Global dimming and urbanization: did stronger SSR trends collocate with regions of population growth?

Author's response to review comments

We thank the two reviewers for their valuable feedback and their suggestions for the improvement of the manuscript. Here we address (black) all of the specific criticisms and suggestions (*grey italic*) and propose changes to the manuscript (blue). We answer the reviews in the order in which they were published in the discussion section.

Note that our response to the comments by referee #1 has already been posted on the 16th November 2015 (AC C9312).

Anonymous referee #1

This study addressed the issue whether urbanization has an important impact on the observed dimming rate of surface incident solar radiation. There are a number of studies on this issue and different conclusions have been derived. The authors designed complicated methods to do their job and their conclusions are similar to recent publications.

We are using 0.08° resolution population density data and devise a population index PI. The PI of a site is the sum over all population density grid cell of the dataset within a certain radius of the site. We introduced an inverse distance-weighting that gives greater weight to grid cells closer to a site. We do not consider the use of a PI as complicated. We performed sensitivity tests and showed that the results are robust against the choice of parameters (radius around the site, distance weighting) for the PI.

Our results are similar to the results found for Israel (Stanhill and Cohen, 2009) and for Japan (Stanhill and Cohen, 2008). Moreover, given the fact that we do not find any correlation between the temporal change of the population pattern surrounding a site and the SSR trend measured at sites for the sites in Europe and Japan, we are in line with the findings by Wang et al. (2014). However, the conclusions drawn from our study are different from the study by Alpert and Kishcha (2008), who argued that an urbanization effect exists for the GEBA sites.

I have several comments to help the author in presenting their results more clearly: (1) How the population index (PI) and its increase relate to the urban-rural contrast of their impact on the observed global dimming? It is unclear in the current manuscript. What the increasing and decreasing of PI should impact the urban-rural contrast of dimming? and what was the observed values?

The issue with the urban-rural contrast and the potential for spurious biases when urban and rural sites from different regions are compared is thoroughly discussed by Wang et al. (2014). We refer to this important finding in the present manuscript (MS hereafter). Our study avoids aggregating sites into urban and rural ones, as this requires a (somewhat arbitrary) PI-threshold. The urban-rural contrast needs to be certainly considered, if sites are aggregated into groups and average SSR trends are calculated, which we do not do in the present study. See also [P31142, L20-L24]

The estimated SSR trends can be seen in e.g. Fig. 3 in the MS.

(2) The observations of China have shown to be impacted by the quality and their performance of the instruments used (Wang et al., 2015). How the authors addressed this issue? It should be discussed at
40 *least. Wang, K., Q. Ma, Z. Li, and J. Wang (2015), Decadal variability of surface incident solar radiation over China: Observations, satellite retrievals, and reanalyses, J. Geophys. Res. Atmos., 120,*
42 *6500–6514, doi:10.1002/2015JD023420.*

We are fully aware of potential data heterogeneities in the used GEBA dataset. GEBA sites data quality
44 is discussed by Gilgen and Ohmura (1999). We refer to this in the MS. We are using only GEBA sites that received the highest quality flags (section 2.1 on P31137). We were not aware of the recently
46 reported inhomogeneity and sensitivity drift issues for Chinese sites (Wang et al., 2015).
A treatment of data inhomogeneity and the sensitivity drift issues for the Chinese sites is beyond the
48 scope of this study. Note that we were not focusing on absolute SSR trends, but on statistical relationships between SSR trends and different urbanization indicators. Furthermore we stress, that we
50 are not claiming an urbanization impact on SSR for the Chinese sites, but that we cannot rule it out (P31143, L7) given the urbanization indicators used. We agree with you that further research for the
52 Chinese sites is required. We therefore propose following changes to section 4 (discussions and conclusions):

54 We add the following sentence at the end of the discussion section (Sect. 4):

Particularly for the Chinese GEBA sites complementary studies are necessary given potential data
56 inhomogeneity and instrumentation issues which were recently reported by Wang et al. (2015).

References added:

58 Wang, K., Q. Ma, Z. Li, and J. Wang, Decadal variability of surface incident solar radiation over China: Observations, satellite retrievals, and reanalyses, J. Geophys. Res.
60 Atmos., 120, 6500–6514, doi:10.1002/2015JD023420, 2015.

(3) For the significant correlation of PI and dimming rate in China. During the study period, China
62 *population increased significantly and surface solar radiation decreased at same time. It is easy to understand the significant positive correlation between PI and dimming rate. However, the physical*
64 *background is lacking here.*

We presume you mean negative (instead of positive) correlation in the above excerpt from your original
66 comment. Note that we are not comparing correlations between single SSR time series and PI time series for every site – we are estimating SSR trends and comparing these against the respective PI
68 change of regional groups of sites. This does not necessarily imply a significant correlation.

The physical background is not discussed in this study, because this study is not aiming at answering
70 the question what caused the global dimming. We are focusing on relationships between the change in population pattern around a site (expressed in terms of a population index) and the SSR trends to see
72 whether SSR trends go hand in hand with PI increases of the site.

PI can has a significant positive correlation with any data that show significant decreasing trend
74 *during the period. How to avoid the spurious correlation that they just occurred concurrent?*

Our study shows that the first statement in the above comment is not correct: e.g. the sites in Japan
76 experienced large average increase of the (n=1) PI from 1960-1990. The average increase was even

larger than the average increase of the sites in the "Asia" group as can be seen in Fig. 2. Nonetheless, no negative correlation between the change in PI and the SSR trends (Fig. 3) was found.

