## Introduction

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As global temperatures continue to rise, urban areas are expected to experience more frequent and intense heat waves, which present significant challenges to urban resilience. By 2050, summer temperatures in urban areas could increase by as much as 3°C (Huang et al., 2019). The increasing frequency and intensity of heat waves have adverse effects on urban ecosystems, particularly by inhibiting vegetation growth and affecting water resources (Ganeshan et al., 2013). Furthermore, heat waves negatively impact various aspects of urban socio-economic activities, including increased energy consumption, reduced resident comfort, and even higher mortality risks (Santamouris, 2020; Huang et al., 2024; Gao et al., 2023). As the harmful effects of urban heat waves receive growing attention, finding effective solutions to regulate urban microclimates and mitigate their impacts has become one of the most urgent environmental challenges cities face today, requiring coordinated efforts at both local and global levels.

Among the various strategies for mitigating urban heat waves, the creation and arrangement of green spaces have proven to be among the most effective methods. Green spaces not only help cool the environment but also provide a wide range of ecological benefits. The size of green spaces has been widely studied as a key factor influencing their cooling effect. Most studies indicate that as the area of green spaces increases, both the cooling intensity and the cooling range of surrounding areas expand significantly (Cao et al., 2010; Peng et al., 2021; Gomez-Martinez et al., 2021). However, uncertainty remains regarding the effects of green space configuration. For example, a study involving multiple Asian cities found a positive correlation between the landscape shape index (LSI) and the urban cool island effect caused by vegetation. In contrast, studies in some African and Chinese cities have shown a negative correlation between these two factors (Ekwe et al., 2021; Zhou et al., 2019; Fan et al., 2019). Therefore, the relationship between green space configuration and cooling effect is influenced by factors such as region and season, and further investigation is required. Additionally, surrounding urban characteristics, including land cover patterns and three-dimensional morphology, play a critical role in determining the strength and extent of green space cooling effects (Qiu et al., 2020; Liao et al., 2023). While most current research focuses on two-dimensional factors, three-dimensional factors have yet to be fully explored. Buildings not only affect the absorption and release of ground radiation but also influence airflow channels. Some studies suggest that three-dimensional geometric structures may have a more significant impact on urban thermal environments (Yin et al., 2018; Tian et al., 2019; Unger, 2009). Therefore, greater emphasis should be placed on the impact of three-dimensional urban morphology, particularly the characteristics of buildings.

Current methods for investigating the cooling effects of green spaces primarily include remote sensing analysis, model simulations, and on-site measurements. Model simulations simplify real-world conditions to some extent, while remote sensing analyses rely on surface temperature data, which often differ significantly from air temperatures measured at pedestrian height (Cao et al., 2021). This discrepancy arises because surface temperature is directly influenced by solar radiation and the thermal properties of surface materials, leading to greater variability. In contrast, air temperature, primarily driven by surface radiation, exhibits relatively smaller fluctuations (Sheng et al., 2017). Consequently, while on-site measurements are more time- and labor-intensive, they provide a more accurate and detailed representation of local microclimatic conditions (Lin et al., 2017; Qi et al., 2022). Existing field studies often rely on a limited number of monitoring points, resulting in sparse spatial coverage, which makes it difficult to capture continuous variations in meteorological variables across surrounding urban areas. As a result, such studies may fail to accurately capture fine-scale spatial patterns, especially in the vicinity of large green spaces. To address these challenges, it is essential to establish a high-density meteorological monitoring network to enhance on-site monitoring of the thermal environment around green spaces. This approach will allow for a more comprehensive assessment of the environmental factors shaping these patterns and provide valuable insights into the interactions between green spaces and their surrounding urban environments.

Urban green spaces not only play a vital role in regulating surrounding temperatures but also significantly influence the relative humidity of the air through processes such as evapotranspiration. For instance, in high-density urban environments like Hong Kong, small parks have been shown to have both humidifying and cooling effects (Cheung et al., 2021). While these green spaces can effectively lower temperatures, an increase in relative humidity may enhance the sensation of mugginess, partially offsetting the improvements in thermal comfort achieved through temperature reduction. Therefore, the combined effects of temperature and humidity are crucial factors in determining overall thermal comfort. Unlike temperature, which is a single variable, thermal comfort is closely linked to human perception of heat stress and provides a more precise standard for evaluating satisfaction with the thermal environment (Wang, 2019). When assessing the impact of thermal conditions on individuals or groups, thermal comfort is a more comprehensive indicator than traditional meteorological factors like temperature alone. It better captures people's experiences in varying environmental contexts, providing a more robust foundation for urban design and planning. However, current research on the effects of urban green spaces on the surrounding thermal environment has predominantly focused on temperature changes. There remains a significant gap in understanding how relative humidity and temperature together influence thermal comfort in urban areas near green spaces. Furthermore, the role of surrounding urban morphology and other factors warrants further exploration.

