Global Dimming and Brightening

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Martin Wild

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Abstract

A fundamental determinant of climate and life on our planet is the solar radiation (sunlight) incident at the Earth's surface. Any change in this precious energy source affects our habitats profoundly. Until recently, for simplicity and lack of better knowledge, the amount of solar radiation received at the Earth surface was assumed to be stable over the years. However, there is increasing observational evidence that this quantity undergoes significant multi-decadal variations, which need to taken into account in discussions of climate change and solar energy generation. Coherent periods and regions with prevailing declines ("dimming") and inclines ("brightening") in surface solar radiation have been detected in the worldwide observational networks, often in accord with anthropogenic air pollution patterns. This paper highlights the main characteristics of this phenomenon, and provides a conceptual framework for its causes as well as an overview over potential environmental implications.

Keywords

Solar energy • Global dimming and brightening • Earth radiation budget • Decadal climate variations • Air pollution and climate

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M. Wild
Eidgenössiche Technische Hochschule (ETH) Zurich, Institute for Atmospheric and Climate Science, Zurich, Switzerland
e-mail: martin.wild@env.ethz.ch

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Introduction

The major anthropogenic impact on climate and environments occurs through a modification of the Earth's radiation balance by changing the amount of greenhouse gases and aerosol in the atmosphere. The amount of solar radiation reaching the Earth's surface is thereby particularly important as it provides the primary source of energy for life on the planet and states a major component of the surface energy balance which governs the thermal and hydrological conditions at the Earth's surface. On a more applied level, knowledge on 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 on nuclear- and carbon-free energy sources. Any change in this precious energy source could therefore affect our life and environments profoundly (Wild 2012).

Observational and modeling studies emerging in the past two decades indeed suggest that surface solar radiation (SSR) is not necessarily constant on decadal timescales as often assumed for simplicity and lack of better knowledge, but shows substantial decadal variations. Largely unnoticed over a decade or more, 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.

Observational Evidence and Possible Causes

Monitoring of SSR began in the early twentieth century at selected locations and since the mid-century on a more widespread basis. Many of these historic radiation measurements have been collected in the Global Energy Balance Archive (GEBA, Gilgen et al. 1998) at ETH Zurich and in the World Radiation Data Centre (WRDC) of the Main Geophysical Observatory, St. Petersburg. In addition, more recently, high-quality surface radiation measurements, such as those from the Baseline Surface Radiation Network (BSRN, Ohmura et al. 1998) and from the Atmospheric Radiation Measurement Program (ARM), have become available. These networks measure surface radiative fluxes at the highest possible accuracy with well-defined and calibrated state-of-the-art instrumentation at selected worldwide distributed sites.

Changes in SSR from the beginning of widespread measurements in the 1950s up to the 1980s have been analyzed in numerous studies (e.g., Ohmura and Lang 1989; Gilgen et al. 1998; Stanhill and Cohen 2001 and references therein; Liepert 2002; Wild 2009 and references therein). These studies report a general decrease of SSR at widespread locations over land surfaces between the 1950s and 1980s. This phenomenon is now popularly known as "global dimming" (see Fig. 5.1 upper panel, for a schematic illustration).

Increasing air pollution and associated increase in aerosol concentrations are considered a major cause of the observed decline of SSR (e.g., Stanhill and Cohen 2001;

