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Quantification of the effect of urbanization on solar dimming

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[1] During the 25-year period (1964–1989), a noticeable decline in surface solar radiation, termed global dimming, over worldwide sites was essentially a local phenomenon associated with human activity as expressed by the sites' population density. Specifically, our findings indicate that solar dimming was observed only over a limited part (~30%) of the total land area, restricted to highly-populated sites with population density higher than 10 person/km^2. Dimming was dominated by anthropogenic aerosol emissions: the decline in surface solar radiation intensified from -0.05 W/m^2/yr to -0.32 W/m^2/yr, with population density increasing from 10 to 200 person/km^2. At sites with population density >200 person/km^2, a saturation effect was observed: declining trends were much less pronounced than those over sites with a lower population density. Overall, it is demonstrated that urban areas obtained less solar radiation, compared to rural areas, in the amount of ~12 W/m^2 which is equivalent to about 8%. **Citation:** Alpert, P., and P. Kishcha (2008), Quantification of the effect of urbanization on solar dimming, *Geophys. Res. Lett.*, *35*, L08801, doi:10.1029/2007GL033012.

1. Introduction

[2] Analyses of worldwide surface observations, as well as satellite data, have revealed that solar dimming took place from the 1960s up to the 1980s, followed by solar brightening from the late 1980s onward [*Stanhill and Cohen*, 2001; *Liepert*, 2002; *Gilgen et al.*, 1998; *Wild et al.*, 2005; *Pinker et al.*, 2005; *Romanou et al.*, 2007]. The cause of dimming is not fully understood and its global character is called into question. As shown in our previous study [*Alpert et al.*, 2005], solar dimming from 1964 to 1989 was dominated by large urban sites with population greater that 0.1 million people. However, we obtained a yet quite noticeable -0.16 W/m^2/year average annual decline in surface radiation even for the urban sites with population less than 0.1 million people [*Alpert et al.*, 2005]. Therefore, even those less-populated sites are also steady sources of anthropogenic pollutants such as fossil fuels, sulfates, nitrates and black carbon (soot). This suggests further research of the effects of urbanization on sunlight availability, by using population figures related to all available radiation-measurement sites, including sparsely populated ones.

[3] The current study was aimed at analyzing dimming within a wide range of population densities. This was carried out by quantifying the effect of increasing population density on solar dimming during the 25-year period of solar dimming, from 1964 to 1989, by using the Gridded Population of the World Version 3 (GPWv3) [*Socieconomic Data and Applications Center (SEDAC)*, 2004] database of population density.

[4] As discussed in our previous study [*Alpert et al.*, 2005], the use of population as a proxy for anthropogenic pollution levels carries with it some approximations. During the 25-year period under consideration (1964–1989), however, air quality regulations were minimal and limited to only a few developed countries. Therefore, we assume that population figures, as a proxy for anthropogenic activity, are quite applicable for analyzing solar dimming until its reversal to brightening, in the late 1980s. Note that after the reversal to brightening, such an assumption may not be applicable due to effective air pollution regulations resulting in a significant decrease in the emission of air pollutants, from the late 1980s up to the present [*Sliggers and Kakebeeke*, 2004; *Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe*, 2004]. Note that the population stayed stable or even increased over the same period.

[5] Using MODIS-based aerosol optical depth from 2001 to 2003, *Ramanathan et al.* [2007] analyzed relationships between population in mega-cities and the direct radiation forcing of the aerosols (natural and anthropogenic): no such relationship was found. The aerosol forcing was estimated by multiplying the MODIS aerosol optical depth by the model-simulated aerosol forcing efficiency [*Ramanathan et al.*, 2007, Figure 7]. In our study, pyranometer network measurements of surface solar radiation (global radiation monthly means) from the Global Energy Balance Archive (GEBA) [*Gilgen et al.*, 1998] from 1964 to 1989 were used for analysis. The pyranometer data, however, include both cloud and aerosol effects on surface solar radiation.