This study focuses on Chongqing Central Park, utilizing mobile measurement methods to conduct fine-scale, high-density measurements of meteorological variables around the park. By analyzing temperature, relative humidity, and thermal comfort, and combining relevant evaluation indicators, the study aims to explore the impact of green spaces on the surrounding thermal environment. The specific objectives of this study are: (1) to analyze the microclimate characteristics of the environment surrounding the green space; (2) to quantify the intensity and extent of the green space's impact on the surrounding thermal environment; and (3) to assess the influence of environmental factors and background temperature on the thermal effects of the green space. The results of this study will deepen our understanding of the thermal environment around green spaces and their interactions with surrounding environmental characteristics. It will also provide scientific evidence and references for urban green space planning in different climatic contexts.

## Data and Methods

### Study area

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Chongqing, located in the upper reaches of the Yangtze River in southwestern China, is a major metropolitan area. Over the past two decades, the city's urban population has rapidly increased from 6 million in 2000 to 10 million in 2020. The city experiences a subtropical monsoon climate, characterized by cold and damp winters from December to January, and hot, humid summers from May to September. Chongqing typically experiences up to 40 days annually with temperatures exceeding 35°C, with peak temperatures reaching as high as 43°C.

Chongqing Central Park, situated in the northern part of the city, covers an area of approximately 1.6 square kilometers. The park has a rectangular shape, extending 2 kilometers in the north-south direction and 0.8 kilometers east-west, making it the largest urban park in Chongqing (Fig. 1). The park is surrounded by newly developed residential and commercial areas, which include high-rise towers, low-rise buildings, and villas. As this is a newly developed district, pedestrian and vehicular traffic is relatively low, resulting in minimal human impact on the thermal environment.

This study will conduct field measurements of the thermal environment in the areas surrounding Chongqing Central Park, with a particular focus on assessing temperature, relative humidity, and thermal comfort.

### Field measurement

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Chongqing experiences a typical summer from May to September, with July and August being the hottest months. For meteorological data collection, this study focused on August 2023. To minimize the impact of rainy weather on the regional thermal environment and ensure representative data, six predominantly clear and sunny days were selected. These days were specifically chosen to capture typical summer conditions while avoiding weather variability that could skew the results.

Measurements were taken at two distinct times on each of these six days: 14:00 for daytime data and 21:00 for nighttime data. Daytime measurements, conducted during the hottest part of the day, were chosen to capture the period when strong sunlight significantly influences the spatial distribution of meteorological variables, particularly temperature. Nighttime measurements, taken after solar radiation had weakened, were expected to still reflect the urban heat island effect, which becomes more pronounced as heat is released from buildings and other impervious surfaces. According to data from a nearby standard meteorological station, temperatures at 14:00 on these six days ranged from 27.7°C to 35.9°C, with relative humidity values between 44% and 66%, representing typical midsummer conditions in Chongqing. A summary of the basic meteorological conditions for these measurement days is provided in Table 1.

This study focuses on fine-scale meteorological measurements, utilizing high-density sampling points through a mobile measurement method. During the field measurements, six parallel routes were selected, each oriented east-west and perpendicular to Chongqing Central Park. Each route began at the park’s boundary and extended 500 meters into the surrounding residential area. This route design was intended to capture spatial variations in the thermal environment both within and around the park, a critical area of focus for the study.

Six volunteers were assigned to simultaneously collect data along the designated routes. They traveled at a pace of 10 meters per minute, stopping for at least 40 seconds at each measurement point to record data for subsequent analysis. Each route consisted of 50 measurement points, yielding a total of 300 measurement points across the study area. To minimize the influence of potential obstacles, such as vegetation, the measurement points were positioned as far as possible from street trees and other shaded areas. The sampling duration for each route was approximately 50 minutes, ensuring adequate time for data collection across the entire route.

To account for temporal differences between measurement points, two fixed reference points were established approximately 500 meters from the park. These fixed points were selected to ensure that the meteorological data collected at these locations were not influenced by the park’s microclimate. The locations of these fixed reference points are shown in Figure 1. In the analysis, the start time of each measurement cycle served as the reference time. By calculating the difference in meteorological variables between the average values at the fixed reference points and the reference time for each measurement cycle, the mobile measurement data were adjusted accordingly. This adjustment allowed for a comparative analysis of all datasets based on a unified reference time, ensuring consistency across the study area.

For data collection, the TESTO 175H1 data logger was used to measure air temperature and relative humidity. This device is highly accurate, with a temperature measurement error of ±0.1°C and a relative humidity measurement error of ±0.1%, providing precise and reliable data. The data logger was configured to automatically record measurements every 60 seconds, ensuring consistent data capture throughout the fieldwork.

