Observed reductions of surface solar radiation at Sites in the United States and worldwide from 1961 to 1990

Beate G. Liepert

Lamont - Doherty Earth Observatory of Columbia University, 61 Route 9W, Palisades, New York 10964, USA

(Present address: Max-Planck Institute for Meteorology, Bundesstrasse 55, D-20146 Hamburg, Germany).

ABSTRACT

Surface solar radiation revealed an estimated 7W/m^2 or 4% decline at sites worldwide from 1961 to 1990. Here I find that the strongest declines occurred in the United States sites with 19W/m^2 or 10%. The clear sky optical thickness effect accounts for -8 W/m^2 and the cloud optical thickness effect for -18 W/m^2 in three decades. If the observed increases in cloud cover frequencies are added to the clear sky and cloud optical thickness effect, the higher all sky reduction in solar radiation in the United States can be explained. It is shown that solar radiation declined below cloud-free sky because of the reduction of the cloud-free fraction of the sky itself and because of the reduction of clear sky optical thickness. Solar radiation exhibits no significant changes below cloud-covered sky because reduced cloud optical thickness is compensated by increased frequencies of hours with overcast skies.

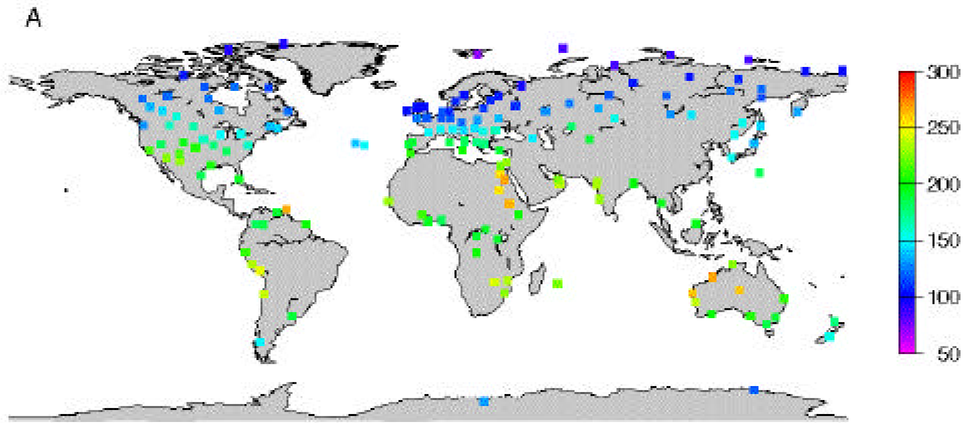
1. Introduction

Measurements of solar radiation at the surface are important to discussions of climate change and global warming because they can indicate anthropogenic disturbances (Ramanathan et al., 2001). Solar radiation is affected by clouds, which in turn are affected by global warming due to greenhouse gases. Second, increasing air pollution especially anthropogenic particulate matter such as sulfate, soot, etc. pollute the troposphere over major parts of the continents and oceans. These aerosol particles scatter sunlight back into space and hence reduce surface heating on a highly variable time and space scale (Haywood et al., 1997). Some aerosols (e.g. carbonaceous, dust aerosols) also absorb solar energy and therefore heat the atmospheric layer and not the surface itself. Third, aerosol particles can act as cloud condensation nuclei and modify cloud lifetime and cloud transmissivity altering surface solar radiation (Ackerman et al., 1993). In general, surface solar radiation is a most valuable but rarely used climate parameter. Broadband solar radiation is routinely recorded at many sites worldwide since the International Geophysical Year in 1957-58. From early on calibration and maintenance procedures have been standardized, which make a long-term study feasible even though the accuracy is debated and there is room for further improvement (World Climate Research Programme, 1991).