2. Methodology

[6] The period from 1964 to 1989 was chosen for the analysis of solar dimming because of the large number of radiation measurement sites, where pyranometer measurements were taken over a long period. The Global Energy Balance Archive (GEBA) [*Gilgen et al.*, 1998] of pyranometer network data (global radiation monthly means) were used for analysis. This database is maintained by the World Radiation Monitoring Center located at the Swiss Federal Institute of Technology. Full-year data covering the period from 1964 to 1989 for 317 sites all over the world were selected for this study. For each of these sites full-year data were available for more than 10 years. Version 3 GPWv3 gridded population density data of the year of 2000 were acquired from the Center for International Earth Science Information Network (CIESIN), SEDAC of Columbia University (http://sedac.ciesin.columbia.edu/). To obtain popu-

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Table 1. Average Surface Solar Radiation Fluxes (F), Standard Deviation (sd), and Resulting Trends (α) for Long-Term Variations (1964–1965) Averaged Within the Specified Group in Accordance With Their Population Density (Pd)[a]

Pd of the Specified Group of Sites, person/km^2	Number of Sites Used	F ± sd, W/m^2	α, W/m^2/yr	S-W Test	p
Worldwide Sites					
All sites used	317	152 ± 3	−0.26	Normal	<0.004
Pd < 10	44	159 ± 3	−0.06	Normal	Not significant
10 ≤ Pd < 100	109	155 ± 3	−0.26	Normal	<0.002
100 ≤ Pd < 200	56	150 ± 4	−0.32	Normal	<0.001
200 ≤ Pd < 400	53	148 ± 3	−0.21	Normal	<0.001
Pd ≥ 400	55	147 ± 4	−0.24	Normal	<0.013
Latitudinal Zone 40°N–70°N					
All sites used	201	152 ± 3	−0.23	Normal	<0.002
Pd < 10	29	163 ± 4	−0.27	Normal	<0.003
10 ≤ Pd< 100	67	154 ± 4	−0.31	Normal	<0.003
100 ≤ Pd< 200	40	149 ± 4	−0.17	Normal	Not significant
Pd ≥ 200	65	147 ± 3	−0.14	Normal	Not significant
Latitudinal Zone 40°S–40°N					
All sites used	109	151 ± 5	−0.38	Normal	<0.001
Pd < 15	21	151 ± 6	0.17	Normal	Not significant
10 ≤ Pd< 100	39	156 ± 5	−0.29	Normal	<0.030
100 ≤ Pd< 200	15	153 ± 8	−0.87	Normal	<0.001
Pd ≥ 200	43	147 ± 5	−0.50	Normal	<0.001

[a]The decision based on the Shapiro–Wilk normality test for residuals (S-W test) and the significance level (p) are also displayed; the latter parameter characterizes how linear trends fit to the long-term variations.

lation density at any specific site, the GRWv3 data were averaged within the area of ±0.5° latitude and longitude around the selected site.

[7] Our approach for estimating the effect of increasing population density on solar dimming was based on analyzing year-to-year variations of annual radiation fluxes, averaged separately for sites within the following groups of population density (person/km^2): <10, 10–100; 100–200; 200–400, ≥400 for all 317 sites. Note that at latitudes 40°S–40°N, in order to enlarge the limited number of sparsely populated sites, we analyzed sites with population densities <15 person/km^2 instead of <10 person/km^2. Averaged annual fluxes were obtained after prior data correction for latitudinal variations of solar radiation, in accordance with the methodology described in our previous paper [*Alpert et al.*, 2005]. A linear fit was used to determine the resulting radiation trend of the data within each of the population density groups. To assure that the linear trend fits produce normally distributed residuals, the residuals were required to pass the Shapiro–Wilk normality test. Obtained in accordance with the aforementioned approach, the variations of surface solar radiation trends as a function of population density provide a way of analyzing the effect of increasing population density on solar dimming.

3. Results and Discussion

[8] Our findings have shown that, in general, the average surface solar radiation flux (F), based on worldwide pyranometer measurements, decreases with population density as a monotonic function, as shown in Table 1. In particular, for the group of the lowest population density <10 person/km^2, F is equal to about 159 W/m^2, while for the group of the highest population density ≥400 person/km^2 F decreases to 147 W/m^2 (Table 1). This indicates that during the period under consideration, urban areas obtained less solar radiation, compared to rural areas, in the amount of ~12 W/m^2 that is equivalent to about 8%.

[9] The contribution of large cities to solar dimming could be obtained by analyzing year-to-year variations of annual radiation fluxes, averaged within each specified group of worldwide sites. These variations for 317 worldwide sites from 1964 to 1989 are shown in Figure 1. We can see that the disorderly scattered points for the group of the lowest population density <10 person/km^2 do not conform to a linear fit for determining tendencies of radiation fluxes. To be specific, we estimated and plotted the resulting slope for this group, even though this slope was not statistically significant, as indicated in Table 1. The fact that this group did not show significant declining trends indicates that there were numerous sites, located far from mega-cities, which

