

Article

The Impact of the Urban Heat Island Effect on Ground-Level Ozone Pollution in the Sichuan Basin, China

Xingtao Song ^{1,2}, Haoyuan Shi ^{1,3}, Langchang Jin ¹, Sijing Pang ¹ and Shenglan Zeng ^{1,*}

¹ Plateau Atmosphere and Environment Key Laboratory of Sichuan Province, School of Atmospheric Sciences, Chengdu Plain Urban Meteorology and Environment Observation and Research Station of Sichuan Province, Chengdu University of Information Technology, Chengdu 610225, China; 202312030051@nuist.edu.cn (X.S.); shihy39@mail2.sysu.edu.cn (H.S.); 3230101068@stu.cuit.edu.cn (L.J.); 2021013080@stu.cuit.edu.cn (S.P.)

² School of Atmospheric Physics, Nanjing University of Information Science and Technology, Nanjing 210044, China

³ School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai 510275, China

* Correspondence: zengsl@cuit.edu.cn

Abstract: With urbanization, ozone (O₃) pollution and the urban heat island (UHI) effect have become increasingly prominent. UHI can affect O₃ production and its dilution and dispersion, but the underlying mechanisms remain unclear. This study investigates the spatial and temporal distribution of O₃ pollution and the UHI effect, as well as the influence of UHI on O₃ pollution in the Sichuan Basin. Atmospheric pollution data for O₃ and NO₂ from 2020 were obtained from local environmental monitoring stations, while temperature and single-layer wind field data were sourced from ERA5-Land, a high-resolution atmospheric reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The results indicate the following: (1) O₃ concentrations in the Sichuan Basin exhibit distinct seasonal variations, with the highest levels in spring, followed by summer and autumn, and the lowest in winter. In terms of spatial variation, the overall distribution is highest in western Sichuan, second highest along the Sichuan River, and lowest in central Sichuan. (2) There are significant regional differences in UHI across Sichuan, with medium heat islands (78.63%) dominating western Sichuan, weak heat islands (82.74%) along the Sichuan River, and no heat island (34.79%) or weak heat islands (63.56%) in central Sichuan. Spatially, UHI is mainly distributed in a circular pattern. (3) Typical cities in the Sichuan Basin (Chengdu, Chongqing, Nanchong) show a positive correlation between UHI and O₃ concentration (0.071–0.499), though with an observed temporal lag. This study demonstrates that UHI can influence O₃ concentrations in two ways: first, by altering local heat balance, thereby promoting O₃ production, and second, by generating local winds that contribute to the diffusion or accumulation of O₃, forming distinct O₃ concentration zones.

Keywords: air pollution; O₃ concentration; UHI; UHI; correlation analysis



Academic Editor: Kei Sato

Received: 19 November 2024

Revised: 15 December 2024

Accepted: 24 December 2024

Published: 26 December 2024

Citation: Song, X.; Shi, H.; Jin, L.; Pang, S.; Zeng, S. The Impact of the Urban Heat Island Effect on Ground-Level Ozone Pollution in the Sichuan Basin, China. *Atmosphere* **2025**, *16*, 14. <https://doi.org/10.3390/atmos16010014>

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

With the accelerated process of urbanization and rapid economic development in China, air pollution has become an increasingly severe global environmental challenge. Particulate matter (PM_{2.5}) and ground-level ozone (O₃) are the primary pollutants responsible for air pollution in many cities and regions across the country [1]. In recent years, significant progress has been made in controlling pollutant emissions, particularly in the treatment of particulate matter, such as PM_{2.5}. In many cities, the concentration of PM_{2.5} has decreased substantially [2,3]. However, ozone pollution remains a prominent issue, especially during

the summer, when ozone concentrations often exceed environmental standards [4]. Unlike particulate matter pollution, ozone (O_3) pollution is more difficult to monitor directly, and its increasing severity and early onset are often not easily detected. Consequently, the growing problem of ozone pollution warrants increased attention [5]. Both domestic and international studies have extensively explored the formation mechanisms of ozone pollution [6–8], the current state of pollution [9], its spatiotemporal distribution patterns, and mitigation strategies [10]. In studies on urban ozone formation mechanisms, the focus has primarily been on precursors and other influencing factors, using both observational and numerical simulation methods for mechanism and source analysis [11]. Furthermore, accelerated urbanization has exacerbated the urban heat island (UHI) effect. Rapid urbanization has altered the nature and structure of the urban underground environment, and, combined with air pollution and artificial waste heat emissions, this disruption of the urban heat balance has contributed to the formation of UHI. The UHI phenomenon refers to the higher temperatures in urban areas compared to surrounding suburban regions. On near-surface temperature maps, suburban temperatures show little variation, while urban areas appear as prominent high-temperature “islands” surrounded by cooler “oceans,” hence the term “urban heat island.” Current research has identified several factors influencing the urban heat balance, including changes in urban substrates [12], anthropogenic heat emissions [13,14], and urban building layout and design [15].

The main factors influencing changes in ozone concentration are precursor emissions and meteorological conditions [16,17]. However, ozone concentrations vary between cities, and their background levels differ [18]. These factors include ozone precursor emissions, meteorological conditions, and the urban heat island (UHI) effect. Research by Zhuang et al. [19] indicates that the relationship between O_3 and its precursors is nonlinear, and the impact on O_3 differs by region and time. Chen et al. found that ozone concentration is significantly negatively correlated with NO_2 and CO concentrations ($p < 0.001$) and significantly correlated with SO_2 concentrations, with the strongest correlation found with NO_2 (-0.553) [20]. Meteorological conditions, a crucial regulatory factor in atmospheric pollution, play a vital role in influencing the concentration changes of ozone and other pollutants. Research by Fang et al. shows that ozone concentration is positively correlated with temperature and linearly correlated with solar radiation [21]. Similarly, Chen et al. found no significant correlation between ozone concentration and precipitation ($p < 0.05$) [20]. Ozone concentration is positively correlated with sunshine hours, wind speed, maximum temperature, and minimum temperature, with correlation coefficients of 0.158, 0.267, 0.724, and 0.703, respectively. An increase in temperature typically raises the reaction rate of ozone precursors, thus promoting ozone formation. Wind speed and atmospheric pressure affect the diffusion and accumulation of ozone, while humidity may further regulate ozone concentration by influencing the rate of photochemical reactions [22].

Moreover, studies have shown that the increase in ozone and precursor emissions caused by the UHI effect and changes in urban meteorological conditions are directly or indirectly related to higher ozone concentrations [23]. While other pollutants, such as PM_{10} , $PM_{2.5}$, and nitrogen oxides, may also be related to maximum temperature effects, their sources, formation, and diffusion mechanisms are more complex, and their relationship with maximum temperature is not as direct. For example, PM_{10} and $PM_{2.5}$ concentrations are primarily influenced by emission sources (such as traffic, industry, and construction) and meteorological factors (such as wind speed and humidity) [24]. The generation and diffusion of these pollutants are more intricate, and their relationship with extreme temperatures is more indirect, requiring more complex models and long-term data for analysis. In contrast, the impact of the UHI effect on cities is mainly reflected in temperature (urban temperatures being higher than those in suburban areas) and wind field changes caused

by UHI (urban winds). Over the years, both domestic and international researchers have conducted in-depth studies on the relationship between the UHI phenomenon and O₃ pollution [25,26]. Existing studies have found that the UHI effect may exacerbate ozone generation and concentration increases by altering local meteorological conditions such as temperature and wind speed [27,28]. For example, an increase in temperature can promote the reaction rate of ozone precursors, while changes in wind fields may influence the diffusion and accumulation of ozone [29]. Wang et al. found a positive correlation between the urban heat island index and O₃ levels in the Yangtze River Delta region [30]. Gray et al. found that in the Chicago area, rising summer temperatures were not the primary cause of increased summer ozone concentrations, as the spatial distribution of ozone did not completely align with the UHI paths [31]. Khiem Mai et al. demonstrated through numerical simulation that UHI plays a significant role in the formation of high ozone concentrations in urban areas [23]. In contrast, Wang Chuhan reported that in the Beijing area, the correlation between the UHI intensity index (UHII) and O₃ concentrations was generally weak, with many stations even showing a negative correlation [27]. Shi et al. conducted research in Chengdu and found a positive correlation between the UHI effect and ozone concentration [32]. In contrast, Zeng et al. showed that the relationship between the UHI effect and ozone concentration is not linear; it is influenced by various natural factors and can exhibit different correlations under different environmental contexts [29].

As a key region in western China, the Sichuan Basin has experienced rapid urban development over the past few decades. This development has led to increased emissions of nitrogen oxides (NO_x) and other ozone precursors due to motor vehicle emissions, industrial pollution, and construction dust. Additionally, natural factors, such as high temperatures and radiation, coupled with reduced precipitation and ongoing industrialization, have contributed to rising O₃ concentrations [33]. Simultaneously, the Sichuan Basin's unique geographical setting has severely limited the diffusion and transport of pollutants [34]. Surrounded by high mountains, the basin effectively shields the movement of external pollutants, resulting in the severe accumulation of pollutants, especially ozone, within the region. Local urban heat island effects and changes in meteorological conditions within the basin may further exacerbate ozone pollution levels. Although some studies have investigated the relationship between ozone and the heat island effect, research specifically focused on southwestern China, particularly the Sichuan Basin, remains limited. Therefore, this study will focus on the Sichuan Basin, exploring the impact mechanisms of urban heat island effects on ozone pollution, analyzing how meteorological changes influence ozone concentrations at the local scale, and providing a scientific basis for air quality management in the region.

2. Materials and Methods

2.1. Overview of the Study Area

The Sichuan Basin, one of China's four major basins, is located in the south-central part of the Asian continent, within southwest China. It encompasses the central-eastern part of Sichuan Province and is encircled by the Qinghai–Tibet Plateau, the Daba Mountains, the Huaying Mountains, and the Yunnan–Guizhou Plateau. The surrounding mountains mostly range in elevation from 1000 to 3000 m, covering an area of approximately 100,000 square kilometers. In contrast, the central basin floor, characterized by lower elevations between 250 and 750 m, spans about 160,000 square kilometers. The Sichuan Basin experiences a humid subtropical monsoonal climate, exhibiting distinct temperature variations across its topography. The eastern part of the basin is warmer than the western part, the southern part is warmer than the northern part, and temperatures are higher at the basin floor than at the edges, creating concentric circles in the isotherm distribution [35].

During summer, average temperatures range from 24 °C to 28 °C, with extreme highs reaching between 36 °C and 42 °C. In winter, average temperatures vary from 4 °C to 8 °C, with extreme lows dipping between −8 °C and −2 °C. Annual precipitation in the Sichuan Basin ranges from 1000 to 1300 mm, but this rainfall is unevenly distributed throughout the year [36]. Winter and spring tend to be dry, while summers are characterized by floods, and autumns experience continuous rainfall. Notably, 70–75% of the annual rainfall occurs during the summer months, from June to October.

