GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L17802, doi:10.1029/2005GL023320, 2005

# Global dimming or local dimming?: Effect of urbanization on sunlight availability

Pinhas Alpert,[1] Pavel Kishcha,[1] Yoram J. Kaufman,[2] and Rotem Schwarzbard[1]

Received 22 April 2005; revised 4 July 2005; accepted 22 July 2005; published 2 September 2005.

[1] From the 1950s to the 1980s, a significant decrease of surface solar radiation has been observed at different locations throughout the world. Here we show that this phenomenon, widely termed global dimming, is dominated by the large urban sites. The global-scale analysis of year-to-year variations of solar radiation fluxes shows a decline of 0.41 W/m$^2$/yr for highly populated sites compared to only 0.16 W/m$^2$/yr for sparsely populated sites (<0.1 million). Since most of the globe has sparse population, this suggests that solar dimming is of local or regional nature. The dimming is sharpest for the sites at 10°N to 40°N with great industrial activity. In the equatorial regions even the opposite trend to dimming is observed for sparsely populated sites. **Citation:** Alpert, P., P. Kishcha, Y. J. Kaufman, and R. Schwarzbard (2005), Global dimming or local dimming?: Effect of urbanization on sunlight availability, *Geophys. Res. Lett.*, *32*, L17802, doi:10.1029/2005GL023320.

## 1. Introduction

[2] Global or solar dimming is perhaps one of the most prominent examples indicative of anthropogenic disturbances. This term relates to a widespread decrease in surface solar radiation from the 1950s and until the 1980s, on average as much as 1.4–2.7% per decade [*Cohen et al.*, 2004; *Stanhill and Cohen*, 2001; *Liepert*, 2002; *Gilgen et al.*, 1998]. Climate simulations suggest that the interactions of greenhouse gas forcing plus direct, semi-direct and indirect aerosol effects on clouds could explain this phenomenon [*Liepert et al.*, 2004]. The paradox, however, is that the observed decline in broadband global solar radiation concurred with the observed temperature increases over land, by 0.09 K per decade, between 1951 and 1989 [*Intergovernmental Panel on Climate Change*, 2001]. This puzzling evidence could, by all appearances, put in doubt the dimming trend. Nevertheless, based on climate simulations with the aid of a general circulation model, *Liepert et al.* [2004] argued in favour of the real existence of solar dimming, which they attributed to interactions of greenhouse gas forcing combined with aerosol effects. They found that reductions in surface solar radiation are only partly compensated by enhanced down-welling longwave radiation from the warmer and moister atmosphere. It is noteworthy that since the late 1980s a reversal of solar dimming to brightening was found recently by using newly available surface and satellite observations [*Wild et al.*, 2005; *Pinker et al.*, 2005]. The recent brightening may be a consequence of two reasons: (1) reduced aerosol emissions due to more effective clean-air regulations, and (2) the decline in the economy in Eastern European countries in the late 1980s. This was clearly illustrated by the reversal in atmospheric transmission under cloud-free conditions in the 1980s, which directly relates to the changes in aerosol optical thickness [*Wild et al.*, 2005, Figure S4].

[3] The current study of solar dimming was aimed at finding circumstantial evidence that links human activity to the observed decrease in surface radiation. Such evidence was obtained with the aid of a comprehensive analysis of surface solar radiation changes, both in highly populated cities and in sparsely populated sites. Large cities with population greater than 0.1 million people, in contrast to sparsely populated sites, are in general steady sources of anthropogenic pollutants, like fossil fuel, sulfates, nitrates and black carbon (soot). These pollutants are released into the atmosphere together with increasing emissions of greenhouse gases. Consequently, it would appear reasonable to suggest that the radiation changes, measured in large cities, could indicate a more significant decline than is indicated by radiation measurements in sparsely populated sites [*Stanhill and Kalma*, 1995; *Schwarzbard-Ahuvia*, 2004]. For definiteness, it should be noted that urban development is also associated with factors other than anthropogenic aerosols, e.g. heat island, changes in surface albedo, forest removal etc. (A. Arking, personal communication, 2005). These factors carry with them some uncertainty in our estimates as discussed in section 4 (Discussion).

