## Introduction

* 随着全球变暖的持续，热浪的频率和强度不断增加。
* 城市热岛效应是指城市气温显著高于周边农村地区的现象（Oke, 1995），这一现象使城市热环境面临更大的风险。
* 研究表明，到2050年，夏季城市气温可能会上升高达3℃（Huang et al., 2019）。
* 愈加频繁和强烈的城市热浪更可能引发暴雨等极端气象灾害事件（Ganeshan et al., 2013）。此外，这些热浪对城市的社会经济活动产生了多方面的负面影响，包括增加能源消耗、干扰城市植被生长、降低居民的生活舒适度，甚至提高居民的死亡风险（Santamouris, 2020; Huang et al., 2024; Gao et al., 2023）。
* 随着人们对城市热岛效应危害的认识逐渐加深，如何有效缓解城市热岛效应和调节城市小气候，已成为当前最为紧迫的城市环境问题之一。

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* As global warming continues, the frequency and intensity of heatwaves are steadily increasing.
* The urban heat island effect, a phenomenon where urban temperatures are significantly higher than those in surrounding rural areas (Oke, 1995), further exacerbates the risks to the urban thermal environment.
* Research suggests that by 2050, summer temperatures in cities could increase by up to 3°C (Huang et al., 2019).
* More frequent and intense urban heatwaves are likely to trigger extreme weather events such as heavy rainfall (Ganeshan et al., 2013). These heatwaves also have multiple negative impacts on urban socio-economic activities, including increased energy consumption, disruption of urban vegetation growth, reduced living comfort for residents, and even higher mortality rates (Santamouris, 2020; Huang et al., 2024; Gao et al., 2023).
* As awareness of the dangers associated with the urban heat island effect grows, effectively mitigating this phenomenon and regulating the urban microclimate has become one of the most urgent environmental challenges for cities today.
* 城市热岛效应的重要原因之一是城市中不透水表面的覆盖率显著高于乡村地区。为应对这一挑战，可以采用多种策略来降低城市温度，例如增加城市植被、使用凉爽的屋顶和凉爽的人行道（Khare et al., 2021; Wang et al., 2021）。
* 绿色空间的利用已成为缓解极端热浪负面影响的重要手段。城市植被通过遮阴和蒸散作用减少热量吸收，从而降低局部气温。
* 目前，已有大量基于遥感技术的研究分析了绿地的降温效果及其影响因素。研究表明，绿地的面积和景观配置等特征是影响地表热通量和温度缓解效果的重要因素。
* 例如，一项在墨西哥进行的研究发现，绿地面积对其降温强度的解释率可达30%（Gomez-Martinez et al., 2021）。此外，研究还发现，地表城市热岛（UHI）强度与绿地斑块密度和平均斑块形状呈负相关，而与绿地边缘密度呈正相关。
* 除了绿地自身特征外，绿地周围环境的特征，如建筑密度和不透水面积比例，也对其降温效果的强度和影响范围起着重要作用（Qiu et al., 2020; Liao et al., 2023）。更高的不透水面比例倾向于降低公园的降温效应（Han et al., 2023）。

