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Impact of global dimming and brightening on global warming

Martin Wild,[1] Atsumu Ohmura,[1] and Knut Makowski[1]

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[1] Speculations on the impact of variations in surface solar radiation on global warming range from concerns that solar dimming has largely masked the full magnitude of greenhouse warming, to claims that the recent reversal from solar dimming to brightening rather than the greenhouse effect was responsible for the observed warming. To disentangle surface solar and greenhouse influences on global warming, trends in diurnal temperature range are analyzed. They suggest that solar dimming was effective in masking greenhouse warming, but only up to the 1980s, when dimming gradually transformed into brightening. Since then, the uncovered greenhouse effect has revealed its full dimension, as manifested in a rapid temperature rise (+0.38°C/decade over land since mid-1980s). Recent solar brightening cannot supersede the greenhouse effect as main cause of global warming, since land temperatures increased by 0.8°C from 1960 to 2000, even though solar brightening did not fully outweigh solar dimming within this period. **Citation:** Wild, M., A. Ohmura, and K. Makowski (2007), Impact of global dimming and brightening on global warming, *Geophys. Res. Lett.*, *34*, L04702, doi:10.1029/2006GL028031.

1. Introduction

[2] Solar radiation reaching the ground is a key determinant of surface temperature. Various studies suggest that solar energy at the surface has not been stable over time but showed significant changes on decadal timescales ('global dimming / brightening') [*Ohmura and Lang*, 1989; *Dutton et al.*, 1991; *Gilgen et al.*, 1998; *Stanhill and Cohen* 2001; *Liepert*, 2002; *Wild et al.*, 2004, 2005; *Pinker et al.*, 2005]. Atmospheric aerosols from anthropogenic air pollution are considered important contributors to these changes [*Streets et al.*, 2006]. Such changes are likely to have an effect on surface temperature [*Ramanathan et al.*, 2001; *Wild et al.*, 2005]. In addition, increasing anthropogenic emissions of greenhouse gases are expected to induce an increasing flux of thermal (longwave/terrestrial) radiation from the atmosphere to the surface, thereby reducing thermal cooling of the Earth surface and enhancing surface temperature according to greenhouse theory. Concerns have been raised that increases in aerosol from anthropogenic air pollution and associated dimming of surface solar radiation could have masked to a large extent the temperature rise induced by increasing greenhouse gases, so that the observed temperature records would not reflect the entire dimension of greenhouse warming [*Andreae et al.*, 2005]. This would imply that we underestimate the sensitivity of the climate system to increased levels of greenhouse gases, which has potentially major implications for predictions of future climate. On the other hand, the emerging evidence for a widespread decline of solar dimming during the 1980s and reversal to a brightening thereafter [*Wild et al.*, 2005; *Pinker et al.*, 2005] may give raise to speculations that recent global warming could be due to surface solar brightening rather than the greenhouse effect. We intend to disentangle the effects of changes in surface solar and thermal (greenhouse) radiation on global warming in the following.

2. Observational Data

[3] We investigate this issue by using, in addition to the surface radiation data at the authors' institute from the Global Energy Balance Archive (GEBA) [*Gilgen and Ohmura*, 1999] and the Baseline Surface Radiation Network (BSRN) [*Ohmura et al.*, 1998], a gridded surface temperature dataset. This dataset is provided by the Climate Research Unit (CRU), University of East Anglia and contains information on observed surface air temperatures over land on a 0.5° grid [*Mitchell and Jones*, 2005]. It includes mean, daily maximum and daily minimum temperatures on a monthly basis from 1900 to 2002. Annual values of global and hemispheric temperature estimates are approximately accurate to ±0.05°C (two standard errors) for the period since 1951 [*Brohan et al.*, 2006]. Surface radiation measurements from BSRN reach an absolute accuracy of 5 Wm^{-2} in both surface downward solar and thermal radiation, with a 2 Wm^{-2} relative accuracy (changing sensor sensitivity) [*Ohmura et al.*, 1998]. Historic radiation data from GEBA are of variable accuracy depending on the individual station [*Gilgen et al.*, 1998; *Wild et al.*, 1995]. We focus on land surfaces, where our knowledge of the common variation in surface radiation and temperature is best. We confine our analysis to the period from 1958, when widespread measurements of surface radiation were initiated during the International Geophysical Year (IGY), up to 2002, where data are available.