## 2. Methodology

[4] Population figures in large cities with a population greater than 0.1 million people, from 1964 to 2000, were taken from United Nation Demographic yearbooks.

[5] For radiation, a quality-tested global database of surface radiation time series, the Global Energy Balance Archive (GEBA), was used for analysis. (http://bsrn.ethz.ch/gebastatus/geba_main_frame_set.html). This database is maintained by the World Radiation Monitoring Center located at the Swiss Federal Institute of Technology. It includes approximately 156000 monthly data of pyranometer measurements [*Gilgen et al.*, 1998] (global radiation monthly means). The 25-year period from 1964 to 1989 was chosen because of the large number of radiation measurement sites conducting measurements over a long period. Full-year data covering the period from 1964 to 1989 for 318 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. Following population figures of 1998–2000, the selected sites were divided into two groups:

[1]Department of Geophysics and Planetary Sciences, Tel Aviv University, Tel-Aviv, Israel.
[2]NASA Goddard Space Flight Center, Greenbelt Maryland, USA.


0094-8276/05/2005GL023320$05.00

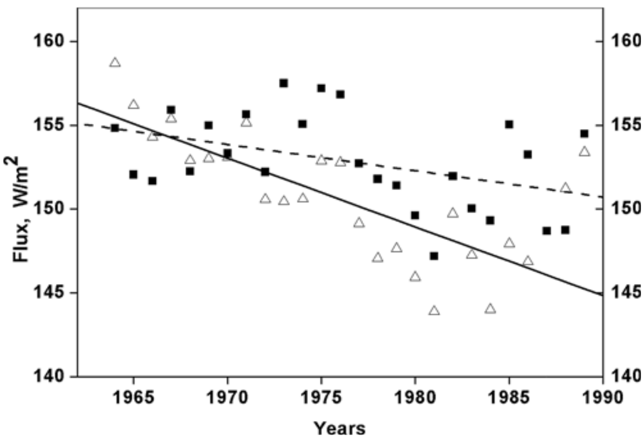


**Figure 1.** Year-to-year variations (1964–1989) of annual radiation fluxes averaged for each year within the selected groups of sites: population > 0.1 million (triangles, N = 144 sites used) population < 0.1 million (squares, N = 174). The solid and dashed lines designate linear trends respectively for highly and sparsely populated sites.

144 highly populated (with population > 0.1 million) and 174 sparsely populated sites (with population < 0.1 million). It is worth noting that the errors of yearly data in the GEBA archive were estimated as 2% [*Gilgen et al.*, 1998].

[6] Our approach to estimating large cities' contribution to solar dimming was based on analyzing year-to-year variations of annual radiation fluxes, averaged separately for highly populated sites and for sparsely populated ones. Averaged annual fluxes were obtained after prior data correction for latitudinal variations of solar radiation. The latitude 45° was chosen since it relates to highly populated mid-latitudes, where we were interested in keeping the original radiation flux values from being significantly corrected. The latitudinal variations of solar radiation were analyzed by using a scatter plot between the flux of solar radiation, averaged between 1964 and 1989 at 318 sites, and cosine of latitude (not shown). As averaged fluxes were used, the obtained latitudinal variations do not include dimming trends depending on time. According to *Stanhill and Cohen* [2001], the latitudinal variations of annual insolation is assumed to be a function of $\cos^3 \varphi$ where $\varphi$ stands for latitude. In the current study, these latitudinal variations were approximated by the following expression:

$$I_\varphi = a + b_1 \cdot \cos\varphi + b_2 \cdot \cos^2\varphi + b_3 \cos^3\varphi \quad (1)$$

where $I_\varphi$ designates fluxes at latitude $\varphi$, a = 645.43 W/m$^2$, $b_1$ = −2674.79 W/m$^2$, $b_2$ = 4106.97 W/m$^2$ and $b_3$ = −1855.51 W/m$^2$. The polynomial fit was found to be highly significant ($R^2 = 0.79$, $p < 0.001$). Therefore, in accordance with this polynomial fit, the flux correction was carried out by the following formula:

$$I_{45} = I_\varphi + b_1 \cdot (\cos 45^\circ - \cos\varphi) + b_2 \cdot \left(\cos^2 45^\circ - \cos^2\varphi\right) + b_3 \cdot \left(\cos^3 45^\circ - \cos^3\varphi\right) \quad (2)$$

where $I_{45}$ designates fluxes at latitude 45°.

