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Impact of Urbanization on Sunshine Duration from 1987 to 2016 in Hangzhou City, China

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Abstract: Worldwide solar dimming from the 1960s to the 1980s has been widely recognized, but the occurrence of solar brightening since the late 1980s is still under debate—particularly in China. This study aims to properly examine the biases of urbanization in the observed sunshine duration series from 1987 to 2016 and explore the related driving factors based on five meteorological stations around Hangzhou City, China. The results inferred a weak and insignificant decreasing trend in annual mean sunshine duration ($-0.09 \text{ h/d decade}^{-1}$) from 1987 to 2016 in the Hangzhou region, indicating a solar dimming tendency. However, large differences in sunshine duration changes between rural, suburban, and urban stations were observed on the annual, seasonal, and monthly scales, which can be attributed to the varied urbanization effects. Using rural stations as a baseline, we found evident urbanization effects on the annual mean sunshine duration series at urban and suburban stations—particularly in the period of 2002–2016. The effects of urbanization on the annual mean sunshine duration trends during 1987–2016 were estimated to be $-0.16$ and $-0.35 \text{ h/d decade}^{-1}$ at suburban and urban stations, respectively. For urban stations, the strongest urbanization effect was observed in summer ($-0.46 \text{ h/d decade}^{-1}$) on the seasonal scale and in June ($-0.63 \text{ h/d decade}^{-1}$) on the monthly scale. The notable negative impact of urbanization on local solar radiation changes was closely related to the changes in anthropogenic pollutions, which largely reduced the estimations of solar radiation trends in the Hangzhou region. This result highlights the necessity to carefully consider urbanization impacts when analyzing the trend in regional solar radiation and designing cities for sustainable development.

Keywords: sunshine duration; solar radiation; change trend; urbanization effect

1. Introduction

Anthropogenic interference with climate and the hydrological cycle occurs primarily through modification of radiative fluxes in the climate system [1]. Heavily populated cities consume significant amounts of fossil energy sources [2,3]. Consequently, a large number of pollutants are emitted into the atmosphere, which increases the concentration of aerosols in urbanized and industrialized areas [4,5]. Aerosols can attenuate incoming surface solar radiation (SSR) through direct (scattering and solar radiation absorption) and indirect (increasing cloud reflectivity and lifetime) radiative forcings [5,6]. Natural factors—including cloud cover variability and radiatively active gases—can also influence the change in SSR [7–9]. The reduction of solar energy may affect the sustainable development of cities that focus on the use of clean energy. Therefore, determining the long-term changes in SSR and the dominant driving forces is critically important for understanding regional climatic changes and sustainable development of cities [10,11].
Based on SSR data and that of its proxies—such as sunshine duration (SSD) and diurnal surface air temperature range (DTR)—previous studies inferred worldwide solar dimming from the 1960s to the 1980s [12–14]. In contrast, solar brightening since the late 1980s occurred in many regions around the world, including Northwest Italy [11] and South America [15]. However, these observations may contain certain biases from urbanization effects, as many meteorological stations are located within or close to cities (i.e., urban or suburban stations). For example, based on the 172 pairs of urban and nearby rural stations in China, Wang et al. found that the declining rate of sunshine duration in rural areas is around two-thirds of that in urban areas in the dimming phase [12]. Compared with remote stations away from urban areas (i.e., rural stations), urbanization effects—such as increasing atmospheric aerosol—on solar radiation are more pronounced at urban stations [16]. Based on the large Tel Aviv pyranometer network in Israel, Stanhill and Cohen found a maximum urban dimming effect of 7% that was significantly negatively related to the number of vehicles on the roads [17]. This finding highlights the need to further investigate urbanization effects on the long-term changes in solar radiation.

