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Key Points:

- Urbanization has small impacts on mean and trend of surface solar radiation
- Our estimates are based on urban-rural stations pairs
- Previous estimates include substantial spatial biases

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Urban impacts on mean and trend of surface incident solar radiation

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Abstract Anthropogenic aerosols over urban areas may have important effects on surface incident solar radiation (R_s). Studies have claimed that R_s decreased significantly more in urban areas than in rural areas from 1964 to 1989. However, these estimates have substantial biases because they ignored the spatial inhomogeneity of R_s measurements. To address this issue, we selected urban-rural station pairs collocated within 2° × 2° and found 105 such pairs based on the Global Energy Balance Archive (GEBA). On average, the impact of urban aerosols on mean and trend of R_s is 0.2(0.7, median) ± 11.2 W m^{-2} and 0.1(−0.7, median) ± 6.6 W m^{-2} per decade from 1961 to 1990, respectively. Hence, the averaged urban impacts on the mean and trend of R_s over Europe, China and Japan from 1961 to 1990 are small although they may be significant at specific sites.

1. Introduction

Urbanization may have an important impact on the local climate and environment. Human activities in urban areas release a large amount of pollutants into the air, including primary aerosols and pollutant gases that may form secondary aerosols under suitable conditions. Aerosols reduce the surface incident solar radiation (R_s) through scattering and absorption effects. Aerosols also impact R_s through the complex aerosol-cloud interactions, which may increase or decrease the R_s [*Koren et al.*, 2008; *Stevens and Feingold*, 2009; *Wild*, 2009]. The overall impact of aerosols on R_s has been identified as one of the largest uncertainties in the current understanding of climate change [*Rosenfeld et al.*, 2014; *Stevens*, 2013].

The lack of observations is one of the factors that have hampered a better understanding of the radiative forcing of anthropogenic aerosols [*Rosenfeld et al.*, 2014]. The contrast between urban-rural anthropogenic aerosols provides an opportunity to evaluate the radiative forcing of anthropogenic aerosols. Such studies have been performed by examining the impacts of urbanization on the mean and trend of R_s [*Alpert and Kishcha*, 2008; *Alpert et al.*, 2005; *Stanhill and Cohen*, 2009]. In these studies, the observed R_s records were divided into urban and rural categories according to population density, and their means and trends were averaged into global and hemispheric values [*Alpert and Kishcha*, 2008; *Alpert et al.*, 2005]. The findings indicated that urban areas received 12 W m^{-2} less R_s than rural areas [*Alpert and Kishcha*, 2008], based on the R_s data from the Global Energy Balance Archive (GEBA) [*Gilgen and Ohmura*, 1999]. Furthermore, the R_s decreased by −4.1 W m^{-2} per decade from 1964 to 1989 over urban areas, and by only −1.6 W m^{-2} per decade over rural areas [*Alpert et al.*, 2005]. These results were used as evidence by the fourth Intergovernmental Panel on Climate Change (IPCC) assessment report to refute the "global dimming" of R_s [*Trenberth et al.*, 2007].

To attribute these differences to urban impacts, the methods have an implicit assumption that the urban and rural R_s measurements were homogeneously distributed at global and hemispheric scales. In fact, this assumption is faulty [*Wild*, 2009]. Therefore, the results of *Alpert et al.* [2005] may include significant biases.

We paired closely proximate urban and rural measurements of R_s. For an urban-rural pair, we restricted the differences in longitude and latitude of the R_s measurements from paired urban-rural stations to less than 2°. We found 105 pairs of urban-rural R_s measurements based on the GEBA data, the same data set that was used by *Alpert et al.* [2005] and *Alpert and Kishcha* [2008]. We found that, on average, the urban impact on mean and trend of R_s is 0.2(0.7, median) ± 11.2 W m^{-2} and 0.1(−0.7, median) ± 6.6 W m^{-2} per decade from 1961 to 1990. These results indicate that urbanization has no obvious impact on the mean and trend of R_s although it may be significant at specific sites.