[7] In order to analyse the existing tendencies in solar radiation versus population changes, the cumulative slope was estimated in accordance with the following formula:

$$\overline{\alpha}_n = \overline{\alpha}_{n-1} + \frac{\alpha_n}{N} \quad (3)$$

where $\overline{\alpha}_n$ designates the cumulative slope for n consecutive sites arranged according to their population changes. N stands for the total number of sites used in cumulative slope calculations.

[8] Besides, the relative flux changes (*dI*) was obtained by using the following expression:

$$dI = (I(80 \div 89) - I(64 \div 73)) \cdot 100\% / I(64 \div 73) \quad (4)$$

Where I(80 ÷ 89) and I(64 ÷ 73) stand for the averaged flux for the 10-year periods 1980–1989 and 1964–1973 respectively.

## 3. Results

[9] Large cities' contribution to solar dimming could be obtained by analyzing year-to-year variations of annual radiation fluxes, averaged within each specified group of sites. These variations for sites at all latitudes from 1964 to 1989 are shown in Figure 1. One can see that year-to-year variations for both highly populated sites and sparsely populated sites reveal a decline in surface solar radiation. Moreover, the decline for highly populated sites during the 25-year period under investigation was approximately 2.6 times as large as the decline for sparsely populated sites. In particular, the slope for large cities was estimated to be −0.41 W/m$^2$/yr compared to −0.16 W/m$^2$/yr for sparsely populated sites (Table 1). The goodness-of-fit measure ($R^2$) of 0.52 at the significance level $p < 0.001$ indicates a good fit of the linear trend for highly populated sites. This estimate is in agreement with the decline in surface solar radiation, described by *Stanhill and Cohen* [2001], as between −0.60 and −0.34 W/m$^2$/yr. However, it is twice as large as the estimate of solar dimming described by *Liepert* [2002], as −0.23 W/m$^2$/yr. For sparsely populated sites, on the contrary, dimming was very weak. Besides, as shown in Table 1, it is associated with a relatively low value of $R^2$ (0.18). Note that the overall period under consider-

**Table 1.** Resulting Slopes (α) for Long-Term Variations (1964–1989) Averaged Within the Specified Group of Sites Located in the Specified Latitudinal Zones[a]

| Latitudinal Zone | Number of Sites Used | α, W/m$^2$/yr | $R^2$ | p |
|---|---|---|---|---|
| | All sites | | | |
| Global scale | 318 | −0.27 | 0.43 | <0.001 |
| | Highly populated sites | | | |
| Global scale | 144 | −0.41 | 0.52 | <0.001 |
| 15°S–15°N | 27 | −0.98 | 0.84 | <0.001 |
| 10°N–40°N | 37 | −1.25 | 0.68 | <0.001 |
| 40°N–70°N | 84 | −0.19 | 0.27 | <0.010 |
| | Sparsely populated sites | | | |
| Global scale | 174 | −0.16 | 0.18 | <0.040 |
| 15°S–15°N | 21 | 0.58 | 0.58 | <0.001 |
| 10°N–40°N | 31 | −0.18 | 0.05 | Not significant |
| 40°N–70°N | 117 | −0.27 | 0.35 | <0.002 |

[a]The goodness-of-fit measure ($R^2$) and the significance level (p), which are also displayed, characterize how linear trends fit to the long-term variations.