2. All Sky Solar Radiation

Here I use a new quality-tested global database of monthly mean surface solar radiation time series, the Global Energy Balance Archive (GEBA), which is maintained by the World Radiation Data Center (Gilgen et al., 1998). For this study 252 records covering the entire 1961 to 1990 time period and additionally 43 time series from the United States National Solar Radiation Database (Maxwell et al., 1995) were selected. For each station I calculated monthly averages for the following three decades: 1961 to 1970, 1971 to 1980 and 1981 to 1990. Figure 1A shows the distribution of surface solar radiation for the 1981 to 1990 baseline period. The average surface solar radiation is 182W/m^2. Note that this average does not represent a global mean. The temporal variability of these time series reveal an averaged drop of 4 W/m^2 from the 1970s to the 1980s and 7W/m^2 from the 1960s to the 1980s (Table 1), which means a reduction of about 4% in three decades. Here the differences of the decadal monthly means for the 1961 to 1970 or the 1971 to 1980 and the 1981 to 1990 baseline period were calculated for each station separately and the anomalies were only considered if all twelve months exist. The anomalies were then added to the 1981-90 baseline mean. The resulting decline is slightly more than what Stanhill and Cohen (2001) calculated for a reduced global data set of yearly averages. Their analysis shows globally averaged differences of 5 W/m^2 or 3% in surface solar radiation between the 1958 annual average and the 1992 average. Gilgen et al. (1998) who analyzed only spatial averages of varying temporal length report declining tendencies in many regions as well.

Solar radiation declined most strongly in North America with all but one station showing reductions between the 1960s and the 1980s and 29 out of 34 showing reductions from the 1970s to the 1980s (see Fig 1B). This result is also illustrated in Figure 2A where the decadal mean cycles of the surface solar radiation for the United States sites are plotted. The averaged reduction of 19W/m^2 from the 1960s to the 1980s with the strongest decline in the second decade is remarkable (Table 1). The surface solar radiation also declined in areas of the Former Soviet Union (FSU) as shown in Figure 2B. But the mean decrease during the 1960s to the 1980s time period is only 2W/m^2. See also Abakumova et al. (1996) and Russak (1990). Similarly, declining tendencies have been found around the Mediterranean Sea in Israel, Egypt and Turkey (Stanhill and Ianetz, 1997, Omran, 2000, and Aksoy, 1997). As indicated in Figure 1B and reported elsewhere (Liepert et al., 1993 and De Bruin et al., 1995) the interdecadal trends in surface solar radiation in Western Europe are rather mixed. A critical point is that the stations are often located in vicinities of major cities where local pollution may not represent the desirable background conditions (see for example Jauregui, 1999). On the other hand, even extremely remote sites show reductions in solar radiation (see for example Dutton and Bodhaine, 2001).



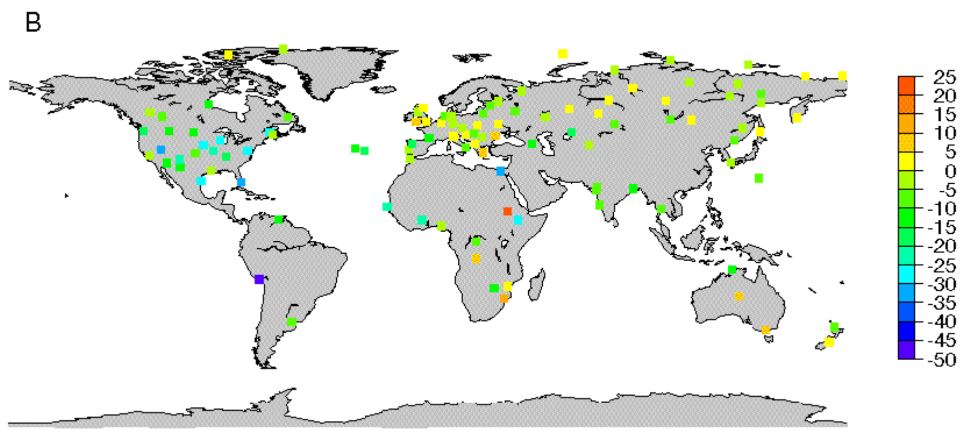


Figure 1. Decadal means and trends of surface solar radiation. (**A**) 1981 to 1990 mean surface solar radiation. (**B**) Difference in surface solar radiation from 1961 to 1970 period minus 1981 to 1990 baseline period.

