}, 1\sigma \text{ uncertainty estimate } 0.42 \text{ Wm}^{-2}\text{a}^{-1}),$ surface solar radiation seems to level off in more recent years at these Japanese sites. As in Europe, also in Japan the reduction in air pollution and associated atmospheric aerosol loading may have reached a bottom level which cannot easily be further reduced with current air quality measures. Changes in cloud characteristics may also contribute to some extent to the variations in surface solar radiation in these areas [Norris and Wild, 2009]. Note that the Korean and many Japanese sites show negative insolation anomalies in the year 2003, at the same time as the central European sites show large positive anomalies (cf. Figure 2 and Tables 1 and 2). This may be a consequence of the quasi-stationary planetary wave in summer 2003 as discussed in section 3.1 [Ogi et al., 2005].

3.7. India

[19] India is one of the few regions around the world that shows a continuous and steady dimming from the 1960s to 2000 [*Wild et al.*, 2005; *Ramanathan et al.*, 2005]. Also the recent period 2000–2005 shows some indications for a continuation of the decrease (Figure 12). Whether the slight

tendency toward a stabilization of surface solar radiation since the late 1990s in two of the sites is sustainable remains to be seen in coming years.

3.8. Worldwide Sites From BSRN, NOAA, and Global Atmosphere Watch Networks

[20] The Baseline Surface Radiation Network (BSRN) aims at monitoring changes in surface solar radiation at the highest possible accuracy at worldwide distributed sites [Ohmura et al., 1998]. BSRN became operational in the early 1990s with a few sites and is gradually increasing its network. Results from those BSRN sites which provide data up to 2005 were already discussed in sections 3.2 and 3.4. In this section we provide in addition an overview over the longest time series from BSRN, for which both all-sky and clear-sky time series could be established (not necessarily reaching 2005), as an extension and update of the Wild et al. [2005] study. Linear changes in annual mean surface solar radiation at the 17 longest BSRN records are given in Table 3, for both all-sky and clear-sky conditions. From Table 3 it becomes evident that surface solar radiation has been increasing at most of the BSRN sites over the period covering data from 1992 to 2005, in both clear and all-sky conditions. Under all-sky conditions, 15 of the 17 sites show an increase, 9 of them exceeding the 1σ uncertainty. Only one site (Lindenberg) shows a decrease which exceeds the 1σ uncertainty. Under cloud free conditions, all 17 sites show an increase, 13 of them exceeding the 1σ uncertainty, while none of the sites shows a decrease. The increase averaged over all 17 sites is under all-sky conditions, at $0.51 \text{ Wm}^{-2}a^{-1}$, very similar to the clear-sky conditions $(0.49 \text{ Wm}^{-2}\text{a}^{-1})$. These results support the findings of *Wild* et al. [2005] of overall similar increases in all-sky and clearsky surface solar radiation, but now based on a more



Figure 12. Evolution of annual mean surface solar radiation from 1990 to 2005 as measured at sites in India. The updated focal period 2000-2005 is visually separated from the preceding 1990-2000 period. Units are given in Wm⁻².

extended data set. While eight sites with a total of 75 years of BSRN data were given by *Wild et al.* [2005], here we include 17 sites with a total of 175 years of data. On an individual station basis, we can find, however, substantially differing changes under all-sky and clear-sky conditions at some of the sites that warrant further study.

[21] Updating only the eight sites used by *Wild et al.* [2005], reduces the increase in clear-sky surface solar radiation of originally 0.68 Wm⁻²a⁻¹ determined by *Wild et al.* [2005], to 0.49 Wm⁻²a⁻¹. This indicates to some extent a slight slowing down of clear-sky brightening, in line with the general findings here, which is partly also favored by a lesser weighting of the Pinatubo influences in the early 1990s. A tendency toward leveling off or some renewed dimming after 2000 is also apparent in the highquality network consisting of five remote sites maintained by NOAA/ESRL [*Dutton et al.*, 2006], while this network also showed a predominant brightening during the 1990s.

[22] Surface solar radiation is also measured as part of the Global Atmosphere Watch (GAW) Program at worldwide distributed sites. The radiation data from this network, with the earliest stations reaching back to the mid-1990s, are stored in the WRDC in St. Petersburg. Here we present data from those sites which cover the focal period 2000–2005. These include eight stations as shown in Figure 13. Added at each site are again linear changes over the entire data records and over the 2000–2005 records, respectively. Figure 13 illustrates some of the aspects noted in the previous sections. All but one of the sites show an increase in surface solar radiation over their entire record (with five of the seven sites above the 1σ uncertainty estimates as given in Figure 13). At the majority of the sites, the increase over the period 2000-2005 is smaller than over the entire record. The substantial increase at the European sites after 2000 and the peak in 2003 is also documented in the GAW data set.