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* One of the main causes of the urban heat island effect is the significantly higher coverage of impervious surfaces in urban areas compared to rural areas. To address this challenge, various strategies can be employed to reduce urban temperatures, such as increasing urban vegetation, using cool roofs, and installing cool pavements (Khare et al., 2021; Wang et al., 2021).
* The use of green spaces has become an important means of mitigating the negative impacts of extreme heatwaves. Urban vegetation reduces heat absorption through shading and evapotranspiration, thereby lowering local temperatures.
* Numerous studies based on remote sensing technology have analyzed the cooling effects of green spaces and their influencing factors. Research indicates that characteristics such as the area and landscape configuration of green spaces are critical factors affecting surface heat flux and temperature mitigation.
* For example, a study conducted in Mexico found that green space area could explain up to 30% of the variation in cooling intensity (Gomez-Martinez et al., 2021). Additionally, the study found that the intensity of the urban heat island (UHI) is negatively correlated with green space patch density and average patch shape, but positively correlated with green space edge density.
* Beyond the intrinsic characteristics of green spaces, the surrounding environmental features, such as building density and the proportion of impervious surfaces, also play a significant role in determining the intensity and extent of their cooling effects (Qiu et al., 2020; Liao et al., 2023). Higher proportions of impervious surfaces tend to reduce the cooling effect of parks (Han et al., 2023).
* 目前，研究绿地降温的主要手段包括遥感分析、模型模拟和现场实测。
* 模型模拟不可避免地对实际情况进行一定程度的简化，而遥感分析则基于地表温度，与行人高度的气温存在一定差异。
* 例如，深圳的一项研究发现，地表温度和气温的冷热点分布并不一致（Cao et al., 2021）。此外，由于地表温度直接受太阳辐射驱动，而气温主要受地表辐射影响，两者的时间变化特征及其影响因素也有所不同(Sheng et al., 2017)。因此，基于现场实测的分析能够更准确地反映当地微气候的实际状况。
* 目前已有一些基于实测数据的绿地降温研究案例。例如，北京的一项研究发现，北京奥林匹克公园内外的温差可达4.8°C (Yan et al., 2018)。此外，在高密度城市香港的研究中，发现口袋公园的降温效果受到建筑密度和建筑面积比等环境变量的影响（Lin et al., 2017）。
* 然而，当前关于绿地降温的实测研究主要集中在绿地周边的个别站点，对于大型绿地周边热环境的精细尺度空间格局及其驱动因素仍不够清楚。
* **未来研究方向**：为此，有必要建立高密度的气象监测网络，以实现对绿地周边热环境的现场监测，进一步量化绿地周边气温、相对湿度和热舒适度的精细尺度时空格局及其受环境因素影响的情况。

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* Currently, the main methods for studying the cooling effects of green spaces include remote sensing analysis, model simulation, and field measurements.
* Model simulations inevitably involve some degree of simplification of real-world conditions, while remote sensing analysis is based on surface temperature, which can differ from air temperature at pedestrian height.
* For example, a study in Shenzhen found that the distribution of hot and cold spots in surface temperature does not align with air temperature (Cao et al., 2021). Additionally, surface temperature is directly driven by solar radiation, while air temperature is primarily influenced by surface radiation, leading to differences in their temporal variation characteristics and influencing factors (Sheng et al., 2017). Therefore, field measurements provide a more accurate reflection of the actual local microclimate.
* There are already some examples of field measurement studies on the cooling effects of green spaces. For instance, a study in Beijing found that the temperature difference between the inside and outside of the Olympic Park could reach 4.8°C (Yan et al., 2018). Furthermore, research in the high-density city of Hong Kong showed that the cooling effect of pocket parks is influenced by environmental variables such as building density and floor area ratio (Lin et al., 2017).
* However, current field measurement studies on green space cooling effects are mainly focused on individual sites around green spaces, leaving the fine-scale spatial patterns of the thermal environment around large green spaces and their driving factors still unclear.
* Therefore, it is necessary to establish a high-density meteorological monitoring network to enable on-site monitoring of the thermal environment around green spaces, thereby further quantifying the fine-scale spatiotemporal patterns of air temperature, relative humidity, and thermal comfort around green spaces, as well as their relationship with environmental factors.

* **绿地对城市微气候的影响**：需要注意的是，绿地不仅影响城市微气候的温度，还对湿度的时空格局有显著影响。根据Zhang等(2013)的观测结果，尽管绿地在亚热带城市中能够降低气温达5°C，但同时也使相对湿度增加了8%。在香港的高密度城市环境中，小型公园的增湿和减湿效应均有观测到（Cheung et al., 2021）。
* **热舒适度的综合考虑**：尽管绿地周边的温度有所下降，但温度与相对湿度综合作用下的热舒适度时空格局仍不完全明了，特别是在夏季高温背景下。而对于城市居民来说，与气温相比，热舒适度与他们的热感知更加直接相关。
* **未来研究需求**：因此，有必要基于高密度监测网络对绿地周边的热环境进行监测，从多个气象指标的角度，更全面地理解大型城市绿地对周边热环境的影响。