We acknowledge that you are raising an important point. This issue applies not just to our study but obviously to all the population-based approaches. In light of the limitation of what the population data might have indicated, the conclusions derived from our analysis are kept conservative in the current MS. It is important to note, that we are not claiming that there is an urbanization effect for China. However we can't preclude it when PIs are used. This is stressed in the MS [Line 6 on page 31143].

(4) The author divided their result areas into Europe and Japan, Asia (China and Russia). It may introduce misunderstandings. It looks like the Japan is not in Asia, and Russia is in Asia not in Europe.

The "Asia" group in our study consists of 39 Chinese, 22 Russian and 4 remaining, i.e. non-Chinese and non-Russian sites. Russia is a transcontinental country and belongs to both Europe and Asia. Since most of the Russian sites used in the present study are in the East we added the Russian sites to the "Asia" group. Note that the "Asia" group was split later for a separate analysis. Data abundance in Japan (45 sites) was comparably large. Hence we aggregated it into a separate group.

Although the site distribution map in Fig. 1 in the manuscript should resolve potential misunderstandings, we will stress in the MS that by "Asia" we mean mostly Russian and Chinese sites as well as four other sites in the Asian region, excluding Japan. We propose following changes:

1). Rephrase the sentence at P31137, L13 to

This was fulfilled by 39 sites in China, 47 sites in Europe, 47 sites in Japan, 22 sites in Russia and four sites in North Korea, Macau and Mongolia. The latter four sites were aggregated with the Chinese and Russian sites into the group "Asia". The geographic distribution and the grouping of the 157 sites are shown in Fig. 1.

2.) Rephrase the caption of Fig. 1:

Distribution of the 157 GEBA sites analysed in this study. The group "Europe" consists of 47 sites (blue circles) and "Japan" consists of 45 sites (red triangles). The 39 Chinese, 22 Russian and 4 remaining Asian sites were aggregated into the "Asia" group (green squares).

3.) Indicate region names and the corresponding number of sites in Fig. 1.

Anonymous referee #2

This paper is a useful contribution to past discussion on the causes of Global Dimming (GD). Though the paper does not add to the physical understanding of suggested causes of that phenomenon, it does clarify the relation with increases in population or population density, or rather the lack of such relation for Europe and Japan.

The importance of this question was demonstrated (and perhaps exaggerated) by its treatment in the IPCC's AR4 report. There, a large and increasing number of studies of GD were downplayed as representing local effects of air pollution, purely on the basis of the paper of Alpert & Kishcha (2008) associating GD trends with population increase. That work also left the physical mechanism implicit and unquantified, so the current paper can be seen as closer analysis of the claimed relationship.

That GD does not correlate at all well with PI increase, or PI in 2000, across the whole dataset is unsurprising. Even if local air pollution in the vicinity of sensor sites was a predominant cause of GD, presumably through direct or indirect aerosol effects, the relation to population density would be highly uncertain and dependent on the industrial and economic profile and lifestyle of that population. It is easy to see that the negative correlation of PI with SSR trend (or positive correlation with GD) in China and Russian Asia could be the product of (especially) coal-fired industrialisation, even as clean-air initiatives or moves to high-technology industry and better public transport produced the opposite effect in other places.

The authors of the current paper are right to avoid such speculation, which should be addressed with studies relating SSR change directly to industrial activity, urban transport, and other sources of aerosol, and to actual measurements and models of aerosol concentrations. Such studies also need to go beyond the question of statistical correlations of trends to consider the actual amounts and optical or microphysical properties of aerosols in relation to observed SSR change.

The focus of this paper is to address the question raised by Alpert & Kishcha; whether population increase or density can be used to explain changes in SSR as a local anthropogenic effect. Imamovic et al. usefully demonstrate that PI, when calculated carefully and with adjustment of weighting to examine sensitivity, does not serve this purpose.

I have no difficulty recommending it for publication largely unchanged.

Minor corrections:

P 31138, line 3: "Rationales ..." (not "Rationals ...")

Changed to "Rationales"

P 31138, line 8: It might be better to use a symbol other than "d" for the area weighting of population cells, as it invites confusion with the use of "d(s,y)" for site to population cell distance. Is the exponent "n" in 1/dˆn the same as the exponent in "1/d(s,y)ˆn"? If so, what is the reason? Is this not just the correction from population density rho(y,t) to actual population in a cell? In that case, there would be no exponent "n".

Thank you for pointing to the ambiguous use of the symbol d.

142 All population density cells surrounding the site are weighted, i.e. also the cell (the coordinate of the center denoted as y_s) that contains the measurement site under consideration (coordinate s). For measurement sites very close to the center of the cell (small $d(s,y_s)$) the weight $1/d(s,y_s)^{\wedge}n$ and
144 consequently the PI become large. This is artificial given that the population density data set is discrete.

146 This motivates the use of an alternative distance (the d we initially used) for the weighting of the cell that contains the site. We choose to use the square root of the area A of the cell as a metric for its spatial extent. The area A of the cell can be calculated exactly via spherical integration. It can be approximated
148 with

150 $A=\cos(\text{latitude})*(2*\text{pi}*R_E*\text{dphi}/360°)^2$ (dphi=0.08° angular resolution of the population data set and R_E=6371 km radius of the Earth)

152 A cell at 30° latitude has an approximate extent of 8.3 km, while a cell further north has smaller spatial extent, e.g. for 60° latitude the extent is approximately 6.3 km.

154 In order to avoid confusion with the use of d we propose to use the symbol l instead and to rephrase the sentence starting on line 7 on P31138 as follows:

156 If $1/d(s, y)^n$ is used for the weighting of the population density cell that contains the site, an artificially large weight will result for cells whose center is very close to the measurement site. For consistency the population density cell that contains the measurement site is not weighted with the inverse of the
158 physical distance between the site and the center of the cell to the nth power $1/d(s, y)^n$ but with the inverse of the spatial extent l of the cell to the nth power $1/l^n$ instead. For the spatial extent l of a
160 population density cell we take the square root of the area of the 0.08° cell. For cells in the mid-latitudes l is approximately 7 km.