In general, the impacts of urbanization on climate change can be estimated by comparing the difference between the climatic time-series of urban and rural stations [18–20]. This method referred to as urban minus rural (UMR), has been frequently applied in previous urban warming research, with relatively effective and reliable results [21,22]. The UMR method has also been applied to estimate the effects of urbanization on solar radiation changes. For example, based on 105 urban-rural station pairs across the world, Wang et al. found that the impact of urbanization on mean solar radiation at urban stations varied from −30 to 30 W m\(^{-2}\) during 1961–1990 [10]. The UMR method assumes that the SSD trends of rural stations are rarely affected by urbanization, which highlights the importance of accurately identifying and classifying rural stations. The population is one of the most frequently used indexes to reflect the degree of urbanization for station classification [4,12]. While population information is spatially generalized and outdated [17], the urban fraction (UF)—the proportion of urban built-up areas surrounding stations—is a more current and accurate representation of urbanization level [22]. Different indexes used to classify stations may lead to errors in the results, as discussed in existing studies [18,23,24].

China has experienced a dramatic environmental change in response to rapid urbanization, particularly in developed regions [23]. Many studies have reported pronounced urbanization effects on solar radiation in China. For example, using the UMR method, Wang et al. showed that urbanization largely contributed to solar dimming during 1960–1989 in urban areas of China [12]. Based on temperature data at 549 stations, Qian reported that urbanization-related land use/cover change caused a DTR change of −0.051 °C decade\(^{-1}\) during 1979–2008 in East China, inferring a negative impact on solar radiation [13]. Song et al. found that urbanization caused an SSD trend of −0.065 h/d decade\(^{-1}\) during 1961–2014 in East China [14]. In contrast, Wang et al. inferred a small urbanization effect on the solar radiation trend over China during 1961–1990 [10]. The above-mentioned divergences are likely associated with the representativeness of rural stations and the quality of the datasets used [25]. Selecting rural stations with less representative regional climate conditions may underestimate the urbanization effect [24]. Inhomogeneities in the climatic time-series, mainly relating to station relocation, are rarely considered in previous results, which may lead to large uncertainties when estimating urbanization effects on solar radiation [7,23]. Urbanization effects on solar radiation and the uncertainties in detections contributed to the debate on the occurrence of solar brightening since the late 1980s in China [4,6,12].

Previous studies generally attributed urbanization effects on solar radiation to atmospheric pollutions [4,12,26,27]. However, the impact of urbanization on other climatic factors could also affect the variation in solar radiation, which was rarely considered. Notably, cloud cover, which can block the sun, is generally higher in cities than in rural areas due to the urban rain island effect [28]. Therefore, it is necessary to consider the role of the cloud in SSD variations in urban areas. Moreover, urbanization effects may vary...
seasonally and monthly owing to fluctuations in climatic and atmospheric conditions [29], highlighting the need for this research at different temporal scales.

This study thus aims to properly examine how the observed SSD changes are influenced by urbanization from 1987 to 2016 in Hangzhou City, China, at different temporal scales. The findings will answer whether the impact of urbanization will affect the estimation of solar brightening trends and what are the main driving factors. This study would improve our understanding of regional environmental and climatic changes caused by human activities.

2. Materials and Methods

2.1. Study Area

Hangzhou City is located on the East coast of China (Figure 1); it is the capital of Zhejiang province and a central city of the Yangtze River Delta. Hangzhou has a subtropical monsoon climate, with a mean annual precipitation of 1421.7 mm and a mean annual temperature of 16.2 °C [16,30]. The city has experienced rapid urbanization and increased energy consumption in response to economic and population growth since the 1980s. In 2019, Hangzhou’s population size and urbanization level reached 10.36 million and 78.5%, respectively. Urbanization has led to severe environmental issues, including elevated concentrations of anthropogenic aerosols in the Hangzhou region [31].

2.2. Data and Preprocesses

The daily SSD dataset obtained from the National Meteorological Station of China was provided by the China Meteorological Data Service Center (http://data.cma.cn/en). The unit of daily SSD is h/d. Quality control procedures, such as consistency checks and extremum checks, were applied to the SSD dataset. The SSD dataset has been used in many studies on climate variability in China [12].

