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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 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 h/d decade^{-1} at suburban and urban stations, respectively. For urban stations, 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 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

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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].

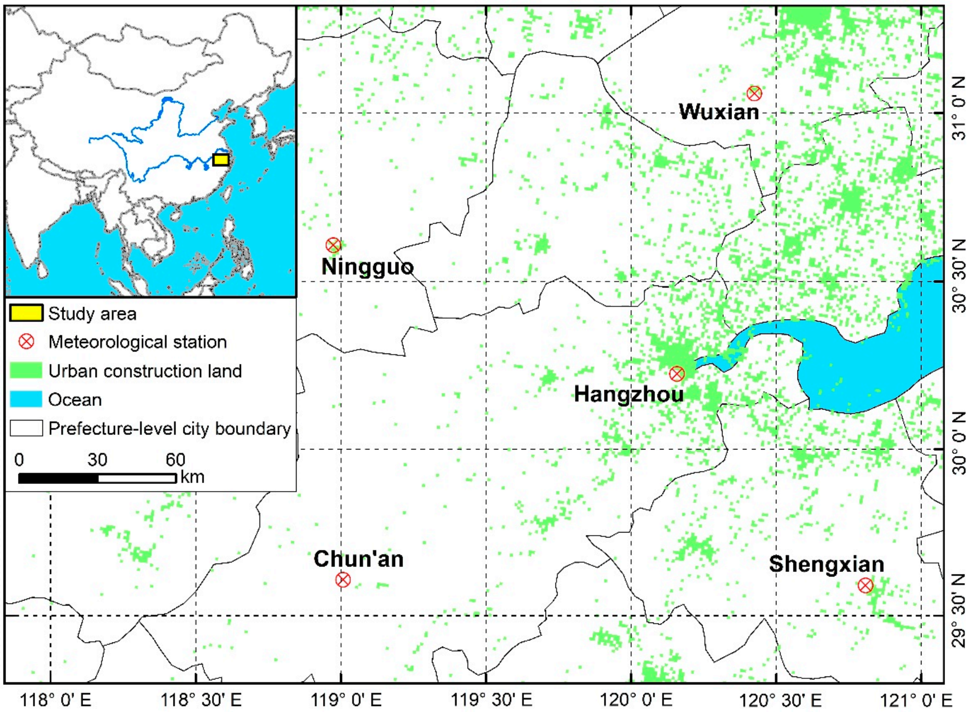

Figure 1. Locations of the five meteorological stations near Hangzhou City, China.

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 *SSD*s 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 *SSD*s of adjacent days. Monthly, seasonal, and annual mean *SSD*s 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)	UF_{1990} [3] (%)	UF_{2015} [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 (UF_{2015} < 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:

$$\Delta SSD = SSD_{\mathrm{u}} - SSD_{\mathrm{r}}, \quad (1)$$

where ΔSSD 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 ΔSSD from 1987 to 2016 were examined using ordinary least-squares regression [3]. The increasing (decreasing) trend in ΔSSD 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.