Morphologically, the Sichuan Basin is nearly elliptical, covering an area of about 260,000 square kilometers and supporting a population of over 100 million. According to the urban economic development plan, the Sichuan Basin is divided into three regions: the West Sichuan Economic Zone, the Chuanjiang Economic Zone, and the Central Sichuan Economic Zone (Figure 1). The West Sichuan Economic Zone, also known as the West Sichuan Economic Belt, is located in the western part of the Sichuan Basin and includes Chengdu, Deyang, Leshan, Meishan, Ya'an, and Ziyang, with Chengdu serving as the central city. The Chuanjiang Economic Zone occupies the eastern and southern parts of the basin and includes Chongqing, Dazhou, Guang'an, and the Southern Sichuan Economic Zone, which comprises Yibin, Luzhou, Neijiang, and Zigong, with Chongqing as the central city. The Central Sichuan Economic Zone is situated in the north-central part of the basin, encompassing Nanchong, Suining, Guangyuan, Bazhong, and Mianyang, with Nanchong as the central city.

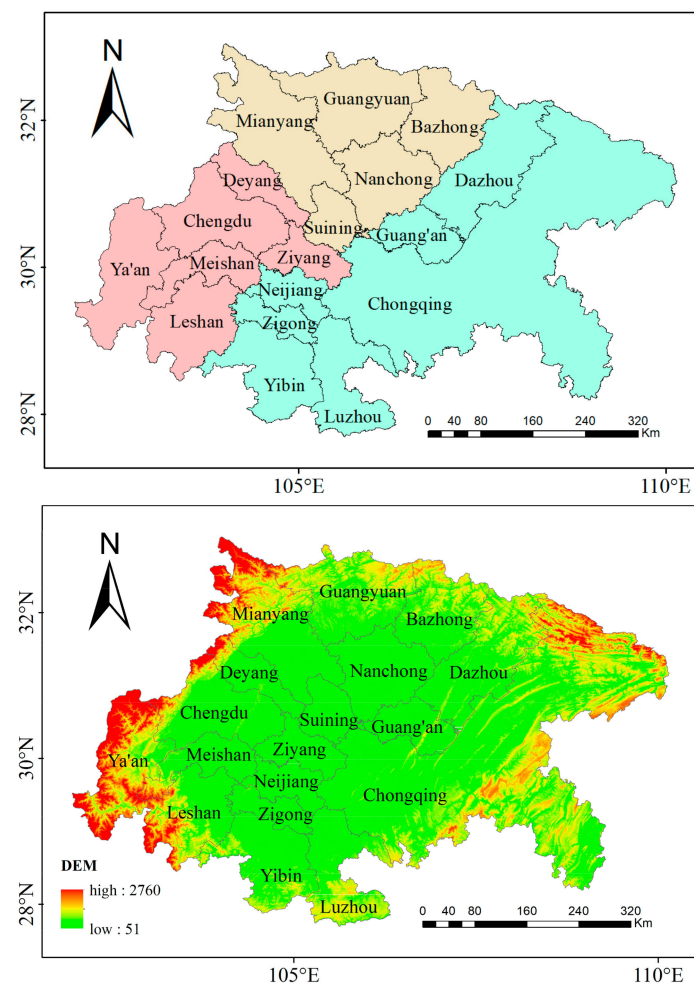


Figure 1. Administrative divisions and topographic elevation map of the Sichuan Basin.

2.2. Profile Overview

The data for O₃ and NO₂ used in this study were sourced from the hourly measurements of 93 monitoring sites across the Sichuan Basin for the years 2020 and 2021, as provided by the China Air Quality Data. The data were meticulously screened in accordance with the Ambient Air Quality Standards (GB3095–2012), and any missing measurements were excluded to ensure accuracy and reliability.

Temperature and wind field data were obtained from the ERA5-Land hourly dataset for 2 m temperatures and the ERA5 single-level horizontal dataset for the 10 m wind u and v components, covering the same period of 2020 and 2021. Due to the complex terrain of Sichuan Province, data from some stations are often missing. Even though there are 156 meteorological monitoring stations, on average, each city only has 2–3 available observation stations. This results in significant spatial discrepancies compared to the 93 pollution monitoring stations. ERA5-Land provides high-quality global grid data, ensuring consistent meteorological information across the entire study area for the entire period, which is crucial for our analysis. Furthermore, the ERA5-Land dataset, provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), has high temporal (hourly) and spatial ($0.1^\circ \times 0.1^\circ$) resolution, offering consistent and reliable meteorological data that meet the temporal and spatial requirements of our study. In contrast, the temporal and spatial resolution of ground-based meteorological stations may be insufficient to meet the analysis requirements. Therefore, this study selected the ERA5 grid data for meteorological analysis.

Since the intensity of the ground-level urban heat island (UHI) effect varies significantly across different times of the day (e.g., daytime and nighttime) [37], regions (e.g., northern and southern China) [38], and seasons [39], selecting data from an entire year helps better reflect the seasonal variations and diurnal differences in the UHI effect. At the same time, long-term UHI studies have shown that the UHI effect undergoes significant changes with the progress of urbanization [40]. In Sichuan, rapid urban development has occurred due to the “Great Western Development” policy, which has led to a rapid change in the UHI effect. To effectively capture these changes and avoid the complexities associated with long time series, this study selects data from 2020–2021, covering all four meteorological seasons.

In recent years, driven by emission reduction policies, particulate matter pollution in the Sichuan Basin has been alleviated to some extent, but ozone pollution has become increasingly severe [41]. Ozone pollution depends on weather conditions and precursor factors [16,17]. Moreover, many studies on the impact of the urban heat island effect on pollutants have shown that the relationship between the urban heat island effect and ozone is more closely related [29,32]. Therefore, we chose ozone and its precursors as the research subjects, as they are currently the most severe pollutants in the Sichuan Basin, rather than all pollutants.

2.3. Data Processing

According to the meteorological classification of seasons, March to May is classified as spring, June to August as summer, September to November as autumn, and December to February as winter for the year 2020.

In this study, O₃ pollution days were identified based on the primary ($100 \mu\text{g}/\text{m}^3$) and secondary ($160 \mu\text{g}/\text{m}^3$) standards specified in the environmental quality standards, allowing us to determine the number of exceedance days for each city in the Sichuan Basin in 2020. The 8 h sliding average was applied to the hourly O₃ concentration data to assess the pollution levels for each day. The 90th percentile of the daily maximum value of the 8 h sliding average of ozone was utilized as the criterion for the seasonal average of O₃ concentrations. ArcGIS 10.8 software was employed to generate the spatial distribution of

O₃ concentrations using the inverse distance weighting interpolation method based on the O₃ concentration data from the national control monitoring stations.

Urban heat island intensity (UHII) is the difference between the average temperature in the central part of the city and the average temperature in the surrounding suburbs, which is used to indicate the intensity of the urban UHI. In this paper, all the cities studied are divided into two parts, urban area and suburban area, using the data of their own county boundaries, and the difference between the average surface temperature of the two parts is the UHII of that time period. According to previous studies [32], UHII is typically classified into five categories: −0.5–0.5 °C (no heat island), 0.5–1.5 °C (weak heat island), 1.5–2.5 °C (medium heat island), 2.5–3.5 °C (strong heat island), and above 3.5 °C (very strong heat island). Based on these classifications, we calculated UHII for the Sichuan Basin in 2020 and determined the percentage of days within each UHII category throughout the year. Using county boundary data, the study divided all 18 cities in the Sichuan Basin into urban and suburban areas. The 2 m hourly temperature data from ERA5 was used to calculate the temperature difference between urban and rural areas, providing hourly UHII values for each city. These values were then averaged to analyze the daily UHII variation. Additionally, the hourly UHII values were averaged to obtain quarterly UHII, and the Kriging interpolation method was applied to analyze the spatial distribution of UHII across different seasons in the Sichuan Basin.

The UHII equation [32] is as follows:

$$T_{UHI} = T_{urban} - T_{rural} \quad (1)$$

$$T_{urban} = \frac{T_{u1} + T_{u2} + \dots + T_{un}}{n} \quad (2)$$

$$T_{rural} = \frac{T_{r1} + T_{r2} + \dots + T_{rm}}{m} \quad (3)$$

where T_{UHI} is UHII; T_{urban} is the average temperature in the urban area, T_{un} is the ambient temperature at the n th site in the city, T_{rural} is the average temperature in the suburban area, and T_{rm} is the ambient temperature at the m th site in the suburban area.

The urban heat island intensity (UHII) provides an overall measure of the UHI effect within a city but falls short of capturing its spatial distribution. To address this limitation, this paper introduces the concept of local UHII characterization, which reflects the spatial characteristics of UHI by calculating UHII for each grid point within the study area. This approach allows for a more detailed and granular understanding of the UHI's spatial variation across different parts of the city.

The equation for local UHII is as follows:

$$I_{UHIIlocal} = (T_{skin} - T_{mean}) / T_{mean}, \quad (4)$$

where $I_{UHIIlocal}$ is the local UHII of an image element, T_{skin} is the surface temperature of a grid point, and T_{mean} is the average surface temperature.

To qualitatively analyze the influence of urban heat islands (UHI) on ozone (O₃) pollution, we examined the correlation between O₃ concentration and UHII in three central cities within the Sichuan Basin—Chengdu, Chongqing, and Nanchong. These cities were selected as typical representatives based on the urban economic development plan. The analysis revealed statistically significant correlations at the two-sided 0.01 level. Previous studies have indicated that O₃ concentrations tend to lag 1–2 h behind temperature changes [42]. Therefore, this study incorporates a lagged correlation analysis to account for this temporal discrepancy. Using the daily average UHII calculated by the previously described method, Chengdu, Chongqing, and Nanchong were categorized into five UHI

intensity levels for the year 2020. The corresponding O₃ concentrations for each UHI level were then analyzed to investigate the impact of urban UHI on O₃ pollution. The statistical analysis and calculations were performed using MATLAB R2021b software.

3. Results

3.1. Spatial and Temporal Distribution Characteristics of O₃

3.1.1. Overview of O₃ Contaminated Areas

As shown in Table 1, in 2020, the number of days when the O₃ concentration in the Sichuan Basin exceeded the ambient air pollutant concentration limit level 1 standard (100 µg/m³) varied between 20% and 50%. Zigong recorded the highest number of exceedance days, accounting for 52.75%. The number of days surpassing the ambient air pollutant concentration limit level 2 standard (160 µg/m³) ranged from 1% to 15%, with Bazhong experiencing the highest proportion at 14.84%. The day-by-day variation in O₃ levels across western Sichuan, the Sichuan River region, and central Sichuan exhibits a consistent pattern. There are more days exceeding the O₃ concentration limits during spring and summer compared to autumn and winter, with the highest O₃ concentrations typically occurring in June and the lowest values predominantly in December (Figure 2).

Table 1. Number of days when O₃ concentration exceeds the standard for cities in the Sichuan Basin in 2020.