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* It is important to note that the influence of green spaces on urban microclimates is not limited to temperature; they also significantly affect the spatiotemporal patterns of humidity. According to observations by Zhang et al. (2013), while green spaces in subtropical cities can reduce temperatures by up to 5°C, they can also increase relative humidity by up to 8%. In the high-density urban environment of Hong Kong, both humidifying and dehumidifying effects of small parks have been observed (Cheung et al., 2021).
* Although temperatures around green spaces may decrease to some extent, the spatiotemporal patterns of thermal comfort, which are influenced by both temperature and relative humidity, are not yet fully understood, especially in the context of high summer temperatures. For urban residents, thermal comfort is more directly related to their thermal perception than temperature alone.
* Therefore, it is necessary to establish a high-density monitoring network to assess the thermal environment around green spaces. By considering multiple meteorological indicators, we can gain a more comprehensive understanding of the impact of large urban green spaces on the surrounding thermal environment.

* 为此，本研究选取了重庆中央公园，采用移动测量方法对公园周边的气象变量进行了精细尺度的高密度测量。研究旨在从温度、湿度及其综合效应的角度，深入理解绿地周边的热环境特征，并量化各影响因素的作用。
* 具体研究目标如下：（1）分析绿地周边环境的微气候特征；（2）探讨在不同距公园距离下，环境因素如何影响气象变量；（3）量化绿地的降温强度和范围，并分析相关影响因素的作用。
* 本研究的结果将有助于进一步深入理解绿地周边的热环境特征及其与周边环境特征的交互作用。

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* To this end, this study selected Chongqing Central Park and employed mobile measurement methods to conduct fine-scale, high-density meteorological measurements of the park's surrounding areas. The aim is to understand the thermal environment characteristics around the green space from the perspective of temperature, humidity, and their combined effects, and to quantify the roles of various influencing factors.
* The specific research objectives are as follows: (1) Analyze the microclimate characteristics of the environment surrounding the green space; (2) Investigate how environmental factors affect meteorological variables at different distances from the park; (3) Quantify the intensity and extent of the cooling effect of the green space and analyze the roles of influencing factors.
* The results of this study will contribute to a deeper understanding of the thermal environment characteristics around green spaces and their interactions with surrounding environmental features.

## 数据和方法

### 2.1 研究区

* 重庆概况：重庆是中国西南地区的一座特大城市，位于长江流域上游。在过去二十多年里，重庆的城市人口迅速增长，从2000年的600万增加到2020年的1000万。
* 气候特征：重庆属于亚热带季风气候。冬季主要集中在12月至1月，天气阴冷潮湿；夏季在5月至9月之间，高温天气频繁。每年气温超过35°C的高温天气多达40天，日最高气温可达43°C。
* 中央公园概述：中央公园位于重庆市区北部，占地约1.6平方公里，呈规则的长方形布局，南北长约2公里，东西宽约0.8公里，是重庆市最大的城市公园。公园周边主要是新建的住宅区和商业区，包括高层塔式建筑、低层板式建筑和别墅等。
* 人类活动的影响：由于该区域是新开发城区，人流量和车流量较少，因此人类活动对该区域热环境的影响可以忽略不计。
* 研究目的：本研究将对中央公园及其对周边地区的降温效应进行实地测量和研究。

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Chongqing is a major city in southwestern China, located in the upper reaches of the Yangtze River. Over the past two decades, its urban population has grown rapidly, increasing from 6 million in 2000 to 10 million in 2020.

Chongqing has a subtropical monsoon climate. The winter season spans from December to January, characterized by cold and humid weather. The summer season lasts from May to September, with frequent heatwaves. There are around 40 days annually when temperatures exceed 35°C, with the daily maximum temperature reaching up to 43°C.

Chongqing Central Park is located in the northern part of Chongqing's urban area, covering approximately 1.6 square kilometers. It has a regular rectangular layout, measuring about 2 kilometers from north to south and 0.8 kilometers from east to west, making it the largest urban park in Chongqing. The park is surrounded by newly developed residential and commercial areas, including high-rise tower buildings, low-rise slab buildings, and villas.