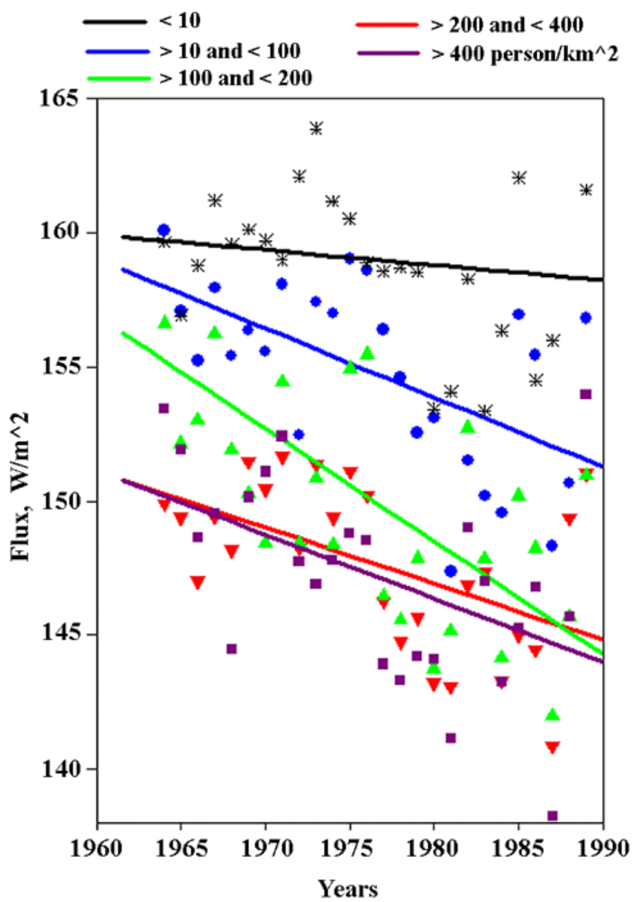

Figure 1. Year-to-year variations (1964–1989) of annual radiation fluxes averaged for each year within the selected groups of worldwide sites: black stars correspond to population density Pd < 10 person/km^2, blue circles to 10 ≤ Pd < 100 person/km^2, green triangles to 100 ≤ Pd < 200 person/km^2, red triangles to 200 ≤ Pd < 400 person/km^2, and purple triangles to Pd ≥ 400 person/km^2. The coloured lines designate linear trends.

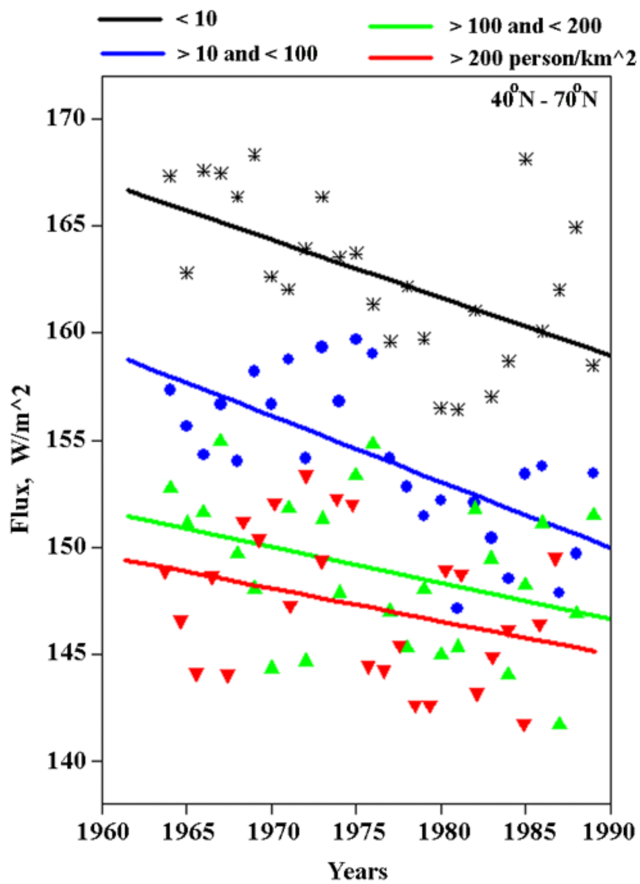

Figure 2. Year-to-year variations (1964–1989) of annual radiation fluxes averaged for each year within the selected groups of sites at latitudes 40°N–70°N: black stars correspond to population density Pd < 10 person/km^2, blue circles to 10 ≤ Pd < 100 person/km^2, green triangles to 100 ≤ Pd < 200 person/km^2, and red triangles to Pd ≥ 200 person/km^2. The coloured lines designate linear trends.

did not experience enough anthropogenic aerosol influence to be part of the dimming phenomenon. Indeed, due to long-range transport and atmospheric circulation patterns, the sites located far from mega-cities may also experience some anthropogenic aerosol influence apart from the natural variability in cloud cover, particularly sites located downwind of anthropogenic aerosol sources. However, while transported over long distances, the aerosols spread over a large area. Hence, in general, anthropogenic aerosol concentrations over remote sites are much lower than over highly populated sites. Therefore, it is reasonable to suggest that natural variability in cloud cover was the dominant factor determining year-to-year variations in surface solar radiation over remote sites.