Region	City	Days	Exceeds Level 1 Standard	Exceeds Level 2 Standard
Central Sichuan	Guangyuan	364	24.45%	1.37%
	Bazhong	364	41.21%	14.84%
	Nanchong	357	16.25%	1.12%
	Suining	362	27.62%	3.87%
	Mianyang	364	32.42%	7.14%
Western Sichuan	Chengdu	364	32.97%	6.87%
	Leshan	364	33.52%	5.49%
	Deyang	364	30.22%	6.87%
	Meishan	364	29.12%	3.85%
	Yaan	364	21.98%	1.92%
	Ziyang	347	29.39%	2.59%
Sichuan River	Zigong	364	52.75%	2.75%
	Luzhou	364	30.22%	4.12%
	Neijiang	339	30.09%	3.83%
	Yibin	361	32.41%	5.54%
	Chongqing	348	25.29%	5.17%
	Dazhou	361	17.45%	0.28%
	Guangan	364	25.82%	3.30%

3.1.2. Daily Variation of O₃ Concentration

As depicted in Figure 3, the intra-day variation of O₃ concentrations in western Sichuan, the Sichuan River region, and central Sichuan follow a “single peak and single valley” pattern, with O₃ levels reaching their lowest point around 08:00 and peaking around 16:00. This pattern aligns with the findings of Li, Boland et al. [43] and can be explained by the chemical and diffusion processes governing O₃ generation and dissipation. At night, O₃ concentrations decrease due to atmospheric photochemical reactions and near-surface deposition [44]. Additionally, the atmospheric boundary layer height is lower at night [45], and the stabilization of the atmospheric layer inhibits the dilution and diffusion of pollutants. During this period, diesel motor vehicle exhaust emissions may increase,

leading to high concentrations of NO, which continuously consumes O_3 , thus maintaining lower O_3 levels. During the morning peak period around 08:00, significant emissions of pollutants, such as NO_x and VOCs, occur. The resulting increase in NO concentration reacts with O_3 , suppressing its levels and causing minimum values to appear. As the sun rises, NO₂ accumulated overnight begins to photolyze, producing OH radicals that oxidize VOCs. The resulting RO₂ reacts with NO, leading to the accumulation of O_3 . Throughout the afternoon, the strengthening solar radiation, rising temperatures, and increased turbulence enhance the downward transport of O_3 , leading to a peak concentration around 16:00 [42]. After 16:00, the evening peak period causes NO concentrations to rise again, consuming O_3 and reducing its concentration. In addition to these diurnal processes, stationary sources such as transportation, petrochemical industries, coal combustion plumes, and biomass burning emit O_3 precursors. Long-range transport of these pollutants can further elevate O_3 concentrations, contributing to the observed “single peak, single valley” pattern [32].

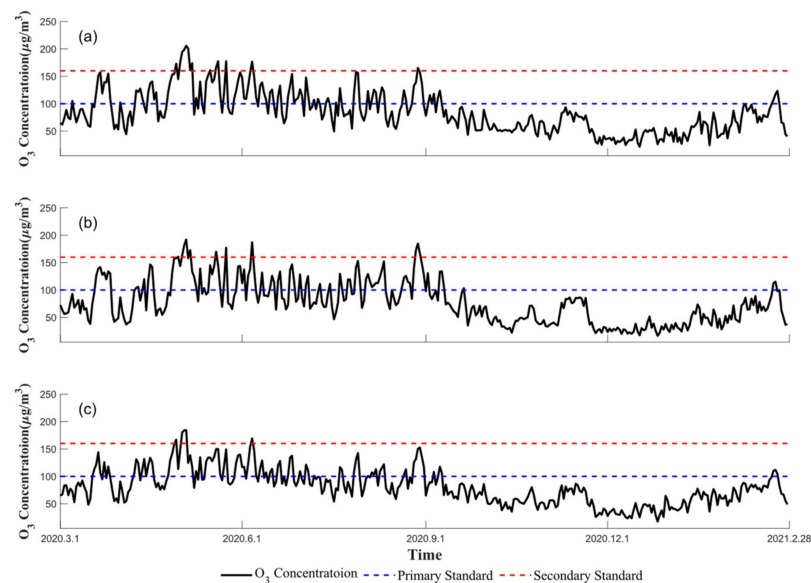


Figure 2. Day-by-day O_3 concentration values in the Sichuan Basin in 2020 ((a): Western Sichuan, (b): Sichuan River, (c): Central Sichuan).

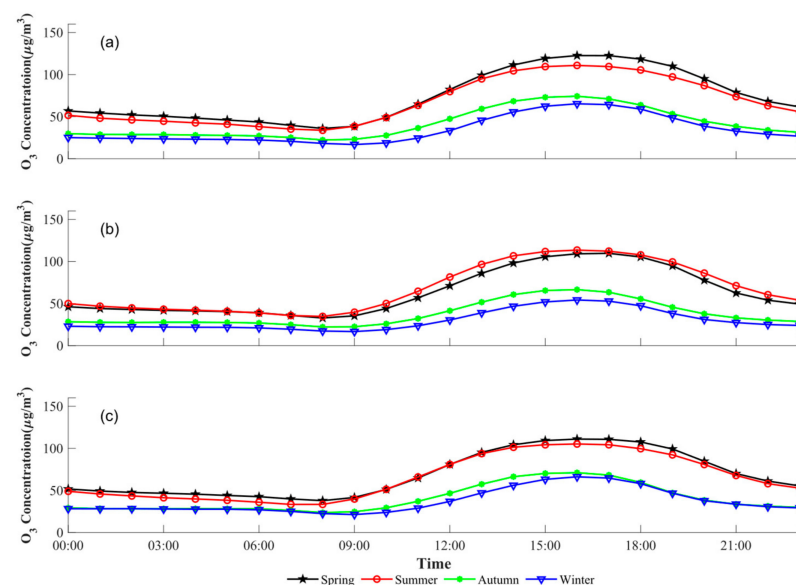


Figure 3. Intraday variation of O_3 concentration in Sichuan Basin in 2020 ((a): Western Sichuan, (b): Sichuan River, (c): Central Sichuan).

3.1.3. Seasonal Variation of O₃ Concentrations

As shown in Figure 4, the seasonal distribution of O₃ concentrations in the Sichuan Basin exhibits a clear pattern, with concentrations highest in spring, followed by summer and autumn, and lowest in winter. Starting from March 2020, the region experienced significantly low precipitation levels, with the most severe drought conditions occurring in May. During this period, average temperatures in May and June were approximately 4–5 °C higher than in previous years [46]. These conditions—low humidity, rising temperatures, still winds, and low precipitation—created an environment highly conducive to elevated O₃ concentrations. Furthermore, the full resumption of work and production in May and June resulted in substantial emissions of O₃ precursors, significantly increasing the contribution of anthropogenic sources. The combination of increased human activity and unfavorable meteorological conditions led to severe O₃ pollution and higher concentrations in the Sichuan Basin during spring. In summer, high levels of sunshine and elevated temperatures accelerate the photochemical reactions that produce O₃. Coupled with more frequent still wind conditions in the Sichuan Basin [47], which hinder pollutant dispersion, these factors contribute to secondary reactions that elevate O₃ concentrations. During winter, a thicker inversion layer and stable atmospheric structure reduce convection, limiting the dispersion of pollutants. This stability leads to the accumulation of NO_x (Nitrogen Oxides, which typically refer to a mixture of NO and NO₂), VOCs (Volatile Organic Compounds), and other O₃ precursors near the surface. Additionally, weaker solar radiation and lower temperatures in winter slow the photochemical reaction rates, resulting in fewer secondary pollutants, including O₃, from primary pollutants like CO, NO_x, and NMHCs (Non-Methane Hydrocarbons). According to Cai Yanfeng et al. [48], high concentrations of particulate matter increase the optical thickness of aerosols, which attenuates UV radiation and can subsequently reduce O₃ formation [49]. Higher PM_{2.5} concentrations in winter further diminish solar radiation, weakening photochemical activity and thus leading to lower O₃ production.

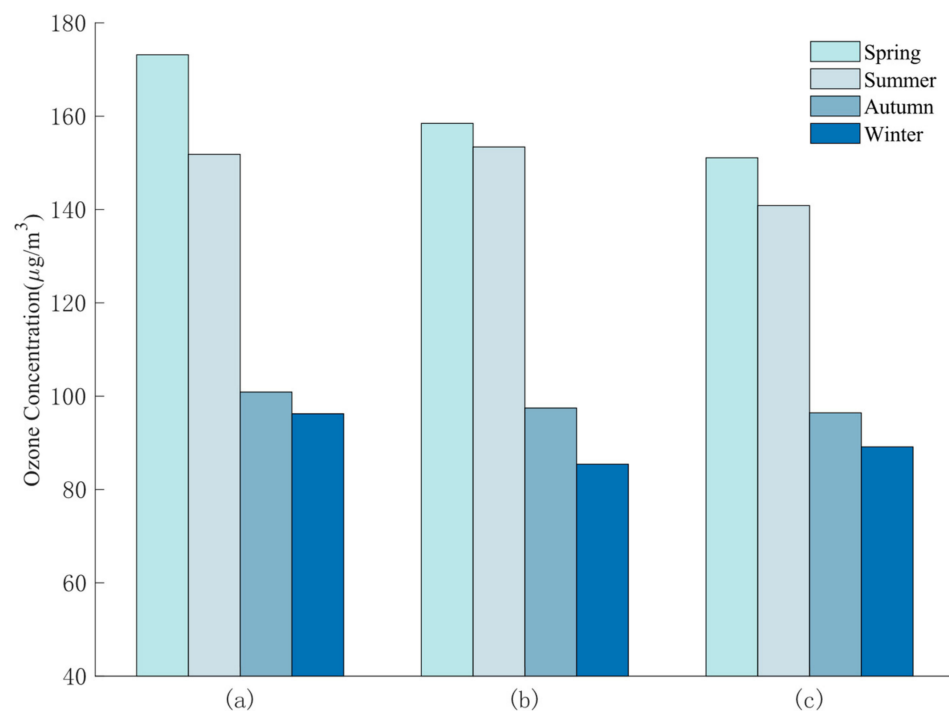


Figure 4. O₃ concentration in the Sichuan Basin by season in 2020 ((a): Western Sichuan, (b): Sichuan River, (c): Central Sichuan).

3.1.4. Spatial Distribution Characteristics of O₃ Concentration

As depicted in Figure 5, the spatial distribution of O₃ concentrations in the Sichuan Basin is highest in western Sichuan, followed by the Sichuan River region, with central Sichuan showing the lowest levels. The region encompassing Chengdu and its surrounding areas in western Sichuan is the economic hub of southwest China. It has a high population density and car ownership, leading to significantly higher emissions of O₃ precursors from anthropogenic sources compared to the Sichuan River and central Sichuan regions. Additionally, this area frequently experiences stagnant and light wind conditions, thick cloud cover, and temperature inversions, which inhibit the dilution and dispersion of O₃, thereby exacerbating ground-level pollution. The Sichuan River region, including Guang'an and its surroundings, is situated in the east-central part of the Sichuan Basin. This region features a topography of central hills and eastern parallel canyons and mountains. The meteorological conditions, characterized by frequent static winds and high humidity, reduce the ability to disperse pollutants. Furthermore, the primary and secondary industries are well-developed in this area, with numerous polluting industrial sources [50]. The central Sichuan region, encompassing Nanchong and its surroundings, experiences cyclonic flow fields due to the unique topography of the Sichuan–Chongqing urban agglomeration, which is higher in the south and lower in the north. This topography facilitates the interaction of winds moving in a counterclockwise direction among cities within the basin, creating a “pollutant stagnation zone” around Zigong and Neijiang. This stagnation weakens regional pollutant transport between cities and hinders the long-distance dispersion of pollutants [51]. In 2020, Bazhong implemented the “Year of Promoting Major Projects” initiative, significantly advancing secondary industry development, following the full resumption of production in May and June. This industrial surge led to severe pollution, and insufficient government control of particulate matter exacerbated O₃ pollution in summer and autumn. Chongqing’s main urban area houses numerous manufacturing enterprises. After the full resumption of production in June, emissions of pollutants increased significantly. The special topography of Chongqing, which is high in the north and south and low in the middle, traps pollutants in the southern part of the city, preventing their diffusion and resulting in high O₃ concentrations during summer.