To avoid the impact of inhomogeneities in the SSD time-series on analysis results caused by station relocation, we only selected meteorological stations that have not been relocated. We selected stations with records covering the period 1987–2016, which is a period of solar brightening [12], dramatic warming [20], and rapid urbanization in China [32]. A total of five stations located near Hangzhou City were selected for this
study (Figure 1). The altitudes of the five stations ranged from 17.5 to 171.4 m, and their mean annual SSDs ranged from 4.5 to 5.1 h/d (Table 1). Missing values at each station accounted for less than 0.05% of the total records, which were estimated using the average SSDs of adjacent days. Monthly, seasonal, and annual mean SSDs were then calculated based on the daily SSD data for each station over the period 1987–2016. Seasons were defined in terms of the international standard of season division, in which spring includes March–May, summer includes June–August, autumn includes September–November, and winter includes December–February [14].

Table 1. Basic information for the selected five meteorological stations near Hangzhou City, China.

| Station Name | Latitude (degree) | Longitude (degree) | Altitude (m) | Distance 1 (km) | SSD 2 (h/d) | UF1990 3 (%) | UF2015 4 (%) | Category |
|--------------|-------------------|--------------------|--------------|----------------|-------------|--------------|--------------|----------|
| Chun'an      | 29.62             | 119.02             | 171.4        | 130            | 5.0         | 0.6          | 1.3          | Rural    |
| Hangzhou     | 30.23             | 120.17             | 41.7         |                | 4.5         | 29.2         | 55.2         | Urban    |
| Ningguo      | 30.62             | 118.98             | 89.4         | 120            | 4.6         | 5.8          | 11.0         | Suburban |
| Shengxian    | 29.60             | 120.82             | 104.3        | 94             | 4.7         | 9.1          | 16.2         | Suburban |
| Wuxian       | 31.07             | 120.43             | 17.5         | 97             | 5.1         | 3.2          | 7.8          | Rural    |

1 distance from a given station to Hangzhou station; 2 mean annual sunshine duration from 1987 to 2016; 3 urban fraction in 1990, which is equal to the proportion of urban built-up areas in the 7 km circular buffer surrounding each meteorological station in 1990. 4 same as 3, but for 2015.

Land cover maps of China in 1990 and 2015 with a resolution of 1 km were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The land-use dataset was acquired by the digital interpretation method using high-resolution remotely sensed images: Landsat 8 OLI and GF-2 remote sensing images [33]. The land cover map contained six land-use types: cultivated land, forest, grassland, water bodies, built-up areas, and unused land. In this study, built-up areas were used to calculate the UF surrounding each meteorological station.

In addition, this study adopted total cloud cover (TCC), total population (TP), and the total number of motor vehicles (TMV) to explore the changes in the atmospheric environment in the urban district of Hangzhou City. TCC data with a resolution of 0.25 degrees were obtained from the fifth-generation ECMWF reanalysis data (ERA5), which were provided by the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/home). This parameter is the proportion of a grid box covered by cloud and varies from 0 to 100%. City data, including TP and TMV, were from Statistical Yearbook issued by the Hangzhou Statistic Bureau (http://tjj.hangzhou.gov.cn/).

