

ENLIGHTENING GLOBAL DIMMING AND BRIGHTENING

BY MARTIN WILD

Recent research on the phenomenon of substantial decadal variation in sunlight received at Earth's surface reveals far-reaching environmental implications and proposes a conceptual framework which ties it to prevailing atmospheric aerosol levels.

The sun is the only significant energy source for the global ecosystem. Essential for living conditions on Earth is the amount of sunlight that penetrates through the atmosphere and reaches Earth's surface. This energy flow governs a wide range of physical and chemical processes. It heats our environments, induces pressure gradients and related wind systems, generates evaporation to fuel the global water cycle, melts away snow and ice, and enables photosynthesis and associated plant growth and cultivation. It thereby ensures the abundant supply of water and nutrition, as well as livable ambient temperatures, the essential ingredients for an inhabitable planet. Our habitats are therefore particularly sensitive and vulnerable to changes in the availability of solar energy at Earth's surface.

On a more applied level, knowledge of changes in this quantity is also crucial for the planning and management of the rapidly growing number of solar power plants in support of the world's pressing demands for nuclear- and carbon-free energy sources.

Recent observational evidence suggests that substantial changes in surface solar radiation (SSR; also known as global radiation) indeed occur over time and may profoundly affect our environments. This evidence comes from the worldwide networks of pyranometers, the measurement devices that record SSR. Monitoring of SSR with pyranometers began in the early twentieth century at selected locations and since midcentury on a more widespread basis.

WHAT OBSERVATIONS TELL. Early studies carried out in the 1990s pointed to a remarkable decline of SSR at selected observation stations between the 1950s and the 1980s. These pioneering studies were based on sites in Europe (Ohmura and Lang 1989), the Baltic (Russak 1990), the South Pole (Dutton et al. 1991), different regions globally (Stanhill and Moreshet 1992), Germany (Liepert et al. 1994), and the former Soviet Union (Abakumova et al. 1996). By now a comprehensive literature exists that confirms declines of SSR during this period in many places around the globe (e.g., Gilgen et al. 1998; Stanhill and Cohen 2001 and references therein; Liepert 2002; Ohmura 2009; Wild 2009 and

AFFILIATION: WILD—ETH Zurich, Institute for Atmospheric and Climate Science, Zurich, Switzerland

CORRESPONDING AUTHOR: Martin Wild, ETH Zurich, Institute for Atmospheric and Climate Science, Universitätsstr. 16, Zurich, Switzerland
E-mail: martin.wild@env.ethz.ch

The abstract for this article can be found in this issue, following the table of contents.

DOI:10.1175/BAMS-D-11-00074.1

In final form 8 July 2011

©2012 American Meteorological Society

references therein). This phenomenon is popularly described as “global dimming” (Stanhill and Cohen 2001) (see Fig. 1 left, for a schematic illustration). Note that “global” thereby originally referred to “global radiation,” a synonym for SSR, rather than to a global-scale dimension of the phenomenon.

Qualitative SSR tendencies in those parts of the globe with best availability of long-term observations are compiled in Fig. 2. The left column illustrates the overall decline of SSR measured at sites in America, Europe, China, and Japan between the 1950s and 1980s (the “dimming phase”). Magnitudes of the tendencies (in $W\ m^{-2}$ per decade) as prevalent in the literature are also added in Fig. 2 for illustration, but note that considerable spread exists in these regional estimates with undefined uncertainty ranges.

More recent studies using SSR records updated to the year 2000 found, however, a trend reversal and partial recovery at many of the sites since the 1980s. The term “brightening” was thereby coined to emphasize that the decline in SSR and associated global dimming no longer continued after the 1980s (Wild et al. 2005) (Fig. 1, right). Particularly in industrialized areas, the majority of the sites show some recovery from prior dimming, or at least a leveling off, between the 1980s and 2000 (the “brightening phase”) (Fig. 2, middle

column). The brightening is somewhat less coherent than the preceding dimming, with trend reversals at widespread locations but still some regions with continued decrease (e.g., India; Kumari and Goswami 2010). Note that observed brightening has generally not fully compensated for prior dimming, so that insolation levels at the turn of the millennium were typically still below those in the 1950s. Literature estimates for the overall SSR decline during dimming range from 3 to 9 $W\ m^{-2}$, and from 1 to 4 $W\ m^{-2}$ for the partial recovery during subsequent brightening (Stanhill and Moreshet 1992; Liepert et al. 1994; Abakumova et al. 1996; Gilgen et al. 1998; Stanhill and Cohen 2001; Alpert et al. 2005; Kvalevag and Myhre 2007; Kim and Ramanathan 2008; Wild 2009) (Fig. 1), with more likely values closer to the lower bound because of possible inherent urbanization effects (Alpert et al. 2005; Kvalevag and Myhre 2007) (see below).

The latest updates on developments beyond the year 2000 show mixed tendencies (Fig. 2, right column). Overall, observed brightening is less distinct after 2000 compared to the 1990s at many sites. Brightening continues beyond 2000 at sites in Europe and the United States but levels off at Japanese sites, and there are some indications for a renewed dimming in China after a phase of stabilization during the 1990s, while