[10] One can see, however, that year-to-year variations for sites with population densities higher than 10 person/km^2 reveal a significant decline in surface solar radiation (Figure 1). Moreover, dimming is essentially dominated by anthropogenic emissions: a decline in surface solar radiation became sharper at sites with population density increasing from 10 up to 200 person/km^2 (Figure 1). This is in line with previous publications [*Romanou et al.*, 2007; *Alpert et al.*, 2005]. In particular, as shown in Table 1, the declining trend for cities with population densities from 100 to 200 person/km^2 was estimated to be −0.32 W/m^2/yr compared to −0.26 W/m^2/yr for cites with population densities from 10 to 100 person/km^2. Following the Shapiro–Wilk normality test, the linear fits produced normally distributed residuals, and the declining trends were statistically significant (Table 1). It was also noticed that saturation took place at highly populated sites: the declining trend in surface solar radiation at sites with population density ≥200 person/km^2 was less pronounced than that at sites with a lower population density. Indeed, as shown in Table 1, both declining trends for sites with population densities 200–400 person/km^2 (−0.21 W/m^2/yr) and for sites with the highest population density ≥400 person/km^2 (−0.24 W/m^2/yr) are lower compared to the trend for sites with population densities 100–200 person/km^2 (−0.32 W/m^2/yr). It is worth mentioning that, in the spatial distribution of anthropogenic aerosols, aerosol concentrations over mega-cities stand out as being much higher than over remote sites. Hence, over mega-cities, the direct and indirect effects of anthropogenic aerosols are much stronger than over remote sites. This could account for the saturation in cloud condensation nuclei (CCN) effects on clouds. Note that saturation in the CCN effects on clouds was also observed over the Arabian Sea during the INDOEX project [*Ramanathan et al.*, 2001, their Figure 5].

[11] For comparison purposes, it was interesting to estimate the effect of increasing population density on solar dimming at latitudes to the north of 40°N, where the most developed countries of North America and Europe are located. Pyranometer data for 201 sites at latitudes from 40°N to 70°N, during the 25-year period under consideration, were used (Table 1). As seen in Figure 2, at those latitudes, dimming was observed even over sparsely populated sites with population density <10 person/km^2. It was characterized by the statistically significant declining trend of about −0.27 W/m^2/yr (Table 1). With respect to sites with intermediate population densities from 10 to 100 person/km^2, a strong declining trend of −0.31 W/m^2/yr was observed (Table 1). It is of interest that, neither for the group of sites with population densities from 100 to 200 person/km^2, nor for the group with population densities ≥200 person/km^2, was a linear fit suitable for determining statistically significant tendencies in surface radiation. This indicates a real saturation phenomenon, which was observed over highly populated sites.

[12] In contrast to mid-latitudes (40°N–70°N), at low-latitudes (40°S–40°N), dimming was not observed over sparsely populated sites with population densities <15 person/km^2 (Table 1). Moreover, the distribution of points shows some indication of brightening instead of dimming (Figure 3). Although, as specified in Table 1, the increasing trend is not statistically significant, this fact suggests the lack of anthropogenic aerosols over those sites at low-latitudes. It is possible that year-to-year variations in surface solar radiation over sparsely populated sites at latitudes 40°S–40°N (Figure 3) were determined by the natural cloud variability rather than by the effects of local anthropogenic emissions. It is worth mentioning that the strongest decline (−0.87 W/m^2/yr) in surface solar radiation was observed over highly populated sites with population