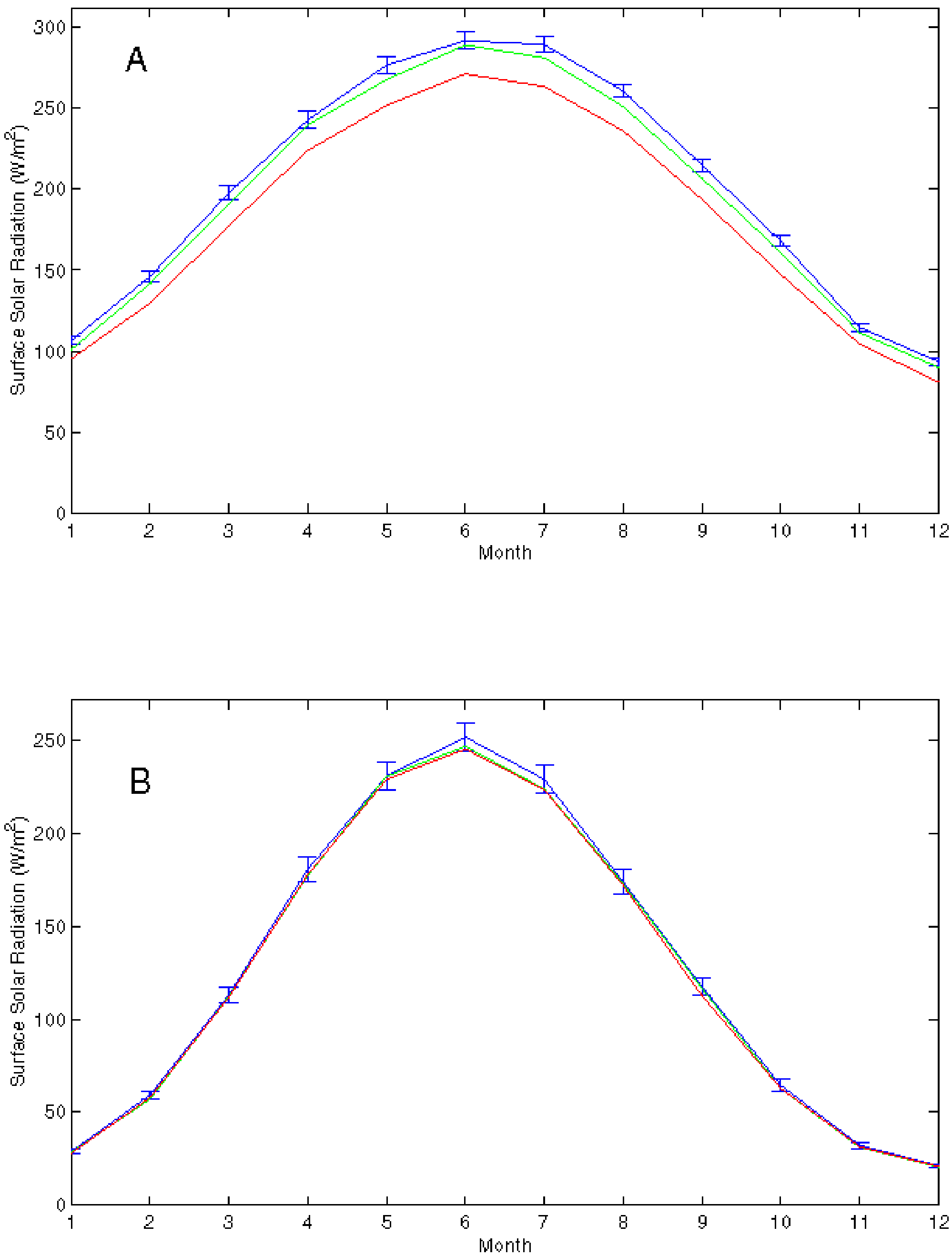


Figure 2. Monthly mean surface solar radiation. Blue line represents 1961 to 1970, green 1971 to 1980 and red 1981 to 1990 for (**A**) United States and (**B**) Former Soviet Union sites.

3. Clear And Overcast Sky Solar Radiation

Aerosol particles scatter and absorb sunlight in the cloud free atmosphere and hence reduce the solar energy reaching the surface. On the other hand, clouds are by far the strongest modifiers of surface solar radiation. Consequently investigations of the possible causes of the observed reductions require separating cloud effects from aerosol effects. Since hourly solar radiation recordings and cloud cover observations from 1961 to 1990 are available for the United States sites these data were utilized for separating solar radiation time series into all sky, clear sky and overcast sky composites for each ten-year period. An hour is defined as clear if the cloud cover is 0 or 1 tenths of sky coverage at the beginning and end of the hour. Overcast is defined at 10 tenths cloud coverage at the beginning and the end of an hour. The monthly mean diurnal cycles are calculated by averaging all means of solar radiation of each hour of the 24-hour day for a month. Composites of diurnal cycles avoid biases due to data sampling like overrepresentation of morning hours.