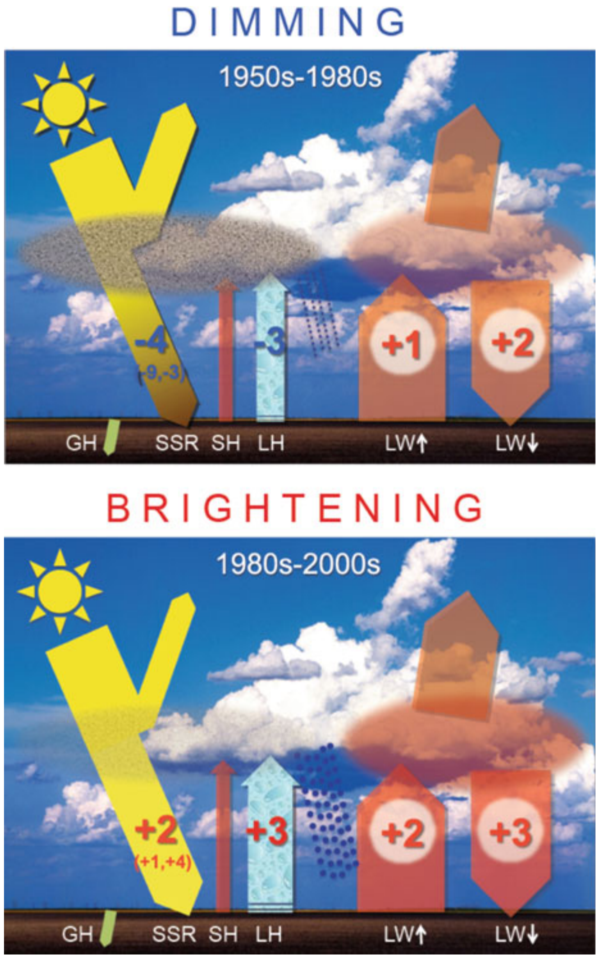

Fig. 5.1 Schematic representation of "dimming" and "brightening" periods over land surfaces. During "dimming" (1950s–1980s, *upper panel*), the decline in surface solar radiation (*SSR*) may have outweighed increasing atmospheric downwelling thermal radiation (*LW*↓) from enhanced greenhouse gases and effectively counteracted global warming, causing only little increase in surface thermal emission (*LW*↑). The resulting reduction in radiative energy at the Earth's surface may have attenuated evaporation and its energy equivalent, the latent heat flux (*LH*), leading to a slowdown of the water cycle. With the transition from "dimming" to "brightening" (1980s–2000s, *lower panel*), 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 Wm^{-2} (ranges of literature estimates for SSR dimming/brightening in parentheses). *Positive*/*red* (*negative*/*blue*) numbers denote increasing (decreasing) magnitudes of the energy fluxes in the direction indicated by the *arrows* (From Wild (2012))

Wild 2009). Changes in cloud amount and optical properties, which may or may not have been linked to the aerosol changes, have also been proposed to contribute to the dimming (e.g., Liepert 2002). An attempt has been made in Norris and Wild (2007) to differentiate between aerosol and cloud impacts on radiative changes over Europe. They show that changes in cloud amount cannot explain the changes in SSR, pointing to aerosol direct and indirect effects as major cause of these variations. Alpert et al. (2005) found that the decline in SSR in the 1950s to 1980s period is particularly large in areas with dense population, which also suggests a significant anthropogenic influence through air pollution and aerosols. Several studies (e.g., Dutton et al. 2006; Wild et al. 2009 and references therein) noted a dimming over the 1950s–1980s period also at remote sites, suggesting that the phenomenon is not of purely local nature and air pollution may have far-reaching effects (a concept on how SSR in remote areas may be modulated by subtle changes in background aerosol levels is introduced below).

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. 5.1, lower panel). Particularly in industrialized areas, the majority of the sites showed some recovery from prior dimming, or at least a levelling off, between the 1980s and 2000. The brightening has been somewhat less coherent than the preceding dimming, with trend reversals at widespread locations, but still some regions with continued decrease, such as in India (see Wild 2009, 2012 for an overview). Brightening is not just found under all sky conditions, but often also under clear skies, pointing once more to aerosols as major causes of this trend reversal (e.g., Wild et al. 2005; Norris and Wild 2007). The transition from decreasing to increasing SSR is in line with a similar shift in atmospheric clear sky transmission determined from pyrheliometer measurements at a number of sites (Fig. 5.2). This transition is also in line with changes in aerosol and aerosol precursor emissions derived from historic emission inventories, which also show a distinct trend reversal during the 1980s, particularly in the industrialized regions (e.g., Streets et al. 2006; Stern 2006). The trend reversal in aerosol emission towards a reduction and the associated increasing atmospheric transmission since the mid-1980s may be related to air pollution regulations and the breakdown of the economy in Eastern European countries. A reduction of aerosol optical depth over the world oceans since 1990, which may be indicative of the global background aerosol level, was inferred from satellite data by Mishchenko et al. (2007). This fits well to the general picture of a widespread transition from dimming to brightening seen in the surface radiation observations at the same time.