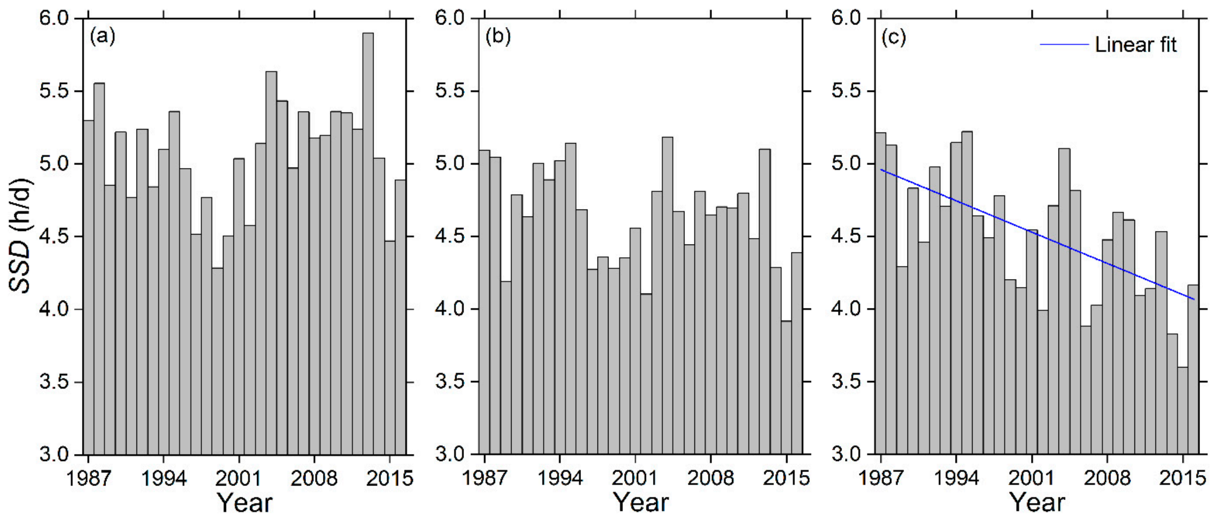

Figure 2. Interannual variation in annual mean sunshine duration (*SSD*) at (**a**) rural, (**b**) suburban, and (**c**) urban stations from 1987 to 2016.

Table 2. Change trends of annual and seasonal mean sunshine duration (*SSD*) at rural, urban, and suburban stations during 1987–2016.

	Trend in *SSD* (h/d decade^{-1})			
	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, *SSD*s 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. *SSD*s 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.

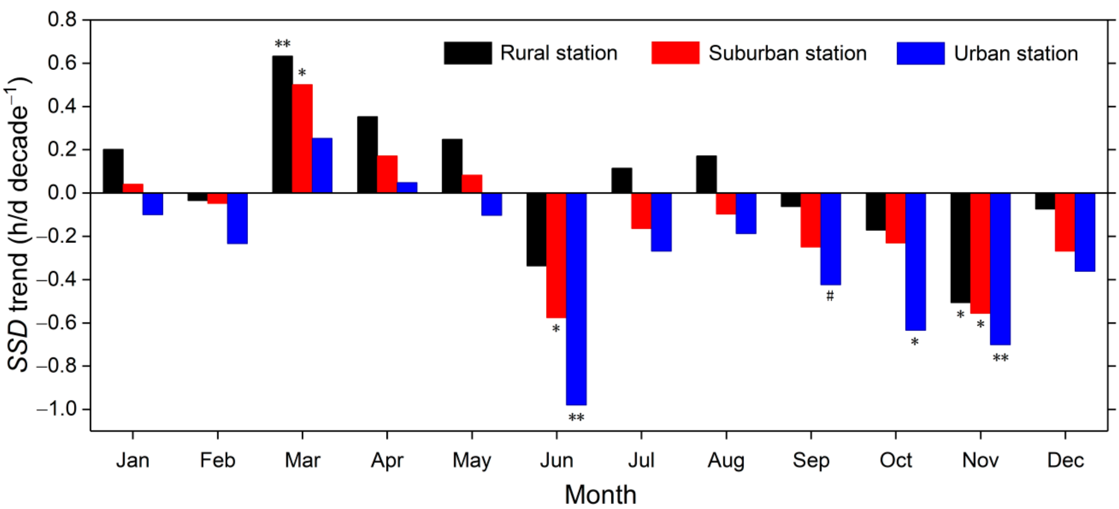

Figure 3. Change trends of monthly mean sunshine duration (*SSD*) at urban, suburban, and rural Scheme 1987. to 2016. #, *, and ** indicate that the trends are significant at the 0.10, 0.05, and 0.01 significance levels, respectively.