162 *P 31150: Why is only one decimal place given in the correlation coefficients for the 22 Russian sites?*

164 We inserted two decimal places for the correlation coefficients for the 22 Russian sites in Figure 5.

Comment to the editor

166 A minor typographical error was found and corrected:

P 31142 line 24 "preculde" changed to "preclude"

Global dimming and urbanization: did stronger negative SSR trends collocate with regions of population growth?

A. Imamovic[1], K. Tanaka[1,2], D. Folini[1], and M. Wild[1]

[1]Institute for Atmospheric and Climate Science, ETH Zürich, Switzerland
[2]National Institute for Environmental Studies (NIES), Tsukuba, Japan

Correspondence to: A. Imamovic (adel.imamovic@env.ethz.ch)

Abstract. Global dimming refers to the decrease in surface solar radiation (SSR) observed from the 1960s to the 1980s at different measurement sites all around the world. It is under debate whether anthropogenic aerosols emitted from urban areas close to the measurement sites are mainly responsible for the dimming. In order to assess this urbanization impact on SSR, we use spatially explicit population density data of $0.08°$ resolution to construct population indices (PI) at 157 high data quality sites. Our study extends previous population-based studies by incorporating distance-weighting as a simple aerosol diffusion model. We measured urbanization in the surrounding of a site as the PI change form 1960 to 1990 and found no negative correlation with the corresponding SSR trends from 1964 to 1989 for the 92 sites in Europe and Japan. For the 39 sites in China the correlation coefficients are significant at the 5 % level and reach around -0.35, while for the 26 remaining Asian, mostly Russian sites the correlation coefficients reach around -0.55 at the 1 % significance level. Results are similar, when the absolute levels of PIs are taken as an indicator for urbanization. Our findings call into question the existence of an urbanization effect for the sites in Europe and Japan, while such an effect cannot be ruled out for the sites in Asia, especially in Russia.

1   Introduction

Surface solar radiation (SSR) is the sum of direct and diffuse solar radiation incident at the surface of the Earth. Systematic and widespread pyranometer-based measurements of SSR started in the mid-twentieth century and were compiled in databases such as the Global Energy Balance Archive (GEBA) at ETH Zürich (Gilgen and Ohmura, 1999). From the 1960s to the 1980s the SSR underwent a prominent negative trend which became known as the global dimming (Ohmura and Lang, 1989). It was first discovered at sites in Europe and later worldwide (Gilgen et al., 1998). The average SSR trend estimates (in $\mathrm{W\,m^{-2}\,decade^{-1}}$) for global land sites during that period range between -2.3 (Liepert, 2002) and -5.1 (Stanhill and Cohen, 2001). A more detailed overview of trend estimates can be found in Table 1 of the review by Wild (2009). The negative trends started to reverse generally in the 1980s and marked the beginning of a global brightening (Wild et al., 2005). This study focuses on the time period from the 1960s to the 1980s, which we refer to as the dimming period.

It is not completely understood what caused the global dimming. Apart from an increasing cloudiness, one of the most prominent explanations is an increasing aerosol optical depth (AOD) caused by rising global anthropogenic aerosol emissions from the 1960s to the 1980s. Simultaneous and systematic measurements of SSR/AOD or SSR/cloudiness during the dimming

period are scarce. A few studies available deliver regionally dependent findings: for example Ohmura (2009) showed for five sites in Europe and Japan with simultaneous measurement of SSR and AOD that the aerosol direct and indirect effects are equally responsible for changing SSR. Norris and Wild (2007) used clear sky data and found that the cloud cover effects are insignificant for the dimming over Europe. In contrast to the sites in Europe, Liley (2009) used lidar-based measurements and showed that the AOD contributions to the dimming in New Zealand are insignificant; from record of sunshine hours an increasing cloudiness was inferred and shown to be more consistent with the observed SSR pattern. This consistency was also found in Japan (Stanhill and Cohen, 2008).

Speculations have arisen that global dimming is only due to local pollution sources (i.e. a growing city or an industry plant) near the measurement sites and not a larger scale phenomenon (Alpert and Kishcha, 2008). This idea of nearby settlements affecting atmospheric measurements is commonly referred as the *urbanization* effect. However, even if aerosols had a significant impact on SSR trends, it is not clear how far the effect persists, i.e. whether the proximity to an aerosol emission source determined the dimming trends. Due to the lack of fine-scale emission data, an estimate of urbanization was restricted to the use of proxy data, from which aerosol emissions could be inferred. Early approaches therefore used data on population to assess potential urbanization impacts on single sites, implicitly assuming that more people lead to more emissions and hence a stronger urbanization impact.

Gilgen et al. (1998) found the sites with the strongest dimming to be concentrated within the populated regions of the northern hemispheric mid-latitudes. Stanhill and Cohen (2001) found no significant correlation between the SSR measured at 854 sites in the years 1958, 1965, 1975, 1985 and 1992 and the corresponding population densities in the one degree ($\simeq 100\,\mathrm{km}$) grid surrounding these sites in the year 2000. Alpert and Kishcha (2008) calculated the SSR trends 1964–1989 for 317 sites worldwide and compared them against the respective population density in the one degree cell surrounding the measurement site in the year 2000. They found a significant dimming only in the group of GEBA sites surrounded by a cell with a population density greater than $10\,\mathrm{km}^{-2}$ and a significant correlation between the strength of dimming and the population density in the year 2000. The group of sites in rural areas was found to have undergone an insignificant change in SSR. A more recent, but alternative approach by Wang et al. (2014) using night-time light data of the year 2000 came to opposite conclusions. Their analysis of 105 pairs of urban-rural sites that were less than two degrees ($\simeq 200\,\mathrm{km}$) apart showed that the geographic proximity to an urban area had small impact on both mean and trend of SSR.