The 1960s, 1970s, and 1980s monthly means of the clear-sky solar radiation are plotted in Figure 3A for the United States sites. Although clear sky solar radiation decreased by 8W/m^2 in three decades (Table 1) - indicating an enhanced direct aerosol effect - the reduction is not as high as under all-sky conditions. Clear sky changes are mainly observed during the 1980s and not during the 1960s or 1970s. A rather different behavior is shown in Germany where during the 1970s to the 1980s positive trends have been observed (Table 1). These declines indicate reductions in the aerosol load and improvements of air pollution. The anthropogenic changes in aerosol concentrations and their effect on surface solar radiation have been calculated with a general circulation model by Tegen et al. (2000) and analyzed by Liepert and Tegen (2002). For the United States sites of this study the model simulates a reduction of 1W/m^2 in three decades. For the German sites the modeled increase in surface solar radiation is 3 W/m^2, which is exactly what is observed.

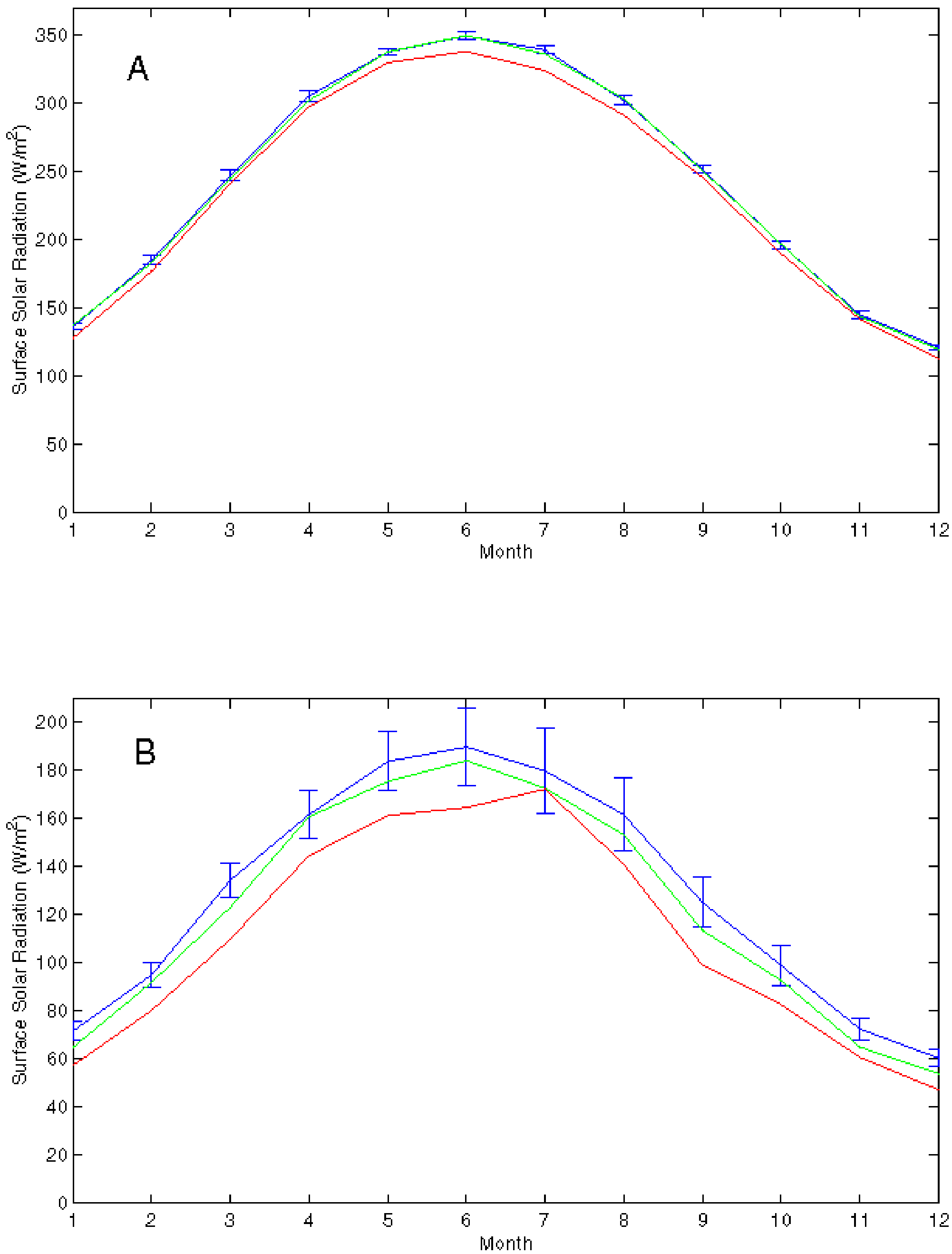


Figure 3. Monthly mean surface solar radiation in United States. Blue line represents 1961 to 1970, green 1971 to 1980 and red 1981 to 1990 period for (**A**) clear sky and (**B**) overcast sky conditions.