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 (−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 (−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	−0.55	−0.33	−0.63	−0.81	−0.45

Overall, the annual mean Δ*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, Δ*SSD* trends showed large divergence on the seasonal and monthly scales (Figures 4 and 5). Δ*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 Δ*SSD* was observed in June (−0.63 h/d decade^{-1}), and the slowest decline in Δ*SSD* was observed in November (−0.19 h/d decade^{-1}) (Figure 5). At suburban stations, the most rapid decline in Δ*SSD* was observed in July (−0.28 h/d decade^{-1}), and the slowest decline in Δ*SSD* was observed in February (−0.01 h/d decade^{-1}) (Figure 5). The declining rates of Δ*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 pollutions 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.

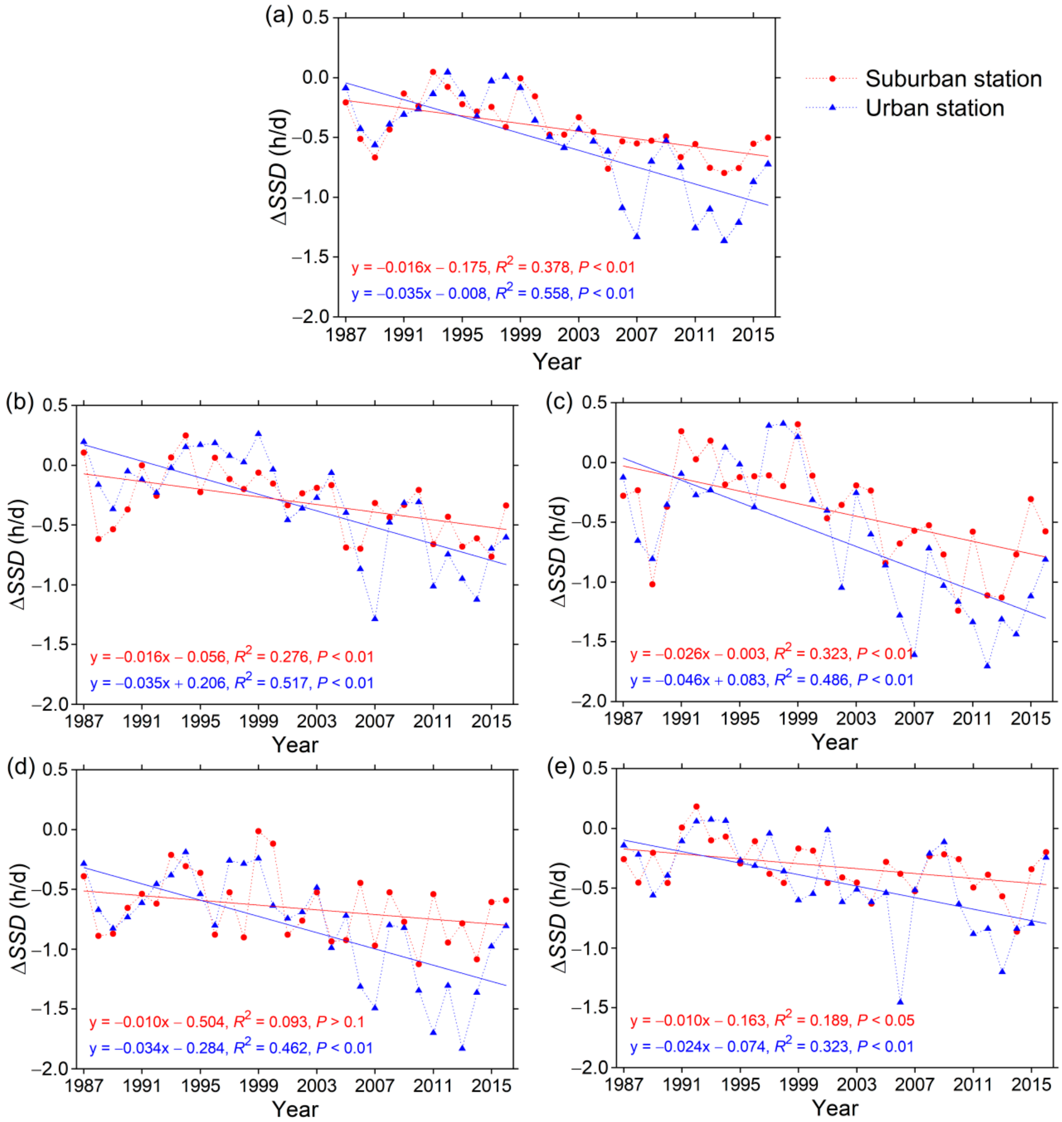

Figure 4. Urbanization effects on (**a**) annual, (**b**) spring, (**c**) summer, (**d**) autumn, and (**e**) winter variations of sunshine duration (Δ*SSD*) at suburban and urban stations from 1987 to 2016.

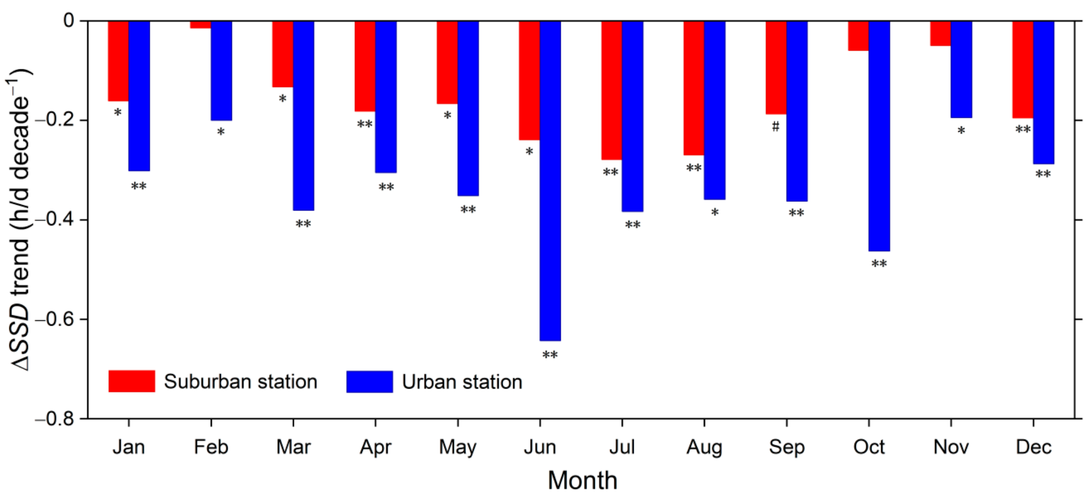

Figure 5. Urbanization effects on the trends of monthly mean sunshine duration (Δ*SSD*) at suburban and urban stations from 1987 to 2016. #, *, and ** indicate that the trends are significant at the 0.10, 0.05, and 0.01 significance levels, respectively.