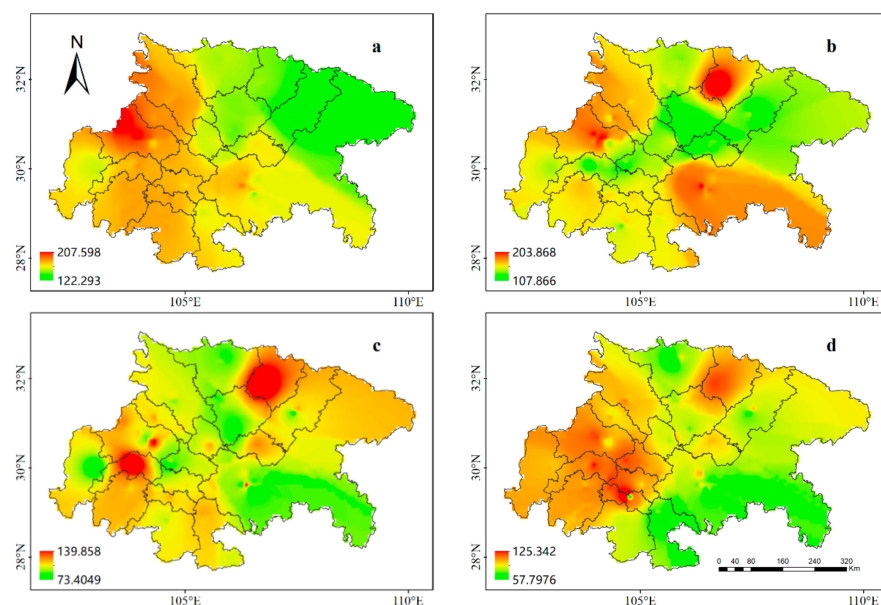


Figure 5. Distribution of O₃ concentration ($\mu\text{g}/\text{m}^3$) in the Sichuan Basin by season in 2020 ((a): spring, (b): summer, (c): autumn, (d): winter).

3.2. Spatial and Temporal Distribution Characteristics of UHI

3.2.1. Characteristics of Temperature Change

As shown in Figure 6, the day-to-day trends in ambient temperature across the Sichuan Basin in 2020 are depicted. The overall temperature patterns are consistent, with notable variations between seasons. In spring, the ambient temperature fluctuates significantly, with a pronounced drop in mid-to-late May. During summer, temperature fluctuations are minimal, consistently hovering around 20 °C. Autumn sees a continuous decline in temperatures, with a marked decrease in late November. Winter temperatures exhibit significant fluctuations, with a warming trend in late January followed by a drop in February. Despite the general consistency in temperature trends across western Sichuan, the Sichuan River region, and central Sichuan, some regional differences are evident. Overall, the Sichuan River region tends to have higher ambient temperatures compared to central and western Sichuan. In 2020, total precipitation across the Sichuan Basin was significantly lower than average, with the Sichuan River region receiving less precipitation than other areas. This region is a major industrial hub, home to numerous manufacturing enterprises that emit substantial anthropogenic pollutants and heat. Consequently, the Sichuan River region experiences higher temperatures than other parts of the basin.

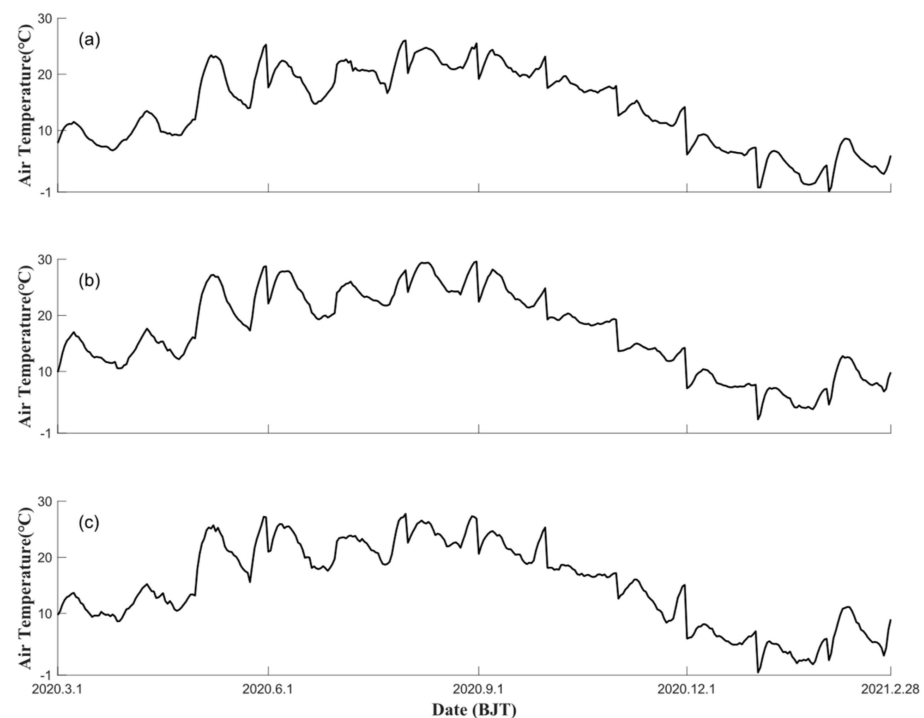


Figure 6. Change in daily average ambient air temperature in the Sichuan Basin in 2020 ((a): Western Sichuan, (b): Sichuan River, (c): Central Sichuan).

As illustrated in Figure 7, ambient temperatures in the Sichuan Basin follow a clear seasonal pattern, with the highest temperatures in summer (approximately 25 °C), followed by autumn and spring, and the lowest in winter (around 5 °C). The central part of the Sichuan Basin, characterized by its low elevation, high population density, significant urbanization, and high car ownership, generally experiences higher temperatures compared to the peripheral cities at the basin's edge, which are at higher elevations and less urbanized. Among the cities within the basin, temperature differences are generally minimal, with the notable exception of Ya'an. Due to its higher altitude, Ya'an consistently exhibits slightly lower temperatures compared to other cities in the region.

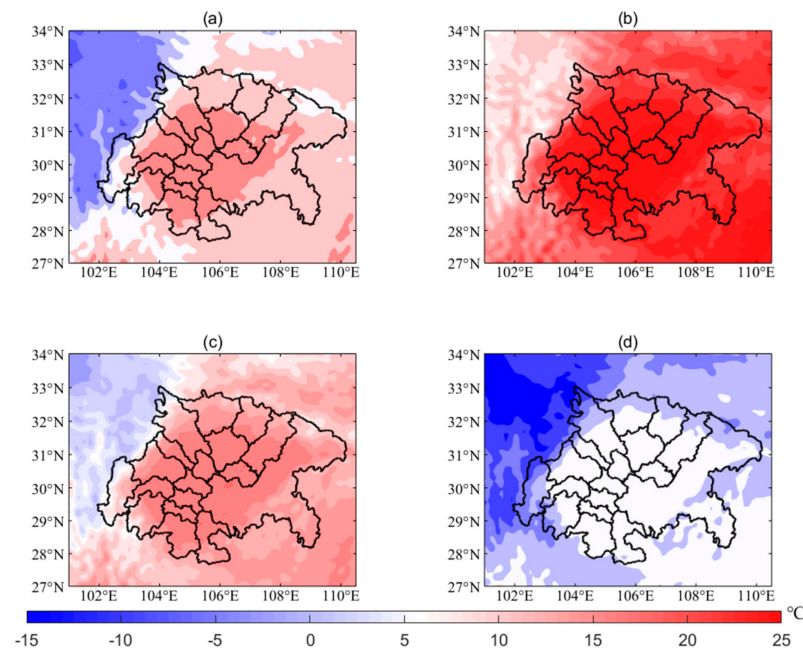


Figure 7. Spatial distribution of seasonal changes in ambient air temperature (°C) in the Sichuan basin ((a): spring, (b): summer, (c): autumn, (d): winter).

3.2.2. Daily Variation of UHII

As shown in Figure 8, the daily variation in urban heat island intensity (UHII) across different regions of the Sichuan Basin is illustrated. In western Sichuan, UHII shows significant fluctuations, with a sharp increase starting at the end of April, peaking in early May, followed by a decreasing trend and another rise in December. In contrast, the Sichuan River and central Sichuan areas exhibit smaller daily variations in UHII. Both regions experience slightly lower UHII values in summer and autumn and slightly higher values in winter and spring. According to the classification method of heat island intensity values (Table 2), western Sichuan predominantly experiences medium heat island conditions (278 days), with 6 days classified as very strong heat island. The Sichuan River region is mostly characterized by weak heat island conditions (302 days) with occasional medium heat island days. Central Sichuan primarily has no heat island (127 days) and weak heat island conditions (232 days). The data indicate that, overall, UHII is highest in western Sichuan, particularly in Chengdu and Ya'an. Chengdu's high UHII can be attributed to its dense population, extensive industrial activities, significant energy consumption, and high anthropogenic heat emissions [52]. Ya'an, on the other hand, has a unique topography, where the main urban area is at a lower altitude while surrounding townships are at higher altitudes. The large vegetative cover in these townships helps regulate temperature, increasing the temperature difference between urban and rural areas [53]. UHII is lowest in central Sichuan, which is much less urbanized compared to Chengdu in western Sichuan and Chongqing in the Sichuan River region. The lower degree of urbanization results in fewer anthropogenic heat emissions and consequently, a lower UHII.

Table 2. Total number of days of heat island rating by region in the Sichuan Basin in 2020.