**Table 2.** Numbers (Percentages) of Sites With Negative and Positive Relative Flux Changes *dI* Within the Selected Intervals of Population Changes *dP*

| | *dP* Interval, Million | | | | |
|---|---|---|---|---|---|
| *dI* | all *dP* | <0 | 0≤ and <0.1 | 0.1≤ and <0.5 | ≥0.5 |
| All values | 122 | 16 | 21 | 56 | 28 |
| <0 | 78 (64%) | 8 (50%) | 11 (52%) | 39 (70%) | 22 (79%) |
| ≥0 | 42 (36%) | 8 (50%) | 10 (48%) | 17 (30%) | 6 (21%) |

ation could be divided into two sub-periods: 1964–78 and 1978–89, in accordance with Figure 1. Strong differences between the highly and sparsely populated sites are observed in their records within the first sub-period, followed by the second sub-period where the evolution seems similar in both groups of sites. This point is commented on further in section 4 (Discussion).

[10] Furthermore, significant differences in radiation dimming for highly populated sites and for sparsely populated ones were obtained at different latitudinal zones (Table 1). In particular, in the equatorial zone, from 15°S to 15°N, sparsely populated sites revealed a significant increase in surface solar radiation, during the period under investigation. The resulting slope was estimated to be as much as 0.58 $W/m^2/yr$. (Note that averaging of annual means for each year within the specified group of sites was carried out when more than 10 sites were available; otherwise, the averaged annual means were not used).

[11] Moving towards the North, the radiation increase for sparsely populated sites gradually changes into a decline at latitudes higher than 40°N. The resulting slope for this northern latitudinal zone is estimated to be as much as −0.27 $W/m^2/yr$ (Table 1). Within the intermediate latitudinal zone from 10°N to 40°N, a linear trend is not suitable for the long-term variations of annual means. To be specific, the resulting slope was formally estimated to be as much as −0.18 $W/m^2/yr$, even though this figure is not significant (Table 1).

[12] In contrast to sparsely populated sites, the long-term variations (1964–1989) of surface solar radiation annual means for highly populated sites reveal a decline in all latitudinal zones. Moreover, the sharpest decline (−1.25 $W/m^2/yr$) took place in the latitudinal zone from 10°N to 40°N (Table 1).

[13] While searching for evidence that large cities contribute much to the production of anthropogenic aerosols, which in turn contribute to global dimming, it is interesting to analyze the relationship between surface radiation decline and population changes in specific sites. It is worth noting, however, some difficulties of such an analysis. First, it was impossible to obtain population changes in sparsely populated sites. Besides, in some highly populated sites decreasing tendencies are observed in their population, as for example in Milan, Hamburg and Budapest. In spite of such decreasing trends, human activity in those sites is assumed to remain at a high level, or probably at an increased level, with no decrease in greenhouse gas emissions and anthropogenic aerosol production.

[14] Population changes were estimated for 122 highly populated sites (Table 2) as differences between population in 1964–1965 and population in 1999–2000. It was noted that the highest population growth was obtained for the following sites: Buenos Aires (∼4.3 million), Bangkok (∼5.9 million) and Hong-Kong (∼6.2 million). In order to analyze the existing tendencies in solar radiation versus population change, the relative flux change (*dI*) as function of population change was obtained for all sites separately (see Section 2, Methodology). It is clearly seen in Table 2 that the percentage of negative *dI* values steadily increases with population change. These results support our suggestion that anthropogenic aerosols are the main reason for solar dimming.

[15] Furthermore, as shown in Figure 2, the cumulative slope for highly populated sites is a monotonically decreasing function of population change. This shows the average dimming for selected groups of large cities. The far-end right-hand-side points in Figure 2 represent the global accumulated slopes for all sites within the selected group. For comparison, the total accumulated slope for highly populated (>0.8 million) sites is approximately twice as much as the one for moderately populated sites (0.1< and <0.8 million).

## 4. Discussion

[16] There is some uncertainty in our estimates of large cities' contribution to solar dimming. This ranges from uncertainty in our basic understanding of air pollution effects on the atmospheric energy balance, to uncertainty in using population as a proxy for human activity. In addition, there are other effects, except air pollution, associated with the urbanization, such as heat island or changes in surface albedo. Moreover, population tends to concentrate in sites that are near rivers, lakes and seas, and where climate and terrain is more hospitable for human settlement. These uncertainties suggest being cautious about our estimates. Nevertheless, the same methods were applied to both highly populated sites and sparsely populated ones.