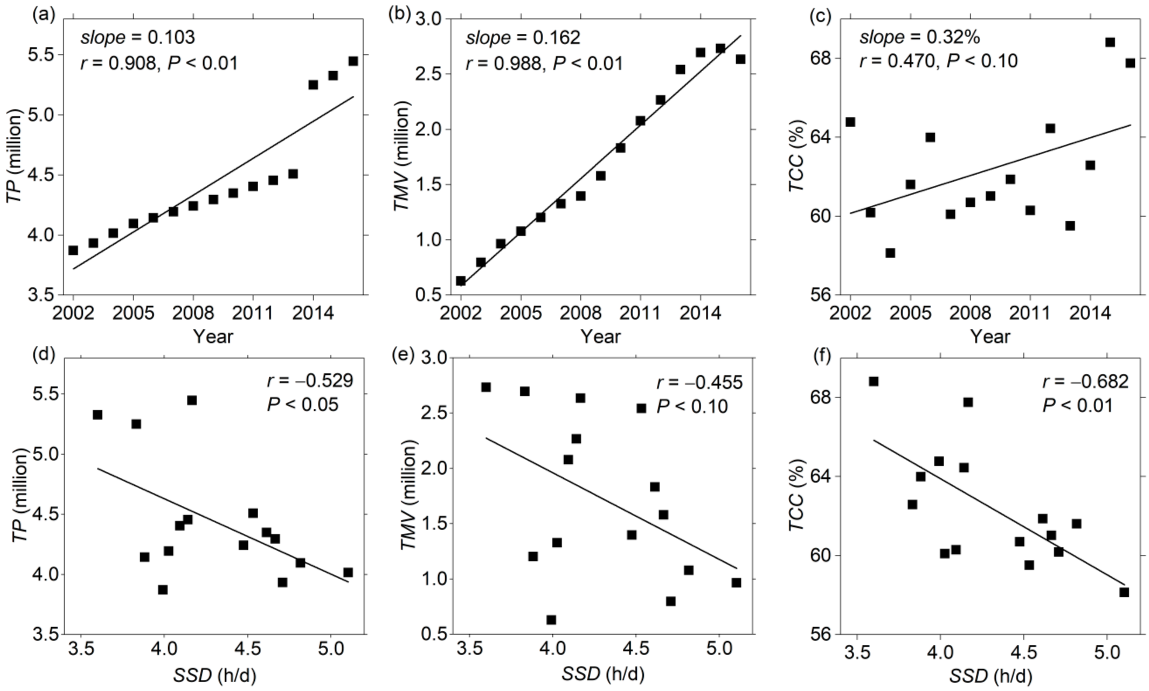

Figure 6. Variations in (**a**) total population (*TP*), (**b**) the total number of motor vehicles (*TMV*), and (**c**) total cloud cover (*TCC*) from 2002 to 2016 in the urban district of Hangzhou City and relationships (**d**) between *TP* and sunshine duration (*SSD*), (**e**) between *TMV* and *SSD*, and (**f**) between *TCC* and *SSD*.

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].

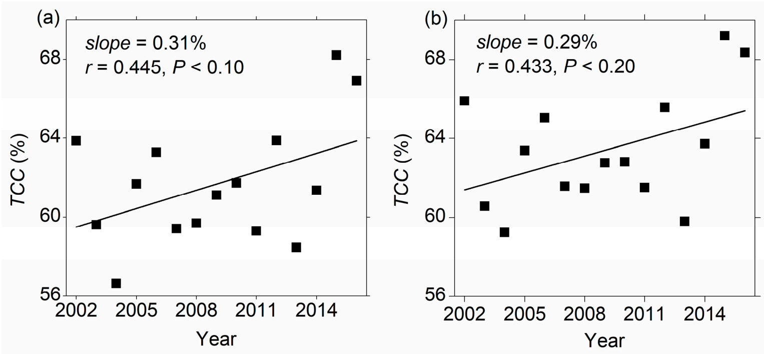

Figure 7. Variations in total cloud cover (*TCC*) from 2002 to 2016 at (**a**) rural and (**b**) suburban stations.

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 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.

Author Contributions: All authors contributed meaningfully to this study. K.J. and S.W. conceived the research topic. K.J., P.Q. designed the methodology, data acquisition, and analysis. P.Q., C.L., and Q.Z. provided methodology support, continuous follow-up of the research process, and K.J. drafted the manuscript. S.W. reviewed the manuscript, provided suggestions on the entire writing process, and polished the manuscript. All authors have read and agreed to the published version of the manuscript.

