Solar Radiation Versus Climate Change

MARTIN WILD
Institute for Atmospheric and Climate Science,
ETH Zurich, Zurich, Switzerland

Article Outline

Glossary

Brightening Describes the evidence for a partial recovery from prior dimming at many locations between the 1980s and 2000.

Dimming Also known as "global dimming," a popular expression coined to describe the evidence for a widespread decline in surface solar radiation between the 1950s and 1980s.

Early brightening Describes the evidence for an increase in surface solar radiation during the 1930s and 1940s seen in the longest surface radiation records in Europe.

Pyranometer Measurement device to record the total flux (diffuse and direct) of solar radiation incident on a horizontal plane at the Earth surface.

Surface solar radiation Also known as "global radiation" or "surface insolation," refers to the solar radiation (sunlight) incident at the Earth's surface.

Definition of the Subject

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

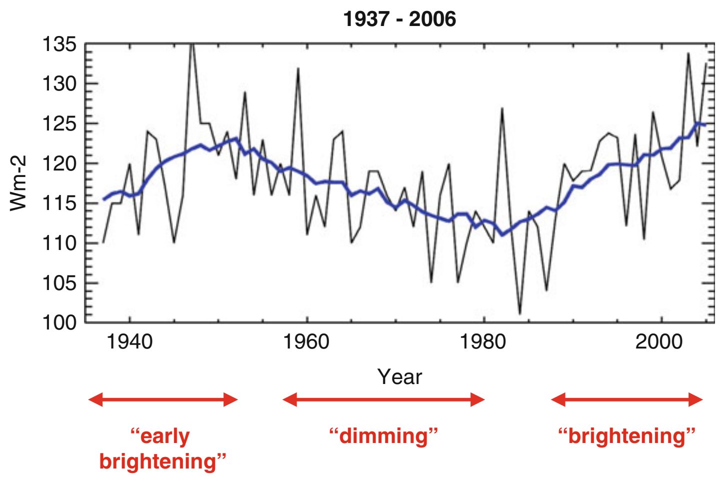
It has also major practical implications, for example, for solar energy technologies and agricultural productivity. Changes in the amount of solar energy reaching the Earth's surface can therefore have profound environmental, societal, and economic implications. There is increasing evidence that the amount of solar radiation incident at the Earth's surface is not stable over the years but undergoes significant decadal variations. This entry discusses the evidence for these changes, their magnitude, their possible causes, their representation in climate models, and their potential implications for climate change.

Introduction

The major anthropogenic impact on climate occurs through a modification of the Earth radiation balance by changing the amount of greenhouse gases and aerosol in the atmosphere. The amount of solar radiation reaching the Earth surface is thereby particularly important as a driver of a variety of climate-relevant physical and chemical processes. Observational and modeling studies emerging in the past two decades suggest that surface solar radiation is not necessary constant on decadal timescales as often assumed for simplicity, but shows substantial decadal variations. Largely unnoticed over a decade or more, this phenomenon recently gained a rapid growth of attention under the popular expressions "global dimming" and "brightening," which refer to decadal decreases and increases in surface solar radiation, respectively. This is, for example, documented in a recent special issue in the *Journal of Geophysical Research* dedicated to the topic of global dimming and brightening [1].

Available Observational Data

Monitoring of surface radiative fluxes started in the early twentieth century at selected sites, predominantly measuring the downwelling solar component (also known as "global radiation," and referred to as surface solar radiation (SSR) in this chapter). For example, continuous measurements of SSR began in 1923 at the Stockholm observatory, and in 1937 at Potsdam (Fig. 1).