Simultaneously, ground surface temperature on asphalt surfaces was measured using the FLUKE 563 infrared thermometer, a handheld device with a temperature measurement error of ±0.1°C. Additionally, a GPS recorder was used to capture geographic information, including the latitude and longitude of each measurement point, ensuring precise spatial referencing of all data.

During measurements, the temperature and humidity logger was installed at a height of approximately 1.5 meters and shielded with a small Stevenson screen to minimize the influence of solar radiation and other external factors, in line with standard meteorological practices (Fig. 2). All instruments were mounted on a mobile vertical pole fixed to a cart. Volunteers pushed the cart forward at a steady pace to ensure accurate and continuous data collection. This mobile setup enabled efficient data gathering across the study area, maintaining high precision and minimizing errors from instrument movement.

### Data

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This study utilized high-resolution GF-2 satellite imagery for land cover classification analysis. The imagery, obtained from the China Remote Sensing Satellite Data Sharing Service Platform, was captured on May 24, 2023, with a spatial resolution of 1 meter.

A supervised classification method was employed to classify the study area into three primary land cover types: vegetation, impervious surfaces (e.g., roads and plazas), and other types (e.g., water bodies or bare land).

Additionally, building information—including location, footprint area, and the number of floors—was sourced from Gaode Maps. Based on typical characteristics of residential buildings in Chongqing, the actual building height was estimated by multiplying the number of floors by 3 meters. This estimated height was then used to calculate various building-related environmental indicators.

### Quantifying the effect of green spaces on the thermal environment

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It is well-established that meteorological variables around green spaces exhibit a gradient pattern. As the distance from a green space increases, temperature typically rises gradually before stabilizing at a certain point. Similarly, variables that decrease with distance, such as relative humidity, show a decline that levels off after reaching a specific threshold. This point, where the trend plateaus, is referred to as the turning point of the variable. Fig. 3 illustrates the variation in temperature as a function of distance.

Previous studies have demonstrated that changes in meteorological variables with distance from green spaces generally follow a cubic function pattern (Jaganmohan et al., 2016). In this study, the turning point is defined as the first inflection point of the fitted cubic polynomial. The distance from the starting point to the turning point is referred to as the penetration distance, while the difference in the values of the meteorological variable at these two points is termed the impact intensity.

In this study, the penetration distances for temperature, relative humidity, and discomfort index (DI) are designated as the Park Cooling Distance (PCD), Park Wetting Distance (PWD), and Park Cooling Distance of Thermal Comfort (PCDTC), respectively. Correspondingly, the impact intensities are termed Park Cooling Intensity (PCI), Park Wetting Intensity (PWI), and Park Cooling Intensity of Thermal Comfort (PCITC).

### Discomfort indexes

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To assess the combined effects of air temperature and humidity on human thermal comfort, the Discomfort Index (DI) was used. Initially proposed by Thom and later refined by Giles, the DI has become a widely accepted metric in studies examining urban thermal comfort (Giles et al., 1990). The formula for calculating the DI is as follows:

* in which Ta is the air dry-bulb temperature (°C) and RH represents the relative humidity (%).

### Driving factors

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Urban climate characteristics result from the combined influence of multiple factors. In this study, we selected environmental variables across three dimensions—land cover characteristics, urban morphology, and relative location—to examine how urban green spaces affect the surrounding thermal environment.

For land cover characteristics, we quantified vegetation coverage using the green space area ratio. In terms of urban morphology, we considered three key variables: average building height, sky view factor (SVF), and street width. Average building height was calculated as the mean height of buildings within the site, weighted by their respective building area. The sky view factor, which represents the ratio of visible sky area to the total sky area at a given location, reflects the degree of sunlight obstruction and openness in the urban environment. Street width was defined as the minimum distance between buildings on either side of a street, with values ranging from 29 to 54 meters for the six selected streets, which remained constant across each street.

It is important to note that the study area predominantly consists of residential zones, where buildings are aligned along east-west roads with relatively consistent orientations. As a result, building orientation was excluded as a variable in this study.

Additionally, the distance between green spaces and measurement points was considered a critical factor, as proximity to green spaces significantly influences the thermal environment. To evaluate these environmental variables and their relationship with meteorological variables, we established a 100-meter radius buffer zone around each measurement point. The buffer size was determined by comparing the correlations between environmental factors and meteorological variables for various buffer sizes, ultimately selecting the one that yielded the strongest correlation.

## Results

### Spatial and temporal patterns of meteorological variables

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Fig. 6 presents boxplots illustrating the daily average air temperature (TA), relative humidity (RH), and discomfort index (DI) across all measurement points in the study area during both daytime and nighttime. The figure clearly demonstrates that nighttime air temperature decreases significantly compared to daytime, while relative humidity increases substantially. These combined changes in temperature and humidity result in a pronounced reduction in DI at night. Specifically, as shown in Table 1, the average air temperature decreases from 32.6°C during the day to 30.2°C at night, representing a reduction of 2.4°C. Concurrently, the average relative humidity rises from 51.5% to 59.7%, an increase of 8.2 percentage points. Correspondingly, DI decreases from 27.7°C during the day to 26.6°C at night. These findings indicate that, despite the increase in nighttime humidity, the cooling effect of green spaces effectively mitigates thermal discomfort and enhances the comfort of the surrounding environment.