Updates on the SSR evolution beyond the year 2000 show mixed tendencies. 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 USA, but levels off at Japanese sites, and shows some indications for a renewed dimming in China after a phase of stabilization during the 1990s, while dimming persists throughout in India (Wild et al. 2009). On the other hand, the longest observational

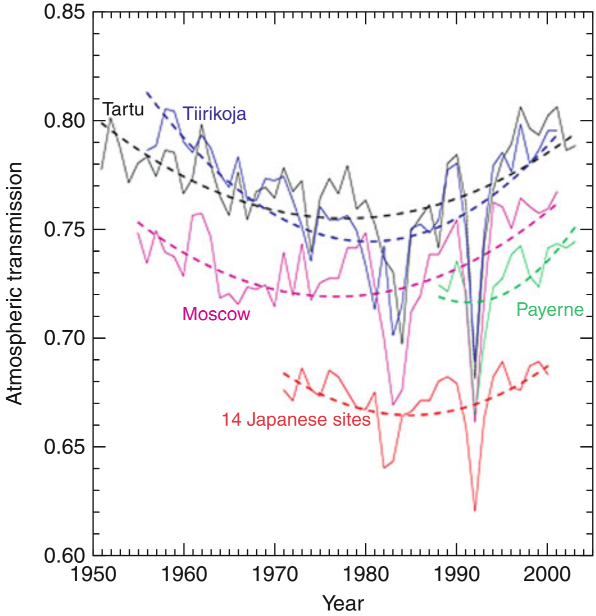

Fig. 5.2 Time series of annual mean atmospheric transmission under cloud-free conditions determined from pyrheliometer measurements at various sites in Russia (*Moscow*), Estonia (*Tartu-Toravere* and *Tiirikoja*), Switzerland (*Payerne*), and Japan (average of *14 sites*) (From Wild et al. (2005), online supporting material)

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).

Wild (2009, 2012) proposed a conceptual framework for the explanation of dimming and brightening, suggesting that aerosol-induced dimming and brightening can be amplified or dampened by aerosol-cloud interactions depending on the prevailing pollution levels. In pristine regions, small changes in cloud condensation nuclei (CCN) can have a much bigger impact on cloud characteristics than in polluted environments, because clouds show a nonlinear (logarithmic) sensitivity to CCN (e.g., Kaufman et al. 2005). Additional CCN due to air pollution 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 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 satellite-derived SSR records (Wild 2009 and references therein).

In polluted regions, on the other hand, cloud microphysics effects tend to saturate with the logarithmic sensitivity to CCN, 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 semi-direct aerosol effect). 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 (Wild 2009, 2012).

Environmental Implications of Dimming and Brightening

A growing number of studies provide evidence that the variations in SSR have a considerable impact on climate and environmental change (see Wild (2009, 2012) for a review). Wild et al. (2007) investigated the impact of dimming and brightening on global warming. They present evidence that SSR dimming was effective in masking and suppressing greenhouse warming, but only up to the mid-1980s, when dimming gradually transformed into brightening. Since then, the uncovered greenhouse effect reveals its full dimension, as manifested in a rapid temperature rise (+0.38 °C/decade over land since mid-1980s). More recently, Wild (2012) pointed out that the absence of global warming from the 1950s to 1980s and the subsequent reversal into rapid warming was most prominently seen on the Northern Hemisphere, while on the Southern Hemisphere rather a steady gradual warming since the 1950s was observed (Fig. 5.3). This fits well to the asymmetric hemispheric evolution of anthropogenic air pollution which strongly increased from the 1950s to the 1980s and declined thereafter on the Northern Hemisphere, while pollution levels on the Southern Hemisphere were an order of magnitude lower and steadily increased with no trend reversal (Wild 2012; Stern 2006). This again points to a possible large-scale influence of aerosol-induced SSR dimming and brightening on global warming. Interestingly enough, the suppression of warming during the dimming period on the Northern Hemisphere was even slightly stronger over ocean than over land areas (Wild 2013) (slight cooling of −0.03 °C per decade over oceans between 1958 and 1985, compared to a slight warming over land with +0.04 °C per decade over the same period, based on data from the Climate Research Unit, Norwich, and the Hadley Centre, Exeter). Even though anthropogenic air pollution sources are located over land, subtle changes in background aerosol levels over the relatively pristine oceans could have amplified SSR trends through effective cloud-aerosol interactions as outlined in the conceptual framework above. This may explain the lack of warming particularly also over oceans during this period (Wild 2013).