Region	No Heat Island	Weak Heat Island	Central Heat Island	Strong Heat Island	Extremely Strong Heat Island
Western Sichuan	0	21	278	60	6
Sichuan River	0	302	63	0	0
Central Sichuan	127	232	6	0	0

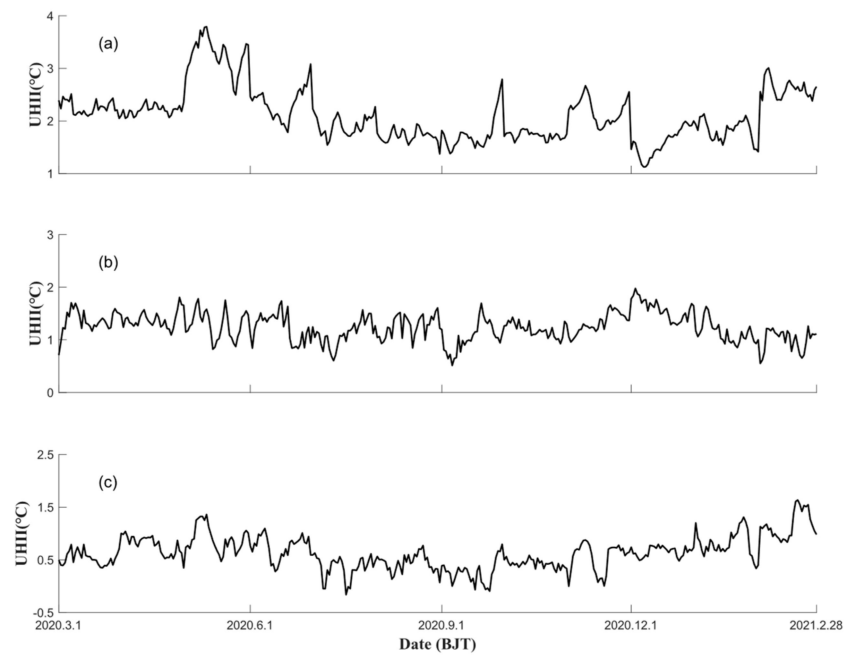


Figure 8. Daily variation of UHII in different areas of the Sichuan Basin in 2020 ((a): Western Sichuan, (b): Sichuan River, (c): Central Sichuan).

3.2.3. Intraday Variation of UHII

As depicted in Figure 9, the intra-day variation of the urban heat island intensity (UHII) in western Sichuan follows a “single-peaked” pattern throughout all seasons, with the peak UHII occurring around 10:00. Seasonally, the intra-day variation of UHII is more pronounced in spring, and the UHII values are significantly higher than in other seasons. In contrast, the intra-day variation of UHII in the Sichuan River region is minimal, with UHII remaining relatively constant between 13:00 and 23:00, and slightly higher in spring compared to other seasons. In central Sichuan, the UHII patterns differ between winter and other seasons. During winter, UHII is higher at night than during the day, reaching a trough at 9:00. In other seasons, daytime UHII is higher than nighttime, peaking between 9:00 and 10:00.

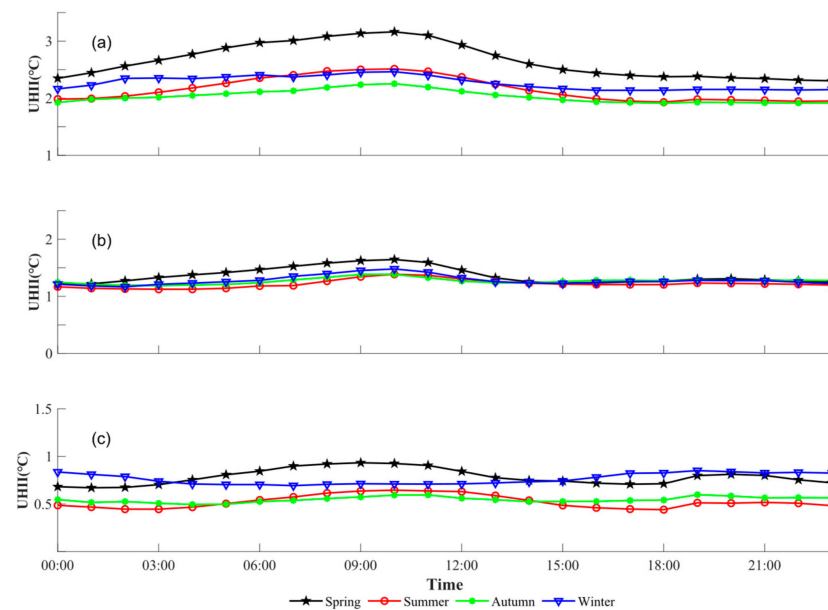


Figure 9. Intraday variation of UHII in different areas of the Sichuan Basin in 2020 ((a): Western Sichuan, (b): Sichuan River, (c): Central Sichuan).

3.2.4. Spatial Variation of UHII

As shown in Figure 10, urban heat island intensity (UHII) in the Sichuan Basin follows a predominantly circular distribution pattern. Central cities, such as Nanchong, Suining, Guang'an, Ziyang, Zigong, and Neijiang, exhibit lower UHII, while higher UHII is observed in cities closer to the center of the basin. UHII decreases towards the basin edges, with some areas even exhibiting a cold island phenomenon. This pattern can be attributed to several factors. The Sichuan Basin is surrounded by mountains with high vegetation coverage, which effectively mitigates the UHI effects, resulting in cold islands in edge cities [54]. Additionally, intermediate cities have smaller sizes and lower population densities compared to areas around Chengdu and Chongqing. Moreover, these intermediate cities experienced more precipitation in 2020, which has a known negative effect on UHI [55]. Ya'an exhibits a higher UHII due to its unique topography, where the main urban area is at a low altitude and the surrounding townships are at higher altitudes with substantial vegetation cover, enhancing temperature differences between urban and rural areas. Mianyang has intensified efforts in attracting investment, developing primary and secondary industries, and accelerating urban development, leading to increased anthropogenic heat emissions and exacerbated UHI. Chongqing's main urban area hosts numerous manufacturing enterprises, and both population and building densities are high. The tall buildings in the urban area reduce wind speeds, hindering the dispersion of heat and pollutants [56], thereby aggravating the UHI effect.

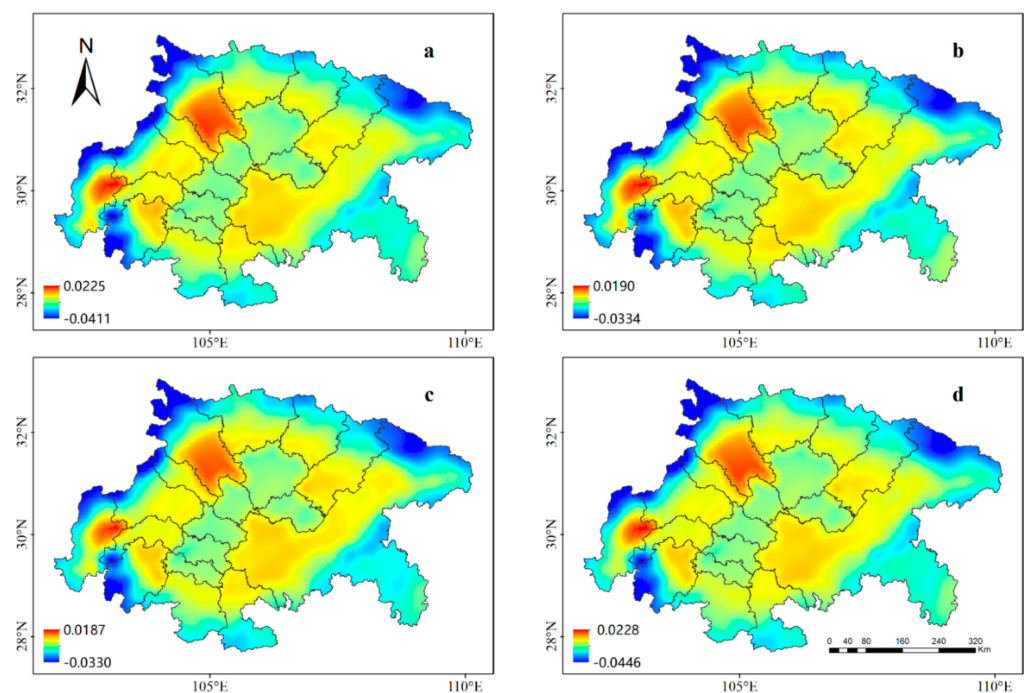


Figure 10. Local UHII distribution (°C) by season in the Sichuan Basin in 2020 ((a): spring, (b): summer, (c): autumn, (d): winter).

3.3. Effect of UHI on O₃ Pollution Characteristics

3.3.1. Correlation Analysis of O₃ Concentration and UHII

As presented in Table 3, the lagged correlation coefficients between O₃ concentration and UHII for each season range from 0.355 to 0.642 in Chengdu, 0.044 to 0.348 in Chongqing, and −0.014 to 0.181 in Nanchong, all of which pass the significance test at the two-sided 0.01 level. Despite the lag effect, a positive correlation between O₃ concentration and UHII is generally observed. Urban UHI alters the regional heat balance, accelerating local temperature changes and enhancing the activity of urban atmospheric photochemical

reactions, which in turn increases O_3 concentration. Additionally, stored heat post-sunrise can maintain higher temperatures even as sunlight intensity decreases, causing a lag in peak O_3 concentration. Xin Li et al. reported a 1–2 h lag of O_3 concentration relative to temperature, supporting the observed lag correlation [42]. Furthermore, He Jing et al. found that O_3 production and consumption are primarily controlled by local photochemical reactions and are closely related to precursor concentrations (NO , NO_2 , NO_x), alongside meteorological factors such as solar radiation [57]. This also highlights the weak direct relationship between the UHII and O_3 concentrations. Dan Shang Ming et al. noted that water bodies can buffer urban UHI effects, contributing to the lower correlation between the UHII and O_3 in Chongqing and Nanchong due to the influence of the Jialing River [58].

Table 3. Intraday variation of O_3 concentration and UHII in typical cities of the Sichuan basin by season.

City		Spring	Summer	Autumn	Winter	Year-Round
Chengdu	Correlation	0.642 **	0.574 **	0.355 **	0.401 **	0.499 **
	Hysteresis	9	9	9	9	9
Chongqing	Correlation	0.159 **	0.348 **	0.149 **	0.044 **	0.167 **
	Hysteresis	8	6	7	7	7
Nanchong	Correlation	0.181 **	0.078 **	−0.014 **	0.103 **	0.071 **
	Hysteresis	1	5	1	1	1

** Indicates significant correlation at the 0.01 level (two-sided).

As illustrated in Figure 11, the daily trends of O_3 and UHII in Chengdu and Chongqing across different seasons, as well as in Nanchong during winter, generally follow a “single peak and single valley” pattern. However, in Nanchong, the UHII pattern in other seasons shows “multiple peaks and multiple valleys.” There is a notable lag between the peak UHII and O_3 concentrations (Table 3). In Chengdu, the peak O_3 concentration lags 9 h behind peak UHII, while in Chongqing and Nanchong, the lag varies seasonally: in Chongqing, the peak O_3 concentration lags 8 h in spring, 6 h in summer, and 7 h in autumn and winter; in Nanchong, the lag is 1 h in spring and autumn and 5 h in summer. This lag is influenced by the diurnal variations in solar radiation and the dynamics of O_3 production and consumption.