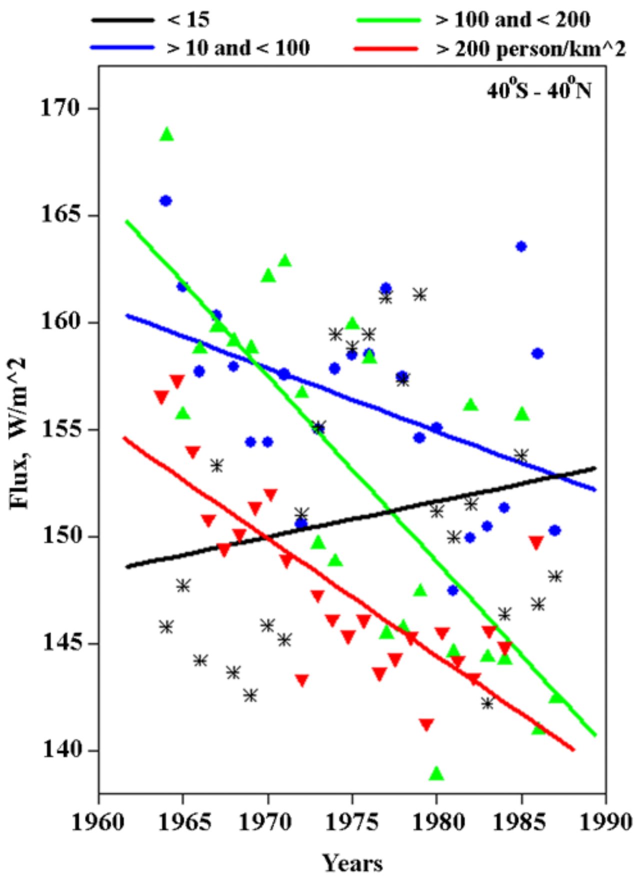

Figure 3. Year-to-year variations (1964–1989) of annual radiation fluxes averaged for each year within the selected groups of sites at latitudes 40°S–40°S. Designations are the same as in Figure 2.

densities from 100 to 200 person/km^2. Moreover, in contrast to mid-latitudes (40°N–70°N), at low-latitudes (40°S–40°N), statistically significant dimming (−0.50 W/m^2/yr) was observed even over sites with the highest population densities ≥200 person/km^2 (Table 1). However, as shown in Figure 3 (red triangles), the distribution of points for the latter group displays a strong declining trend only from the 1960s to the late 1970s. Later, variations in solar fluxes do not show dimming and are similar to variations over the same group of sites located at latitudes 40°N–70°N.

[13] As clearly seen in Table 1, without considering the differences in population density, dimming was observed for the "all-worldwide-sites" average. Moreover, statistically significant declining trends were also observed for the "all-sites-used" average at latitudes 40°N–70°N, as well as at latitudes 40°S–40°N. Therefore, starting from those figures, one can mistakenly conclude that solar dimming is a global phenomenon. However, our analysis of dimming, within a wide range of population densities, highlights the fact that, in general, the solar dimming phenomenon is significantly dominated by urban sites with population densities higher than 10 person/km^2. Based on the gridded population density [*SEDAC*, 2004], only ∼30% of the land area has population densities >10 person/km^2 or about 10% of the global Earth area. Since most of the global land area is sparsely populated, our findings indicate that solar dimming during the period under consideration was essentially a local phenomenon, strongly dominated by the relatively large proportion of urban sites in the GEBA data.

[14] Note that the 317 GEBA stations are not evenly spaced over the globe. Hence, the data used can not fully represent a global distribution of dimming. However, our results show a significant difference between surface solar radiation trends over mega-cities and remote sites. The aforementioned statement that solar dimming during the period under consideration, from 1964 to 1989, was only limited to 30% of the total land area is just a first approximation, based on available data at that time. In the future, a more accurate conclusion could be made, by using currently available satellite measurements with global coverage.

4. Conclusions

[15] Our study was based on the analysis of year-to-year variations of annual radiation fluxes by using worldwide pyranometer network measurements (GEBA) during the 25-year period, from 1964 to 1989. The quantitative characteristics of the effect of urbanization on solar dimming have been obtained by using gridded population density data (GPWv3). Overall, our findings suggest that solar dimming was observed only over a limited part (∼30%) of the total land area, restricted to highly-populated sites with population density higher than 10 person/km^2. Dimming was dominated by anthropogenic aerosol emissions: the decline in surface solar radiation intensified from −0.05 W/m^2/yr to −0.32 W/m^2/yr, with population density increasing from 10 to 200 person/km^2. At sites with population density >200 person/km^2, a saturation effect was observed: declining trends were much less pronounced than those over sites with a lower population density. Over developed countries, at latitudes between 40°N–70°N, dimming formation was more pronounced than that over worldwide sites. In particular, statistically significant declining trends were observed even at sparsely populated sites with population density <10 person/km^2. This was accompanied by a saturation effect at sites with population density ≥100 person/km^2. By contrast, at latitudes between 40°S–40°N, dimming was not observed over sparsely populated sites with population density less than ∼10 ÷ 15 person/km^2. It is demonstrated that urban areas (population density ≥400 person/km^2) obtained less solar radiation, compared to rural sites (population density <10 person/km^2), in the amount of ∼12 W/m^2 which is equivalent to about 8%.

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