As shown in Figure 3B, the solar radiation under overcast conditions dropped drastically by 18 W/m^2 or 14% in three decades at the United States and 5 W/m^2 or 11% at the German sites (Table 1). The surface solar radiation decreased even more under the optically thicker "opaque" clouds with a decline of 20 W/m^2 or 21% in three decades in the United States. "Opaque" clouds are defined as clouds that "prevent observing the sky or higher cloud layers" (Maxwell et al., 1995), which excludes cirrus and lower level thin clouds. The declines may be due to increasing sulfate aerosol concentrations that increase cloud optical thickness and lifetime. But over the continental mid-latitudes the indirect aerosol effect is presumably not as dominant. In Liepert and Lohmann (2001) we investigate the indirect aerosol effect on surface solar radiation with a general circulation model that includes a coupled sulfur chemistry cycle and cloud scheme. The simulations show reductions of surface solar radiation at overcast skies of about $4W/m^2$ or 4% for the sites in the United States, which is only one fifth of what is observed.

4. Cloud Cover Changes

In this study surface solar radiation is analyzed for subsets of clear sky and overcast sky conditions. A clear sky effect of DF_{cl} = $8W/m^2$ and a cloud optical thickness effect of DF_o = 18 W/m^2 for three decades have been detected. The all sky solar radiation records, however, consist of a clear, and a overcast portion as defined in chapter 3 and a cloudy portion. The observed all sky reduction is DF = 19 W/m^2. Here I use the calculated averages of clear sky F_{cl} and overcast sky F_o solar radiation to estimate the cloudy sky solar radiation. Solar radiation F is separated into a portion below cloud-free sky and below cloud-covered sky. The linear partitioning is shown in equation 1. Clear sky solar radiation decadal means F_{cl} are multiplied with the clear sky frequency f_{cl} plus f_{cd} (1- A_c^*) to estimate the below cloud-free sky solar radiation F_{cf}. The below cloud-covered sky solar radiation F_{cc} is calculated with the overcast sky solar radiation decadal means F_o multiplied by overcast sky frequencies f_o plus f_{cd} A_c^*. f_{cd} is the cloudy sky frequency and A_c^* is the cloudy sky areal coverage as defined in equation 1. A_c^* is larger than the total cloud coverage A_c which does include the two extremes clear sky and overcast sky (Table 2). The cloud-covered portion of solar radiation F_{cc} is a lower limit because cloud optical thickness tends to increase with increasing cloud coverage and F_{cc} is calculated with the solar radiation at overcast cloud coverage.

$$F = F_{cl} \cdot f_{cl} + F_o \cdot f_o + F_o \cdot f_{cd} \cdot A_c^* + F_{cl} \cdot f_{cd} \cdot (1 - A_c^*) \quad (1)$$
$$\text{with} \quad A_c^* = \sum_{c_i} f_{c_i} \cdot c_i, \quad \text{with} \quad c_i = i/10;\ i = 2,\ldots,9$$
$$f_{cd} = 1 - f_{cl} - f_o$$

With equation 1 all sky changes of solar radiation can be estimated under different conditions. If exclusively the clear sky and overcast sky solar radiation changed over time the combined effect would be $DF=F_{1960s} - F_{1980s}$ =13W/m^2. The modeled aerosol effect (direct plus first indirect) would account for only DF = 2.6 W/m^2. These results are not enough to explain the observed 19 W/m^2 all-sky decline of this study. Note that the observed total cloud coverage A_c did not change at these United States sites during the three decades (Table 2). However, the frequencies of the occurrence of hours with overcast and clear skies f_{cl} and f_o changed. f_o increased from 23% to 31% and f_{cl} declined from 32% to 26% in thirty years. Consequently the combined effect DF reaches a 20W/m^2 reduction in surface solar radiation in three decades in the United States when these cloud frequency changes are included. This result matches the independently calculated all-sky reduction of DF = 19 W/m^2. Noteworthy is that the below cloud-covered sky solar radiation does not change over time anymore because increasing cloud optical thickness and increasing cloud frequency effect cancel each other. Rather the below cloud-free sky solar radiation exhibits a strong decline due to accumulation of the increasing clear sky optical thickness and the declining clear sky frequency.