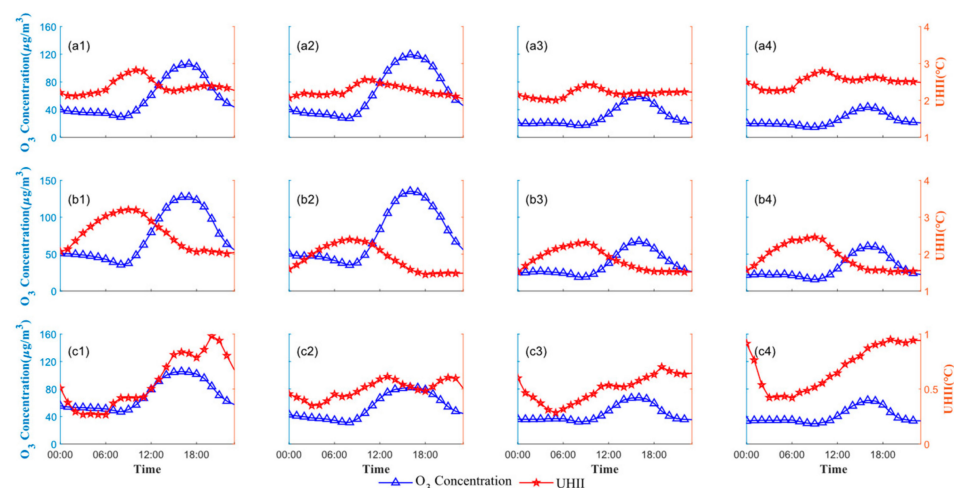


Figure 11. Daily variation of O_3 concentration and UHII in typical cities in the Sichuan basin ((a): Chengdu, (b): Chongqing, (c): Nanchong; (1): spring, (2): summer, (3): autumn, (4): winter).

3.3.2. Effect of UHI on the Spatial Distribution Characteristics of O_3 Pollution

As shown in Figures 12 and 13, the spatial distribution differences of O_3 across various UHII levels are illustrated. Under the influence of a very strong heat island effect,

O₃ concentration and UHI are relatively high in the main urban areas of Chengdu (Jinniu District and Chenghua District) and the northern parts of these districts, as well as in Chongqing's Hechuan District, Changshou District, and Fengdu County. Conversely, O₃ concentration and UHI are lower in areas like Dujiangyan City and Chongzhou City in western Chengdu, and Wuhou District, southern Jinjiang District, and northern Shuangliu District in Chengdu, and Banan District and Nan'an District in Chongqing.

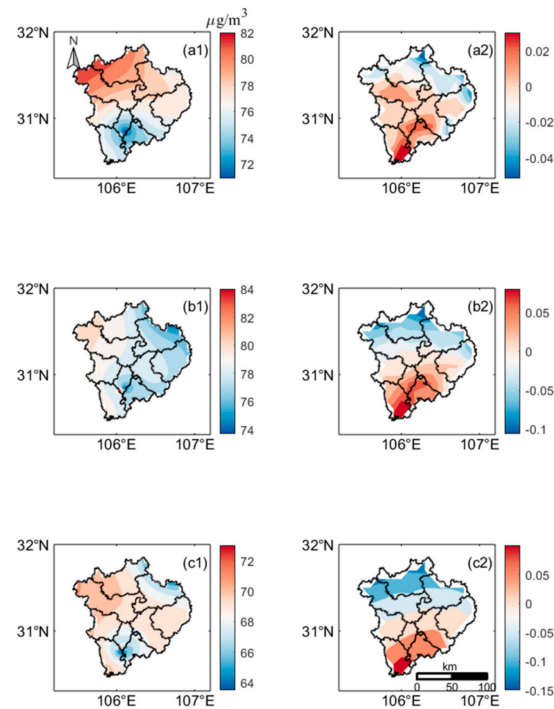


Figure 12. Spatial distribution of O₃ concentration (left) and heat island intensity (right) under the influence of the heat island effect in Nanchong city at each level ((a–c) are in order of no heat island, weak heat island, and medium heat island).

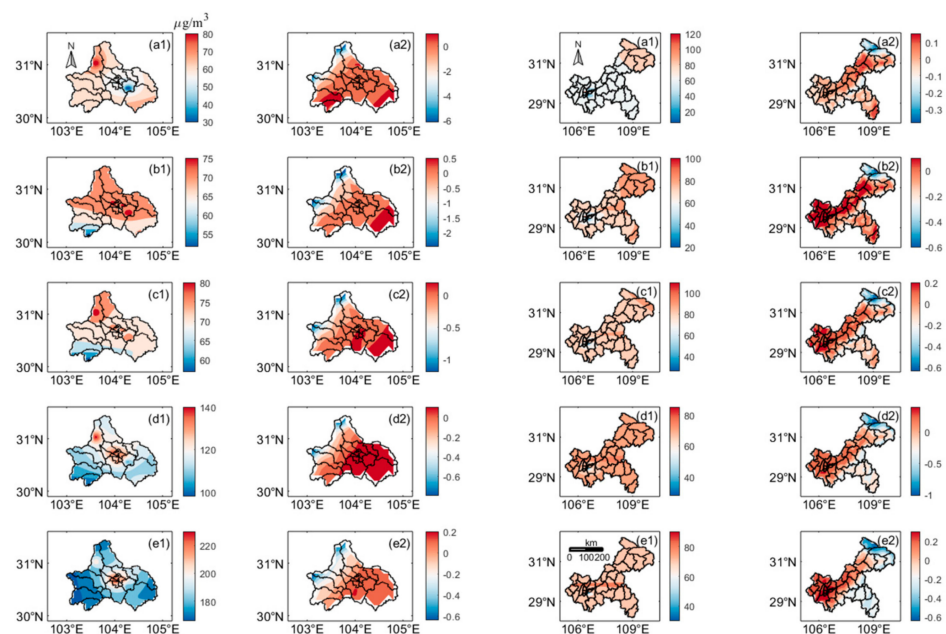


Figure 13. Spatial distribution of O₃ concentration (left) and heat island intensity (right) under the influence of the heat island effect in Chengdu (left) and Chongqing (right) city at various levels ((a–e) are in order of no heat island, weak heat island, medium heat island, strong heat island, and very strong heat island).

Under a strong heat island effect, most of Chengdu's main urban areas (Jinniu and Qingyang Districts) have high UHII and O₃ concentrations. However, Chenghua District, Jinjiang District, and the eastern areas and main urban areas of Chongqing have high UHII but relatively low O₃ concentrations. Dujiangyan City and Chongzhou City in western Chengdu exhibit relatively high O₃ concentrations but low UHII. Other areas in Chongqing, excluding the main urban area, show average O₃ concentrations with no distinct high-value areas, while places like Zhongxian in the central city have high UHII but are not extreme O₃ concentration areas.

Under a medium heat island effect, central areas like the main city of Chengdu and Zhongxian County in Chongqing still have high UHII values, but O₃ concentration is not very strong. Western areas such as Dujiangyan City in Chengdu, northern areas such as Wuxi County and Chengkou County in Chongqing, and Jialing District in Nanchong show high O₃ concentrations but relatively low UHII. Southwestern areas like Bishan District and Banan District in Chongqing and the junction of Jialing District and Gaoping District in Nanchong have low O₃ concentrations and relatively high UHII. Additionally, northern regions like Langzhong City and Yilong County also have relatively low O₃ and UHII values, with no obvious extreme values appearing.

Under a weak heat island effect, main urban areas such as Jinniu District and Chenghua District in Chengdu, Kaizhou District and Yunyang County in Chongqing, and Pengan County in Nanchong show relatively high O₃ concentrations and correspondingly high UHII. Areas like Dujiangyan City and Chongzhou City in western Chengdu, Fengdu County in Chongqing, and Yilong County and Yingshan County in Nanchong have low O₃ concentrations and correspondingly low UHII. Areas like southern Wuhou District and Jinjiang District in Chengdu, southeastern Qianjiang District in Chongqing, and northern Langzhong City and Nanan County in Nanchong have low O₃ concentrations but relatively high UHII. Furthermore, Jinyang City, Jintang County, and Gaoxin East District in Chengdu exhibit high UHII values, while O₃ concentrations do not show significant variations.

Under no heat island effect, areas such as Pujiang County, Jinyang City, Gaoxin East District, and southeastern Pengzhou City in Chengdu, Liangping District, Zhong County, and Wanzhou City in Chongqing, and Shunqing District and Gaoping District on the south side of Nanchong show high UHII values but relatively low O₃ concentrations. Conversely, areas like Dujiangyan City in Chengdu, the main city of Chongqing, and the northwest side of Langzhong City and Nanan County in Nanchong, have high O₃ concentrations but low UHII values.

As the UHII level decreases, UHII in central and eastern Chengdu also decreases, with the high UHII area moving eastward and the low O₃ concentration area gradually shifting from the southeast to the northwest. The south side of the main urban area, such as Jinjiang District and Gaoxin South District, remains a low O₃ concentration area, while high O₃ concentration areas and low UHII areas remain relatively unchanged, primarily located in the northwest side of Dujiangyan City. In Chongqing, high O₃ concentration areas gradually move northward, while low O₃ concentration areas in Shapingba and extreme UHII areas show minimal change as the heat island level decreases. Overall, O₃ concentration first increases and then gradually decreases, peaking under medium heat island intensity, with minimal changes under very strong and strong heat island levels. The southeastern area, including Qianjiang District, and UHII values in Chengkou County and Wuxi County, show a trend of first weakening and then strengthening. In Nanchong, high O₃ concentration areas keep moving from southeast to northwest, while low O₃ concentration areas at the intersection of Shunqing District, Gaoping District, and Jialing District with extreme UHII areas show little change. As the heat island level decreases, high UHII areas in Nanchong gradually decrease, while low UHII areas gradually increase.

Chongqing, as UHI decreases, wind speed first decreases and then increases, corresponding to the observed trend of increasing and then decreasing O_3 concentrations. Low wind speeds hinder O_3 dilution and diffusion, leading to higher O_3 concentrations at lower UHI levels. As the UHI grade decreases, the wind direction shifts from southerly to northerly, causing high O_3 concentration areas to move northward. In Nanchong, the wind direction remains predominantly northerly, regardless of the UHI class. However, wind speed decreases with decreasing UHI levels, reducing O_3 dilution and diffusion, resulting in higher O_3 concentrations under no heat island and weak heat island conditions compared to medium heat island levels. High O_3 concentration areas tend to move from southeast to northwest as the UHI levels decrease. Additionally, northwest regions, such as Langzhong City, experience O_3 transport from Guangyuan City, leading to higher O_3 concentrations compared to other areas.

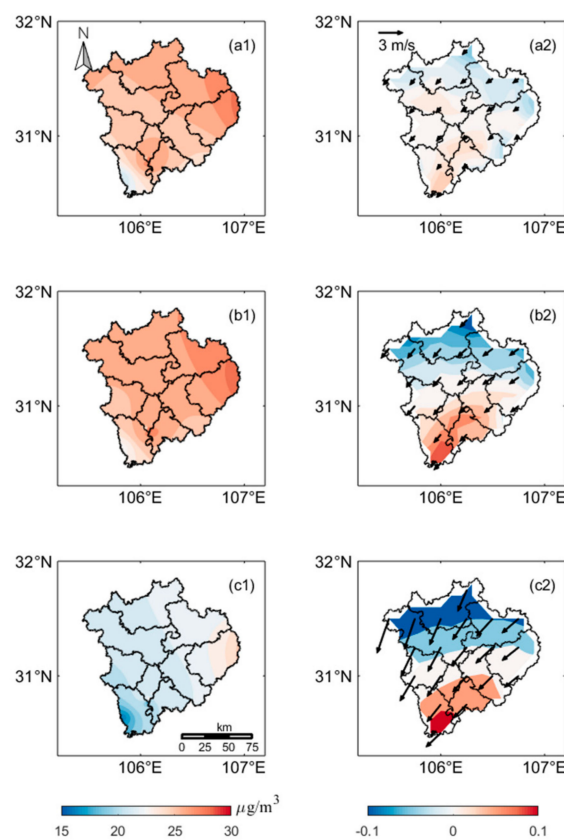


Figure 15. Spatial distribution of NO_2 concentration (left) and wind field (right) under the influence of heat island effect in Nanchong at each level ((a–c) are in order of no heat island, weak heat island, and medium heat island).