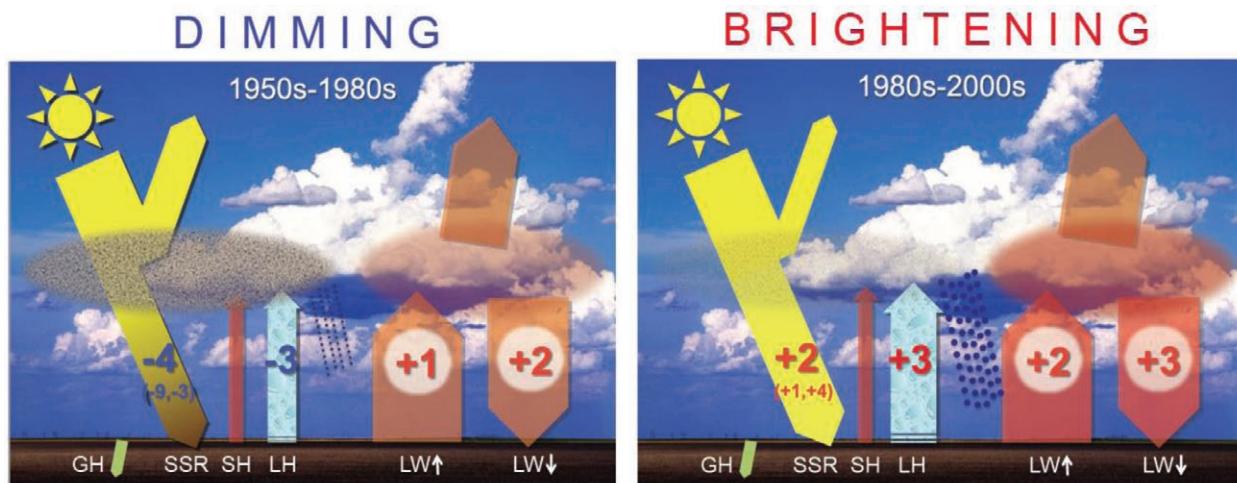


FIG. 1. Schematic representation of “dimming” and “brightening” periods over land surfaces. (left) During dimming (1950s–80s) the decline in surface solar radiation (SSR) may have outweighed increasing atmospheric downwelling thermal radiation ($LW\downarrow$) from enhanced greenhouse gases and effectively counteracted global warming, causing only little increase in surface thermal emission ($LW\uparrow$). The resulting reduction in radiative energy at Earth’s surface may have attenuated evaporation and its energy equivalent, the latent heat flux (LH), leading to a slowdown of the water cycle. (right) With the transition from dimming to brightening (1980s–2000s), the enhanced greenhouse effect has no longer been masked, causing more rapid warming, stronger evaporation/LH, and an intensification of the water cycle. Values denote best estimates of overall changes in surface energy fluxes over both periods in $W\ m^{-2}$ (ranges of literature estimates for SSR dimming/brightening in parentheses). Positive (negative) numbers, shown in red (blue), denote increasing (decreasing) magnitudes of the energy fluxes in the direction indicated by the arrows. Changes in ground heat flux (GH) and sensible heat flux (SH) are considered small compared to the above mentioned flux changes.

dimming persists throughout in India (Wild et al. 2009).

On the other hand, the longest observational records, which go back to the 1920s and 1930s at a few sites in Europe, further indicate some brightening tendencies during the first half of the twentieth century, known as “early brightening” (Ohmura 2009; Wild 2009).

Open issues. A number of issues related to dimming/brightening are still not well established and under debate, such as the quality and representativeness of the underlying observational data as well as the large-scale significance of the phenomenon.

The available historic radiation records are of variable quality and not always properly homogenized. Rigorous quality control is therefore necessary to avoid spurious trends (Gilgen et al. 1998; Dutton et al. 2006; Shi et al. 2008; Tang et al. 2011). Still, the similar results obtained in various independent studies based on a large number of records and different analysis techniques support the existence of non-spurious decadal changes in SSR. Since the mid-1990s, high-quality data with known accuracy are becoming increasingly available from newly installed sites of the Baseline Surface Radiation Network (BSRN) and the Atmospheric Radiation Measurement program (ARM), which allow the determination of SSR variations with unprecedented accuracy (Ohmura et al. 1998).

Despite the impressive number of studies now available, significant regions are insufficiently covered by direct surface radiation observations, such as vast areas of Africa and South America, as well as ocean areas in general, which prevents a true global assessment. SSR estimates inferred from satellites have the distinct advantage of providing a near-global picture. Such estimates are available since the early 1980s, thus covering mainly the brightening phase (Hatzianastassiou et al. 2005; Pinker et al. 2005; Hinkelman et al. 2009). SSR cannot be directly measured from satellites but has to be inferred from the top-of-atmosphere reflectances using models to correct for atmospheric attenuation. The historic satellite records may suffer to some extent from changes in satellites and viewing geometries, as currently debated (e.g., Evan et al. 2007). Available satellite-derived products qualitatively agree on a brightening from the mid-1980s to 2000 globally as well as over

oceans (Hatzianastassiou et al. 2005; Pinker et al. 2005; Hinkelman et al. 2009). Over land, the trends in the different satellite-derived SSR products are less consistent. Variations in aerosol attenuation, considered relevant for the decadal SSR changes particularly over land (see below), are difficult to infer from satellites and may cause the differences.

Another way of extending the evidence for SSR dimming/brightening both in time and space is the use of proxy information from related, more widely observed quantities. For example, decadal variations in pan evaporation and sunshine duration measurements provide independent indication for dimming and subsequent brightening in various regions of the globe, such as in Europe, China, the former Soviet Union, South America, New Zealand, and on Pacific islands (Roderick and Farquhar 2002; Qian et al. 2006; Sanchez-Lorenzo et al. 2008, 2009; Liley 2009; Raichijk 2011). The widely available data on the diurnal temperature range (DTR; the difference between daily maximum and minimum temperature) were shown to contain information on decadal changes in SSR, as they allow us to disentangle the solar (daytime) and thermal (nighttime) surface radiative heating (Liu et al. 2004; Wild et al. 2007; Makowski et al. 2009; Ye et al. 2010). Terrestrial DTR observations display overall a distinct decrease from the 1950s to the 1980s caused by a decline in daily maximum temperatures, which are particularly affected by SSR dimming (Wild et al. 2007). However, since the mid-1980s, the DTR no longer declined, but rather stabilized, in line with the transition from dimming to brightening. This distinct signature in

Observed tendencies in surface solar radiation

	1950s-1980s	1980s-2000	after 2000
USA	-6 	5 	8 
Europe	-3 	2 	3 
China/Mongolia	-7 	3 	-4 
Japan	-5 	8 	0 
India	-3 	-8 	-10 

FIG. 2. Changes in surface solar radiation observed in regions with good station coverage during three periods. (left column) The 1950s–1980s show predominant declines (“dimming”), (middle column) the 1980s–2000 indicate partial recoveries (“brightening”) at many locations, except India, and (right column) recent developments after 2000 show mixed tendencies. Numbers denote typical literature estimates for the specified region and period in $W m^{-2}$ per decade. Based on various sources as referenced in Wild (2009).

the global terrestrial DTR evolution may provide additional indication for a large-scale dimension of the dimming/brightening phenomenon.