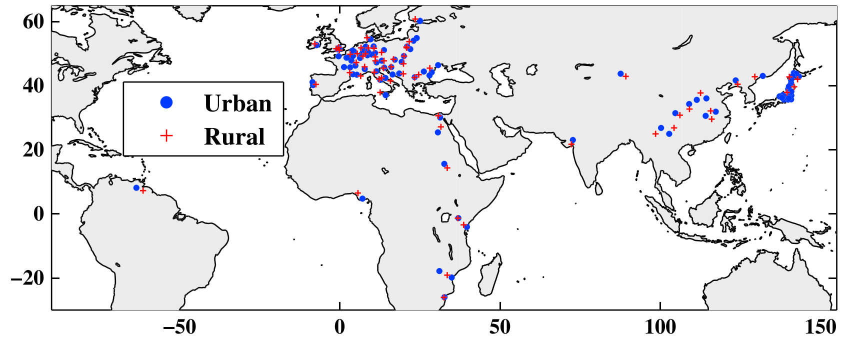

Figure 1. A map of the Global Energy Balance Archive (GEBA) stations where the data duration of surface incident solar radiation (R_s) was longer than 120 months from 1961 to 1990. We paired the R_s measuring urban-rural stations by requiring that their differences in latitude and longitude are less than 2°.

2. Data and Methodology

We used monthly R_s data from the GEBA [*Gilgen and Ohmura*, 1999]. To divide the R_s measurements into urban and rural categories, we used nighttime light data derived from the Defense Meteorological Satellite Program Operational Linescan System (DMSP/OLS) at a spatial resolution of 30 arc-seconds (~1 km) (Version 4) (http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html). The nighttime light data have been widely accepted for use in urban detection [*Hansen et al*., 2010; *Peng et al*., 2012], and the definition of urban areas by *Hansen et al*. [2010] was used here. For comparison with *Alpert et al*. [2005] and *Alpert and Kishcha* [2008], the nighttime light data for the year 2000 were used. In contrast to *Alpert et al*. [2005], we paired the urban-rural stations by requiring that the spatial difference (both latitude and longitude) of each pair was less than 2°. To derive the urban impacts for each month, we only used the R_s data when they were available at both the urban and rural stations. We also required that the lengths of the R_s records at both urban and rural stations to be no less than 120 months (10 years). We found a total of 105 urban-rural pairs that met the above requirements. Most of the available data were from Europe, China, and Japan (Figure 1). The monthly R_s data were used to calculate means and monthly anomalies for trend calculation. The monthly anomalies were calculated by subtracting multi-year averaged monthly R_s from monthly R_s at each station.

3. Results

Our estimates of the urban impact on the mean and trend of R_s are shown in Figure 2. The impact of urbanization on mean R_s differs significantly at specific stations, from $-30\ \mathrm{W\,m^{-2}}$ to $30\ \mathrm{W\,m^{-2}}$. This may be partly caused by the indirect effect of anthropogenic aerosols on clouds, which is related to the climate regimes of the urban-rural pairs [*Koren et al*., 2008] and their relative location. For example, if the rural site is located upwind of the urban areas, it is less likely to reflect the impact of the aerosol indirect effect on the R_s. Other factors, such as synoptic weather systems or topography around the urban and rural stations which may influence the formation of clouds, may partly explain the large spread of urban impact on mean of R_s. Measurement uncertainties may also have a significant impact on the urban-rural contrast of R_s [*Wang et al*., 2012a, 2013]. On average, the impact of urbanization on the mean of R_s is 0.2(0.7, median value) $\pm$ 11.2 $\mathrm{W\,m^{-2}}$.

Similarly, urbanization impacts on trends of R_s vary significantly from station to station (Figure 2). On average, R_s decreased at a rate of $-1.6\ \mathrm{W\,m^{-2}}$ per decade over urban stations and at a rate of $-1.7\ \mathrm{W\,m^{-2}}$ per decade over rural stations from 1961 to 1990. This indicates that urban impact on the trend of R_s is 0.1($-$0.7, median value) $\pm$ 6.6 $\mathrm{W\,m^{-2}}$ per decade.