In summary, the relationship between UHI and O_3 is not simply linear. UHI affects O_3 concentration in two main ways: first, by altering the local heat balance to promote O_3 generation and second, by forming local wind patterns that influence the diffusion or accumulation of O_3 , resulting in distinct O_3 concentration zones.

4. Discussion and Conclusions

4.1. Discussion

This study considers multiple cities of varying development scales, sizes, and geographic locations, providing a comprehensive analysis that is not limited to a single city. By including diverse urban settings, the study offers a broader understanding of the UHI effect and its impact on O_3 concentrations across different urban environments within

the Sichuan Basin. The results reveal a generally positive correlation between UHI and O_3 concentrations, though this correlation varies significantly across different regions. In typical cities within the Sichuan Basin, the correlation between UHI and O_3 concentrations is stronger, especially in areas with high urbanization and pronounced UHI effects. This correlation is likely influenced by precursor emissions from traffic and industry, as urbanized areas with intense UHI effects tend to have more pollution sources.

Although the correlation between UHI and O_3 concentrations varies regionally, previous studies also highlight this relationship's spatial variability. Wang et al. [27] found that due to geographic differences, urban heat island intensity and O_3 concentrations exhibit significant spatial variation. Shi et al. [32] found a positive correlation between ozone concentrations and the UHI effect in Chengdu. In contrast, Zeng et al. demonstrated that the relationship between the UHI index (UHII) and O_3 is not a simple linear one, as it is influenced by various natural factors, including climate conditions and geographical settings [29]. Therefore, the relationship between UHI and O_3 concentrations varies under different environmental contexts.

In addition to the UHI effect, other factors may also influence urban ozone concentrations. Vertical mixing and transport play a key role in the diurnal variation of O_3 concentrations, as highlighted by Yang et al. in the Pearl River Delta region [60]. Chen et al. also found that urban O_3 concentrations are influenced by stratospheric ozone [61]. Thus, aside from the UHI effect, other meteorological factors, such as humidity, pressure, and wind speed, as well as large-scale weather systems, could significantly impact regional pollution.

Although this study did not delve deeply into the specific impacts of these meteorological factors, we recognize their importance in influencing pollutant concentrations. Future research will expand the range of meteorological variables and perform multivariate regression analyses to assess the independent effects of these factors. Additionally, we plan to further investigate the contribution of atmospheric circulation and long-range transport to pollution in the Sichuan Basin. Future studies could also explore the impact of UHI on other pollutants such as PM_{10} , $PM_{2.5}$, VOCs, NO_x , CO_2 , and SO_x .

By integrating meteorological data with pollution measurements, this study provides a solid framework for understanding the dynamic interactions between UHI and O_3 formation. Future research could further explore the potential effects of climate change and continued urbanization on the dynamics of UHI and O_3 pollution, providing valuable insights for urban planning and public health policy development.

4.2. Conclusions

The O_3 concentration in the Sichuan Basin exhibits distinct seasonal variations, with the highest levels observed in spring, followed by summer and autumn, and the lowest in winter. Daily fluctuations in O_3 concentration follow a “single peak, single valley” pattern. Spatially, the highest O_3 concentrations are found in western Sichuan, followed by the Sichuan River region, while the lowest concentrations are located in central Sichuan.

Ambient temperatures in the Sichuan Basin show a consistent daily trend, with large fluctuations in spring and smaller fluctuations in summer. The interior of the basin experiences higher temperatures compared to the surrounding areas.

The urban heat island intensity (UHII) varies significantly across Sichuan. Western Sichuan is dominated by medium heat islands, the Sichuan River region has weak heat islands, and central Sichuan experiences either no heat islands or weak heat islands. Spatially, UHII generally follows a circular distribution pattern, with lower values in central cities (such as Nanchong, Suining, Guang'an, Ziyang, Zigong, and Neijiang) and higher

values in cities closer to the center of the basin. UHII decreases towards the edges of the basin, where cold islands may even form.

In typical cities of the Sichuan Basin, including Chengdu, Chongqing, and Nanchong, there is a positive correlation between UHII and O₃ concentration, although with a time lag. The UHI effect influences O₃ concentration in two main ways: first, by altering the local heat balance, which promotes O₃ production, and second, by generating local winds that facilitate the diffusion and accumulation of O₃, resulting in distinct zones of high O₃ concentration.

Author Contributions: X.S.: Resources, Data curation, Writing—Original draft preparation, Writing—Review and Editing. H.S.: Software, Validation, Methodology. L.J.: Investigation. S.P.: Writing—Review and Editing. S.Z.: Conceptualization, Supervision, Project administration, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded under the auspices of the national key research and development program of China (No. 2023YFC3709303), the National Science Foundation of Sichuan Province (No. 2022NSFSC1006), the Science and Technology Innovation Capability Improvement Plan Project of Chengdu University of Information Technology in 2022 (No. KYQN202215), and the National Science Foundation of China (No. 41505122).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The O₃ and NO₂ data selected in this paper were obtained from the hourly O₃ and NO₂ data of 93 monitoring sites in the Sichuan basin in 2020 and 2021 from the China Air Quality Data, and the data were strictly screened with reference to the Ambient Air Quality Standards. Some of the missing measurements were excluded (<https://quotsoft.net/air/#archive>), accessed on 5 March 2022. The temperature and wind field data are derived from the 2 m temperature in the ERA5-Land hourly data and the 10 m wind u and v components in the ERA5 single-level horizontal data in 2020 and 2021, respectively (<https://cds.climate.copernicus.eu/#!/home>), accessed on 5 March 2022.

Conflicts of Interest: The authors have no competing interests to declare that are relevant to the content of this article.

References

1. Yan, Y.; Shi, W.; Wang, C.; Chen, Y. Pollution Characteristics of PM_{2.5} and O₃ under Atmospheric Circulation Types in the Yangtze River Delta Region during 2014–2019. *Environ. Monit. Forewarning* **2024**, *16*, 53–62. [CrossRef]
2. Xu, Y.; Tang, K.; Wei, C.; Li, N. Impact of gaseous pollutants reduction on PM_{2.5} in China from 2015 to 2020. *Acta Sci. Circumstantiae* **2024**, *44*, 217–225. [CrossRef]
3. Zeng, D.; Chen, C. Spatial-Temporal Characteristics and Influence Factors of PM_{2.5} Concentrations in Chengdu-Chongqing Urban Agglomeration. *Res. Environ. Sci.* **2019**, *32*, 1834–1843. [CrossRef]
4. Jiang, H.; Gao, J.; Li, H.; Chu, W.; Chai, F. Preliminary Research on Theoretical Framework of Cooperative Control of Air Pollution in China. *Res. Environ. Sci.* **2022**, *35*, 601–610. [CrossRef]
5. Dong, S.; Li, B. Source and characteristics of ozone pollution and the significance of ozone monitoring. *Environ. Dev.* **2019**, *31*, 189. [CrossRef]
6. Crutzen, P.J. Photochemical Reactions Initiated by and Influencing Ozone in Unpolluted Tropospheric Air. *Tellus* **1974**, *26*, 47–57. [CrossRef]
7. Haagen-Smit, A.; Fox, M. Ozone Formation in Photochemical Oxidation of Organic Substances. *Chem. Innov.* **1956**, *48*, 1484–1487. [CrossRef]
8. Liu, R.; Yan, W. Cause and Countermeasures of Ground Surface Ozone Pollution. *Mod. Chem. Res.* **2017**, *12*, 58–59.
9. Meng, X.; Gong, Z.; Zhang, X.; Wang, S.; Sun, H. Pollution Characteristics of Ozone in China and Key Regions. *Environ. Monit. China* **2017**, *33*, 17–25. [CrossRef]
10. Lu, J.; Huang, C.; Wang, H.; Wang, Q.; Yan, R.; Jing, S. Scientific understanding of ozone pollution and history of its control in the United States. *Environ. Pollut. Control* **2020**, *42*, 1171–1175+1181. [CrossRef]