The role of urbanization in affecting SSR during the global dimming period has remained an open question. In particular, it is not clear whether or not the population growth in the surroundings of a site adequately explains the global dimming. This study tackles this question by using a finer spatially explicit population data set ($\Delta x \simeq 10\,\mathrm{km}$) to devise a population index (PI). The PI of a site is the weighted mean of the population density within a radius of $500\,\mathrm{km}$ from the site (Sect. 2). We extend the previous approaches that used unweighted data on population (Stanhill and Cohen, 2001; Alpert and Kishcha, 2008) in the following ways. The SSR trends from 1964 to 1989 of 157 high quality GEBA sites in Asia, Europe and Japan are compared against (a) the PI changes from 1960 to 1990, (b) the PI in 2000 and (c) the unweighted population density in the 0.08° cell containing the site in the year 2000. The third approach is methodologically consistent with previous studies (Alpert and Kishcha, 2008; Stanhill and Cohen, 2001), as argued in Sect. 3. In doing so, we attempt to answer the question whether

the sites considered in this study show a correlation between SSR trends and PI changes from 1960 to 1990 or a correlation between SSR trends and absolute levels of PI in the year 2000. With our analysis, we aim to contribute to the debate on whether global dimming is influenced by urbanization.

2 Data and methods

2.1 Surface solar radiation

Data on annual average SSR since the 1960s were taken from the GEBA. Measurement error estimates for annual mean SSR are 2% (Gilgen and Ohmura, 1999). We selected the same high quality sites as used in the model data comparison by Skeie et al. (2011) and retained sites with at least 15 SSR annual averages in each 20-year time frame from 1960 to 1990. This was fulfilled by ~~65 sites in Asia~~39 sites in China, 47 sites in Europe, ~~and~~ 45 sites in Japan~~. Their geographic distribution is~~, 22 sites in Russia and four sites in North Korea, Macau and Mongolia. The latter four sites were aggregated with the Chinese and Russian sites into the group "Asia". The geographic distribution and the grouping of the 157 sites are shown in Fig. 1. For every GEBA site, the SSR trend for the period 1964–1989, i.e. the same period as used by Alpert and Kishcha (2008), was estimated using a bi-square regression.

2.2 Population data and the population index

We used the global population density data of the History Database of the Global Environment (HYDE), which is available at a spatial resolution of approximately $0.08°$ $(\simeq 10\,\mathrm{km})$ and a temporal resolution of ten years for the years $t = 1960, 1970, 1980, 1990$ and 2000. Error estimates for population density per grid cell are $\pm 1\%$ (Klein Goldewijk et al., 2010).

In order to compare the surroundings of different GEBA sites, we converted the two dimensional population distribution around single sites into PI values. The PI is the weighted mean of the population density distribution within a radius of $500\,\mathrm{km}$ from the site: the weights are $w_n(s,y) = 1/d(s,y)^n$ i.e. the inverse of the distance between the measurement site and the population density cell under consideration to the nth power. ~~Rationals~~ Rationales for the choice of n values for this study are explained further below in the text. The distance between a GEBA site at $s = [\theta_s, \varphi_s]$ and the center of a nearby cell at $y = [\theta_y, \varphi_y]$ with population density $\rho(y,t)$ is denoted as $d(s,y)$. The distance is a function of the respective spherical coordinates $\theta_s, \varphi_s, \theta_y,$ and φ_y and can be looked up in mathematical handbooks. ~~For consistency,~~ If $1/d(s,y)^n$ is used for the weighting of the population density cell that contains the site, an artificially large weight will result for cells whose center is very close to the measurement site. For consistency the population density ~~in the 0.08cell surrounding the site is weighted with $1/d^n$, where d denotes~~ cell that contains the measurement site is not weighted with the inverse of the physical distance between the site and the center of the cell to the nth power $1/d(s,y)^n$ but with the inverse of the spatial extent ~~of the corresponding cell (approximately seven kmfor mid-latitude cells).~~ l of the cell to the nth power $1/l^n$ instead. For the spatial extent l of a population density cell we take the square root of the area of the cell. For cells in the mid-latitudes l is approximately 7 km.

We define the PI of a GEBA site s at the time t as the sum of all weighted population density grid cells within the $R = 500\,\text{km}$ surrounding of the site

$$\text{PI}(s,t) = \eta \sum_{y:\ d(s,y) \leq R} \frac{\rho(y,t)}{d(s,y)^n}. \tag{1}$$

With the following definition of the normalization factor η:

$$\eta = \frac{1}{\rho_0 \cdot \sum_{y:\ d(s,y) \leq R} \frac{1}{d(s,y)^n}} \tag{2}$$

the PI becomes dimensionless and equals one for a fictitious site surrounded by a constant population density of $\rho_0 = 10\,\text{km}^{-2}$. The value $R = 500\,\text{km}$ is chosen to reflect the finite lifetime and hence finite diffusion distance of aerosols and is obtained if one assumes a typical lifetime of 2 days at an average diffusion speed of $v = 3\,\text{m\,s}^{-1}$. We repeated the analysis for PIs with $R = 750\,\text{km}$ and $R = 1000\,\text{km}$ and found no significant differences in the results.