Solar Radiation Versus Climate Change. Figure 1
Annual mean surface solar radiation (in W m^{-2}) as observed at Potsdam, Germany, from 1937 to 2006. Five-year moving average in blue. Distinct phases of inclines (1930s–1940s, “early brightening”), declines (1950s–1980s, “dimming”), and renewed inclines (since 1980s, “brightening”) can be seen

More widespread measurements of this quantity with thermopile pyranometers were initiated during the International Geophysical Year (IGY, 1957/1958). Many of these historic measurements have been compiled in the Global Energy Balance Archive (GEBA) at ETH Zürich [2, 3], and in the World Radiation Data Centre (WRDC) of the Main Geophysical Observatory in St. Petersburg, Russia. The data in GEBA underwent different quality checks to assure homogeneity in the records [3]. Homogeneous climatological records assert that any changes and variations in the data are induced by natural phenomena and are not an artifact. The accuracy of these historic measurements has been estimated in [3] at 2% on an annual basis. However, the quality of the measurements, performed predominantly under the auspices of the national weather services, is highly variable and not always well established. Rigorous quality control is necessary to avoid spurious trends in these data [3–5], and not all records are properly homogenized yet. In addition, possible “urbanization effects” in the surface solar radiation data [6] may have to be taken into account and need better quantification.

In the late 1980s the necessity for a reference network of surface radiation measurements with improved and defined accuracy was recognized. As a result, the Baseline Surface Radiation Network (BSRN) was established [7]. The first BSRN sites, equipped with instruments of the highest possible accuracy, became operational in the early 1990s. To date, more than 40 anchor sites in different climate regimes provide data at high temporal resolution (1-min data) for both solar (total, diffuse/direct, and reflected) and thermal (downward and upward) components. The BSRN accuracy targets are for surface solar radiation 2% or 5 W m^{-2} (ventilated pyranometer), for direct solar radiation 1% or 2 W m^{-2} (normal incidence pyrheliometer), for diffuse radiation 4% or 5 W m^{-2} (ventilated shaded pyranometer), for reflected SW radiation 5% (ventilated pyranometer), and for downward and upward thermal radiation ± 2 W m^{-2} (pyrgeometer). Other radiation networks with comparable quality standards were established around the world in recent years: the Atmospheric Radiation Measurement (ARM) Program with several worldwide distributed sites [8, 9], the SURFRAD (SURFace RADiation) network maintained by the National Oceanic and Atmospheric Administration (NOAA) with seven sites within the USA [10], the NOAA Earth System Research Laboratory (ESRL) Network with five worldwide distributed remote sites [4], the Australian Network maintained by the Bureau of Meteorology, and the Alpine Surface Radiation Budget network (ASRB) with seven sites in the Swiss Alps [11].

Despite the increasing number of high-accuracy surface radiation stations, large regions are insufficiently covered by direct surface radiation stations, such as vast areas of Africa, South America, and the Maritime Continent, and particularly ocean areas, which prevent a true global assessment.

Satellite-derived fluxes can provide a near-global picture, but their records are of limited lengths and go back to the early 1980s at most [12–14]. Furthermore, they do not directly measure the surface fluxes, but have to infer them from measurable top-of-atmosphere signals using, in addition, empirical or physical models to remove atmospheric perturbations. Satellite-inferred SSR records may also suffer from potential inhomogeneities due to changes in satellites, viewing geometries, inaccurate positioning, or sensor degradation, particularly in the earlier records [15].

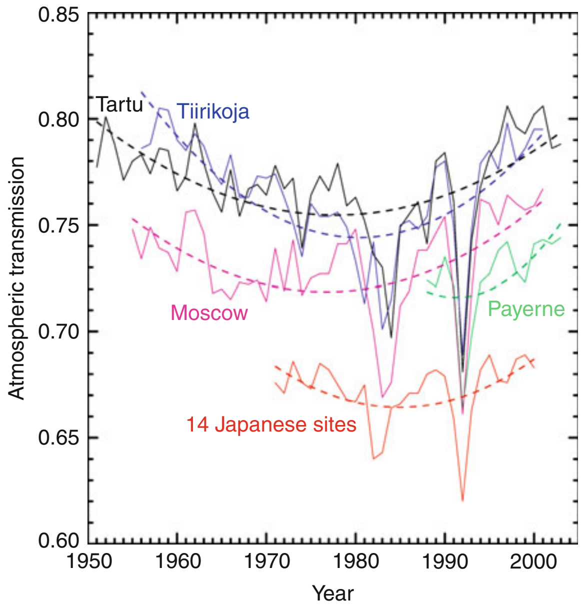
In addition, reconstructions of SSR from more widely performed meteorological measurement quantities may be used to extend the information spatially and temporally, such as surface solar radiation changes inferred from observed changes in sunshine duration, diurnal temperature range, or pan evaporation [16–19].