To summarize, there is increasing surface and satellite-based evidence for substantial large-scale decadal variations in SSR, but further research is required for a better quantification. Radiation sites are often located in urbanized areas, which may induce stronger SSR variations due to high local air pollution levels (Alpert et al. 2005). This possible urbanization effect in the SSR records has not yet been well quantified and is currently debated.

CAUSES OF DIMMING AND BRIGHTENING.

The decadal variations in SSR cannot be explained by changes in the luminosity of the sun, since these are at least an order of magnitude smaller (Willson and Mordvinov 2003). The observed SSR variations therefore have to originate from alterations in the transparency of the atmosphere, which depends on the presence of clouds, aerosols, and radiatively active gases (e.g., Kvalevag and Myhre 2007; Kim and Ramanathan 2008). Cloud cover changes effectively modulate SSR on an interannual basis, but their contribution to the detected longer-term (decadal) SSR trends is not always obvious (e.g., Qian et al. 2006; Norris and Wild 2007). Dimming and brightening has also been observed under cloudless atmospheres at various locations, pointing to a prominent role of atmospheric aerosols (e.g., Wild et al. 2005; Norris and Wild 2007; Sanchez-Lorenzo et al. 2009; Ohvri

et al. 2009; Zerefos et al. 2009). Aerosols can directly attenuate SSR by scattering and absorbing solar radiation (direct effect), or indirectly attenuate SSR through their ability to act as cloud condensation nuclei (CCN), thereby increasing cloud reflectivity and lifetime (first and second indirect effects) (e.g., Ramanathan et al. 2001; Lohmann and Feichter 2005). Most important for the present discussion is the fact that all these effects act towards reducing SSR with increasing aerosol levels.

Anthropogenic air pollution has led to substantial changes in atmospheric aerosol levels over the past decades (Stern 2006; Ruckstuhl et al. 2008; Streets et al. 2009; Wang et al. 2009). Particularly, anthropogenic emissions, such as sulfur and black carbon, increased from the 1950s to 1980s but decreased thereafter in the Northern Hemisphere (Stern 2006) (Fig. 3). This decrease is attributed to the implementation of air quality measures in industrialized countries as well as to major economic crises (e.g., the breakdown of the Communist system in Eastern Europe and Russia in the late 1980s and the Asian financial crisis in the 1990s). These emission histories fit with the observed dimming/brightening tendencies and suggest that anthropogenic air pollution may play a significant role in the explanation of SSR variations (Streets et al. 2009). Distinct aerosol trends that match with dimming/brightening are also observed in remote locations far away from pollution sources, such as in Greenland (McConnell et al. 2007), the Canadian Arctic (Sharma et al. 2004), or over oceans (Mishchenko et al. 2007; Cermak et al. 2010), pointing to the large-scale distribution of these pollutants over the entire Northern Hemisphere, in line with results from atmospheric transport modeling studies (Chin et al. 2007). In the Southern Hemisphere, however, there is less evidence for significant anthropogenic pollution and no sign of trend reversal (Stern 2006) (cf. Fig. 3).

The latest updates on global sulfur emissions indicate a renewed increase of total global sulfur emissions after the year 2000, since the rapidly growing emissions in Asia increasingly outweigh the decreasing emissions in the western world (Streets et al. 2009). This again fits with the lack of a clear overall brightening signal and indications for renewed dimming in China after 2000 (Wild et al. 2009) (cf. Fig. 2, right column).

Recent studies suggest that aerosol–cloud interactions may depend on the level of pollution (Koren et al. 2008; Rosenfeld et al. 2008). In the following, a conceptual framework is outlined suggesting that dimming and brightening can be amplified or

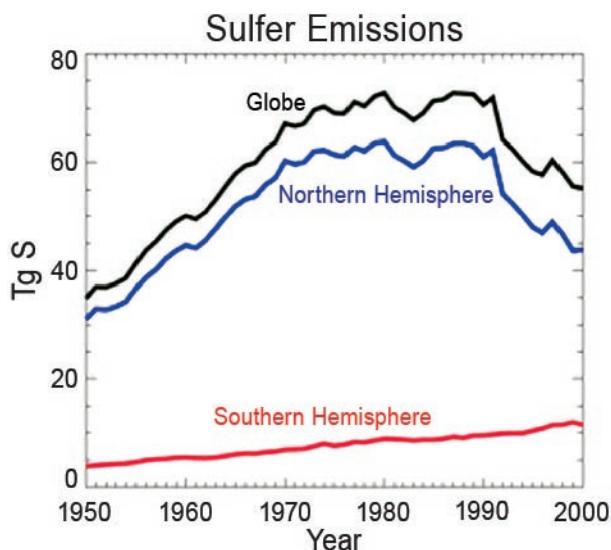


FIG. 3. Annual sulfur emission estimates from 1950–2000 over the NH (blue line), the SH (red line), and the entire globe (black line) according to (Stern 2006). Units are teragrams of sulfur (Tg S).

dampened by aerosol–cloud interactions depending on the prevailing pollution levels.

In pristine regions, small changes in CCN can have a much bigger impact on cloud characteristics than in polluted environments (Koren et al. 2008; Rosenfeld et al. 2008) because clouds show a nonlinear (logarithmic) sensitivity to CCN (e.g., Kaufman et al. 2005). Additional CCN in pristine regions may therefore be particularly effective in increasing the formation, lifetime, and albedo of clouds (Kaufman et al. 2005; Rosenfeld et al. 2006), which all act towards a reduction of SSR through enhanced cloud shading. Thus, aerosol–cloud interactions in pristine environments may cause a strong amplification of dimming (brightening) trends induced by small increases (decreases) in aerosols. This implies that dimming/brightening could be substantial even in areas far away from pollution sources, where small changes in background aerosol levels induced by long-range transports can effectively alter SSR through cloud modifications. This may explain dimming and brightening in remote regions even in the absence of significant direct aerosol radiative effects, as observed, for example, in Dutton et al. (2006) and Liley (2009). This mechanism potentially could also be responsible for the brightening over oceans with decreasing aerosol background levels (Mishchenko et al. 2007) between the mid-1980s and 2000 consistently seen in the aforementioned satellite-derived SSR records (Hatzianastassiou et al. 2005; Pinker et al. 2005; Hinkelman et al. 2009).