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References

1. Zhao, T.B.; Li, C.X.; Zuo, Z.Y. Contributions of anthropogenic and external natural forcings to climate changes over China based on CMIP5 model simulations. *Sci. China Earth Sci.* **2016**, *59*, 503–517. [CrossRef]
2. Grimm, N.B.; Faeth, S.H.; Golubiewski, N.E.; Redman, C.L.; Wu, J.; Bai, X.; Briggs, J.M. Global Change and the Ecology of Cities. *Science* **2008**, *319*, 756–760. [CrossRef]
3. Jin, K.; Wang, F.; Wang, S. Assessing the spatiotemporal variation in anthropogenic heat and its impact on the surface thermal environment over global land areas. *Sustain. Cities Soc.* **2020**, *63*, 102488. [CrossRef]
4. Fu, C.B.; Dan, L.; Chen, Y.L.; Tang, J.X. Trends of the sunshine duration and diffuse radiation percentage on sunny days in urban agglomerations of China during 1960–2005. *J. Environ. Sci.* **2015**, *34*, 206–211. [CrossRef] [PubMed]
5. McNeill, V.F. Atmospheric Aerosols: Clouds, Chemistry, and Climate. *Annu. Rev. Chem. Biomol. Eng.* **2017**, *8*, 427–444. [CrossRef]
6. Tang, W.J.; Yang, K.; Qin, J.; Cheng, C.C.K.; He, J. Solar radiation trend across China in recent decades: A revisit with quality-controlled data. *Atmos. Chem. Phys.* **2011**, *11*, 393–406. [CrossRef]
7. Sanchez-Lorenzo, A.; Calbó, J.; Wild, M. Global and diffuse solar radiation in Spain: Building a homogeneous dataset and assessing their trends. *Glob. Planet. Chang.* **2013**, *100*, 343–352. [CrossRef]
8. Liu, J.; Linderholm, H.; Chen, D.; Zhou, X.; Flerchinger, G.; Yu, Q.; Du, J.; Wu, D.; Shen, Y.; Yang, Z. Changes in the relationship between solar radiation and sunshine duration in large cities of China. *Energy* **2015**, *82*, 589–600. [CrossRef]
9. Wild, M. Decadal changes in radiative fluxes at land and ocean surfaces and their relevance for global warming. *WIREs Clim. Chang.* **2016**, *7*, 91–107. [CrossRef]
10. Wang, K.; Ma, Q.; Wang, X.Y.; Wild, M. Urban impacts on mean and trend of surface incident solar radiation. *Geophys. Res. Lett.* **2014**, *41*, 4664–4668. [CrossRef]
11. Manara, V.; Beltrano, M.C.; Brunetti, M.; Maugeri, M.; Sanchez-Lorenzo, A.; Simolo, C.; Sorrenti, S. Sunshine duration variability and trends in Italy from homogenized instrumental time series (1936–2013). *J. Geophys. Res. Atmos.* **2015**, *120*, 3622–3641. [CrossRef]
12. Wang, Y.; Wild, M.; Sanchez-Lorenzo, A.; Manara, V. Urbanization effect on trends in sunshine duration in China. *Ann. Geophys.* **2017**, *35*, 839–851. [CrossRef]
13. Qian, C. Impact of land use/land cover change on changes in surface solar radiation in eastern China since the reform and opening up. *Theor. Appl. Climatol.* **2016**, *123*, 131–139. [CrossRef]
14. Song, Z.Y.; Chen, L.T.; Wang, Y.J.; Liu, X.P.; Lin, L.J.; Luo, M. Effects of urbanization on the decrease in sunshine duration over eastern China. *Urban Clim.* **2019**, *28*, 100471. [CrossRef]