Notably, the reduction in DI (1.1°C) is smaller than the decrease in air temperature (2.4°C). This discrepancy can be attributed to the moderating effect of increased humidity on thermal discomfort. Relative humidity is a key determinant of DI, as higher humidity levels impede the body’s ability to dissipate heat through evaporation, thereby diminishing the perceived cooling effect. These results underscore the intricate relationship between temperature and humidity in shaping human thermal comfort.

Moreover, Figure 6 highlights that the spatial heterogeneity of air temperature, relative humidity, and discomfort index is more pronounced at night than during the day. This observation is corroborated by the standard deviation data in Table 1: the standard deviations of TA, RH, and DI increase from 0.38°C, 1.25%, and 0.20°C during the day to 0.58°C, 1.61%, and 0.32°C at night, respectively. These findings suggest that microclimatic conditions in the study area become more complex and diverse after sunset. The heightened spatial heterogeneity at night may be influenced by several factors, including the spatial distribution of green spaces, and the characteristics of urban morphology.

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Fig. 7 illustrates the spatial distribution patterns of the daily average air temperature, relative humidity, and thermal comfort across all measurement points. The results reveal significant fluctuations in these meteorological variables within a certain distance from the park, highlighting the park's noticeable impact on the surrounding thermal environment. Specifically, this influence is characterized by increases in air temperature and discomfort index (DI) and decreases in relative humidity. As the distance from the park increases, the intensity of these effects gradually diminishes and stabilizes beyond a certain range. This pattern demonstrates that the park, through its vegetation and open spaces, plays a critical role in regulating the thermal environment of adjacent urban areas.

Further analysis indicates that the park's thermal effects exhibit significant differences between daytime and nighttime. Both the extent and intensity of these effects are markedly greater at night than during the day. Specifically, the influence of air temperature, relative humidity, and DI extends up to approximately 200 meters at night, compared to about 100 meters during the day. In terms of intensity, nighttime air temperature decreases by approximately 2°C, while the daytime reduction is only about 1°C. Similarly, relative humidity increases by around 4% at night, whereas the daytime increase is about 2%. The reduction in DI at night is approximately 2°C, compared to 1°C during the day. These differences underscore the more pronounced regulatory effect of the park on the thermal environment during nighttime.

The observed differences can be attributed to enhanced heat release from urban buildings at night, which amplifies the temperature contrast between built-up areas and green spaces, thereby intensifying the park's thermal effects. Additionally, this phenomenon may also be linked to the park’s ability to mitigate urban heat island effects through processes such as evapotranspiration and shading, which are particularly effective at night. As green spaces accentuate their cooling effects, the heat retention of urban structures further heightens the contrast.

These findings not only explain the significantly wider range of nighttime daily average temperatures observed in Fig. 6 but also underscore the critical importance of green space thermal effects during nighttime. This highlights the need for a temporal perspective in evaluating the contributions of green spaces to urban thermal environments and provides valuable insights for urban planning strategies aimed at improving nighttime thermal conditions in cities.

### 绿地热环境效应的量化

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Fig. 8 and Fig. 9 present boxplots illustrating the impact of Central Park on the surrounding thermal environment, covering air temperature, relative humidity, and discomfort index (DI). Regarding the effect on air temperature, the average cooling distance at night extends to 245 meters, with a maximum of 400 meters. In contrast, the average cooling distance during the day is significantly reduced to 116 meters, with a maximum of 222 meters. Similarly, the cooling intensity shows substantial variation, with an average nighttime cooling intensity of 1.8°C, compared to 0.5°C during the day.

The park's influence on relative humidity follows a similar pattern. The average humidifying distance at night reaches 200 meters, whereas it decreases to 100 meters during the day. Correspondingly, the humidifying intensity declines from approximately 3% at night to around 1% during the day. Under the combined effects of air temperature and relative humidity, the park cooling distance for thermal comfort (PCDTC) and the park cooling intensity for thermal comfort (PCITC) also exhibit notable diurnal differences. Specifically, the average PCDTC and PCITC during the day are 100 meters and 0.5°C, respectively, while at night they increase to 200 meters and 1°C.

These findings further demonstrate that the extent and intensity of the park's thermal effects are significantly greater at night than during the day, underscoring the critical role of Central Park in alleviating nighttime urban heat stress.