11. Geng, F.; Liu, Q.; Chen, Y. Discussion on the Research of Surface Ozone. *Desert Oasis Meteorol.* **2012**, *6*, 8–14. [\[CrossRef\]](#)
12. Bai, Y.; Wang, X.; Jiang, H.; Liu, S. Progress of Urban Heat Island Effect. *J. Meteorol. Environ.* **2013**, *29*, 101–106.
13. Fan, H.; Sailor, D.J. Modeling the impacts of anthropogenic heating on the urban climate of Philadelphia: A comparison of implementations in two PBL schemes. *Atmos. Environ.* **2005**, *39*, 73–84. [\[CrossRef\]](#)
14. Sailor, D.J.; Lu, L. A top-down methodology for developing diurnal and seasonal anthropogenic heating profiles for urban areas. *Atmos. Environ.* **2004**, *38*, 2737–2748. [\[CrossRef\]](#)
15. Liu, S.; Cao, Y.; Jia, Y.; Zhou, T.; Zhou, S. Research progress of Urban Heat Island Effect. *J. Anhui Agric. Sci.* **2019**, *25*, 117–121. [\[CrossRef\]](#)
16. Ding, D.; Xing, J.; Wang, S.; Chang, X.; Hao, J. Impacts of emissions and meteorological changes on China's ozone pollution in the warm seasons of 2013 and 2017. *Front. Environ. Sci. Eng.* **2019**, *13*, 1–9. [\[CrossRef\]](#)
17. Elminir, H.K. Dependence of urban air pollutants on meteorology. *Sci. Total Environ.* **2005**, *350*, 225–237. [\[CrossRef\]](#)
18. Wang, T.; Xue, L.; Brimblecombe, P.; Lam, Y.F.; Li, L.; Zhang, L. Ozone pollution in China: A review of concentrations, meteorological influences, chemical precursors, and effects. *Sci. Total Environ.* **2017**, *575*, 1582–1596. [\[CrossRef\]](#)
19. Zhuang, L. Ground Level Ozone Concentration Characteristics and Formation Sensitivity in China's Three Agglomerations. Master's Thesis, South China University of Technology, Guangzhou, China, 2019.
20. Chen, B.; Yang, X.; Xu, J. Spatio-Temporal Variation and Influencing Factors of Ozone Pollution in Beijing. *Atmosphere* **2022**, *13*, 359. [\[CrossRef\]](#)
21. Fang, C.; Wang, L.; Wang, J. Analysis of the Spatial–Temporal Variation of the Surface Ozone Concentration and Its Associated Meteorological Factors in Changchun. *Environments* **2019**, *6*, 46. [\[CrossRef\]](#)
22. Le, D.; Wang, W.; Wang, Y.; Gao, H.; Zheng, J.; Tan, Z.; Fu, Y. Analysis on meteorological characteristics and causes of ozone pollution in Xianning City from 2020–2022. *Heilongjiang Environ. J.* **2024**, *37*, 30–32. [\[CrossRef\]](#)
23. Khiem, M.; Ooka, R.; Huang, H.; Hayami, H.; Yoshikado, H.; Kawamoto, Y. Analysis of the Relationship between Changes in Meteorological Conditions and the Variation in Summer Ozone Levels over the Central Kanto Area. *Adv. Meteorol.* **2010**, *2010*, 349248. [\[CrossRef\]](#)
24. Yang, R.; Xie, Y.; Hu, Y.; Wang, J.; Zhou, J.; Li, Z. Study on Evolution Characteristics and Meteorological Influencing Factors of PM_{2.5} in Yibin City. *China Resour. Compr. Util.* **2024**, *42*, 188–192.
25. Jonsson, P.; Bennet, C.; Eliasson, I.; Lindgren, E.S. Suspended particulate matter and its relations to the urban climate in Dar es Salaam, Tanzania. *Atmos. Environ.* **2004**, *38*, 4175–4181. [\[CrossRef\]](#)
26. Zhao, S.; Da, L.; Tang, Z.; Fang, H.; Song, K.; Fang, J. Ecological consequences of rapid urban expansion: Shanghai, China. *Front. Ecol. Environ.* **2006**, *4*, 341–346. [\[CrossRef\]](#)
27. Wang, C. Investigation on the Impact of Urban Heat Island Effect on the Pollution Characteristics of Near-Ground Ozone—Taking Beijing as an Example. Master's Thesis, Shantou University, Shantou, China, 2020. Available online: <https://d.wanfangdata.com.cn/thesis/D02083230> (accessed on 12 May 2023).
28. Xu, K.; Liu, Z.; He, M.; Zhang, J. Meteorological Characteristics of O₃ Pollution Near the Ground in Summer of Chengdu. *Environ. Monit. China* **2018**, *34*, 36–45. [\[CrossRef\]](#)
29. Zeng, S.; Shi, H.; Song, X.; Jin, L. Impact of urban heat island effect on ozone pollution in different Chinese regions. *Urban Clim.* **2024**, *56*, 102037. [\[CrossRef\]](#)
30. Wang, Y.; Du, H.; Xu, Y.; Lu, D.; Wang, X.; Guo, Z. Temporal and spatial variation relationship and influence factors on surface urban heat island and ozone pollution in the Yangtze River Delta, China. *Sci. Total Environ.* **2018**, *631–632*, 921–933. [\[CrossRef\]](#)
31. Gray, K.A.; Finster, M.E. *The Urban Heat Island, Photochemical Smog, and Chicago: Local Features of the Problem and Solution*; Department of Civil Engineering Northwestern University: Evanston, IL, USA, 2000.
32. Shi, H.; Song, X.; Zeng, S. Impact of the Urban Heat Island Effect on Ozone Pollution in Chengdu City, China. *Chin. Geogr. Sci.* **2023**, *33*, 1017–1032. [\[CrossRef\]](#)
33. Fu, C.; Zhou, H. Research Progress on the Formation Mechanism and Impact Factors of Urban Ozone Pollution in China. *Environ. Monit. China* **2021**, *37*, 33–43. [\[CrossRef\]](#)
34. Shi, W.; Ku, K.; Yan, Y.; Qiu, P.; Wang, X.; Dong, H. Circulation Classification and Source Analysis of Summer Ozone Pollution in Chengdu. *Acta Sci. Nat. Univ. Pekin.* **2022**, *58*, 565–574. [\[CrossRef\]](#)
35. Li, H.; Li, Z.; Long, W.; Wan, S.; Ding, X.; Wang, S.; Wang, Q. Vertical configuration of Sichuan Basin and its superimposed characteristics of the prototype basin. *J. Chengdu Univ. Technol. (Sci. Technol. Ed.)* **2019**, *46*, 257–267.
36. Luo, Y.; Chen, C.; Ma, Z.; Liu, J.; Li, X.; Yang, R. Journal of Chengdu University of Technology (Science & Technology Edition). *J. Southwest Univ. (Nat. Sci. Ed.)* **2019**, *41*, 128–138. [\[CrossRef\]](#)
37. Gao, P.; Liu, G.; Chen, J.; Xu, Z. Coupling between local climate zones and diurnal urban heat island effect. *J. Nanjing Univ. Inf. Sci. Technol.* **2022**, *14*, 267–276. [\[CrossRef\]](#)
38. Sun, Y.; Wang, R.; Guo, Q.; Gao, C. Estimation of the Urban Heat Island Intensity Change and Its Relationships with Driving Factors Across China Based on the Human Settlement Scale. *Environ. Sci.* **2021**, *42*, 501–512. [\[CrossRef\]](#)

39. Ngarambe, J.; Joen, S.J.; Han, C.H.; Yun, G.Y. Exploring the relationship between particulate matter, CO, SO₂, NO₂, O₃ and urban heat island in Seoul, Korea. *J. Hazard. Mater.* **2021**, *403*, 123615. [[CrossRef](#)]
40. Liang, K.; Ren, X.; Zhang, Y.; Liu, W.; Li, H. Spatio-temporal Variation Analysis of Urban Heat Island and Land Cover in Pearl River Delta. *Geospat. Inf.* **2022**, *20*, 36–40. [[CrossRef](#)]
41. Li, Z.; Yang, L.; Hua, D.; Fang, J.; Huang, W.; Sun, L.; Wang, C. Spatial Pattern of Surface Ozone and Its Relationship with Meteorological Variables in China during 2013–2018. *Res. Environ. Sci.* **2021**, *34*, 2094–2104. [[CrossRef](#)]
42. Li, X.; An, J.; Wang, Y.; Chen, W.; Hu, F.; Chen, H.; Shi, L. Studies on the measurement of atmospheric ozone in summer with Beijing meteorological tower. *China Environ. Sci.* **2003**, *23*, 353–357. [[CrossRef](#)]
43. Li, B.; Luo, B.; Zhang, W.; Zhao, P. Temporal and Spatial Distribution Characteristics and Pollution Characteristics of Ozone in Sichuan Province. *Environ. Sci. Technol.* **2018**, *41*, 293–298. [[CrossRef](#)]
44. Wang, Z.; Li, Y.; Chen, T.; Zhang, D.; Sun, F.; Wang, X.; Huan, N.; Pan, L. Analysis on diurnal variation characteristics of ozone and correlations with its precursors in urban atmosphere of Beijing. *China Environ. Sci.* **2014**, *34*, 3001–3008.
45. Cheung, V.T.F.; Wang, T. Observational study of ozone pollution at a rural site in the Yangtze Delta of China. *Atmos. Environ.* **2001**, *35*, 4947–4958. [[CrossRef](#)]
46. Tian, K.; Zhu, J.; Wang, Z.; Zhang, L. Influence of Meteorological Conditions on the Mass Concentration of Pollutants in Sichuan Basin Cities during the “COVID-19” Pandemic in the First Half of 2020. *Clim. Environ. Res.* **2022**, *27*, 243–262. [[CrossRef](#)]
47. Zhang, L.; Guo, X.; Zhao, T.; Gong, S.; Xu, X.; Li, Y.; Luo, L.; Gui, K.; Wang, H.; Zheng, Y. A modelling study of the terrain effects on haze pollution in the Sichuan Basin. *Atmos. Environ.* **2019**, *196*, 77–85. [[CrossRef](#)]
48. Cai, Y.; Wang, T.; Xie, M.; Han, Y. Impact of Atmospheric Particles on Surface Ozone in Nanjing. *Clim. Environ. Res.* **2013**, *18*, 251–260. [[CrossRef](#)]
49. Deng, X.; Zhou, X.; Wu, D.; Tie, X.; Tan, H.; Li, F.; Bi, X.; Deng, T.; Jiang, D. Influence of atmospheric aerosol on surface ozone change in the Pearl River Delta. *Sci. Sin. Terrae* **2011**, *41*, 93–102. [[CrossRef](#)]
50. Hu, C.; Kang, P.; Wu, K.; Zhang, X.; Wang, S.; Wang, Z.; Ouyang, Z.; Zeng, S.; Xiang, W. Study of spatial distribution of ozone and its influence factors over Sichuan Basin Based on generalized additive model. *Acta Sci. Circumstantiae* **2019**, *39*, 809–820. [[CrossRef](#)]
51. Cao, T.; Wu, K.; Kang, P.; Wen, X.; Li, H.; Wang, Y.; Lv, X.; Li, A.; Pan, W.; Fan, W.; et al. Study on ozone pollution characteristics and meteorological cause of Chengdu-Chongqing urban agglomeration. *Acta Sci. Circumstantiae* **2018**, *38*, 1275–1284. [[CrossRef](#)]
52. Guo, H.; Zhang, C.; Cao, S. Research Status of Urban heat Island Effect. *Agric. Technol.* **2022**, *42*, 113–115. [[CrossRef](#)]
53. Tan, Z.; Xi, S. Analysis on the Evolution of Heat Island Effect and Its Influencing Factors in Ningbo Central City from 1990 to 2015. *J. Hebei Univ. Eng. (Nat. Sci. Ed.)* **2021**, *38*, 69–77. [[CrossRef](#)]
54. Luo, S.; Cai, X.; Zheng, X.; Wang, H.; Liu, M.; Pan, L. A Review of Research on the Influences of Vertical Greenery System on Urban Microclimate. *World For. Res.* **2023**, *36*, 45–50. [[CrossRef](#)]
55. Xie, Z.; Xie, S. Precipitation Change Characteristics of Chengdu City During 1961–2017. *J. Anhui Agric. Sci.* **2019**, *754*, 197–203.
56. Yi, R.; Wang, Y.; Zhang, Y.; Shi, Y.; Li, M. Pollution characteristics and influence factors of ozone in Yangtze River Delta. *Acta Sci. Circumstantiae* **2015**, *35*, 2370–2377. [[CrossRef](#)]
57. He, J.; Yuan, X.; Li, G.; Wang, X.; Deng, W.; Lin, W.; Yang, J. Diurnal Variation Characteristics of Ozone in Urban Area of Changji and Its Correlation with Precursors. *Environ. Prot. Xinjiang* **2018**, *40*, 1–5+23.
58. Dan, S.; An, H.; Dan, B.; Xu, H.; Yang, L.; Chen, G. An Analysis of Urban Heat Island Effects in Chongqing Based on AVHRR and DEM. *Resour. Environ. Yangtze Basin* **2009**, *18*, 680–685. [[CrossRef](#)]
59. Kang, H. Urban Heat Island Cluster Effect Over the Yangtze River Delta. Ph.D. Thesis, Nanjing University of Information Science and Technology, Nanjing, China, 2014.
60. Yang, H.; Lu, C.; Hu, Y.; Chan, P.; Li, L.; Zhang, L. Effects of Horizontal Transport and Vertical Mixing on Nocturnal Ozone Pollution in the Pearl River Delta. *Atmosphere* **2022**, *13*, 1318. [[CrossRef](#)]
61. Chen, Z.; Liu, J.; Qie, X.; Cheng, X.; Shen, Y.; Yang, M.; Jiang, R.; Liu, X. Transport of substantial stratospheric ozone to the surface by a dying typhoon and shallow convection. *Atmos. Chem. Phys.* **2022**, *22*, 8221–8240. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.