2.3. Classification of Meteorological Stations

Based on the study by Song et al. [14], we calculated the UF in the 7 km circular buffer surrounding each station. In general, a larger UF implies a higher urbanization level. However, the thresholds of UF for station classification are inconsistent in previous studies. For example, Liao et al. classified stations with a UF < 15% within circular buffers as rural stations [34]; while Wang and Ge classified stations with a UF > 12% within circular buffers as urban stations [35], Song et al. categorized stations with a UF > 20% as urban stations [14]. In order to reduce the impact of urbanization on the SSD series of rural stations, we adopted a stricter threshold of UF for rural stations (UF2015 < 10%) compared to previous studies mentioned above. Then, the non-rural stations were classified into two categories based on the UF in 2015: a station with low urbanization impact (10% < UF < 20%, suburban station), and a station with a high urbanization impact (UF > 20%, urban station). Finally, Hangzhou station was classified as an urban station, Ningguo and Shengxian stations were classified as suburban stations, and Wuxian and Chun’an stations were classified as rural stations (Table 1). The average distance from Hangzhou station to the remaining four stations is approximately 110 km. Based on previous studies [32,36], the background climate change was expected to be nearly homogenous for these stations. However, the changes in UF from 1990 to 2015 were very different among the five stations, implying different levels in urbanization effects on local climate changes.
2.4. Estimation of Urbanization Effects on SSD Trends

We used SSD as a proxy for solar radiation, as solar radiation and SSD are strongly linearly correlated [25]. We assumed that the trends in SSD at rural stations were free from the effects of urbanization [12]. The SSD reference series was calculated by averaging the SSD series of the two selected rural stations to reflect the impact of background climate change on SSD changes. Based on the UMR method [18], the SSD series of urban and suburban stations were compared with the reference series to quantify the impacts of urbanization on observed SSD changes. The urbanization effect was calculated using the following equation:

\[ \Delta SSD = SSD_u - SSD_r, \]

where \( \Delta SSD \) indicates the difference in the sunshine duration series between urban (suburban) and rural stations in units of h/d; \( SSD_u \) indicates the sunshine duration series of urban or suburban stations (h/d), and \( SSD_r \) indicates the reference series of sunshine duration (h/d).

2.5. Statistical Analysis

Linear trends in annual, seasonal, and monthly mean SSD and \( \Delta SSD \) from 1987 to 2016 were examined using ordinary least-squares regression [3]. The increasing (decreasing) trend in \( \Delta SSD \) indicates an increase (decrease) in SSD in urbanized areas compared to that of the rural areas. In addition, we used ordinary least-squares regression to explore linear trends in annual TCC, TP, and TMV from 2002 to 2016. The significance of the trends in variables was determined using a t-test at significance levels of 0.10, 0.05, and 0.01 [6]. Relationships between TP and SSD, between TMV and SSD, and between TCC and SSD were explored using correlation analyses.

3. Results

3.1. Temporal Changes in SSD

The annual mean SSD series of the three station categories showed similar interannual variations from 1987 to 2016, but their trends were notably different (Figure 2). The annual mean SSD series of rural stations showed a weak and increasing trend during 1987–2016, but that of suburban and urban stations showed decreasing trends. Only the urban station (Hangzhou station) showed a significant change in the annual mean SSD (\( p < 0.01 \)) (Table 2). The annual mean SSD trends for rural, suburban, and urban stations were 0.05, –0.12, and –0.31 h/d decade\(^{-1}\), respectively.

![Figure 2](image-url) Interannual variation in annual mean sunshine duration (SSD) at (a) rural, (b) suburban, and (c) urban stations from 1987 to 2016.
Table 2. Change trends of annual and seasonal mean sunshine duration (SSD) at rural, urban, and suburban stations during 1987–2016.

|                      | Rural Station | Suburban Station | Urban Station | All Stations |
|----------------------|---------------|------------------|---------------|--------------|
| Annual               | 0.05          | −0.12            | −0.31 **      | −0.09        |
| Spring               | 0.41 **       | 0.25 *           | 0.07          | 0.28 *       |
| Summer               | −0.02         | −0.28            | −0.48 *       | −0.21        |
| Autumn               | −0.25         | −0.35 *          | −0.59 **      | −0.35 *      |
| Winter               | 0.11          | 0.01             | −0.13         | 0.02         |

Note: All stations indicate the five selected stations in the Hangzhou region, including two rural stations, two suburban stations, and one urban station. * and ** indicate that the trends in SSD are significant at the 0.05 and 0.01 significance levels, respectively.