In polluted regions, on the other hand, cloud microphysics effects tend to saturate with the logarithmic sensitivity to CCNs, whereas the direct extinction of SSR by aerosols becomes more relevant, which increases proportionally to the aerosol loadings. Absorbing pollution layers further heat and stabilize the atmosphere and attenuate SSR and related surface evaporation. This generally leads to a suppression of convective cloud formation and dissolves clouds in layers heated by absorbing aerosol (known as the semi-direct aerosol effect) (Ramanathan et al. 2001). The associated reduced cloud shading may partly counteract the aerosol-induced reduction of SSR in heavily polluted areas. Thus, in contrast to pristine areas, aerosol–cloud interactions may tend to dampen dimming/brightening trends induced by direct aerosol effects. This may explain a seemingly counterintuitive phenomenon observed in China, where under strongly increasing pollution both SSR and cloud amounts declined between the 1960s and 1990s (e.g., Qian et al. 2006).

Clearly, the general applicability of this conceptual framework needs further evaluation. It may serve as

a guideline to specifically investigate dimming and brightening and the contributions from aerosol–cloud interactions in various parts of the globe under different pollution characteristics and climate regimes.

Further, it cannot be excluded that also nonanthropogenic factors, such as variations in cloudiness induced by natural decadal variability in the atmosphere/ocean system, could have contributed to the changes in SSR (Romanou et al. 2007). The similar temporal variations of the Atlantic multidecadal oscillation (AMO), the Pacific decadal oscillation (PDO), and the dimming/brightening phenomenon may indicate such a dependency. On the other hand, the concepts outlined above may also leave room for dimming/brightening as a potential cause, rather than effect, of atmosphere/ocean variability (Mann and Emanuel 2006). It remains a challenge for future research to disentangle possible cause-and-effect relationships between dimming/brightening and decadal atmosphere/ocean variability.

CLIMATE AND ENVIRONMENTAL IMPLICATIONS.

It becomes increasingly evident that the detected SSR variations play an important role in various aspects of climate change. There are indications that dimming and brightening may have respectively counteracted and added to greenhouse warming over the past decades (Wild et al. 2007). Observed air temperatures over global terrestrial surfaces showed a negligible increase between the 1950s and 1980s, in line with the prevailing SSR dimming, which may have largely offset the increasing greenhouse gas forcing in this period (see schematic illustration in Fig. 1, left). Since the 1980s, with the transition from dimming to brightening, the increasing thermal forcing may have no longer been masked (Fig. 1, right), and rapid warming was observed. For the present synthesis this argument is further developed by utilizing the largely differing air pollution and associated aerosol levels on the Northern and Southern Hemisphere. While the NH exhibits high pollution levels with substantial temporal changes (increasing up to the 1980s and decreasing thereafter; cf. Fig. 3), pollution levels in the SH are an order of magnitude smaller, with only modest increases and no trend reversal (Stern 2006). This seems to be reflected in the observed hemispheric surface temperature records, based on the HadCRUT3 dataset (Brohan et al. 2006) (Fig. 4; Table 1). Warming rates in the NH largely differ between the dimming and brightening periods, with no warming at all during dimming with strong pollution increase ($-0.002^{\circ}\text{C decade}^{-1}$ between the 1950s and

1980s) but strong warming during brightening while pollution levels reduced ($+0.3^{\circ}\text{C decade}^{-1}$ between the 1980s and 2000) (Fig. 4a; Table 1). This points again to a potentially substantial modulation of greenhouse warming by anthropogenic aerosol pollution and associated dimming and brightening. In contrast, in the SH, steady warming is observed throughout, with only slightly stronger warming rates in the 1980s–2000 ($+0.15^{\circ}\text{C decade}^{-1}$) than in the 1950s–1980s ($+0.11^{\circ}\text{C decade}^{-1}$) (Fig. 4b; Table 1). This fits well with the lack of major anthropogenic aerosol variations and the gradually increasing greenhouse gas forcing in this hemisphere.

Climate models as used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; Solomon et al. 2007), on the other hand, do not reproduce these characteristic differences in

interhemispheric warming. Temperature changes simulated during the dimming and brightening phases by 23 models in twentieth-century “all forcings” experiments are shown in Figs. 4c and 4d for the NH and SH, respectively. In the NH, the average warming simulated by the models is too strong during dimming (by $0.12^{\circ}\text{C decade}^{-1}$) and too weak during subsequent brightening (by $0.10^{\circ}\text{C decade}^{-1}$) (Fig. 4c; Table 1). This points to an insufficient representation of the processes causing dimming/brightening in the models to properly dampen and enhance greenhouse warming, respectively (Wild and Schmucki 2011). In contrast, in the SH, where aerosol pollution is much smaller and greenhouse gas forcing dominates, the models perform very well, with warming rates close to observed (within $0.02^{\circ}\text{C decade}^{-1}$ on average over both periods) (Fig. 4d; Table 1). This suggests that climate models simulate decadal warming trends adequately when greenhouse gases act as the sole major anthropogenic forcing as in the SH, but may have difficulties when in addition strong decadal aerosol variations come into play, as in the NH.

Another important issue is the potential impact of dimming/brightening on the water cycle. SSR changes effectively alter the energy available at Earth’s surface to drive evaporation and its energy equivalent, the latent heat flux. Since on a global level evaporation equals precipitation, any SSR-induced change in evaporation/latent heat flux will change the intensity of the water cycle (e.g., Ramanathan et al. 2001; Wild and Liepert 2010). Since the decline in SSR during the 1950s–1980s may have overcompensated the increase in the greenhouse-induced atmospheric downwelling thermal radiation, this implies also a concurrent