The weighting $1/d(s,y)^n$ mimics a simple aerosol transport and diffusion model. By setting $n = 0$ one assumes undiluted transport of all aerosols to the site. For $n = 3$ pure diffusion of a tracer in three-dimensional space is assumed. Given these two bounds for n, we used the set $n = 1, 2, 3$ to calculate PIs. Note that for small n, all cells in the surrounding of the GEBA contribute almost equally to the PI, as they receive almost equal weight. This can be seen mathematically as w_n approaches unity for decreasing n. More precisely, a small $n\ (\simeq 0)$ together with a small R corresponds to previous studies that only used the unweighted population density in the one degree cell containing the site (Alpert and Kishcha, 2008). For increasing n the weight factors converge to a δ-function (which is zero everywhere except for the cell that contains the site), the PI for large n carries mainly information on the closest settlements. The scaling parameter n is thus a control parameter, that enables us to test the relative importance of aerosol travel distances.

3 Results

For each GEBA site analysed in this study the PIs for $n = 1, 2, 3$ and for the years $t = 1960, 1970, 1980, 1990$, and 2000 were calculated. The PIs of the GEBA sites averaged within the three regions Asia, Europe and Japan generally increased from 1960 to 2000 for $n = 1, 2$, and 3 (Fig. 2). The 65 sites in Asia showed an average PI increase of 85 % from 1960 to 2000. The average increase in PI for the sites in Japan is 20–30 %, while the increase was slightly smaller for the European sites. The European sites had both the smallest average increase in PI and the lowest absolute PI (except in 1960 for $n = 1$). The average increase of PI of the sites in Europe and in Japan was similar for $n = 2, 3$ (similar slopes), while the absolute average PI was greater for the Japanese sites.

We investigated the impact of urbanization on SSR trends during the dimming period by calculating the correlation coefficients for SSR trends from 1964 to 1989 vs. the PI change from 1960–1990 (Fig. 3), and vs. the absolute PI in the year 2000 (Fig. 4).

3.1 Europe and Japan

The results for the sites in Europe and Japan are discussed together since they show similar features (second and third row in Fig. 3). The European sites underwent the weakest decrease in SSR (over the time period from 1964 to 1989) with a group average of $-0.17\,\mathrm{W\,m^{-2}\,yr^{-1}}$. The largest decrease measured at a site in the European group was $-0.56\,\mathrm{W\,m^{-2}\,yr^{-1}}$. The average decrease in SSR for the group of Japanese GEBA sites was $-0.30\,\mathrm{W\,m^{-2}\,yr^{-1}}$ The maximum dimming in the group of Japanese sites was $-1.44\,\mathrm{W\,m^{-2}\,yr^{-1}}$. The correlations between SSR trends and PI changes (Fig. 3) for the sites in Europe and Japan are positive and smaller than 0.33 for any choice of the scaling parameter n. It is important to note that the correlation coefficients are not negative, as would be expected from an urbanization impact: SSR trends are actually less negative for larger PI change. They are significant at the 5 % level only for the $n = 1$ case in Europe, and for the $n = 2, 3$ cases in Japan. As shown in Fig. 4 similar correlation coefficients as in Fig. 3 emerge, when we take the PIs of the sites in year 2000 instead of the change in PI from 1960 to 1990. We obtained positive correlation coefficients at a significance level of 5 %, except for Japan for $n = 1$.

For the 47 European and 45 Japanese sites considered in this study, the SSR trends are not well explained by the respective change in population or the absolute population in 2000.

3.2 China and Russia

The largest group-averaged SSR trends ($-0.55\,\mathrm{W\,m^{-2}\,yr^{-1}}$) and the largest changes in PI were reached at the GEBA sites in Asia. Figure 3 shows the SSR trends and the PI changes of the sites. Correlation coefficients for the changes in PI vs. the SSR trends are -0.54, -0.41 and -0.42 for $n = 1, 2$ and 3, respectively, as shown in the first row of plots in Fig. 3. We obtain quantitatively similar correlation coefficients when we compare the SSR trends against the PI in the year 2000, instead of the PI change from 1960 to 1990 (Fig. 4). Note that the largest dimming of approximately $-2.0\,\mathrm{W\,m^{-2}\,yr^{-1}}$ (lowest point in row 1 of Figs. 3 and 4) does not coincide with the site that exhibited the largest PI change or the largest PI in the year 2000. The correlation coefficients for the 30 right-most points in Fig. 3, i.e. the sites that underwent the greatest increase in PI, and correlation coefficients for the 30 left-most points, i.e. the sites with the smallest increase in PI, are both around $\rho = -0.30$.

We split the group of the 65 Asian sites further into the 39 Chinese sites and 26 non-Chinese, mostly Russian (22) GEBA sites (Fig. 5) and repeated the above analysis. As above, the correlation coefficients in these subgroups are quantitatively the same whether one takes the PI change from 1960 to 1990 or the PI in the year 2000 as an indicator for urbanization. The correlation coefficients for the non-Chinese sites are significant at the 1 % level and range between -0.5 and -0.63, while for the Chinese sites the correlation coefficients range between -0.33 and -0.35 and are significant at the 5 % level.

Similar correlation coefficients for the sites in Asia, Europe and Japan (as documented above) are found when the unweighted population density in the year 2000 in the $0.08°$ cell surrounding the GEBA site is compared against the SSR trends. Figure 6 shows that these correlation coefficients are very close to the corresponding correlation coefficients when the $n = 3$ PIs in the year 2000 are used instead (third column in Fig. 4). An explanation for this can be found in Sect. 2.