Variations in Surface Solar Radiation

The earliest studies analyzing extended observational records of surface solar radiation appeared in the early 1990s [20–26] (see [27, 28] for a more complete overview). These pioneering studies presented the first evidence that solar radiation at the Earth's surface had not been constant over time as previously assumed, but showed significant decadal variations. Specifically, they pointed to declines in surface solar radiation since the 1950s in different regions of the globe. The first analyses with comprehensive datasets of sites distributed worldwide, as available from GEBA/WRDC, were performed by [3, 27, 29]. These studies reported an overall decrease of solar radiation at widespread locations over land surfaces on the order of 6–9 W m^{-2} between 1960 and 1990, corresponding to 4–6% over 30 years. The popular term "global dimming" was coined by Stanhill and Cohen (2001) [27] to describe this decrease. Increasing air pollution and associated increases in aerosol concentration have been suggested as major cause of this phenomenon, although changes in cloud amount and cloud optical properties may also contribute (see [28] for an overview). A direct assessment of the origins of surface solar dimming is complicated by the lack of adequate long-term observational datasets on variations of cloud and aerosol properties.

The studies on "global dimming" were all limited to data prior to 1990, since GEBA contained no data after 1990 at the time these studies were completed. More recently, ETH Zürich undertook a major effort to update the worldwide measured surface radiation data in GEBA for the period from 1990 to present. Wild et al. (2005) [30] evaluated the newly available surface observational records from GEBA and BSRN to investigate the trends in solar radiation in the more recent years. This analysis showed that the decline in solar radiation at land surfaces seen in earlier data is no longer visible in the 1990s at many locations. Instead, a brightening is observed since the late 1980s at the majority of the available observation sites (see also [28] for a recent review). A major exception is India, where the records show a persistent dimming throughout [30–32]. The brightening during the 1990s is not just found under all sky conditions, but also seen under clear skies at various sites, pointing to aerosol as a major cause of this trend reversal [28, 30, 33, 34]. The trend reversal is reconcilable with trends in aerosol emission, aerosol optical depth, and atmospheric transmission, which also show a distinct trend reversal during the 1980s [30, 35–39] (Fig. 2, taken from [30]). The trend reversal toward a reduction in aerosol emission and the associated increasing atmospheric transmission since the mid-1980s may be related to the adoption of more stringent air pollution regulations in developed countries, and the breakdown of the economy in the former communist countries. Changes in cloud properties also play a role in some regions and seem to be responsible, for example, for the dimming and brightening in New Zealand [40] and the recent brightening in the USA [41]. Overall, at many sites the brightening could not fully compensate for prior dimming, so that insolation levels around the year 2000 were still below those of the 1950s [28, 42].

The latest updates on solar radiation changes observed at the surface beyond the year 2000 suggest a continuation of the brightening at sites in Europe, in the USA, and in parts of Asia, particularly Korea [43]. Brightening seems to level off at sites in Japan and



Solar Radiation Versus Climate Change. Figure 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 [30], online supporting material)

Antarctica after 2000, while indications for a renewed dimming are seen in China, likely associated with large emission increases in China after 2000. The compensating tendencies in various regions of the globe may tentatively indicate that the overall surface solar radiation signal inferred from ground-based observations did not undergo dramatic changes since 2000 [43]. This fits with the general picture provided by satellite observations, which suggest that the global mean planetary albedo as well as the background aerosol burden of the atmosphere may not have undergone substantial changes in the early 2000s, at least globally [37, 43, 44].