### 环境特征对绿地热环境效应的影响

基于植被覆盖率（VEG）、建筑覆盖率（BLD）、天际视野因子（SVF）和建筑物平均高度（BH），本研究分析了城市环境特征与公园对空气温度、相对湿度和热舒适度影响的关键指标之间的皮尔逊相关性，并在白天和夜间不同条件下进行了比较。研究结果表明，VEG对公园热环境调节的作用相对较弱。具体而言，VEG与各项影响指标的相关系数始终低于0.3，表明其对绿地热调节的贡献有限。相比之下，三维建筑形态指标对热环境的调节作用较为显著，其中建筑覆盖率（BLD）的影响相较于天际视野因子（SVF）和建筑物平均高度（BH）较弱。

在冷却距离方面，BLD、SVF和BH三个环境特征在白天的相关系数分别为0.39、-0.37和-0.47。而在夜间，相关系数分别为0.36、-0.56和-0.48。除BLD外，其余两项环境特征在夜间对冷却距离的影响强度高于白天。就冷却强度而言，BLD、SVF和BH在白天的相关系数分别为0.36、-0.47和-0.50，而在夜间，相关性普遍较弱，仅SW对冷却强度产生显著影响，其相关系数为0.42。总体而言，相较于冷却强度，公园的降温距离受到城市环境特征的影响较为显著。

环境特征对公园湿润效应的影响模式与其对冷却效应的影响模式相似。在夜间，BLD、SVF和BH与湿润距离的相关系数分别为0.29、-0.52和-0.45，其中BLD对湿润距离的影响不显著。相反，在白天，只有BH对湿润距离产生显著影响，其相关系数为-0.47，而BLD则未表现出显著影响。关于湿润强度，环境特征的影响较为有限。在白天和夜间，仅BH和SW与湿润强度显著相关，相关系数分别为-0.44和-0.35。

考虑到空气温度和相对湿度的综合影响，公园热舒适冷却距离（PCDTC）与环境特征的相关性在夜间更为显著，相关系数分别为0.46（BLD）、0.53（SVF）和0.54（BH）。而在白天，仅BLD和BH对PCDTC产生显著影响，且相关系数较夜间有所下降。此外，公园热舒适冷却强度（PCITC）与环境特征的整体相关性较弱，表明其对环境因素的依赖性相对较小。

Based on vegetation coverage (VEG), building coverage (BLD), sky view factor (SVF), and the average building height (BH), this study analyzes the Pearson correlation between urban environmental characteristics and key indicators of park influence on air temperature, relative humidity, and thermal comfort, comparing these correlations under different daytime and nighttime conditions. The results indicate that the role of VEG in regulating the park’s thermal environment is relatively weak. Specifically, the correlation coefficients between VEG and the various impact indicators remain below 0.3, suggesting its limited contribution to thermal regulation in green spaces. In contrast, three-dimensional building form indicators have a more significant effect on thermal environment regulation, with the influence of building coverage (BLD) being weaker than that of sky view factor (SVF) and average building height (BH).

Regarding cooling distance, the correlation coefficients of BLD, SVF, and BH in the daytime are 0.39, -0.37, and -0.47, respectively. At night, these coefficients are 0.36, -0.56, and -0.48, respectively. Except for BLD, the impact of the other two environmental features on cooling distance is stronger at night than during the day. For cooling intensity, the correlation coefficients of BLD, SVF, and BH during the day are 0.36, -0.47, and -0.50, while at night, the correlations are generally weaker, with only SW having a significant effect on cooling intensity, with a correlation coefficient of 0.42. Overall, compared to cooling intensity, cooling distance in parks is more strongly influenced by urban environmental characteristics.

The influence of environmental features on the park’s humidification effect follows a pattern similar to that of cooling. At night, the correlation coefficients between BLD, SVF, and BH and humidification distance are 0.29, -0.52, and -0.45, respectively, with BLD showing no significant effect. In contrast, during the day, only BH has a significant impact on humidification distance, with a correlation coefficient of -0.47, while BLD shows no significant effect. Regarding humidification intensity, the influence of environmental features is limited. During both the day and night, only BH and SW are significantly correlated with humidification intensity, with correlation coefficients of -0.44 and -0.35, respectively.

Considering the combined effects of air temperature and relative humidity, the correlation between park thermal comfort cooling distance (PCDTC) and environmental features is stronger at night, with correlation coefficients of 0.46 (BLD), 0.53 (SVF), and 0.54 (BH). During the day, only BLD and BH have a significant effect on PCDTC, and the correlation coefficients are lower than those observed at night. Additionally, the overall correlation between park thermal comfort cooling intensity (PCITC) and environmental features is weak, indicating a relatively low dependency on environmental factors.