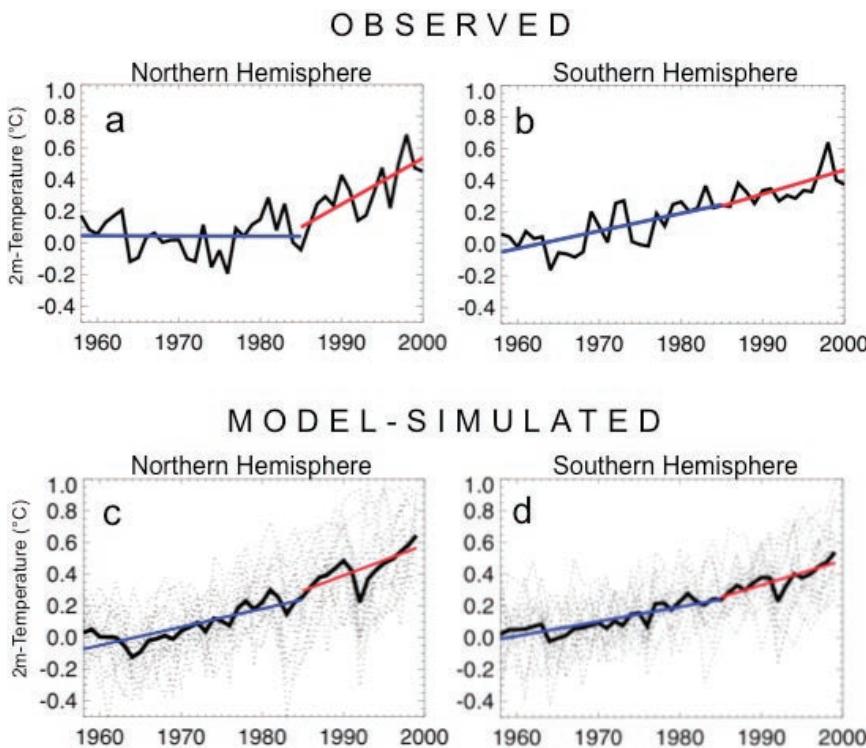


FIG. 4. Annual 2-m temperature anomalies in the NH (a),(c) and SH (b),(d) as observed (a),(b) and simulated by global climate models (c),(d) over the second half of the twentieth century. Observations from HadCRUT3; model results from “all forcings” twentieth-century simulations with 23 IPCC AR4 models (individual models dashed, multimodel-mean solid line). Anomalies are shown with respect to 1960–90. Linear trends over the dimming phase (1950s–80s) are in blue and over the brightening phase (1980s–2000) in red (quantified in Table 1). In the polluted NH, observed warming is much smaller during dimming with strong aerosol increase than during subsequent brightening with aerosol decrease (a). This is not fully captured by the models (c). In the more pristine SH, with greenhouse gases as sole major anthropogenic forcing, observed warming is similar during both periods (b) and in better agreement with the models (d).

TABLE 1. Magnitudes of linear 2-m temperature trends shown in Fig. 4 during dimming and brightening phases in the NH and SH as observed and calculated in global climate models, with 1-sigma uncertainty estimates given in parentheses. Trends in climate models calculated from multimodel-mean of 23 models used in the IPCC AR4 are based on twentieth-century “all forcings” simulations. Observed trends are based on data from the HadCRUT3 dataset (Brohan et al. 2006). Definitions of dimming and brightening phases follow Wild et al. (2007). Units °C decade⁻¹.

	Dimming phase (1958–85)	Brightening phase (1985–2000)
Observed <i>T</i> trend NH	-0.002 (0.03)	0.29 (0.05)
Observed <i>T</i> trend SH	0.11 (0.02)	0.15 (0.04)
Model-calculated <i>T</i> trend NH	0.12 (0.01)	0.19 (0.05)
Model-calculated <i>T</i> trend SH	0.09 (0.01)	0.15 (0.03)

decrease in the energy available at Earth’s surface for evaporation/latent heat flux and a slowdown of the water cycle (see schematic illustration in Fig. 1, left). This is in line with observational evidence for decreasing precipitation over the same period shown in Fig. 5, based on NH land surface data from the Global Historic Climate Network (GHCN; Peterson and Vose 1997). The indicated decline of precipitation on the order of 30–40 mm from the 1950s to 1980s corresponds to a latent heat energy flux equivalent of about 3 W m⁻² over this period. This fits with the magnitudes of the radiation changes over the same period as shown in Fig. 1 (left). In contrast, subsequent solar brightening may have added to the increasing greenhouse-induced downwelling thermal radiation from the 1980s onward and, accordingly, enhanced the surface energy available for evaporation and the water cycle (Liepert and Previdi 2009; Wild et al. 2008; Wild and Liepert 2010) (Fig. 1 right). This fits with the observed intensification of the water cycle during the 1980s–2000s (Fig. 5) and underlines the importance of SSR variations for the understanding of the changes in the water cycle. Wentz et al. (2007) estimated global precipitation changes using satellite observations from the Special Sensor Microwave Imager (SSM/I) for the period 1987–2006, thus covering the brightening phase. Their estimated increase in global mean precipitation of 13.2 ± 4.8 mm yr⁻¹ decade⁻¹ over the period 1987–2006 corresponds to a latent heat flux equivalent of about 2 W m⁻² over the 20-yr period, in reasonable agreement with the estimated radiation changes given in Fig. 1 (right).

Decadal SSR variations may also play a role in modulating regional precipitation systems such as Sahelian rainfall and the Indian monsoon (Rotstayn

and Lohmann 2002; Ramanaathan et al. 2005). They may further explain aspects of observed decadal variations in the surface hydrology, such as soil moisture and evaporation changes in energy-limited environments (Roderick and Farquhar 2002; Qian et al. 2006; Robock and Li 2006; Teuling et al. 2009; Wang et al. 2010). SSR changes have also the potential to affect the cryosphere by modulating the melt processes. This is supported by the evidence that NH snow cover and many mountain glaciers only started

to retreat significantly with the transition from dimming to brightening (Ohmura et al. 2007; Wild 2009). Modeling studies further suggest that dimming/brightening may also impact the terrestrial carbon cycle and plant growth (Mercado et al. 2009). During dimming, plant photosynthesis and associated terrestrial carbon uptake might have been enhanced despite a reduction in SSR, since the stronger aerosol and cloud scattering enlarged the diffuse radiative fraction in this period. Diffuse light penetrates deeper into the vegetation canopies than the direct sunbeam and can therefore be more effectively used by plants