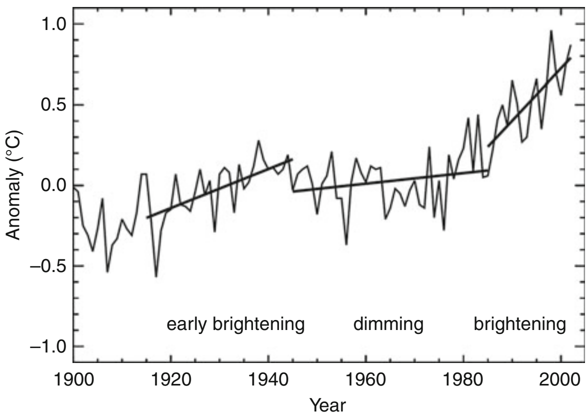
The longest direct observational records, which go back to the 1920s and 1930s at a few sites in Europe, further indicate some brightening tendencies during the first half of the twentieth century, known as "early brightening" [28, 45]. This suggests that dimming, at least in Europe, was restricted to a period between the 1950s and 1980s (see Fig. 1). A potential origin of this early brightening could have been the transition from the use of coal to oil as the main fossil energy source, which temporally reduced the emission of sulfur and black carbon [28, 46].

The early brightening up to the 1950s, the subsequent dimming until the 1980s, and the more recent brightening from the 1980s to 2000 are illustrated in the long-term solar radiation record measured at Potsdam (Fig. 1).

Climate-relevant surface radiative forcing is not only determined by surface solar radiation variations, but also strongly governed by the reduced thermal surface cooling with enhanced greenhouse capacity of the atmosphere, manifest in increased downward thermal radiation from the atmosphere to the surface. Compared to the solar component, much less information from direct observations is available on the temporal evolution of the downward thermal component. Operational monitoring of this quantity started in the 1990s in the abovementioned networks of BSRN, ARM, SURFRAD, and ASRB. The first analyses of the still very short time series of downward thermal radiation indicate an overall average increase in this quantity of 2–3 W m^{-2} per decade since the early 1990s at the globally distributed measurement sites of BSRN [47, 48]. Measurements taken in the Swiss Alps show an even larger increase in downward thermal radiation since 1995 in this particular region [11]. An increase in the downward thermal radiation is in line with the expectations from greenhouse theory and climate model scenarios [49], and gives direct evidence for the real existence of an increasing greenhouse effect [11].

Impacts on the Climate System

A growing number of studies provide evidence that the variations in SSR have a considerable impact on climate change. Wild et al. (2007) [42] investigated the impact of dimming and brightening on global warming. They presented evidence that surface solar dimming was effective in masking and suppressing greenhouse warming, but only up to 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 per decade over land since mid-1980s). The early brightening may have contributed to the rapid warming during the 1930s and 1940s (Fig. 3, taken

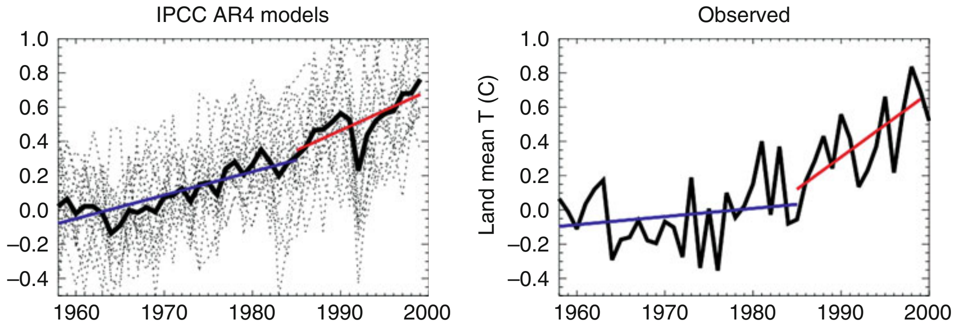


Solar Radiation Versus Climate Change. Figure 3 Two-meter temperature anomalies over global land surfaces during the twentieth century. There is indication for a suppression of greenhouse-induced warming through "global dimming" between the 1950s and 1980s, and an enhancement through "brightening" between the 1920s and 1940s as well as from the 1980s onward. Anomalies are with respect to the twentieth-century average. Unit °C (From [28])