We used the average SSD series of the five selected stations to estimate the average trends in SSD for all stations. On average, the annual mean SSD trends for all stations was −0.09 h/d decade$^{-1}$ during 1987–2016, while the seasonal mean SSD trends for all stations ranged from −0.35 h/d decade$^{-1}$ in autumn to 0.28 h/d decade$^{-1}$ in spring. Moreover, SSDs in the three station categories showed extremely different trends between seasons (Table 2). The seasonal mean SSD trends at the rural station occurred in the following descending order: spring (0.41 h/d decade$^{-1}$) > winter (0.11 h/d decade$^{-1}$) > summer (−0.02 h/d decade$^{-1}$) > autumn (−0.25 h/d decade$^{-1}$). The order of the seasonal mean SSD trends at suburban and urban stations was the same as those of the rural stations. The seasonal mean SSD trends of urban (suburban) stations ranged from −0.59 (−0.35) to 0.07 (0.25) h/d decade$^{-1}$. For each season, the rural station showed the largest SSD trend among the three station categories, while urban stations showed the lowest SSD trend.

For rural stations, the monthly mean SSD of six months (January, March, April, May, July, and August) increased from 1987 to 2016, with the largest increasing trend in March (0.63 h/d decade$^{-1}$, $p < 0.01$). November exhibited the strongest decreasing trend in SSD at −0.51 h/d decade$^{-1}$ ($p < 0.05$) (Figure 3). In contrast, for urban stations, only March and April showed increasing trends in SSD, but the trends were weak and insignificant. SSDs in June, October, and November exhibited strong and significant decreasing trends ($p < 0.05$ or 0.01). The monthly mean SSD trends at the urban (suburban) station ranged from −0.98 (−0.58) h/d decade$^{-1}$ in June to 0.25 (0.50) h/d decade$^{-1}$ in March. Overall, for each month, the SSD trend was the largest in the rural station and the lowest in the urban station. The difference in SSD trends between the three station categories highlights the varying degrees of urbanization effects.

![Figure 3](image-url)  
**Figure 3.** Change trends of monthly mean sunshine duration (SSD) at urban, suburban, and rural Scheme 1987 to 2016. 
#, *, and ** indicate that the trends are significant at the 0.10, 0.05, and 0.01 significance levels, respectively.
3.2. Urbanization Effects on SSD Change

On average, the difference in annual mean SSD from 1987 to 2016 between rural and suburban (urban) stations was $-0.42 \pm 0.55$ h/d (Table 3), indicating less SSD in urban areas than that in rural areas due to urbanization effects (e.g., anthropogenic pollution). This phenomenon was also observed at a seasonal scale, particularly in autumn. Additionally, the effect of urbanization on SSD was more severe since the beginning of the 21st century (Figure 4). On average, the urbanization effect on the annual mean SSD from 2002 to 2016 at suburban (urban) stations was $-0.58 \pm 0.87$ h/d, which was more severe than that during 1987–2001 (Table 3). This divergence was also evident for the four seasons—particularly for summer. The average effect of urbanization on summer mean SSD from 2002 to 2016 at the urban station was $-1.09$ h/d, which was more severe than that during 1987–2001 ($-0.18$ h/d).