4 Discussions and conclusions

Some studies argued that the observed negative SSR trends during the global dimming period from the 1960s to the 1980s are restricted to urban areas. In order to assess the urbanization impact on SSR, previous studies used spatially explicit population density data in the one degree cell surrounding the site in the year 2000 (Alpert and Kishcha, 2008; Stanhill and Cohen, 2001).

5   We extended these studies by comparing the PI change from 1960 to 1990 of individual sites, calculated from a ten times finer resolved population data set, against the SSR trend from 1964 to 1989 (i.e. the same period as in Alpert and Kishcha, 2008). The PI of a GEBA site is the distance-weighted mean of the population distribution within a radius of 500 km from the site. Distance weights are used to mimic a simple aerosol diffusion model.

Overall we found positive but insignificant correlation coefficients between the SSR trends and the change in PIs from 1960

10   to 1990 for the GEBA sites in Europe and Japan. Note that an urbanization impact would require a negative correlation. We conclude for the groups of sites in Europe and Japan that urbanization measured as a population increase in the surrounding of the site does not go hand in hand with a stronger negative SSR trend. This is in line with the findings of Stanhill and Cohen (2009) for the SSR measurement sites in Isreal, where SSR trends during the dimming period and the respective rates of change in population were found to be unrelated. Our findings for Europe and Japan are also consistent with the study by Wang et al.

15   (2014), who showed that urbanization (inferred from night-time light data) had no discernible impact on the SSR trends.

On the contrary our findings for the 92 sites in Europe and Japan are not consistent with Alpert and Kishcha (2008), who exclusively focused on population density of the year 2000 as an urbanization indicator. The present study does not discern an urbanization impact for the sites in Europe and Japan, irrespective of the choice of indicators: PI changes from 1960 to 1990, absolute PI in the year 2000 or population density in the year 2000. In contrast to Alpert and Kishcha (2008) we furthermore

20   avoided aggregating sites into two single urban and rural groups, as this may induce spurious biases in their average SSR trends due to the different geographical distribution of the sites in the two groups (Wang et al., 2014).

Unlike for the sites in Europe and Japan, the present study does not ~~preculde~~ preclude an urbanization impact for the sites in Asia. The correlations for the 39 Chinese and 26 non-Chinese, mostly Russian sites are negative and significant at the 5 % level. The correlation coefficients (SSR trend vs. PI change from 1960 to 1990) for the non-Chinese sites in Asia are the largest

25   found and range from −0.5 to −0.63. For the Chinese sites the correlation coefficients range between −0.3 to −0.34, while the average SSR trends there are stronger than in the group of non-Chinese sites in Asia.

Our findings suggest that changes in PI from 1960 to 1990 or absolute levels of PI in the year 2000 (and hence any crude use of population density) provide no convincing evidence that global dimming is mostly an urban and hence local phenomenon for the sites in Europe and Japan. However, an urbanization effect for the sites in China and, particularly, for those in Russia cannot

30   be ruled out. Particularly for the Chinese GEBA sites complementary studies are necessary, given potential data inhomogeneity and instrumentation issues which were recently reported by Wang et al. (2015).

Further research is required to clarify the importance of urbanization for SSR trends during the dimming period.

Data availability

The SSR data and the population data used in this study are publicly accessible. They were taken from www.geba.ethz.ch and ftp://ftp.pbl.nl/hyde/, respectively.

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References

Alpert, P. and Kishcha, P.: Quantification of the effect of urbanization on solar dimming, Geophys. Res. Lett., 35, L08801, doi:10.1029/2007GL033012, 2008.

Gilgen, H. and Ohmura, A.: The global energy balance archive, B. Am. Meteorol. Soc., 80, 831–850, doi:10.1175/1520-0477(1999)080<0831:TGEBA>2.0.CO;2, 1999.

Gilgen, H., Wild, M., and Ohmura, A.: Means and trends of shortwave irradiance at the surface estimated from global energy balance archive data, J. Climate, 114, 2042–2061, doi:10.1175/1520-0442-11.8.2042, 1998.

Klein Goldewijk, K., Beusen, A., and Janssen, P.: Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1, Holocene, 20, 565–573, doi:10.1177/0959683609356587, 2010.

Liepert, B. G.: Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990, Geophys. Res. Lett., 29, 61.1–61.4, doi:10.1029/2002GL014910, 2002.

Liley, J. B.: New Zealand dimming and brightening, J. Geophys. Res., 114, D00D10, doi:10.1029/2008JD011401, 2009.

Norris, J. R. and Wild, M.: Trends in aerosol radiative effects over Europe inferred from observed cloud cover, solar "dimming," and solar "brightening", J. Geophys. Res., 112, D08214, doi:10.1029/2006JD007794, 2007.

Ohmura, A.: Observed decadal variations in surface solar radiation and their causes, J. Geophys. Res., 114, D00D05, doi:10.1029/2008JD011290, 2009.

Ohmura, A. and Lang, H.: Secular variation of global radiation in Europe, in: IRS'88: Current Problems in Atmospheric Radiation, edited by: Lenoble, J. and Geleyn, J.-F., A. Deepak, Hampton, VA, 298–301, 1989.

Skeie, R. B., Berntsen, T. K., Myhre, G., Tanaka, K., Kvalevåg, M. M., and Hoyle, C. R.: Anthropogenic radiative forcing time series from pre-industrial times until 2010, Atmos. Chem. Phys., 11, 11827–11857, doi:10.5194/acp-11-11827-2011, 2011.

Stanhill, G. and Cohen, S.: 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, Agr. Forest Meteorol., 107, 255–278, doi:10.1016/S0168-1923(00)00241-0, 2001.

Stanhill, G. and Cohen, S.: Solar radiation changes in Japan during the 20th century: evidence from sunshine duration measurements, J. Meteorol. Soc. Jpn., 86, 57–67, doi:10.2151/jmsj.86.57, 2008.