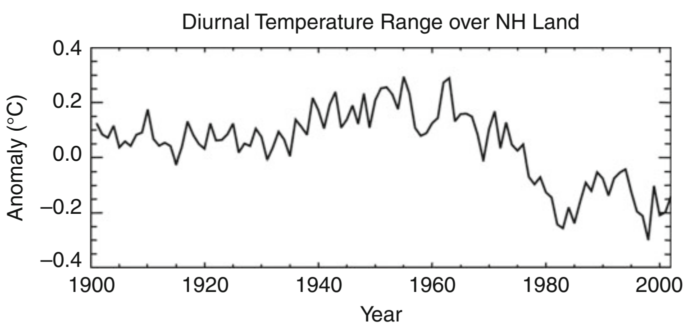
from [28]). Ruckstuhl et al. (2008) [50] and Philipona et al. (2009) [51] came to similar conclusions for the area of Europe, where brightening due to the substantial reduction in aerosol optical depth (up to 60% since 1986 at six remote locations in Europe) may have significantly contributed to the recent rapid warming in this region. Brightening, however, cannot supersede the greenhouse effect as main cause of global warming, since land temperatures increased by 0.8°C since 1960, even though solar brightening did not fully outweigh prior dimming over this period [42].

The climate models used in IPCC-AR4 do not seem to fully account for these observed decadal modulations of global warming through solar dimming and brightening, even if all known forcings are included in the models (Fig. 4) [52, 53]. They underestimate the suppression of warming through dimming between the 1950s and 1980s over global land surfaces, and simulate a higher rate of temperature rise than observed during this period (Fig. 4). On the other hand, for the more recent decades the models underestimate the rate of global warming, indicative of a lack of brightening (Fig. 4) [52]. The potential explanations that have been put forward for these modeling problems include the large uncertainties in historic emission inventories and associated aerosol burdens in the atmosphere, which may not consider the full extent of decadal variations, the inadequate representation of the direct and indirect aerosol forcings, as well as a general underestimation of the unforced natural variability in the models [52–54].

Wild et al. (2007) [42] provided further evidence for a strong impact of dimming and brightening on global warming, based on analyses of decadal changes in observed daily maximum and minimum temperatures and related diurnal temperature range (DTR). They found a slight decrease in the daily maximum temperatures over the "dimming" period from the 1960s to the 1980s, which is in line with the reduction of SSR over this period. Daily minimum temperatures, on the other hand, have been increasing over the same period, causing a decline in DTR. In contrast, since the mid-1980s, observed minimum and maximum temperatures increase at a very similar pace. This is indicative of a major change in the surface radiative forcing regime, where the maximum temperature rise is no longer suppressed as in the decades before, due to the transition from dimming to brightening [42]. The close correlation between DTR and SSR changes may also allow a reconstruction of SSR trends back to the first part of the twentieth century, when radiation measurements were lacking, but DTR observations were already abundant. This is at least feasible for the Northern Hemisphere with much more long-term observational temperature records than for the Southern Hemisphere (P. Jones, personal communication 2008). Figure 5 (taken from [28]) depicts the annual mean DTR evolution over Northern Hemisphere land surfaces during the twentieth century, as determined here from the CRU dataset. The figure not only suggests a downward tendency in DTR predominantly between the 1950s and 1980s and a leveling off thereafter as discussed above, but also a slight upward tendency in the 1930 and 1940s. This gives, on the one hand, support for two episodes of "brightening," one at the end of the twentieth century, and a second one in the 1930s and 1940s ("early brightening"). On the other hand, it implies that "global dimming" was essentially a phenomenon confined to about a 30–40 years period in the second half of the twentieth century [28]. This behavior is again not found in the IPCC-AR4 models [28].