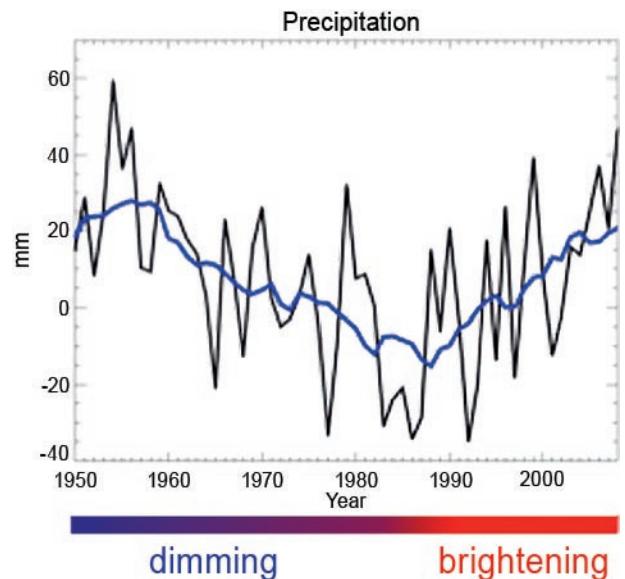


FIG. 5. Observational estimates of annual precipitation anomalies from 1950–2008 over the NH land masses. Data are from the Global Historic Climate Network (Peterson and Vose 1997). Reference period for anomalies is 1961–90; 11-yr running mean in blue. Units are mm.

for photosynthesis. Finally, studies indicate that dimming and brightening tendencies are particularly pronounced in the ultraviolet spectral range (Zerefos et al. 2009; McKenzie et al. 2011), with associated biological and erythral implications.

Further research will be required to establish and quantify more thoroughly the emerging evidence for substantial impacts of dimming and brightening on a variety of essential climate and environmental processes.

RECENT DEVELOPMENTS AND PERSPECTIVES. The latest updates on solar radiation changes observed since the new millennium show no globally coherent trends anymore (see above and Fig. 2). While brightening persists to some extent in Europe and the United States, there are indications for a renewed dimming in China associated with the tremendous emission increases there after 2000, as well as unabated dimming in India (Streets et al. 2009; Wild et al. 2009).

We cannot exclude the possibility that we are currently again in a transition phase and may return to a renewed overall dimming for some years to come. On the one hand, air pollution mitigation potential is approaching saturation in many of the industrialized nations (Ruckstuhl et al. 2008; Streets et al. 2009), thus confining further human-induced brightening in these areas, while on the other hand air pollution increase and associated dimming may continue for a while in developing and emerging nations. The recent renewed increase in global sulfur emissions (particularly originating from Asia) (Streets et al. 2009), the evidence for renewed declines in visibility (Wang et al. 2009) and in satellite-derived SSR (Hinkelman et al. 2009; Hatzianastassiou et al. 2011), and the lack of warming in the early 2000s may be interpreted as additional indicators for such a development. However, such renewed dimming and associated impacts would likely have a limited persistence, since emerging nations will be forced to implement air quality measures in face of increasingly pressing health problems. Thus, with the foreseeable inevitability and undisputable necessity for clean air regulations and aerosol reductions also in emerging nations, potential dampening of global warming by a renewed dimming could only be temporary, and greenhouse gases will ultimately become the sole major anthropogenic forcing factor of climate change.

Under these perspectives, only the rapid worldwide implementation of both rigorous greenhouse gas reduction and air quality measures will allow us to minimize adverse climate and health impacts

and ensure sustainable living conditions for future generations on Earth.

ACKNOWLEDGMENTS. The support from the National Centre for Competence in Climate Research (NCCR Climate) of the Swiss National Science Foundation is acknowledged. This synthesis highly profited from invaluable discussions with numerous colleagues and from two dedicated and very constructive reviewers.

REFERENCES

- Abakumova, G. M., E. M. Feigelson, V. Russak, and V. V. Stadnik, 1996: Evaluation of long-term changes in radiation, cloudiness, and surface temperature on the territory of the former Soviet Union. *J. Climate*, **9**, 1319–1327.
- Alpert, P., P. Kishcha, Y. J. Kaufman, and R. Schwarzbard, 2005: Global dimming or local dimming? Effect of urbanization on sunlight availability. *Geophys. Res. Lett.*, **32**, L17802, doi:10.1029/2005GL023320.
- Brohan, P., J. J. Kennedy, I. Harris, S. F. B. Tett, and P. D. Jones, 2006: Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *J. Geophys. Res.*, **111**, D12106, doi:10.1029/2005JD006548.
- Cermak, J., M. Wild, R. Knutti, M. I. Mishchenko, and A. K. Heidinger, 2010: Consistency of global satellite-derived aerosol and cloud data sets with recent brightening observations. *Geophys. Res. Lett.*, **37**, L21704, doi:10.1029/2010GL044632.
- Chin, M., T. Diehl, P. Ginoux, and W. Malm, 2007: Intercontinental transport of pollution and dust aerosols: Implications for regional air quality. *Atmos. Chem. Phys.*, **7**, 5501–5517.
- Dutton, E. G., R. S. Stone, D. W. Nelson, and B. G. Mendonca, 1991: Recent interannual variations in solar radiation, cloudiness, and surface temperature at the South Pole. *J. Climate*, **4**, 848–858.
- , D. W. Nelson, R. S. Stone, D. Longenecker, G. Carbaugh, J. M. Harris, and J. Wendell, 2006: Decadal variations in surface solar irradiance as observed in a globally remote network. *J. Geophys. Res.*, **111**, D19101, doi:10.1029/2005JD006901.
- Evan, A. T., A. K. Heidinger, and D. J. Vimont, 2007: Arguments against a physical long-term trend in global ISCCP cloud amounts. *Geophys. Res. Lett.*, **34**, L04701, doi:10.1029/2006GL028083.
- Gilgen, H., M. Wild, and A. Ohmura, 1998: Means and trends of shortwave irradiance at the surface estimated from global energy balance archive data. *J. Climate*, **11**, 2042–2061.