SSR is also a major determinant of surface evaporation and thereby the main driver of the global water cycle (Wild and Liepert 2010). Wild et al. (2004) suggested that surface solar energy reductions outweighed the increasing thermal energy from the greenhouse effect from the 1960s to 1980s, resulting in a reduction of surface net radiation and associated evaporation over land surfaces, causing an attenuation of the intensity of the associated water cycle (Figs. 5.1 and 5.4). In contrast, for the more recent period 1980s–2000s, Wild et al. (2008) pointed out that SSR brightening adds to the increasing

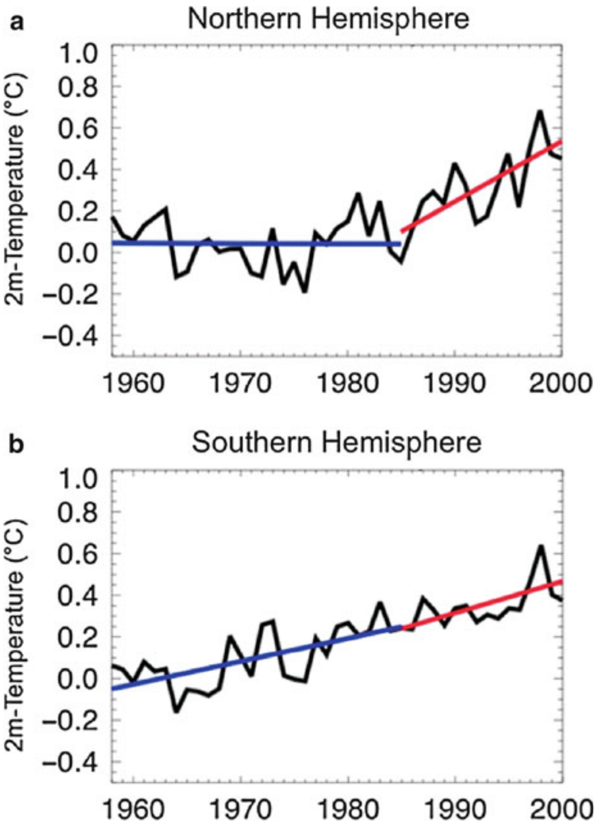

Fig. 5.3 Annual 2-m temperature anomalies observed on the Northern (**a**) and Southern Hemispheres (**b**). Observations from HadCRUT3, anomalies with respect to 1960–1990. Linear trends over the dimming phase (1950s–1980s) in *blue*, over the brightening phase (1980s–2000s) in *red*. On the polluted Northern Hemisphere, observed warming is much smaller during dimming with strong aerosol increase than during subsequent brightening with aerosol decrease. On the more pristine Southern Hemisphere, with greenhouse gases as sole major anthropogenic forcing, observed warming is similar during both periods (Adapted from Wild (2012))

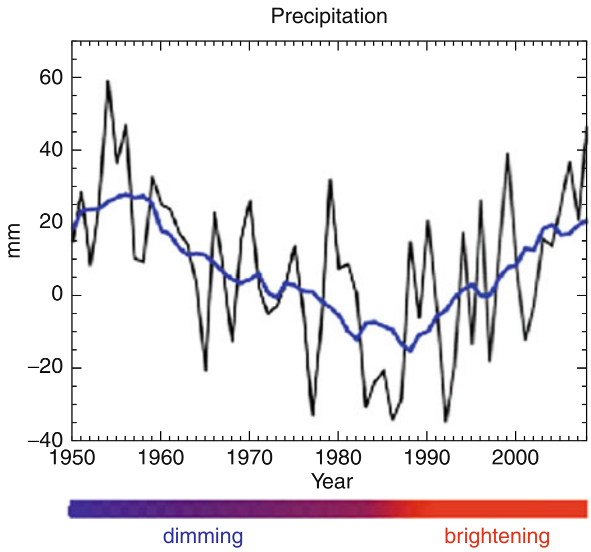

Fig. 5.4 Observational estimates of annual precipitation anomalies from 1950 to 2008 over the Northern Hemisphere land masses. Data from the Global Historic Climate Network. Reference period for anomalies is 1961–1990. Eleven-year running mean in *blue*. Units mm (From Wild (2012))

energy from the enhanced greenhouse effect, leading to higher evaporation and an intensification of the global terrestrial water cycle since the 1980s (Figs. 5.1 and 5.4). Impacts of the transition from dimming to brightening can further be seen in the more rapid retreats of glaciers and snow cover, which became evident since the 1980s as soon as the dimming disappeared (Wild 2009 and references therein).

Modeling studies further suggest that SSR 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 for photosynthesis.

Further research will be required to establish the full dimension of impacts of dimming and brightening on climate and environmental change.

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