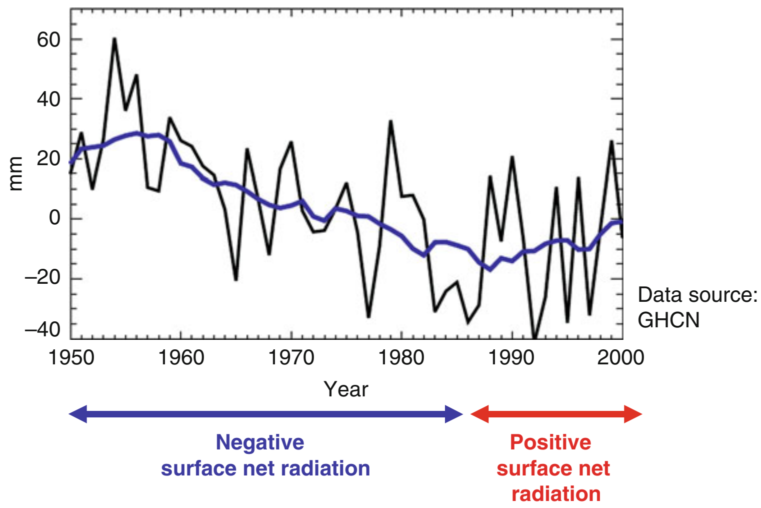
Solar Radiation Versus Climate Change. Figure 4
Annual mean temperature anomalies (°C) over land surfaces from 1958 to 1999, as simulated by 18 Global Climate Models in "all forcings" twentieth-century experiments performed for the Fourth IPCC assessment report (*left panel*), and as observed (*right panel*). Multimodel mean given as thick black lines. Individual model realizations shown as dashed lines. Linear regressions for the periods 1958–1985 in blue and 1985–1999 in red. Observations from the CRU dataset [60]. Reference period for anomalies is the entire twentieth century (From [52])



Solar Radiation Versus Climate Change. Figure 5
Annual mean diurnal temperature range (°C) anomalies averaged over Northern Hemispheric land surfaces, from 1900 to 2002. Variations of diurnal temperature range may provide a useful proxy for variations in surface solar radiation. Data from CRU [60]. Anomalies are shown with respect to the 1961–1990 mean (From [28])

Solar energy available at the earth's surface is also a major determinant of surface evaporation and thereby the main driver of the global water cycle. Wild et al. (2004) [55] 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 hydrological cycle (Fig. 6). In contrast, for the more recent period 1980s to 2000, Wild et al. (2008) [48] pointed out that the surface solar brightening adds to the increasing energy from the enhanced greenhouse effect, leading to higher evaporation and an intensification of the global terrestrial water cycle since the 1980s (Fig. 6). Again, current climate models are not capable of adequately reproducing these decadal variations in the hydrological cycle [28, 56]. Robock and Li (2006) [57] used the dimming phenomenon to explain the increasing soil moisture and decreasing evaporation between the 1960s and 1980s, as seen in long-term soil moisture records in the Ukraine. 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 [28, 58].

There are also indications that dimming and brightening may impact the terrestrial carbon cycle



Solar Radiation Versus Climate Change. Figure 6
Northern Hemispheric terrestrial precipitation anomalies (in mm) during the second half of the twentieth century. During the "dimming" phase (1950s–1980s), the decline in downwelling solar radiation may have outweighed increasing downwelling thermal radiation from enhanced greenhouse gases, and thereby reduced the surface net radiation, causing reductions in evaporation and associated intensity of the hydrological cycle. During the "brightening" phase (1980s–2000), the disappearance of the dimming no longer compensated for the enhanced greenhouse effect, leading to an increase in surface net radiation and an intensification of the hydrological cycle. Data from the Global Historic Climate Network (GHCN)

and plant growth [59]. During dimming, plant photosynthesis and associated terrestrial carbon uptake might have been enhanced despite a reduction in surface solar radiation, since the stronger aerosol and cloud scattering increased the diffuse radiative fraction during 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. The modeling results of this study suggests that the effect of the increasing diffuse fraction dominates over the reduced surface solar radiation during dimming, leading to an enhanced terrestrial carbon uptake in this period, which fades thereafter during the brightening period with declining diffuse fraction [59].