- Hatzianastassiou, N., C. Matsoukas, A. Fotiadi, K. G. Pavlakis, E. Drakakis, D. Hatzidimitriou, and I. Vardavas, 2005: Global distribution of Earth's surface shortwave radiation budget. *Atmos. Chem. Phys.*, **5**, 2847–2867.
- , C. D. Papadimas, C. Matsoukas, K. Pavlakis, A. Fotiadi, M. Wild, and I. Vardavas, 2011: Recent regional surface solar radiation dimming and brightening patterns: Inter-hemispherical asymmetry and a dimming in the Southern Hemisphere. *Atmos. Sci. Lett.*, doi:10.1002/asl.361, in press.
- Hinkelman, L. M., P. W. Stackhouse, B. A. Wielicki, T. P. Zhang, and S. R. Wilson, 2009: Surface insolation trends from satellite and ground measurements: Comparisons and challenges. *J. Geophys. Res.*, **114**, D00D20, doi:10.1029/2008JD011004.
- Kaufman, Y. J., I. Koren, L. A. Remer, D. Rosenfeld, and Y. Rudich, 2005: The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean. *Proc. Natl. Acad. Sci. USA*, **102**, 11 207–11 212.
- Kim, D. Y., and V. Ramanathan, 2008: Solar radiation budget and radiative forcing due to aerosols and clouds. *J. Geophys. Res.*, **113**, D02203, doi:10.1029/2007JD008434.
- Koren, I., J. V. Martins, L. A. Remer, and H. Afargan, 2008: Smoke invigoration versus inhibition of clouds over the Amazon. *Science*, **321**, 946–949.
- Kumari, B. P., and B. N. Goswami, 2010: Seminal role of clouds on solar dimming over the Indian monsoon region. *Geophys. Res. Lett.*, **37**, L06703, doi:10.1029/2009GL042133.
- Kvalevag, M. M., and G. Myhre, 2007: Human impact on direct and diffuse solar radiation during the industrial era. *J. Climate*, **20**, 4874–4883.
- Liepert, B. G., 2002: Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990. *Geophys. Res. Lett.*, **29**, 1421, doi:10.1029/2002GL014910.
- , and M. Previdi, 2009: Do models and observations disagree on the rainfall response to global warming? *J. Climate*, **22**, 3156–3166.
- , P. Fabian, and H. Grassl, 1994: Solar radiation in Germany—Observed trends and assessment of their causes. Part I: Regional approach. *Beitr. Phys. Atmos.*, **67**, 15–29.
- Liley, J. B., 2009: New Zealand dimming and brightening. *J. Geophys. Res.*, **114**, D00D10, doi:10.1029/2008JD01140.
- Liu, B. H., M. Xu, M. Henderson, Y. Qi, and Y. Q. Li, 2004: Taking China's temperature: Daily range, warming trends, and regional variations, 1955–2000. *J. Climate*, **17**, 4453–4462.
- Lohmann, U., and J. Feichter, 2005: Global indirect aerosol effects: A review. *Atmos. Chem. Phys.*, **5**, 715–737.
- Makowski, K., E. B. Jaeger, M. Chiacchio, M. Wild, T. Ewen, and A. Ohmura, 2009: On the relationship between diurnal temperature range and surface solar radiation in Europe. *J. Geophys. Res.*, **114**, D00D07, doi:10.1029/2008JD011104.
- Mann, M. E., and K. A. Emanuel, 2006: Atlantic hurricane trends linked to climate change. *Eos*, **87**, 233, doi:10.1029/2006EO240001.
- McConnell, J. R., and Coauthors, 2007: 20th-century industrial black carbon emissions altered arctic climate forcing. *Science*, **317**, 1381–1384.
- McKenzie, R. L., P. J. Aucamp, A. F. Bais, L. O. Bjorn, M. Ilyas, and S. Madronich, 2011: Ozone depletion and climate change: Impacts on UV radiation. *Photochem. Photobiol. Sci.*, **10**, 182–198.
- Mercado, L. M., N. Bellouin, S. Sitch, O. Boucher, C. Huntingford, M. Wild, and P. M. Cox, 2009: Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, **458**, 1014–1087.
- Mishchenko, M. I., and Coauthors, 2007: Long-term satellite record reveals likely recent aerosol trend. *Science*, **315**, 1543–1543.
- Norris, J. R., and M. Wild, 2007: Trends in aerosol radiative effects over Europe inferred from observed cloud cover, solar “dimming” and solar “brightening.” *J. Geophys. Res.*, **112**, D08214, doi:10.1029/2006JD007794.
- Ohmura, A., 2009: Observed decadal variations in surface solar radiation and their causes. *J. Geophys. Res.*, **114**, D00D05, doi:10.1029/2008JD011290.
- , and H. Lang, 1989: Secular variations of global radiation in Europe. *IRS '88: Current Problems in Atmospheric Radiation*, J. Leonoble and J. F. Geleyn, Eds., A. Deepak, 98–301.
- , and Coauthors, 1998: Baseline surface radiation network (BSRN/WCRP): New precision radiometry for climate research. *Bull. Amer. Meteor. Soc.*, **79**, 2115–2136.
- , A. Bauder, H. Muller, and G. Kappenberger, 2007: Long-term change of mass balance and the role of radiation. *Ann. Glaciol.*, **46**, 367–374.
- Ohvriil, H., and Coauthors, 2009: Global dimming and brightening versus atmospheric column transparency, Europe, 1906–2007. *J. Geophys. Res.*, **114**, D00D12, doi:10.1029/2008JD010644.
- Peterson, T. C., and R. S. Vose, 1997: An overview of the global historical climatology network temperature database. *Bull. Amer. Meteor. Soc.*, **78**, 2837–2849.
- Pinker, R. T., B. Zhang, and E. G. Dutton, 2005: Do satellites detect trends in surface solar radiation? *Science*, **308**, 850–854.