[17] Our findings highlight the fact that the solar dimming phenomenon is significantly dominated by large cities' contributions to the atmospheric pollution. As seen in Figure 1, the majority of differences between the long-term trend for highly populated sites and that for sparsely

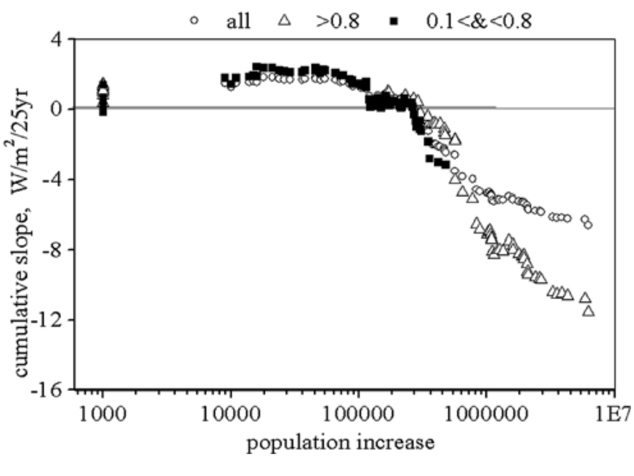


**Figure 2.** Cumulative slopes for moderately populated (squares, population is less than 0.1 and greater than 0.8 million) and highly populated sites (triangles, population greater than 0.8 million) as a function of population change. The circles designate cumulative slopes for both of these groups together.

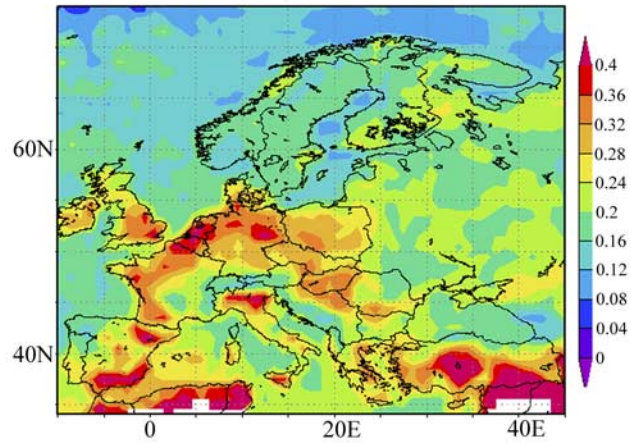


**Figure 3.** The distribution of aerosol optical thickness over Europe averaged between May 2004 and September 2004 based on the MODIS Online Visualization and Analysis System (MOVAS) products. Large industrial/urban areas like N. Italy, SE England, N. Germany can be noticed.

populated sites seems to be due to the differences in the first ~14 years of the analyzed period (1964–1978). During that period, clear-air regulations had still limited effects. However, after approximately 1978 the evolution seems similar in highly and sparsely populated sites, which is in line with the findings of a trend reversal in the late 1980s by *Wild et al.* [2005] and *Pinker et al.* [2005]. This indicates that a linear trend in Figure 1 might not be the best approximation.

[18] The sharper decline in surface solar radiation corresponds mainly to the latitudinal zone from 10°N to 40°N. This zone is nearly coincident with the zone of the local maximum of fossil fuel emissions in the Northern hemisphere, obtained from 1960 to 1990, by *Stanhill and Cohen* [2001]. This zone with the steepest slopes is limited in its southern border by the equatorial zone with a smaller decline. This may be explained by the vicinity of the intertropical convergence zone, where intensive rainfall reduces the direct aerosol effects (as to the indirect effects see later). At the northern boundary, the zone with extreme slopes is limited by a relatively slight decline in the Arctic region. During winter and spring, incursions of polluted air give rise to the Arctic haze characterized by high levels of anthropogenic pollution, leading to significant radiative forcing of the Arctic climate [*Stanhill*, 1995; *Eckhardt et al.*, 2003].