5. Conclusions

The observed 19 W/m^2 or 10% decline in surface solar radiation in the United States from the 1960s to the 1980s is strong compared to sites in other regions of the globe with a 7 W/m^2 or 4% decline in three decades. Nonetheless, the uncertainty range of the data cannot be ignored. Increasing direct and indirect aerosol effects through increasing air pollution alone can explain about 3 W/m^2 of the observed decline in the United States when simulated with state-of-the-art general circulation models. Increasing frequencies of overcast skies and declining frequencies of clear skies with simultaneously constant cloud coverage indicate more fractional or multi-layered cloud coverage. This is in line with the strongest reduction of surface solar radiation under optically thick "opaque" clouds and also the observed slight reduction of A_c^*. Similar results have been shown in a study of cloud type, cloud coverage and solar radiation changes for German sites (Liepert, 1997). One possible explanation might be a combination of greenhouse gas and aerosol forcing. Tselioudis and Rossow (1994) suggest that greenhouse gas warming leads to increasing cloud optical thickness at overcast conditions (through increasing cloud height and liquid water content). Increasing optical thickness reduces surface solar radiation and cools the surface. Albeit, in general the troposphere is still heated through greenhouse gas warming and water vapor is still augmented. Furthermore, absorbing aerosols that heat the atmospheric layer may enhance this warming. Consequently tropospheric warming and surface cooling might occur (see also Roeckner et al., 1999). It is worth noting that the reductions in surface solar radiation are simultaneous with an observed missing increase in surface air temperature in the United States for the last three decades (Hansen et al., 2001). More model simulations are needed and strongly encouraged to explain the reductions of surface solar radiation.

References

Abakumova, G. M., Feigelson, E. M., Russak, V., & Stadnik, V. V. Evaluation of long-term changes in radiation, cloudiness, and surface temperature on the territory of the former Soviet Union. *J. Climate* 9, 1319-1327 (1996).

Ackerman, A., Toon, O. B., & Hobbs, P. V. Dissipation of marine stratiform clouds and collapse of the marine boundary layer due to the depletion of cloud condensation nuclei by clouds. *Science* 262, 226-228 (1993).

Aksoy, B. Variations and trends in global solar radiation for Turkey. *Theor. Appl. Climatol.* 58, 71-77 (1997).

De Bruin, H. A. R., Van den Hurk, B. J. J. M., Welgraven, D. A series of global radiation at Wageningen for 1928-1992. *Int. J. Climatol.* 15, 1253-1272 (1995).

Dutton, E., & Bodhaine, B. Solar irradiance anomalies caused by clear-sky transmission variations above Mauna Loa: 1958-99. *J. Climate* 14, 3255-3262 (2001).

Gilgen, H., Wild, M., & Ohmura, A. Means and trends of shortwave irradiance at the surface estimated from global energy balance archive data. *J. Climate* 11, 2042-2061 (1998).

Hansen, J. E., et al. A closer look at United States and global surface temperature change. *J. Geophys. Res.* 106 D20, 23,947-23,963 (2001).

Haywood, J. M., Roberts, D. L., Slingo, A., Edwards, J. M., & Shine, K. P. General circulation model calculations of the direct radiative forcing by anthropogenic sulfate and fossil-fuel soot aerosol. *J. Climate* 10, 1562 (1997).

Jauregui, E. & Luyando, E. Global radiation attenuation by air pollution and its effects on the thermal climate in Mexico City. *Int. J. Climatol.* 19, 683-693 (1999).

Liepert, B. G. Recent Changes in Solar Radiation under Cloudy Conditions in Germany. *Int. J. Climatol*., 17, 1581-1593 (1997).

Liepert, B. G., & Kukla, G. J. Declines in global solar radiation with increased horizontal visibility in Germany between 1964 and 1990. *J. Climate* 10, 2391-2401 (1997).