### 热浪日与非热浪日的绿地热环境效应比较

在六个研究测量日中，有三天的最大日温度超过了35°C。基于这一温度阈值，研究日被划分为热浪日和非热浪日，并分析了在这两种天气条件下绿地热环境效应的差异。研究结果表明，无论是白天还是夜间，绿地的整体热环境效应在热浪日均显著高于非热浪日。

白天，公园冷却距离（PCD）的平均值从非热浪日的100米增加至热浪日的120米，而公园冷却强度（PCI）的平均值从1°C增加至1.2°C。夜间，变化更加显著，PCD的平均值从非热浪日的150米增加至热浪日的190米，PCI的平均值从1°C增加至1.3°C。

公园湿润效应呈现出类似的趋势。白天，公园湿润距离（PWD）的平均值从非热浪日的100米增加至热浪日的120米，而公园湿润强度（PWI）的平均值从1°C增加至1.2°C。夜间，PWD和PWI的平均值分别从100米和1°C增加至120米和1.2°C。

关于绿地对热舒适度的影响，观察到类似的趋势，热浪日的影响较非热浪日更为显著。白天，热舒适冷却距离（PCDTC）和热舒适冷却强度（PCITC）的平均值分别从非热浪日的100米和1°C增加至热浪日的120米和1.2°C。夜间，PCDTC的平均值增加了20米，PCITC则增加了0.2°C。

此外，独立样本t检验结果表明，公园对周边气温和热舒适度的影响在热浪日与非热浪日之间存在显著差异，而对相对湿度的影响则无显著差异。

Among the six research measurement days, three recorded maximum daily temperatures exceeding 35°C. Based on this temperature threshold, the research days were classified into heatwave and non-heatwave days, and the differences in the thermal environment effects of green spaces under these two weather conditions were analyzed. The results indicate that, regardless of daytime or nighttime, the overall thermal environment effects of green spaces were significantly greater on heatwave days compared to non-heatwave days.

During the daytime, the mean Park Cooling Distance (PCD) increased from 100 meters on non-heatwave days to 120 meters on heatwave days, while the mean Park Cooling Intensity (PCI) rose from 1°C to 1.2°C. The changes were even more pronounced at night, with the mean PCD increasing from 150 meters on non-heatwave days to 190 meters on heatwave days, and the mean PCI rising from 1°C to 1.3°C.

The park's wetting effect showed a similar trend. During the daytime, the mean Park Wetting Distance (PWD) increased from 100 meters on non-heatwave days to 120 meters on heatwave days, while the mean Park Wetting Intensity (PWI) increased from 1°C to 1.2°C. At night, both PWD and PWI increased from 100 meters and 1°C to 120 meters and 1.2°C, respectively.

In terms of the impact of green spaces on thermal comfort, a similar pattern was observed, with heatwave days having a more pronounced effect than non-heatwave days. During the daytime, the mean Park Cooling Distance of Thermal Comfort (PCDTC) and Park Cooling Intensity of Thermal Comfort (PCITC) increased from 100 meters and 1°C on non-heatwave days to 120 meters and 1.2°C on heatwave days, respectively. At night, the mean PCDTC increased by 20 meters, and the mean PCITC increased by 0.2°C.

Furthermore, the independent samples t-test results showed that the impact of parks on surrounding air temperature and thermal comfort was significantly different between heatwave and non-heatwave days, whereas no significant difference was found in terms of relative humidity.

## Discussions

### 基于气温与基于地表温度的公园周边热环境比较

In previous studies, numerous scholars have analyzed the cooling effect of large urban green spaces based on remote sensing land surface temperature (LST). However, whether LST can adequately represent air temperature remains an unresolved issue. Therefore, this study systematically compared and analyzed the differences between air temperature and LST in the study area to gain a deeper understanding of the distinctions between these two metrics in cooling effect assessments.

Figure 1 presents box plots of LST and air temperature for six streets in the study area during the day and night. The results indicate that, both during the day and at night, air temperature is significantly lower than LST. Specifically, the daytime air temperature ranges from 31°C to 32.2°C, while LST ranges from 54.2°C to 57.1°C. At night, the difference between air temperature and LST narrows, with air temperature ranging from 30°C to 30.8°C and LST ranging from 35.8°C to 43.1°C. These findings suggest that the difference between air temperature and LST not only exists but also varies during the day and night.

Further analysis of Figure 1b shows that as the distance from the park increases, LST tends to rise, which is similar to the trend observed for air temperature. However, whether the increase in air temperature with distance from the park aligns with the trend of increasing LST remains a question. Therefore, we further compared cooling indices based on both air temperature and LST, as shown in Figure 2.

During the day, the correlation coefficient between air temperature and LST is 0.43, indicating a moderate positive correlation but a relatively weak one. At night, the correlation coefficient increases to 0.56, suggesting a stronger correlation, although the difference remains statistically significant. To further validate these differences, an independent t-test was conducted on the daytime and nighttime data, and the results indicated that the differences between air temperature and LST were statistically significant.