15. Raichijk, C. Observed trends in sunshine duration over South America. *Int. J. Climatol.* **2012**, *32*, 669–680. [CrossRef]
16. Li, H.; Meier, F.; Lee, X.; Chakraborty, T.; Liu, J.; Schaap, M.; Sodoudi, S. Interaction between urban heat island and urban pollution island during summer in Berlin. *Sci. Total Environ.* **2018**, *636*, 818–828. [CrossRef]
17. Stanhill, G.; Cohen, S. Is solar dimming global or urban? Evidence from measurements in Israel between 1954 and 2007. *J. Geophys. Res.* **2009**, *114*. [CrossRef]
18. Ren, G.; Li, J.; Ren, Y.; Chu, Z.; Zhang, A.; Zhou, Y.; Zhang, L.; Zhang, Y.; Bian, T. An integrated procedure to determine a reference station network for evaluating and adjusting urban bias in surface air temperature data. *J. Appl. Meteorol. Climatol.* **2015**, *54*, 1248–1266. [CrossRef]
19. Xu, Y.L. Characteristics of Precipitation in Hangzhou City from 1951 to 2014. *J. Yangtze River Sci. Res. Inst.* **2018**, *35*, 25–29. (In Chinese) [CrossRef]
20. Chao, L.; Huang, B.; Yang, Y.; Jones, P.; Cheng, J.; Yang, Y.; Li, Q. A new evaluation of the role of urbanization to warming at various spatial scales: Evidence from the Guangdong-Hong Kong-Macau region, China. *Geophys. Res. Lett.* **2020**, *47*, e2020GL089152. [CrossRef]
21. Bian, T.; Ren, G.; Yue, Y. Effect of Urbanization on Land-Surface Temperature at an Urban Climate Station in North China. *Bound. Layer Meteorol.* **2017**, *165*, 553–567. [CrossRef]
22. Tysa, S.K.; Ren, G.; Qin, Y.; Zhang, P.; Ren, Y.; Jia, W.; Wen, K. Urbanization effect in regional temperature series based on a remote sensing classification scheme of stations. *J. Geophys. Res. Atmos.* **2019**, *124*, 10646–10661. [CrossRef]
23. Wang, J.; Yan, Z.W. Urbanization-related warming in local temperature records: A review. *Atmos. Ocean. Sci. Lett.* **2016**, *9*, 129–138. [CrossRef]
24. Jin, K.; Wang, F.; Yu, Q.; Gou, J.; Liu, H. Varied degrees of urbanization effects on observed surface air temperature trends in China. *Clim. Res.* **2018**, *76*, 131–143. [CrossRef]
25. Stanhill, G.; Cohen, S. Solar radiation changes in Japan during the 20th century: Evidence from sunshine duration measurements. *J. Meteorol. Soc. Jpn.* **2008**, *86*, 1503–1512. [CrossRef]
26. Alpert, P.; Kishcha, P.; Kaufman, Y.J.; Schwarzbard, R. Global dimming or local dimming?: Effect of urbanization on sunlight availability. *Geophys. Res. Lett.* **2005**, *32*, L17802. [CrossRef]
27. Wang, Y.; Yang, Y.; Zhao, N.; Liu, C.; Wang, Q. The magnitude of the effect of air pollution on sunshine hours in China. *J. Geophys. Res. Atmos.* **2012**, *117*, D00V14. [CrossRef]
28. Liang, P.; Ding, Y. The Long-term Variation of Extreme Heavy Precipitation and Its Link to Urbanization Effects in Shanghai during 1916–2014. *Adv. Atmos. Sci.* **2017**, *34*, 321–334. [CrossRef]