Table 3. Average effects of urbanization on the annual and seasonal mean sunshine duration (SSD) series at suburban and urban stations over different periods.

| Period       | Suburban Station (h/d) | Urban Station (h/d) |
|--------------|------------------------|---------------------|
|              | Annual | Spring | Summer | Autumn | Winter | Annual | Spring | Summer | Autumn | Winter |
| 1987–2001    | $-0.27$ | $-0.16$ | $-0.16$ | $-0.54$ | $-0.23$ | $-0.24$ | $-0.03$ | $-0.18$ | $-0.51$ | $-0.23$ |
| 2002–2016    | $-0.58$ | $-0.45$ | $-0.66$ | $-0.77$ | $-0.42$ | $-0.87$ | $-0.63$ | $-1.09$ | $-1.11$ | $-0.67$ |
| 1987–2016    | $-0.42$ | $-0.30$ | $-0.41$ | $-0.66$ | $-0.32$ | $-0.51$ | $-0.33$ | $-0.63$ | $-0.81$ | $-0.45$ |

Overall, the annual mean $\Delta$SSD trends at suburban and urban stations were estimated to be $-0.16$ and $-0.35$ h/d decade$^{-1}$, respectively, from 1987 to 2016 ($p < 0.01$) (Figure 4a). Moreover, $\Delta$SSD trends showed large divergence on the seasonal and monthly scales (Figures 4 and 5). $\Delta$SSD trend was stronger in summer than that in spring, autumn, and winter, with the rates of $-0.26$ and $-0.46$ h/d decade$^{-1}$ at suburban and urban stations, respectively. At the urban station, the most rapid decline in $\Delta$SSD was observed in June ($-0.63$ h/d decade$^{-1}$), and the slowest decline in $\Delta$SSD was observed in November ($-0.19$ h/d decade$^{-1}$) (Figure 5). At suburban stations, the most rapid decline in $\Delta$SSD was observed in July ($-0.28$ h/d decade$^{-1}$), and the slowest decline in $\Delta$SSD was observed in February ($-0.01$ h/d decade$^{-1}$) (Figure 5). The declining rates of $\Delta$SSD indicate that urbanization exhibited an increasingly strong impact on SSD in urban areas, particularly in summer.

3.3. Environmental Variations Associated with SSD in Hangzhou City

Because data associated with the atmospheric environment are not available from the earlier period, we adopted TP and TMV to reflect the change in atmospheric aerosols and pollutants resulting from human activities during 2002–2016. TP and TMV exhibited a dramatic increase during 2002–2016 in the urban district of Hangzhou City, which may result in an increase in atmospheric pollution (Figure 6a,b). Moreover, TCC exhibited an increasing trend of 3.2% decade$^{-1}$ during 2002–2016 in the urban district of Hangzhou City ($p < 0.10$) (Figure 6c). Correlation analyses suggested that SSD change was significantly and negatively correlated with the changes in TCC ($r = -0.682$, $p < 0.01$), TP ($r = -0.5292$, $p < 0.05$), and TMV ($r = -0.455$, $p < 0.10$) in Hangzhou City (Figure 6d–f). These results suggested that the increased cloud cover and anthropogenic pollutions could lead to a decrease in SSD in Hangzhou City.
Figure 4. Urbanization effects on (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter variations of sunshine duration ($\Delta$SSD) at suburban and urban stations from 1987 to 2016. Overall, the annual mean $\Delta$SSD trends at suburban and urban stations were estimated to be $-0.16$ and $-0.35$ h/d decade$^{-1}$, respectively, from 1987 to 2016 ($P < 0.01$) (Figure 4a). Moreover, $\Delta$SSD trends showed large divergence on the seasonal and monthly scales (Figures 4 and 5). $\Delta$SSD trend was stronger in summer than that in spring, autumn, and winter, with the rates of $-0.26$ and $-0.46$ h/d decade$^{-1}$ at suburban and urban stations, respectively. At the urban station, the most rapid decline in $\Delta$SSD was observed in June ($-0.63$ h/d decade$^{-1}$), and the slowest decline in $\Delta$SSD was observed in November ($-0.19$ h/d decade$^{-1}$) (Figure 5). At suburban stations, the most rapid decline in $\Delta$SSD was observed in July ($-0.28$ h/d decade$^{-1}$), and the slowest decline in $\Delta$SSD was observed in February ($-0.01$ h/d decade$^{-1}$) (Figure 5). The declining rates of $\Delta$SSD indicate that urbanization exhibited an increasingly strong impact on SSD in urban areas, particularly in summer.