4. Conclusions

[23] Updates of observational records of surface solar radiation for selected worldwide regions beyond the year 2000 have been brought together from the major surface

Table 3. All-Sky and Clear-Sky Changes in Annual Mean SurfaceSolar Radiation Determined at the Longest Records AvailableFrom BSRN^a

Station	Years	Period	All-Sky	Clear-Sky
Ny Alesund/Spitzbergen,	11	1993-2003	0.80 (0.39)	0.86 (0.21)
Norway				
Barrow, Alaska	10	1993-2002	0.18 (0.27)	0.85 (0.22)
Lindenberg, Germany	8	1995-2002	-0.71 (0.68)	0.27 (0.36)
Fort Peck, Montana	10	1996-2005	0.33 (0.48)	0.53 (0.51)
Payerne, Switzerland	11	1993-2003	1.08 (0.54)	0.10 (0.13)
Rock Springs, Wyoming	7	1999-2005	-0.75 (1.40)	0.39 (0.26)
Table Mountain, Colorado	10	1996-2005	0.55 (0.38)	0.60 (0.21)
Boulder, Colorado	12	1992-2003	0.96 (0.26)	0.63 (0.13)
Bondville, Illinois	11	1995 - 2005	1.45 (0.42)	0.55 (0.29)
Desert Rock, Nevada	7	1999-2005	0.53 (0.89)	0.92 (0.75)
South Great Plain, USA	9	1996-2004	0.75 (0.48)	0.43 (0.24)
Goodwin Creek, USA	11	1995-2005	0.48 (0.52)	0.14 (0.41)
Bermuda	12	1992-2003	0.53 (0.34)	0.12 (0.13)
Kwajalein	11	1993-2003	0.54 (0.67)	0.59 (0.11)
Syowa, Antarctica	9	1994-2002	0.20 (0.37)	0.13 (0.11)
Georg von Neumayer, Antarctica	13	1993-2005	1.34 (0.32)	0.67 (0.16)
South Pole	13	1992-2004	0.41 (0.15)	0.54 (0.14)
Average over 17 sites			0.51	0.49

^aClear-sky detection based on the algorithm from *Long and Ackerman* [2000]. Changes expressed as linear regressions with 1σ uncertainty estimates given in parentheses. Stations ordered by latitude from north to south. Units are given in Wm⁻²a⁻¹.



Figure 13. Evolution of annual mean surface solar radiation at eight sites of the Global Atmosphere Watch network, centrally stored at the WRDC in St. Petersburg. The total lengths of records as currently available at the WRDC are shown. Linear changes are determined over the entire record length and the focal period 2000–2005. Standard errors (1 σ uncertainty estimates) are only determined for the longer (total) records. Units are given in Wm⁻².

radiation observation networks. The period after 2000 is particularly interesting, since ambitious satellite programs started to become operational around this time. Information from the surface networks can provide independent complementary information to these major space-borne programs. They may also be used for the validation of satellite-derived surface solar radiation estimates, as well as surface flux fields determined in global climate models, reanalyses, and atmospheric chemistry transport models, which cover the years following 2000 in their simulations. The main purpose of this study was to provide an update on the recent evolution in surface downwelling solar radiation on the basis of direct observations at the surface, as a reference for these various applications in the post-2000 satellite era.

[24] The tendencies for an increase in surface solar radiation (brightening) discussed in earlier studies for the 1990s are sustained at the beginning of the 2000s in several parts of the world, as documented at sites in Europe, the United States and Korea. Stations in other regions suggest that the brightening levels off after 2000 (sites in Japan and Antarctica), or provide some indications for a reversal back to a dimming (sites in China and central America). These findings are illustrated in a qualitative way in Figure 14.

[25] In summary, many sites still continue to observe an increase in surface solar radiation in the years following 2000, but the overall signal is not as evident and coherent as during the 1990s, with more sites showing stabilizing or even declining insolation. The establishment of significant changes at individual sites by a rigorous trend analysis is rarely 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 the similar results from different independent data sets gives support to the conclusions above.

[26] The compensating tendencies in various regions of the globe may tentatively indicate that the overall surface solar radiation signal inferred from the ground-based observations did not undergo dramatic changes since the year 2000. This fits to the general picture provided by the

Region	1990s	2000-2005
USA	1	/
Central America	-	1
Europe	~	-
China/Mongolia		\rightarrow
Japan	-	\rightarrow
Korea	1	-
India	1	1
Antarctica	-	\rightarrow

Figure 14. Qualitative tendencies in surface solar radiation at sites in various regions around the world. The 1990s tendencies are shown in the left column, and the 2000–2005 tendencies are show in the right column.

satellite community, which suggest that the planetary albedo as well as the background aerosol burden of the atmosphere may not have undergone substantial changes between 2000 and 2005, at least globally [Loeb et al., 2007a, 2007b; M. Mishchenko, personal communication, 2007]. This is also in line with recent Earthshine observations, which indicate a fairly stable planetary albedo after 2000 [Pallé et al., 2009]. Further, air pollution control measures seem to have saturated lately in some of the industrialized regions, which may prevent further brightening in these areas [e.g., Ruckstuhl et al., 2008; D. G. Streets et al., submitted paper, 2009]. One may also speculate that the recent lack of a significant overall brightening may favor a more moderate temperature increase in the early 2000 compared to the 1990s, when brightening has more substantially added to the greenhouse-induced warming [Wild et al., 2007, 2008]. Overall global warming since the turn of the millennium may therefore be more readily attributable to the enhanced greenhouse effect, and no longer suppressed by surface solar dimming as in the period from the 1950s to 1980s or enhanced by surface solar brightening as from the 1980s to 2000. However, further investigations based on both modeling and observational approaches will be required to get more insight into the origins and impacts of the changes documented in this study.

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