This difference can be explained by the physical properties of the two parameters. LST is directly influenced by solar radiation, and during the day, when the air temperature is higher, the land surface temperature increases significantly due to the absorption of solar radiation. In contrast, air temperature is primarily regulated by longwave radiation emitted from the ground and is more affected by local airflow, wind speed, and other factors. At night, despite significant surface radiative cooling, air temperature changes remain relatively stable due to the thermal conductivity of the atmosphere. Therefore, the difference between LST and air temperature exhibits distinct variations between day and night.

In conclusion, temperature analysis or cooling intensity calculations based on LST do not effectively represent the results derived from air temperature measurements. This suggests that while remote sensing analyses based on LST can provide spatial distribution information for urban green space heat island effect studies, they may not be as accurate in assessing the actual cooling impact of green spaces on the surrounding environment.

### 大型城市公园对周边热环境的影响

Urban green spaces play a vital role as cooling sources, with temperatures not only lower than the surrounding environment but also significantly reducing the temperature of nearby areas (Park et al., 2021; Qi et al., 2022). Current research on the effects of large urban green spaces on the surrounding thermal environment predominantly focuses on air temperature, while studies on relative humidity and thermal comfort, which are closely related to human perception, remain limited, particularly at fine spatial scales (Dronova et al., 2018; Fan et al., 2019). Utilizing a high-density monitoring network and integrating both two-dimensional (2D) and three-dimensional (3D) environmental factors, this study systematically analyzed the comprehensive effects of Chongqing Central Park on the temperature, humidity, and thermal comfort of the surrounding areas.

The study found that the average nighttime cooling intensity of Chongqing Central Park was 1.7°C, with a cooling influence range of 200–300 meters. In comparison, Yin et al. (2022) reported a similar cooling intensity for Purple Mountain in Nanjing, but with a cooling distance exceeding 500 meters—significantly larger than the results observed in this study. This discrepancy is likely due to the smaller size of Chongqing Central Park compared to Purple Mountain. Furthermore, our findings align with results from a park in Guangzhou and related studies in Japan (Qi et al., 2022; Hamada et al., 2010), indicating that the conclusions of this study are representative of the general cooling characteristics of large urban parks.

Through a day-night comparison, this study further revealed that green spaces exhibit stronger cooling effects at night. This phenomenon is primarily attributed to the heat released from surrounding buildings, which elevates temperatures in built-up areas and enhances the temperature differential between the buildings and the park, thereby amplifying the cooling effect.

Unlike previous studies, this research also systematically examined the impact of green spaces on surrounding humidity levels. The results showed that the effect of green spaces on humidity is opposite to their impact on temperature, which aligns with theoretical expectations. As temperatures rise, saturation vapor pressure increases, leading to a reduction in relative humidity when the moisture content remains constant. Additionally, areas experiencing significant temperature drops often benefit from the inflow of cool, humid air from green spaces, resulting in increased moisture content in those areas. Considering the combined effects of temperature and humidity, this study found that while green spaces increase relative humidity in nearby areas, their primary contribution to thermal comfort is through their cooling effects. The increase in humidity is insufficient to offset the cooling effect, demonstrating that green spaces significantly improve thermal comfort during the summer.

### 环境因素的影响

关于公园周围热环境的降温渗透距离，本研究发现，三维（3D）指标的影响较土地覆盖特征更为显著。现有关于蓝绿空间土地覆盖对降温效应的影响研究较为有限，且结论不尽一致。例如，Du等人（2022）研究表明，西安公园周围的绿化程度越高，降温效应越显著；然而，Jiang等人（2021）则发现上海一些植物覆盖率较高的区域可能会抑制降温效应（RCE）。

为了解决这一争议，亟需深入探讨城市绿地如何通过不同机制影响公园降温效应。一方面，植被通过增强蒸散作用有效降低气温；另一方面，公园周围城市区域的植被增加可能引发路径上的温度梯度，进而削弱整体降温强度。这些相互作用的机制使得绿地对公园周围温湿度的影响变得复杂。本研究未观察到绿地覆盖比例对公园热环境效应的显著影响，这可能是由于上述正负效应相互抵消所致。

此外，本研究还发现，随着建筑物高度的增加，降温渗透距离显著减少。类似的结论也出现在一项关于水体对武汉城市区域降温强度影响的研究中（Lu et al., 2024）。这一现象可解释为较高的建筑物形成了更强的物理屏障，限制了公园降温效应的扩展，使得来自绿地的冷空气流动更快消散。与此同时，街道宽度对降温距离也具有负面影响。较宽的街道降低了高度与宽度的比率及周围建筑物的密度，从而削弱了绿地冷空气的有效积聚能力。

研究还揭示了建筑覆盖面积与公园热环境效应之间存在正相关关系。尽管这一效应较建筑高度和街道宽度的影响较弱，但较大的建筑覆盖面积依然能够增强公园的热环境效益。这可能归因于较高建筑覆盖率区域内的街道通常较窄，从而有助于提高冷空气的积聚能力。

Regarding the cooling penetration distance of the thermal environment around parks, this study found that three-dimensional (3D) indicators have a more significant impact than land cover characteristics. Existing studies on the influence of land cover in blue-green spaces on cooling effects are limited and yield conflicting results. For instance, Du et al. (2022) observed that higher greenery around parks in Xi'an leads to stronger cooling effects. However, Jiang et al. (2021) found that areas with higher vegetation cover in Shanghai may suppress the cooling effect (RCE).