Figure 5. Urbanization effects on the trends of monthly mean sunshine duration ($\Delta$SSD) at suburban and urban stations from 1987 to 2016. #, *, and ** indicate that the trends are significant at the 0.10, 0.05, and 0.01 significance levels, respectively.
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4. Discussion

In this study, we compared the SSD time-series between two rural stations, two suburban stations, and an urban station (i.e., Hangzhou station) in the Hangzhou region to explore the urbanization effects on SSD at different temporal scales. We observed a weak and insignificant increase in the annual mean SSD at the rural stations from 1987 to 2016, with an average trend of 0.05 h/d decade$^{-1}$. This was consistent with the findings of Tang et al., who inferred stable solar radiation across China since 1990 [6]. However, solar radiation variability generally shows large spatial heterogeneity across China [37]. For example, Haerbin underwent a dimming tendency from 1991 to 2010, but Lhasa underwent a brightening tendency [8]. The brightening tendency since the late 1980s was also observed in Germany [9], Italy [11], South America [15], Japan [25], and New Zealand [38]. In contrast, we observed a rapid and significant dimming tendency at Hangzhou Station from 1987 to 2016, with an annual mean SSD trend of $-0.31$ h/d decade$^{-1}$. Suburban stations also exhibited a certain decrease in annual mean SSD. These results highlight the significant divergence of solar radiation changes—even for a relatively small-scale region.

Changes in solar radiation are generally attributed to the role of aerosols, clouds, and radiatively active gases [6,8,9]. Our results suggested that the increased cloud cover and anthropogenic pollutions could lead to a decrease in SSD in Hangzhou station. The same results were found in other regions, including South China [39], the Mediterranean [40], and Poland [41]. However, further analyses exhibited that the increasing trends in TCC for rural and suburban stations were very close to that of urban stations during 2002–2016 in the Hangzhou region (Figures 6c and 7). This indicates a consistent change in cloud cover among the three station categories. Therefore, the difference in SSD trends among the three station categories is mainly caused by the different levels of urbanization effect related to human activities. Alpert et al. also found greater declines in solar radiation in populated urban areas compared to rural areas, which was attributed to the rapid increase in aerosols due to industry activities [26].
Based on qualitative analysis, Li et al. demonstrated that SSD was strongly correlated with visibility under clear-sky conditions in the low-latitude belt of South China [39]. In this study, we found that urbanization effects on the SSD series increased from 1987 to 2016, with significant SSD trends of $-0.16$ and $-0.35$ h/d decade$^{-1}$ at suburban and urban stations, respectively (Figure 4). Our results are consistent with those of Qian [13] and Wang et al. [42], who observed a rapidly decreasing trend in DTR during the brightening phase in China in response to the urbanization effect. However, Wang et al. demonstrated that the brightening tendency since the late 1980s was closely related to the decrease in aerosol concentration following the implementation of policies to control pollution levels in China [12]. This suggests that the negative effect of urbanization on SSD has been reducing in urban areas. The different results may be caused by the difference in study regions and period. Hangzhou is one of the most prosperous cities in China and has experienced rapid economic development, urbanization, population increase, and energy consumption since the late 1980s [3]. As a result, large amounts of pollutants, such as PM$_{2.5}$ and PM$_{10}$, have been emitted into the atmosphere in the Hangzhou region [31]. Chang et al. suggested that past emission policies were unable to adequately control pollution levels in China [43]. Figure 6d,e showed that SSD change was significantly and negatively correlated with the changes in TP and TMV in Hangzhou City, indicating an important role of anthropogenic pollutions in the decreasing SSD trend.