3. Effects of Solar Dimming/Brightening on Temperature Changes 1958–2002

3.1. Change in Land Mean Temperature

[4] Annual mean temperature changes averaged over land surfaces from 1958 to 2002 as deviations from 1960 are determined in Figure 1 from the CRU dataset. It is evident that the temperature rise was small in the first half of the period, but became significant during the second half. Since we estimated that trends in surface solar radiation showed a widespread reversal from dimming to brightening in the mid-1980s [*Wild et al.*, 2005], we subdivide the temperature records in two sections, before and after 1985. Linear trends

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland.

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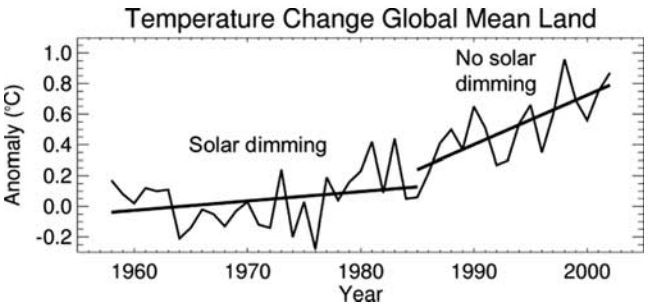

Figure 1. Temperature change over global land surfaces from 1958 to 2002 with respect to 1960. While the temperature rise during the period of solar dimming from the 1960s to the 1980s is moderate, temperature rise is more rapid in the last two decades where dimming was no more present.

over the two periods 1958–1985 and 1985–2002 are given in Table 1. In the timeframe 1958–1985, representing the period of solar dimming, only a marginal temperature increase is found (0.0036°C/year or 0.036°C/decade). The temperature increase during the period 1985–2002, where solar dimming was no longer effective, is an order of magnitude larger (0.038°C/year or 0.38°C/decade). This indicates that changes in surface solar radiation may have significantly influenced the temperature evolution over the past decades and provides motivation to further investigate the relation between surface radiation and temperature.

3.2. Change in Daily Maximum and Minimum Temperature

[5] To disentangle the influence of surface solar and thermal radiation on global warming, we need to focus not only on changes in mean temperature, but also on the daily temperature cycle. Thereby we use the fact that solar and thermal radiation have different effects on the daily temperature cycle. Since the solar flux is only in effect during daylight, it affects the daily maximum temperature (TMAX) more than daily minimum temperature (TMIN). The nighttime minimum temperature, on the other hand, is mainly affected by the thermal radiative exchanges. Nighttime surface radiative cooling depends on the capacity of the atmosphere to absorb and re-emit thermal radiation towards the surface. An analysis of TMIN and TMAX therefore holds the potential to separate the influence of solar and thermal radiation on surface temperature. Note that daytime temperatures are less sensitive to radiative changes than nighttime temperatures, since the radiative energy at the surface can be distributed more effectively by the turbulent fluxes of sensible and latent heat within the predominately convective daytime boundary layer, than during the predominantly stable nighttime conditions [*Ohmura*, 1984; *Dai et al.*, 1999].

[6] Trends in TMIN and TMAX determined from the CRU dataset and averaged over land surface for the above two periods are given in Table 1. It is remarkable that during the period with prevailing solar dimming 1958–1985, TMAX is declining. This decline is consistent with the decreasing availability of solar energy at the surface and supports the assumption that solar dimming had a discernible influence on surface temperature in this period. TMIN on the other hand, less affected by solar dimming, shows an increase, indicative of an increasing greenhouse forcing.

[7] If we assume in a thought experiment that no solar dimming had occurred, one could assume that the mean temperature rise would not have been substantially different from the rise in TMIN (0.11°C/decade, a conservative estimate considering that dimming might also had a cooling effect on nighttime temperatures). Compared to the actually observed mean temperature increase of 0.036°C/decade, this would imply that solar dimming has dampened the mean temperature rise on the order of 60 –70% between 1958 and 1985.

[8] On the other hand, the period 1985–2002, during which solar dimming reversed into brightening, exhibits a significant increase in both TMAX and TMIN (Table 1). The increase in TMAX and TMIN is in this period very similar, with the increase in TMAX being only slightly lower than in TMIN. The change in the linear slope from the 1958–1985 to the 1985–2002 period, given in the last column of Table 1, is thus larger in TMAX than TMIN. This implies that the increase in TMAX has caught up to the increase in TMIN, and is in line with the hypothesis that solar dimming was not present anymore to prevent TMAX from keeping pace with TMIN. Since temperature changes during daytime are less sensitive to radiative changes than during nighttime as outlined above, the similar rise in TMAX and TMIN suggests that during daytime the (solar and thermal) surface radiative forcing was at least as large as, or even larger than, during nighttime. This is in line with the findings that solar dimming levelled off or transitioned to brightening noted by *Wild et al.* [2005].