- Qian, Y., D. P. Kaiser, L. R. Leung, and M. Xu, 2006: More frequent cloud-free sky and less surface solar radiation in China from 1955 to 2000. *Geophys. Res. Lett.*, **33**, L01812, doi:10.1029/2005GL024586.
- Raichijk, C., 2011: Observed trends in sunshine duration over South America. *Int. J. Climatol.*, doi:10.1002/joc.2296, in press.
- Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld, 2001: Atmosphere—Aerosols, climate, and the hydrological cycle. *Science*, **294**, 2119–2124.
- , and Coauthors, 2005: Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. *Proc. Natl. Acad. Sci. USA*, **102**, 5326–5333.
- Robock, A., and H. B. Li, 2006: Solar dimming and CO₂ effects on soil moisture trends. *Geophys. Res. Lett.*, **33**, L20708, doi:10.1029/2006GL027585.
- Roderick, M. L., and G. D. Farquhar, 2002: The cause of decreased pan evaporation over the past 50 years. *Science*, **298**, 1410–1411.
- Romanou, A., B. Liepert, G. A. Schmidt, W. B. Rossow, R. A. Ruedy, and Y. Zhang, 2007: 20th century changes in surface solar irradiance in simulations and observations. *Geophys. Res. Lett.*, **34**, L05713, doi:10.1029/2006GL028356.
- Rosenfeld, D., Y. J. Kaufman, and I. Koren, 2006: Switching cloud cover and dynamical regimes from open to closed Benard cells in response to the suppression of precipitation by aerosols. *Atmos. Chem. Phys.*, **6**, 2503–2511.
- , and Coauthors, 2008: Flood or drought: How do aerosols affect precipitation? *Science*, **321**, 1309–1313.
- Rotstayn, L. D., and U. Lohmann, 2002: Tropical rainfall trends and the indirect aerosol effect. *J. Climate*, **15**, 2103–2116.
- Ruckstuhl, C., and Coauthors, 2008: Aerosol and cloud effects on solar brightening and the recent rapid warming. *Geophys. Res. Lett.*, **35**, L12708, doi:10.1029/2008GL034228.
- Russak, V., 1990: Trends of solar radiation, cloudiness and atmospheric transparency during recent decades in Estonia. *Tellus*, **42B**, 206–210.
- Sanchez-Lorenzo, A., J. Calbó, and J. Martin-Vide, 2008: Spatial and temporal trends in sunshine duration over Western Europe (1938–2004). *J. Climate*, **21**, 6089–6098.
- , —, M. Brunetti and C. Deser, 2009: Dimming/brightening over the Iberian Peninsula: Trends in sunshine duration and cloud cover and their relations with atmospheric circulation. *J. Geophys. Res.*, **114**, D00D09, doi:10.1029/2008JD011394.
- Sharma, S., D. Lavoué, H. Cachier, L. A. Barrie, and S. L. Gong, 2004: Long-term trends of the black carbon concentrations in the Canadian Arctic. *J. Geophys. Res.*, **109**, D15203, doi:10.1029/2003JD004331.
- Shi, G. Y., and Coauthors, 2008: Data quality assessment and the long-term trend of ground solar radiation in China. *J. Appl. Meteor. Climatol.*, **47**, 1006–1016.
- Solomon, S., D. Qin, M. Manning, M. Marquis, K. Averyt, M. M. B. Tignor, H. L. Miller Jr., and Z. Chen, Eds., 2007: *Climate Change 2007: The Physical Science Basis*. Cambridge University Press, 996 pp.
- Stanhill, G., and S. Moreshet, 1992: Global radiation climate changes: The world network. *Climatic Change*, **21**, 57–75.
- , and S. Cohen, 2001: Global dimming: A review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. *Agric. For. Meteorol.*, **107**, 255–278.
- Stern, D. I., 2006: Reversal of the trend in global anthropogenic sulfur emissions. *Global Environ. Change*, **16**, 207–220.
- Streets, D. G., and Coauthors, 2009: Anthropogenic and natural contributions to regional trends in aerosol optical depth, 1980–2006. *J. Geophys. Res.*, **114**, D00D18, doi:10.1029/2008JD011624.
- Tang, W. J., K. Yang, J. Qin, C. C. K. Cheng, and J. He, 2011: Solar radiation trend across China in recent decades: A revisit with quality-controlled data. *Atmos. Chem. Phys.*, **11**, 393–406.
- Teuling, A. J., and Coauthors, 2009: A regional perspective on trends in continental evaporation. *Geophys. Res. Lett.*, **36**, L02404, doi:10.1029/2008GL036584.
- Wang, K. C., R. E. Dickinson, and S. L. Liang, 2009: Clear sky visibility has decreased over land globally from 1973 to 2007. *Science*, **323**, 1468–1470.
- , —, M. Wild, and S. L. Liang, 2010: Evidence for decadal variation in global terrestrial evapotranspiration between 1982 and 2002: 2. Results. *J. Geophys. Res.*, **115**, D20113, doi:10.1029/2010JD013847.
- Wentz, F. J., L. Ricciardulli, K. Hilburn, and C. Mears, 2007: How much more rain will global warming bring? *Science*, **317**, 233–235.
- Wild, M., 2009: Global dimming and brightening: A review. *J. Geophys. Res.*, **114**, D00D16, 10.1029/2008JD011470.
- , and B. Liepert, 2010: The earth radiation balance as driver of the global hydrological cycle. *Environ. Res. Lett.*, **5**, 025003, doi:10.1088/1748-9326/5/2/025203.
- , and E. Schmucki, 2011: Assessment of global dimming and brightening in IPCC-AR4/CMIP3 models and ERA40 based on surface observations. *Climate Dyn.*, **37**, 1671–1688, doi:10.1007/s00382-010-0939-3.

- , and Coauthors, 2005: From dimming to brightening: Decadal changes in solar radiation at earth's surface. *Science*, **308**, 847–850.
- , A. Ohmura, and K. Makowski, 2007: Impact of global dimming and brightening on global warming. *Geophys. Res. Lett.*, **34**, L04702, doi:10.1029/2006GL028031.
- , J. Grieser, and C. Schär, 2008: Combined surface solar brightening and increasing greenhouse effect support recent intensification of the global land-based hydrological cycle. *Geophys. Res. Lett.*, **35**, L17706, doi:10.1029/2008GL034842.
- , B. Trüssel, A. Ohmura, C. N. Long, G. König-Langlo, E. G. Dutton, and A. Tsvetkov, 2009: Global dimming and brightening: An update beyond 2000. *J. Geophys. Res.*, **114**, D00D13, doi:10.1029/2008JD011382.
- Willson, R. C., and A. V. Mordvinov, 2003: Secular total solar irradiance trend during solar cycles 21–23. *Geophys. Res. Lett.*, **30**, 1199, doi:10.1029/2002GL016038.
- Ye, J. S., F. M. Li, G. J. Sun, and A. H. Guo, 2010: Solar dimming and its impact on estimating solar radiation from diurnal temperature range in China, 1961–2007. *Theor. Appl. Climatol.*, **101**, 137–142.
- Zerefos, C. S., and Coauthors, 2009: Solar dimming and brightening over Thessaloniki, Greece, and Beijing, China. *Tellus*, **61B**, 657–665.