Moreover, urbanization negatively impacted the seasonal SSD variability at suburban and urban stations at varying levels (Figure 4). This may be related to the significant seasonal variation in aerosols due to human activities [29,44]. In North China, pollution concentrations are generally higher in winter than in summer due to increased coal combustion for domestic heating [45]. As a result, the urbanization effect on the SSD trend in winter was found to be higher than that in summer in North China [27]. In contrast, we found that urbanization had a stronger effect on the SSD trends in summer ($-0.46$ h/d decade$^{-1}$) and a weaker effect in winter ($-0.24$ h/d decade$^{-1}$) at the Hangzhou station in South China. Song et al. also noticed greater urbanization effect on summer SSD compared to other seasons [14]. This divergent result can be explained by a number of factors. For example, coal is rarely used for domestic heating in South China due to its warmer climate, and anthropogenic pollution may be more in summer than in winter due to many energy consumptions for cooling [46]. Therefore, the work on energy conservation and emission-reduction are imperative in Hangzhou City, particularly during summer. Moreover, the specific reasons for the considerable differences in the urbanization effects on seasonal SSD change need to be further investigated to shed more light on this disparity.

Since urbanized areas only occupy a small portion of the global land area, the impact of urbanization on solar radiation change is considered a local phenomenon [17,26]. In China, the number of meteorological stations with long-term records—especially for solar radiation observations—are very few and are generally located near cities [6,37]. If urban or suburban stations are used to estimate regionally averaged trends in solar radiation, the dimming trend from the 1960s to the 1980s would be overestimated, but the brightening trend since the 1980s would be underestimated [6,12]. For example, based on the five
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stations selected in this study, the average trend of annual mean SSD in the Hangzhou region was estimated to be $-0.09$ h/d decade$^{-1}$ from 1987 to 2016 (Table 2), which is lower than the average SSD trend at rural stations ($0.05$ h/d decade$^{-1}$).

The strong and significant impacts of urbanization on SSD variations at the Hangzhou station—particularly in summer—reflect a reduction in solar energy received by the urban land surface. This urbanization effect may impact the ecosystem, environment, and land surface energy balance of urban areas. These indirect effects, together with the complicated mechanisms of urbanization effects on the SSD change, highlight the need for further consideration in future studies.

5. Conclusions

In this study, we investigated the trends in SSD recorded at rural, suburban, and urban meteorological stations around Hangzhou City in China. The impacts of urbanization on SSD trends at suburban and urban stations and the related driving factors were explored.

Based on the annual mean SSDs at the five selected stations, a solar dimming trend ($-0.09$ h/d decade$^{-1}$) was observed in the Hangzhou region from 1987 to 2016, which was opposite to previous studies in China. However, SSD variability showed large differences between rural, suburban, and urban stations from 1987 to 2016 at different temporal scales. Using rural stations as a baseline, we found evident urbanization effects on the annual mean SSD series at urban and suburban stations—particularly in the period of 2002–2016. Over the three decades, the impacts of urbanization on the annual mean SSD trends at suburban and urban stations were estimated to be $-0.16$ and $-0.35$ h/d decade$^{-1}$, respectively. Therefore, the solar dimming trend since the 1980s in the Hangzhou region is largely attributed to the effects of urbanization. Moreover, urbanization impacts on the SSD trends showed a large divergence between seasons (months). At Hangzhou station, the strongest urbanization effect was observed in summer ($-0.46$ h/d decade$^{-1}$) on the seasonal scale and in June ($-0.63$ h/d decade$^{-1}$) on the monthly scale. The notable negative impacts of urbanization on local SSD were closely related to the changes in the atmospheric environment due to human activities. The urbanization effect on SSD may significantly impact the ecosystem, environment, and land surface energy balance of urban areas. Therefore, urbanization effects must be considered in future solar radiation research. Moreover, we suggested that the effort on energy conservation and emission-reduction need to be enhanced in Hangzhou City, particularly during summer; optimizing urban wind paths can be taken into account when conducting urban planning to improve urban heat environment and air quality.

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