3.3. Change in Diurnal Temperature Range

[9] These tendencies are also evident in changes in the diurnal temperature range (DTR), defined as difference between TMAX and TMIN. In Figure 2, we determined the change in annual land mean DTR for the same period 1958–2002 from the CRU dataset, with respect to the 1960–1990 mean. Several studies reported a decrease in this quantity over much of the 20th Century [*Karl et al.*, 1993; *Easterling et al.*, 1997; *Dai et al.*, 1999]. From Figure 2 it becomes evident that the decrease of DTR over the global land surfaces only lasted into the mid-1980s, but then levelled off (cf. also DTR trends in Table 1). This has also been noted in the recent study by *Vose et al.* [2005] with no further interpretation. Here we want to point to the striking similarity between the distinct change in the DTR regime

Table 1. Changes in Mean, Daily Minimum, and Daily Maximum Temperature as well as Diurnal Temperature Range Over Global Land Surfaces on an Annual Mean Basis for Two Periods: 1958–1985 and 1985–2002[a]. Units °C/decade.

	1958–1985[b]	1985–2002[c]	Relative Change
T mean	0.036 (0.04)	0.38 (0.08)	+0.34
T min	0.11 (0.04)	0.40 (0.08)	+0.29
T max	−0.04 (0.04)	0.37 (0.08)	+0.41
DTR	−0.15 (0.01)	−0.03 (0.02)	+0.12

[a]Determined by linear regression, 1-sigma uncertainty estimates given in parentheses. Derived from CRU temperature dataset [*Mitchell and Jones*, 2005].

[b]The period where significant dimming of surface solar radiation has been observed.

[c]The period where the dimming was no longer present [*Wild et al.*, 2005].

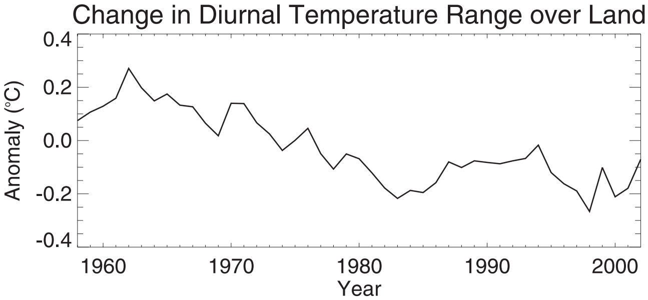

Figure 2. Change in diurnal temperature range averaged over global land surfaces from 1958 to 2002, shown as deviations from the 1961–1990 mean. Diurnal temperature range decreases until the mid-1980 and levels off afterwards.

during the 1980s in Figure 2, and the simultaneous change in the surface solar radiation regime from dimming to brightening noted by *Wild et al.* [2005]. Thus, the evolution of DTR provides independent evidence for a large scale change in the surface radiative forcing regime during the 1980s.

[10] To study the DTR evolution and its relation to surface radiative forcing on a more regional basis, we are in the process of collecting temperature records from a large number of meteorological stations in North America, Europe and Asia [*Makowski*, 2006]. At a majority of these widespread locations, the tendency for a recovery in the DTR is also seen on a station level, in line with the recovery of surface solar radiation [*Makowski*, 2006].

4. Discussion

[11] Surface temperature may only effectively respond to changes in surface solar radiation, if these changes are caused by processes which alter the total amount of solar energy absorbed in the climate system (such as through scattering aerosol, cloud reflectance or variations in the solar flux incident at the top of atmosphere) [*Ramanathan et al.*, 2001; *Wong et al.*, 2006]. However, if the surface radiation changes are merely caused by a redistribution of solar absorption between atmosphere and surface with little effect on the total amount absorbed in the climate system (such as through absorbing aerosol), the temperature change at the surface would be largely suppressed by an opposed temperature change in the energetically tightly coupled troposphere, despite significant changes in surface solar radiation. Latest anthropogenic emission inventories suggest that both scattering sulfur and absorbing black carbon aerosol showed large changes in line with surface solar radiation, with decreasing tendencies since the 1980s after decades of increase, due to effective air pollution measures [*Stern*, 2006; *Streets et al.*, 2006]. This suggests that the variations in surface solar radiation are at least partly caused by scattering processes which change the total amount of solar energy absorbed in the climate system, and are therefore particularly effective in modifying surface temperature as outlined above.