Stanhill, G. and Cohen, S.: Is solar dimming global or urban? Evidence from measurements in Israel between 1954 and 2007, J. Geophys. Res., 114, 2156–2202, doi:10.1029/2009JD011976, 2009.

Wang, K., Ma, Q., Wang, X., and Wild, M.: Urban impacts on mean and trend of surface incident solar radiation, Geophys. Res. Lett., 41, 4664–4668, doi:10.1002/2014GL060201, 2014.

Wang, K., Ma, Q., Li, Z., and Wang, J.: Decadal variability of surface incident solar radiation over China: Observations, satellite retrievals, and reanalyses, Geophys. Res. Atmos.,120, 6500–6514, doi:10.1002/2015JD023420, 2015.

Wild, M.: Global dimming and brightening: a review, J. Geophys. Res., 114, D00D16, doi:10.1029/2008JD011470, 2009.

Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C. N., Dutton, E. G., Forgan, B., Kallis, A., Russak, V., and Tsevetkov, A.: From dimming to brightening: decadal changes in solar radiation at Earth's surface, Science, 308, 847–850, doi:10.1126/science.1103215, 2005.
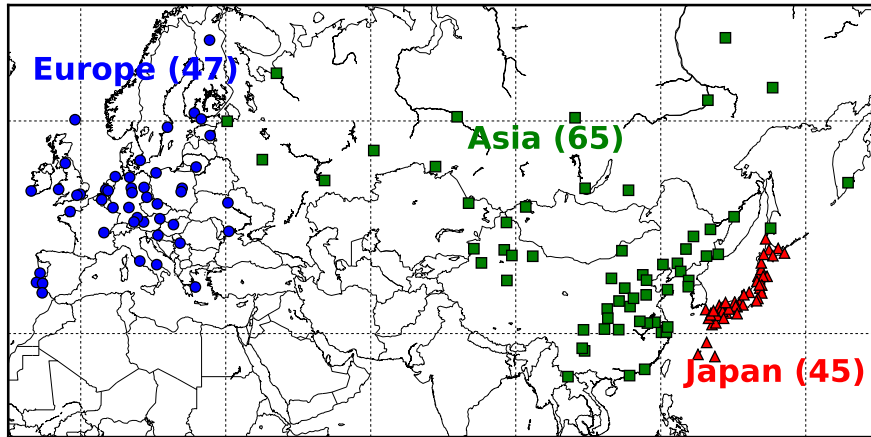
Figure 1. Distribution of the 157 GEBA sites analysed in this study. ~~: 65 Asian (green squares; 39~~ The group "Europe" consists of ~~these are Chinese),~~ 47 ~~European~~ sites (blue circles) and "Japan" consists of 45 ~~Japanese~~ sites (red triangles). The 39 Chinese, 22 Russian and 4 remaining Asian sites were aggregated into the "Asia" group (green squares).
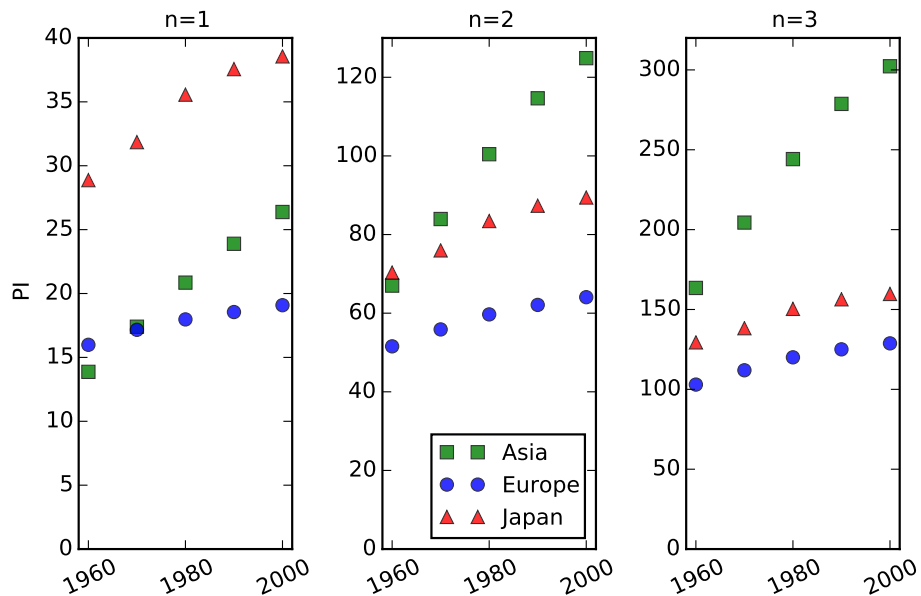

Figure 2. Evolutions of the region-averaged PIs of the sites in Asia, Europe and Japan for the scaling parameters $n = 1, 2$ and 3 (from left to right).