To address this issue, it is necessary to further explore the mechanisms through which urban green spaces affect park cooling effects. On one hand, vegetation enhances evapotranspiration, thereby lowering temperatures. On the other hand, an increase in vegetation around urban areas adjacent to parks may result in a temperature gradient along the path, which weakens the overall cooling intensity. These opposing mechanisms complicate the influence of green spaces on the temperature and humidity of park surroundings. In this study, no significant impact of green cover proportion on the thermal environment effects of parks was observed, likely due to the offsetting of the aforementioned positive and negative effects.

Additionally, this study found that as building height increases, the cooling penetration distance significantly decreases. A similar conclusion was drawn in a study on the cooling intensity of water bodies in urban areas of Wuhan (Lu et al., 2024). This is understandable, as taller buildings create stronger physical barriers, obstructing the park’s cooling effects and causing the cool airflows from green spaces to dissipate more rapidly. Similarly, street width negatively impacts the cooling distance. Wider streets reduce the height-to-width ratio and the surrounding building density, thereby weakening the ability of cool air from green spaces to accumulate effectively.

The study also revealed a positive correlation between building coverage area and the thermal environment effects of parks. Although this effect is relatively weaker compared to building height and street width, larger building coverage areas still enhance the thermal benefits of parks. This may be attributed to the narrower streets in areas with higher building coverage, which improve the accumulation capacity of cooling air.

### 对城市规划的意义

With the rapid urbanization process in China, numerous new urban areas are under construction, while older districts are undergoing significant renewal. The findings of this study provide valuable practical guidance for the planning and design of areas surrounding large urban green spaces. The results indicate that the cooling effect of green spaces is not only influenced by the intrinsic characteristics of the green spaces themselves but is also closely tied to the design of the surrounding urban morphology. Therefore, urban planning around green spaces should place greater emphasis on three-dimensional morphological indicators, such as building height and street width, rather than solely focusing on land cover analysis. This shift in perspective is crucial for maximizing the ecological benefits of green spaces.

To improve the thermal environment during summer, future urban planning should consider reducing building heights in areas surrounding parks. This strategy can mitigate the heat storage and nocturnal heat release effects of buildings, thereby enhancing thermal comfort. This approach is particularly critical for residential areas where outdoor activities are more frequent during the early morning and evening hours. Furthermore, increasing building density and optimizing street layouts, such as designing narrower streets, can further amplify the cooling effects of green spaces by facilitating the effective diffusion of cooler air into adjacent areas.

However, when increasing building density, attention must be paid to avoiding potential negative impacts on ventilation and natural lighting due to excessive density. Multi-objective optimization methods are therefore essential to balance the enhancement of green space cooling effects with the overall quality of the living environment. Moreover, for specific functional zones, such as commercial and mixed-use areas, planning strategies should be adjusted to accommodate their unique climate regulation needs. This ensures that the benefits of green spaces can be effectively tailored to support the diverse functions of urban areas.

### 研究不足与未来规划

This study has certain limitations. First, it focuses on a single large urban park, which fails to capture the diverse impacts of various types and scales of urban green spaces on the surrounding thermal environment. Characteristics such as the size and shape of a park can significantly influence its capacity to regulate temperature and humidity and improve thermal comfort. Therefore, future research should include a broader range of parks with diverse characteristics to validate the generalizability of these findings.

Second, the data collection in this study is limited to the summer season, which does not provide a comprehensive view of the seasonal variations in the thermal environment around the park. For example, the cooling effect of green spaces may be constrained by lower background temperatures in spring and autumn, while in winter, green spaces may exhibit different microclimate regulation patterns, such as reducing wind chill to enhance thermal comfort. Future research should consider the influence of seasonal climatic factors on the microclimatic effects of green spaces.

Additionally, the spatial scope of this study is primarily focused on residential areas, neglecting the unique thermal environment characteristics and demands of other functional zones. For instance, commercial areas, with their high population density, may have a greater need for thermal comfort, while the heat distribution in industrial areas could interfere with the cooling effects of green spaces. Future studies should expand their scope to include commercial, industrial, and mixed-use zones to provide targeted recommendations for climate regulation in urban multifunctional zoning.

By addressing these research directions, future studies can offer a more comprehensive understanding of the complex relationships between urban green spaces and the thermal environment, thereby providing scientific support for optimizing urban green space planning and improving thermal environmental quality.

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