[12] Potential additional energy from solar brightening noted during the 1990s may not only have gone into heating of the surface, but also into additional evaporation. This is supported by pan evaporation measurements in energy-limited environments which partially indicate, after decades of decrease [*Roderick and Farquhar*, 2002; *Ohmura and Wild*, 2002], a recent recovery, in line with changes in surface solar radiation [e.g., *Liu et al.*, 2004]. The rapid increase in land surface temperature despite evidence for a concurrent increase in evaporative surface cooling also implies a strong increase in surface radiative forcing in the 1990s.

[13] Surface radiative forcing and temperature during the 1990s is not only determined by surface solar 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. Evidence for increasing downward thermal radiation is obtained from the surface measurements of the BSRN [*Ohmura et al.*, 1998], a project of the World Climate Research Program (WCRP) with its data centre at the authors' institute, aimed at detecting important changes in the Earth's radiation fields. Downward thermal radiation measured at 12 worldwide distributed sites from BSRN shows on average an increase of 0.26 Wm^{-2} per year since the beginning of the measurements in 1992, in line with our expectations from greenhouse theory and models.

[14] To estimate the integrated (overall) effect of variations in surface solar radiation over the past 40 years, we analysed the latest update of GEBA. In the majority of the surface solar radiation records from GEBA we find that, despite the widespread trend reversal from dimming to brightening, the amount of solar radiation at the surface has not reached the 1960 level. Despite the fact that surface insolation at the turn of the millennium is rather lower than in the 1960s, land surface temperatures have increased by 0.8°C over this period (Figure 1). This suggests that the net effect of surface solar forcing over the past decades cannot be the principal driver behind the overall temperature increase, since over the past 40 years, cooling from solar dimming still outweighs warming from solar brightening. Rather, the overall temperature increase since the 1960s can be attributed to greenhouse forcing as also evident in the BSRN data outlined above. Thus, speculations that solar brightening rather than the greenhouse effect could have been the main cause of the overall global warming over the past decades appear unfounded.

5. Summary

[15] In the present study we investigated the role of solar dimming and brightening in the context of recent global warming. Our analysis showed that the decadal changes of land mean surface temperature as well as TMAX, TMIN, and DTR are in line with the proposed transition in surface solar radiation from dimming to brightening during the 1980s and with the increasing greenhouse effect. This suggests that solar dimming, possibly favoured by increasing air pollution, was effective in masking greenhouse warming up to the 1980s, but not thereafter, when the dimming disappeared and atmospheres started to clear up. The temperature response since the mid-1980s may therefore be a more genuine reflection of the greenhouse effect than during the decades before, which were subject to solar

dimming. Unlike to the decades prior to the 1980s, the recent rapid temperature rise therefore no longer underrates the response of the climate system to greenhouse forcing and reflects the full magnitude of the greenhouse effect. The observed temperature increase of 0.38°C/decade over land surfaces since the mid-1980s may pose an upper bound on the sensitivity of the climate system to the recently imposed greenhouse forcing, since surface solar forcing, if anything, enhanced rather than dampened the greenhouse-induced temperature increase in this period. On the other hand, the overall temperature increase of 0.8°C at land surfaces since the 1960s (corresponding to 0.2°C/decade) may pose a lower bound on the sensitivity of the climate system to greenhouse forcing over the past decades, since surface solar forcing over the entire past 40 years still decreased rather than increased, despite the recent recovery. This implies a substantial increase in thermal (greenhouse) surface radiative forcing since the 1960s, in order to rise land surface temperatures by 0.8°C despite an overall reduced surface solar heating over the past 40 years. We therefore estimate that, over the past decades, the greenhouse forcing alone has enhanced land surface temperatures by certainly more than 0.20°C per decade, but unlikely much more than 0.38°C per decade. This may help to reduce the uncertainties in our knowledge on the sensitivity of the climate system to increasing levels of greenhouse gases, since it allows to disentangle the influence of surface solar radiation variations on global warming.

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M. Wild, A. Ohmura, and K. Makowski, Institute for Atmospheric and Climate Science, ETH Zurich, Universitätsstrasse 16, CH-8092 Zurich, Switzerland. (matin.wild@env.ethz.ch)