Figure 3. PI Change from 1960 to 1990 of the sites vs. the SSR trend from 1964 to 1989 for the three regions (top to bottom) and for the three scaling parameters $n = 1, 2, 3$ (left to right). The correlation coefficients are indicated within the panels. The * indicates a significant correlation at the 5 % level. The dashed line separates positive and negative SSR trends.
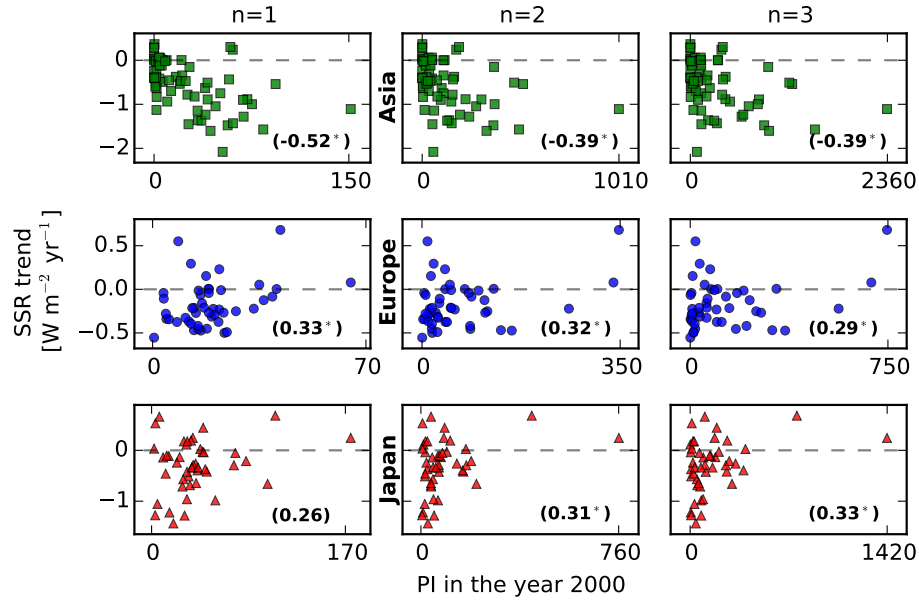

Figure 4. Same as in Fig. 3, but for the absolute PI of the sites in the year 2000 instead of the PI change from 1960–1990.
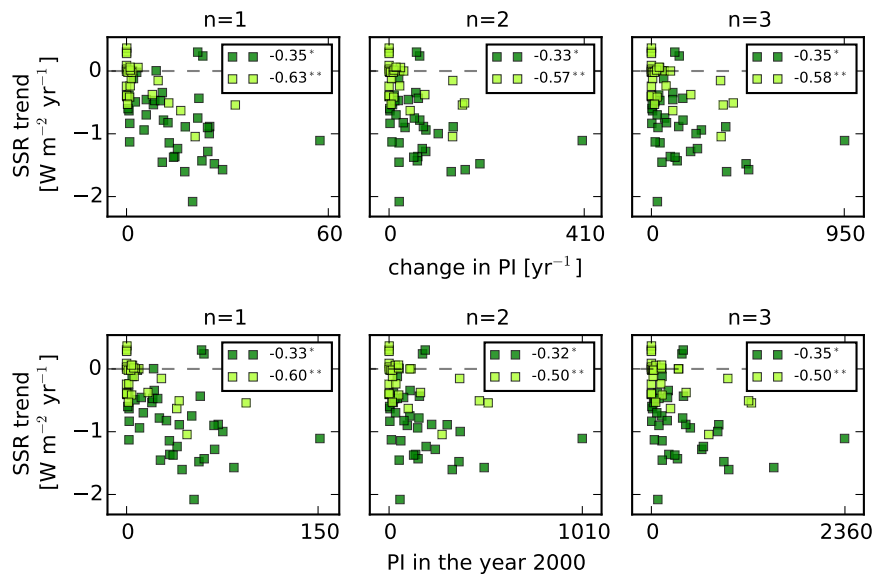
Figure 5. Further split of the 65 Asian sites into the 39 Chinese (darker green) and 26 Non-Chinese, mostly Russian (22) sites (lighter green). The first (second) row of plots shows the same as the first row in Fig. 3 (Fig. 4). The corresponding correlation coefficients are shown in the boxes. Significant correlations at the 5 % (1 %) level are indicated with a * (**).
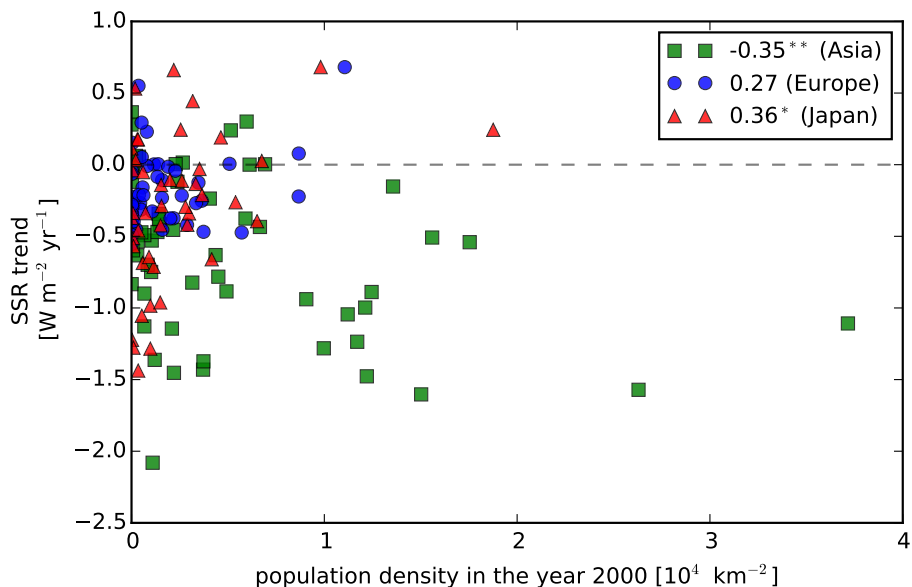

Figure 6. Unweighted population density in the 0.08° cell surrounding the sites in the year 2000 vs. the SSR trend from 1964 to 1989 of the sites in the three regions. Significant correlations at the 5 % (1 %) are indicated with * (**). The dashed line separates positive and negative SSR trends.