The decreasing trend of R_s over rural areas reported here is similar to the trend found by *Alpert et al*. [2005] and *Alpert and Kishcha* [2008], i.e., $-1.7\ \mathrm{W\,m^{-2}}$ per decade versus $-1.6\ \mathrm{W\,m^{-2}}$ per decade. However, the dimming trend of R_s over urban areas estimated in this study is substantially smaller than that previously reported [*Alpert and Kishcha*, 2008; *Alpert et al*., 2005], i. e., $-1.6\ \mathrm{W\,m^{-2}}$ per decade versus $-4.1\ \mathrm{W\,m^{-2}}$ per decade. Figure 3 illustrates the reason for this inconsistency. Previous studies did not use the R_s collected from collocated stations to estimate the urban impact. Figure 3 shows that there are many urban R_s stations

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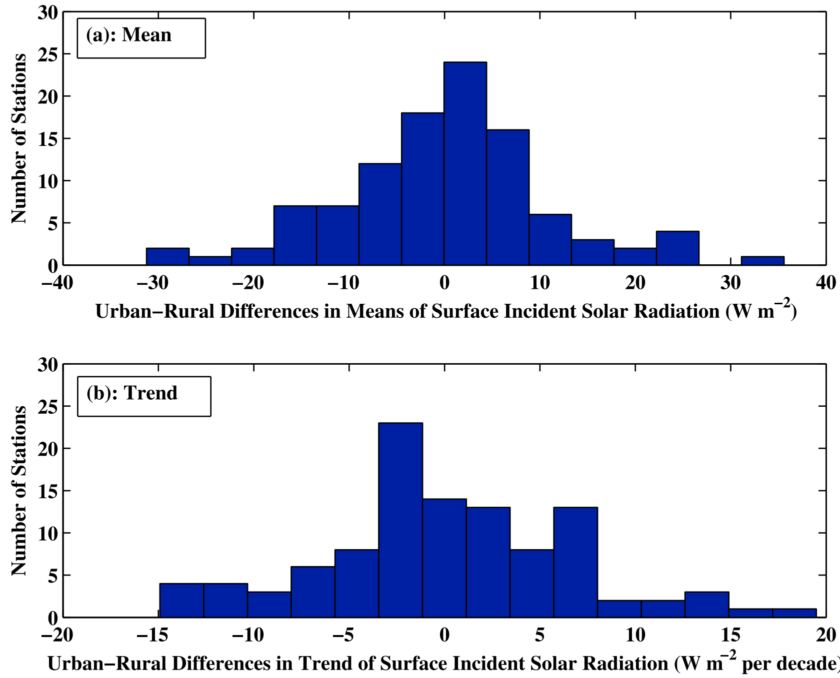

Figure 2. Histograms of the urban-rural differences in (upper) mean and (bottom) trend of the surface incident solar radiation (R_s) at the 105 urban-rural pairs shown in Figure 1. Here the urban-rural differences refer to urban values minus rural values. On average, the impact of urban on mean and trend of R_s is 0.2(0.7, median) ± 11.2 W m^{-2} and 0.1(−0.7, median) ± 6.6 W m^{-2} per decade from 1961 to 1990, respectively.

without rural companions in North America, Africa, and Asia (i.e., India and China) where the R_s decreased at a stronger rate. Long-term R_s trends may be caused by different factors over different areas, i.e., primarily from clouds over the North America [*Augustine and Dutton*, 2013; *Long et al.*, 2009; *Sun et al.*, 2007] and from aerosols in Europe and China [*Norris and Wild*, 2007; *Philipona et al.*, 2009; *Qian et al.*, 2006; *Wang et al.*, 2012b; *Wild*, 2009].

The averaged trend is −1.6 W m^{-2} per decade over urban stations with rural companion stations and is −6.3 W m^{-2} per decade over urban stations without rural companion stations (Figure 3). This introduced substantial bias into the estimates of urban impact on trend of R_s if urban and rural stations in different areas are compared, as performed by *Alpert et al.* [2005] and *Alpert and Kishcha* [2008]. We addressed this issue by quantifying the urban impact on mean and trend of R_s with urban-rural pairs (i.e., Figures 1 and 2).

4. Conclusions and Discussion

Aerosols produced by human activities in urban areas directly reduce the surface incident solar radiation (R_s), whereas they may significantly increase or decrease the R_s through aerosol-cloud interactions. The impact of urbanization on the mean and trend of R_s has been studied by *Alpert et al.* [2005] and *Alpert and Kishcha* [2008] using globally distributed R_s data from GEBA. They found that the R_s decreased significantly more in urban areas than rural areas from 1964 to 1989. These results have been used as evidence by the fourth Intergovernmental Panel on Climate Change (IPCC) assessment report to refute the “global dimming” of R_s [*Trenberth et al.*, 2007].