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

Future Directions

To the extent that decadal variations in surface solar radiation are caused by anthropogenic air pollution, dimming and brightening will depend on future anthropogenic emissions of aerosols and aerosol precursors [28]. These emissions may change substantially in the future in response to economic growth, energy consumption, and air pollution regulations. The tendency toward a renewed dimming seen in the radiation data in China since 2000, for example, is not unexpected, because coal consumption in China has doubled between 2002 and 2007 (data available from the US Energy Information Administration) [28]. On the other hand, not much further brightening might be expected in Western industrialized countries, since aerosol levels stabilized since about 2000 at low values [36, 51]. A renewed overall dimming can therefore not be excluded for a few years to come, with the air pollution mitigation potential approaching saturation in many of the industrialized nations on the one hand, thus preventing further policy-related brightening, and continued increase of air pollution and associated dimming in developing and emerging nations on the other hand. This could also have implications for the near-term global warming. However, such a potential renewed dimming clearly should not be persistent, as in developing countries as well as in East Asia and India, new air pollution regulations will become inevitable to prevent drastic health or environmental problems. Therefore, in the longer run, a turn into brightening can be expected also in these countries. Under these perspectives, effective greenhouse gas mitigation measures call for urgent implementation to prevent drastic temperature rise under foreseeable future brightening.

The continuation of accurate monitoring from both surface and space, along with the development of advanced global modeling systems, will be of utmost importance to diagnose, understand, and control these anticipated fundamental changes in the radiation balance of the globe.

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Solar Radiation, Introduction

Christian A. Gueymard
Solar Consulting Services, Colebrook, NH, USA

Article Outline

Solar Radiation and Sustainability

Solar radiation is ultimately what directly brings two essential conditions that are needed to maintain life on Earth: light and heat. Light is obviously what is most directly needed by photosynthesis to absorb carbon dioxide and produce oxygen. Indirectly, various chemical reactions in the atmosphere induced by solar radiation – particularly in the ultraviolet (UV) – produce some critical elements (such as ozone and oxygen) in the right quantities and at the right altitude. The result of these direct and indirect effects is to maintain atmospheric gases to levels compatible with life as it is known. By extension, the quantity and quality of solar radiation is what totally determines the delicate balance of the Earth's ecosystems, the agricultural and forestry resources needed for human or animal food, and even the development of our civilizations.

In the present era, various factors are contributing to a stronger-than-ever need for a detailed understanding of how constant the sun's energy output is, how it propagates through the Earth's atmosphere, how its local or global variations affect our climate and life forms (including human health and behavior), how human activities induce changes in solar radiation as well as climate, and how or where it can be efficiently harnessed to develop advanced solar technologies. Such "clean" technologies are particularly necessary today to solve three critical and interrelated problems of our industrial civilization: climate change, pollution, and near complete dependence on nonrenewable energy sources. The latter factor is a major cause of the two others, and all three are fundamental reasons why our current civilization is *not* sustainable. The societies of the future will need to be based on a zero-emission renewable energy economy. This is a necessary (but not sufficient) condition to achieve sustainability.

Historical Perspective

Interest for solar radiation, and solar energy applications in general, is not new. Many textbooks or other sources provide historical accounts of discoveries or technological breakthroughs from some solar pioneers since the Antiquity. One barely known pioneer was Frank Schuman (1862–1918), an American engineer who developed various solar thermal engines that could produce steam. These were similar to those that are currently being developed throughout the world with a technology known as Concentrating Solar Power (CSP), which uses parabolic troughs (or other concentrating devices) to heat a fluid, produce steam, and ultimately electricity. Unfortunately, Schuman's inventions, and even a full-scale 88-kW demonstration plant in Egypt, progressively fell into oblivion while the reign of cheap oil was starting. Schuman was not just an engineer, but also a visionary, as exemplified by this surprising statement of his: "*One thing I feel sure of… is*