[19] It is noteworthy that the year-to-year variations of annual radiation fluxes for the period under investigation show just the opposite trend to dimming, i.e. an increase for sparsely populated sites located in the equatorial regions. One could suggest that the observed increase may be attributed to errors introduced by limited number of sites in the tropics. However, these findings are supported by *Pinker et al.* [2005], who found the persistent increase in surface solar radiation over tropic regions (20°S–20°N) by using satellite data. Therefore, the observed trend in the tropics may not be just a sampling problem. As illustrated for the Amazon region by *Koren et al.* [2004], the biomass burning aerosols could reduce the amount of cloudiness around the equator, which may explain this result.

[20] The inhabited areas occupy only a small part of the total land area (estimated 10–20%). As illustrated in Figure 3, even over Europe, with its relatively large industrial activity, the urban aerosol-clouds are clearly seen. Therefore, these findings suggest that "global dimming" is essentially a local phenomenon, observed only on a limited part of the total land area. Particularly in the early stage of the observational records (the 1960s–1970s), there seems to be clear evidence for an urbanization effect (or a local effect of dimming), while probably not so much later on. Note that even for sparsely populated sites (<0.1 million) there is some population/urbanization effect on sunlight availability (a decline of 0.16 W/m2/yr), which was difficult to separate since their population figures were not available. However, most of the land areas throughout the globe and certainly oceans have zero population. It is worth referring here to *Pinker et al.* [2005] who found persistent increase in surface solar radiation over the ocean, by using satellite data. Hence, the obtained change in the radiation trends with population seems to be an important indicator suggesting that solar dimming as a global phenomenon is questionable.

[21] **Acknowledgments.** We thank G. Stanhill, A. Arking, B. Starobinez and anonymous referees for helpful discussions and comments. We gratefully acknowledge the World Radiation Monitoring Center for providing the GEBA database.

## References

Cohen, S., B. Liepert, and G. Stanhill (2004), Global dimming comes of age, *Eos Trans. AGU*, *85*(38), 362–363.

Eckhardt, S., A. Stohl, S. Beirle, N. Spichtinger, P. James, C. Forster, C. Junker, T. Wagner, U. Platt, and S. G. Jennings (2003), The North Atlantic Oscillation controls air pollution transport to the Arctic, *Atmos. Chem. Phys.*, *3*, 1769–1778.

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

Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: The Scientific Basis*, 105 pp., Cambridge Univ. Press, New York.

Koren, I., Y. J. Kaufman, L. A. Remer, and J. V. Martins (2004), Measurement of the effect of Amazon smoke on inhibition of cloud formation, *Science*, *303*, 1342–1345.

Liepert, B. (2002), Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990, *Geophys. Res. Lett.*, *29*(10), 1421, doi:10.1029/2002GL014910.

Liepert, B., J. Feichter, U. Lohmann, and E. Roeckner (2004), Can aerosols spin down the water cycle in a warmer and moister world?, *Geophys. Res. Lett.*, *31*, L06207, doi:10.1029/2003GL019060.

Pinker, R. T., B. Zhang, and E. G. Dutton (2005), Do satellites detect trends in surface solar radiation?, *Science*, *308*, 850–854.

Schwarzbard-Ahuvia, R. (2004), The effects of various aerosols and clouds on the recent climatic variations in the surface insolation, M.Sc. thesis, 83 pp., Tel Aviv Univ., Tel Aviv, Israel.

Stanhill, G. (1995), Solar irradiance, air pollution and temperature changes in the Arctic, *Philos. Trans. R. Soc. London, Ser. A*, *352*, 247–258.

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

Stanhill, G., and J. D. Kalma (1995), Solar dimming and urban heating at Hong Kong, *Int. J. Climatol.*, *15*, 933–941.

Wild, M., H. Gilgen, A. Roesch, A. Ohmura, C. Long, E. Dutton, B. Forgan, A. Kallis, V. Russak, and A. Tsvetkov (2005), From dimming to brightening: Decadal changes in solar radiation at Earth's surface, *Science*, *308*, 847–850.

P. Alpert, P. Kishcha, and R. Schwarzbard, Department of Geophysics and Planetary Sciences, Tel Aviv University, 69978 Tel-Aviv, Israel. (kishcha@gmail.com)

Y. J. Kaufman, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.