Liepert, B. G., & Lohmann, U. A comparison of surface observations and ECHAM4-GCM experiments and its relevance to the indirect aerosol effect. *J. Climate* 14, 1078-1091 (2001).

Liepert, B. G., & Tegen, I. Multi-decadal solar radiation trends in the United States and Germany and direct tropospheric aerosol forcing. *J. Geophys. Res.* in print.

Maxwell, E. L., Marion, W. F., Myers, D. R., Rymes, M. D., & Wilcox, S. M. *Final Technical Report Volume 1+2: National Solar Radiation Database (1961-1990)*, National Renewable Energy Laboratory, Golden, Colerado (1995).

Omran, M. A. Analysis of solar radiation over Egypt. *Theor. Appl. Climatol.* 67, 225-240 (2000).

Ramanathan, V., Crutzen, P. J., Kiehl, J. T., & Rosenfeld, D. Aerosols, climate, and the hydrological cycle. *Science* 294, 2119-2124 (2001).

Roeckner, E. Bengtsson, L., Feichter, J., Levieveld, J., & Rodhe, H. Transient climate change simulations with a coupled atmosphere ocean GCM including the tropospheric sulfur cycle. *J. Climate* 12, 3004-3032 (1999).

Russak, V. Trends of solar radiation, cloudiness and atmospheric transparency during recent decades in Estonia. *Tellus* 42B, 206-210 (1990).

Stanhill, G., & Ianetz, A. Long-term trends in and the spatial variation of global irradiance in Israel. *Tellus* 49B, 112-122 (1997).

Stanhill, G., & Cohen, S. Global dimming, a review of the evidence for a widespread and significant reduction in global radiation with a discussion of its probable causes and possible agricultural consequences. *Agric. For. Meteorol.* 107, 255-278 (2001).

Tegen, I., Koch, D., Lacis, A. A., & Sato, M. Trends in tropospheric aerosol loads and corresponding impact on direct radiative forcing between 1950 and 1990: a model study. *J. Geophys. Res.* 105 D22, 26,971-26,989 (2000).

Tselioudis, G., & Rossow, W. B. Global, multiyear variations of optical thickness with temperature in low and cirrus clouds. *Geophys. Res. Lett.* 21, 2211-2214 (1994).

World Climate Research Programme (WCRP). Baseline Surface Radiation Network (BSRN). WCRP-54, WMO/TD-No. 406, WMO, (1991).

Table 1. Observed 10-year annual means of surface solar radiation (F) for various regions and cloud cover conditions. (The uncertainty ranges are based on the statistical mean error of the decadal average monthly and hourly means for each site.) All stations, NH northern hemisphere records, FSU former Soviet Union records, United States and Germany.

Stations	All	NH	FSU	United States				Germany		
	All sky F (W/m^2)	All sky	All sky	All sky F (W/m^2)	Clear sky F_{cl} (W/m^2)	Overcast F_o (W/m^2)	Opaque F_q (W/m^2)	All sky F (W/m^2)	Clear sky F_{cl} (W/m^2)	Overcast F_o (W/m^2)
1961-70	189±6	163±3	125±4	200±4	243±3	128±10	95±8	124±5	190±4	47±4
1971-80	186±6	160±4	123±4	194±5	242±3	121±11	84±9	122±4	190±4	44±3
1981-90	182±6	156±4	123±4	181±7	235±6	110±14	75±11	120±4	193±3	42±3

Table 2. Observed 10-year annual means of frequencies of clear f_{cl}, overcast f_o sky, total cloud coverage A_c, and cloudy sky areal coverage A_c^* for United States sites. Below cloud-free sky and below cloud-covered sky portion of solar radiation and combined surface solar radiation 10-year annual means calculated from equation 1.

	f_{cl}	f_o	A_c^*	A_c	Cloud-free F_{cf} (W/m^2) ($F_{cl}\ f_{cl} + F_{cl}\ f_{cd}(1-A_c^*)$)	Cloud-covered F_{cc} (W/m^2) ($F_o\ f_o + F_o\ f_{cd}\ A_c^*$)	Combined F (W/m^2)
1961-70	0.32±0.13	0.23±0.11	0.59	0.56	124 (80+44)	61 (28+33)	185
1971-80	0.29±0.13	0.27±0.11	0.58	0.56	116 (70+46)	62 (31+31)	178
1981-90	0.26±0.13	0.31±0.11	0.58	0.56	105 (63+42)	60 (33+27)	165