29. Robaa, S.M. A study of solar radiation climate at Cairo urban area, Egypt and its environs. *Int. J. Climatol.* **2006**, *26*, 1913–1928. [CrossRef]
30. Zhang, M.; Song, K.; Da, L. The Diversity Distribution Pattern of Ruderal Community under the Rapid Urbanization in Hangzhou, East China. *Diversity* **2020**, *12*, 116. [CrossRef]
31. Feng, R. Investigating wintertime air pollution in Hangzhou, China. *Air Qual. Atmos. Health* **2020**, *13*, 321–328. [CrossRef]
32. Jin, K.; Wang, F.; Zong, Q.; Qin, P.; Liu, C. An Updated Estimate of the Urban Heat Island Effect on Observed Local Warming Trends in Mainland China's 45 Urban Stations. *J. Meteorol. Soc. Jpn.* **2020**, *98*, 787–799. [CrossRef]
33. Ning, J.; Liu, J.; Kuang, W.; Xu, X.; Zhang, S.; Yan, C.; Li, R.; Wu, S.; Hu, Y.; Du, G.; et al. Spatio-temporal patterns and characteristics of land-use change in China during 2010-2015. *J. Geogr. Sci.* **2018**, *28*, 547–562. [CrossRef]
34. Liao, W.L.; Wang, D.G.; Liu, X.P.; Wang, G.L.; Zhang, J.B. Estimated influence of urbanization on surface warming in Eastern China using time-varying land use data. *Int. J. Climatol.* **2017**, *37*, 3197–3208. [CrossRef]
35. Wang, F.; Ge, Q.S. Estimation of urbanization bias in observed surface temperature change in China from 1980 to 2009 using satellite land-use data. *Chin. Sci. Bull.* **2012**, *57*, 1708–1715. [CrossRef]
36. Wang, F.; Ge, Q.S.; Wang, S.W.; Li, Q.X.; Jones, P.D. A new estimation of urbanization's contribution to the warming trend in China. *J. Clim.* **2015**, *28*, 8923–8938. [CrossRef]
37. Wang, Y.W.; Yang, Y.H. China's dimming and brightening: Evidence, causes and hydrological implications. *Ann. Geophys.* **2014**, *32*, 41–55. [CrossRef]
38. Liley, J.B. New Zealand dimming and brightening. *J. Geophys. Res.* **2009**, *114*, D00D10. [CrossRef]
39. Li, W.; Hou, M.; Xin, J. Low-cloud and sunshine duration in the low-latitude belt of South China for the period 1961–2005. *Theor. Appl. Climatol.* **2011**, *104*, 473–478. [CrossRef]
40. Founda, D.; Kalimeris, A.; Pierros, F. Multi annual variability and climatic signal analysis of sunshine duration at a large urban area of Mediterranean (Athens). *Urban Clim.* **2014**, *10*, 815–830. [CrossRef]
41. Bartoszek, K.; Matuszko, D.; Soroka, J. Relationships between cloudiness, aerosol optical thickness, and sunshine duration in Poland. *Atmos. Res.* **2020**, *245*, 105097. [CrossRef]
42. Wang, K.; Ye, H.; Chen, F.; Xiong, Y.; Wang, C. Urbanization effect on the diurnal temperature range: Different roles under solar dimming and brightening. *J. Clim.* **2012**, *25*, 1022–1027. [CrossRef]
43. Chang, W.; Zhan, J.; Zhang, Y.; Li, Z.; Xing, J.; Li, J. Emission-driven changes in anthropogenic aerosol concentrations in China during 1970–2010 and its implications for PM2.5 control policy. *Atmos. Res.* **2018**, *212*, 106–119. [CrossRef]
44. Xia, X. Spatiotemporal changes in sunshine duration and cloud amount as well as their relationship in China during 1954–2005. *J. Geophys. Res.* **2010**, *115*, D00K06. [CrossRef]
45. Jiang, L.; Bai, L. Spatio-temporal characteristics of urban air pollutions and their causal relationships: Evidence from Beijing and its neighboring cities. *Sci. Rep.* **2018**, *8*, 1279. [CrossRef] [PubMed]
46. Li, R.; Wang, Z.; Cui, L.; Fu, H.; Zhang, L.; Kong, L.; Chen, W.; Chen, J. Air pollution characteristics in China during 2015–2016: Spatiotemporal variations and key meteorological factors. *Sci. Total Environ.* **2019**, *648*, 902–915. [CrossRef] [PubMed]