However, we found that these estimates of urban impacts have significant biases because urban and rural stations in different areas are compared. From 1961 to 1990, the R_s observations at urban stations in North America, Africa, and India did not have rural companion stations within a 2° × 2° surrounding area. Most urban R_s stations with rural companions were located in Europe, Japan, and China. Furthermore, the trends of R_s from 1961 to 1990 had important spatial variability. R_s decreased at a much stronger rate over North America, India, and China than over Europe and Japan (Figure 3). On average, R_s decreased at a rate of −1.6 W m^{-2}

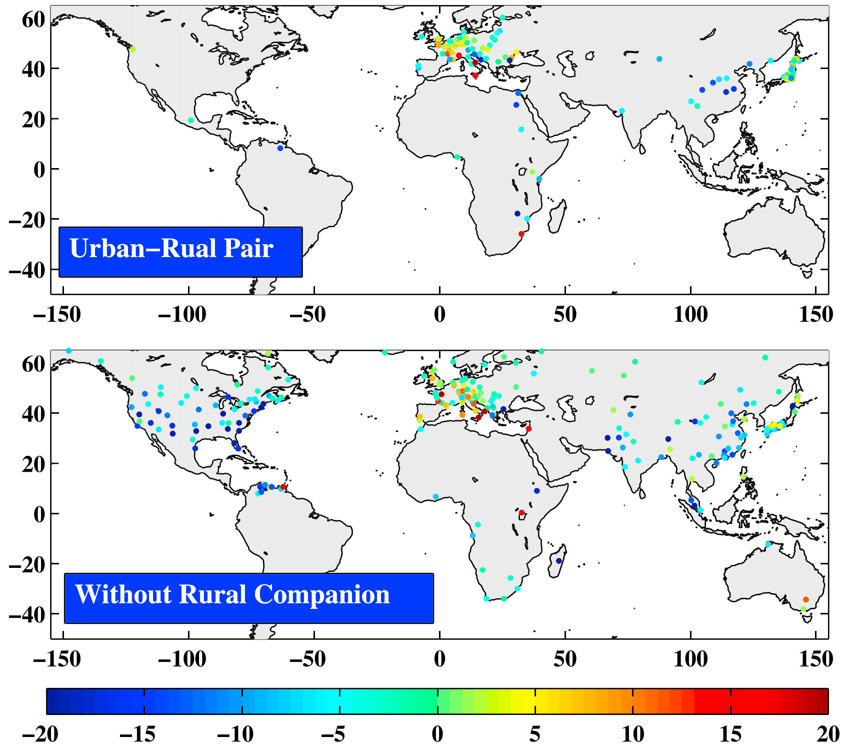

Figure 3. Maps of trends of surface incident solar radiation (R_s) from 1961 to 1990 (unit: W m^{-2} per decade) at urban stations (upper) with and (bottom) without rural companion stations. In this study, we quantified the urban impacts on mean and trend of R_s by using urban stations with rural companion stations (i.e., Figures 1 and 2). There are many urban R_s stations without rural companion stations in North America, Africa, and Asia (i.e., India and China) where the R_s decreased at a stronger rate. The averaged trend was −1.6 W m^{-2} per decade over urban stations with rural companions and was −6.3 W m^{-2} per decade over urban stations without rural companion stations. This introduced substantial biases into the estimates of urban impacts on mean and trend of R_s if urban and rural stations in different areas were compared.

per decade at urban stations with rural companion stations and at a rate of −6.3 W m^{-2} per decade at urban stations without rural companion stations. This introduced significant biases into the estimates of urban impacts on trends.

We investigated the urban impact on mean and trend of R_s by pairing urban and rural stations. We restricted the urban-rural station pairs within 2° × 2° areas, and 105 such pairs were found, mostly located in Europe, Japan, and China. We found that the urban impacts on the mean R_s is 0.2(0.7) ± 11.2 W m^{-2} (the bracketed number is the median value). From 1961 to 1990, the R_s at urban stations decreased by −1.6 W m^{-2} per decade and decreased by −1.7 W m^{-2} per decade at rural stations. The urban impact on the trend of R_s is 0.1(−0.7) ± 6.6 W m^{-2} per decade from 1961 to 1990 (the bracketed number is the median value). Therefore, the averaged urban impact on mean and trend of R_s over Europe, China, and Japan from 1961 to 1990 was small, although it may be significant at specific sites.

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