As the area is newly developed, both pedestrian and vehicle traffic are relatively low. Therefore, the impact of human activities on the local thermal environment can be considered negligible.

This study aims to conduct field measurements and research on Central Park’s cooling effect on the surrounding areas.

### 2.2 测量

* 夏季气候描述与研究背景：重庆的夏季通常从5月持续至9月，其中7月和8月是最炎热的月份。在本研究中，我们选择在2023年8月进行气象数据测量。为尽量减少阴雨天气对区域热环境的影响，并确保所选日子的代表性，我们特意选取了6个少云且晴朗的日子。
* 测量时间安排：在这6天中，我们每天在两个时间段进行测量，分别从14:00和21:00开始，对应白天和夜间。白天的测量时间处于一天中最热的时段，此时日照强烈，对气象变量的空间分布有显著影响。夜间的测量时段虽然日照减弱，但由于建筑物等不透水表面释放的热量，城市热岛效应相对白天更为显著。根据附近标准气象站的监测数据，这6天中14:00的气温在28.5°C至36.8°C之间，相对湿度在44%至56%之间，能代表重庆盛夏的典型天气状况。6个测量日的基本气象状况如表1所示。

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Chongqing's summer typically lasts from May to September, with July and August being the hottest months. In this study, we chose to conduct meteorological data collection in August 2023. To minimize the impact of rainy weather on the thermal environment and ensure the representativeness of the selected days, we specifically chose six days that were mostly clear and cloudless.

During these six days, measurements were taken twice a day, starting at 14:00 and 21:00, representing daytime and nighttime conditions, respectively. The daytime measurement was conducted during the hottest period of the day, when intense sunlight significantly affects the spatial distribution of meteorological variables. At nighttime, although solar radiation decreases, heat released from impervious surfaces, such as buildings, leads to a relatively stronger urban heat island effect compared to daytime. According to data from a nearby standard meteorological station, temperatures at 14:00 during these six days ranged from 28.5°C to 36.8°C, with relative humidity between 44% and 56%, representing typical weather conditions in Chongqing's midsummer. The basic meteorological conditions of the six measurement days are shown in Table 1.

* 测量空间 - 测量方法：本研究关注精细尺度的气象测量，因此测量点的分布密度较高。我们采用移动测量的方法来收集数据。
* 测量空间 - 路线选择：在实地测量过程中，我们选择了6条平行分布的路线，这些路线均呈东西走向，与中央公园垂直。每条路线从公园边缘出发，测量长度为500米。路线两侧主要是住宅区，包括高层塔式建筑、低层板式建筑和别墅等主要建筑形式，如图XX所示。
* 测量空间 - 测量过程：6名测量员同时沿各自的路线进行测量，每分钟前进10米，并在每个测量点采集一次数据，用于后续分析。每条路线设置了50个测量点，整个研究区域共包含300个测量点。所有测量点均避开行道树和其他有阴影的区域，以最大程度地减少植被等遮挡的影响。每条线路的采样时间为50分钟。
* 测量空间 - 参考点设置：考虑到不同测量点的测量时间不一致，我们在6条路线附近设置了2个固定参考点。这两个参考点距离公园约500米，几乎不受公园影响。在后续分析中，我们将每个时间段的开始测量时间作为基准时间点。通过计算固定参考点在各测量时间点与基准时间点之间的气象数据差值，对移动测量点的数据进行调整，从而使所有数据集可以在同一时间点的基准下进行比较分析。

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* This study focuses on fine-scale meteorological measurements, with a high density of measurement points. We employed a mobile measurement approach to collect the data.
* During the field measurements, we selected six parallel routes, all oriented in an east-west direction and perpendicular to Central Park. Each route started from the edge of the park and extended for 500 meters. The areas along the routes mainly consisted of residential buildings, including high-rise tower buildings, low-rise slab buildings, and villas, as shown in Figure XX.
* Six surveyors simultaneously took measurements along their respective routes, advancing 10 meters every minute and collecting data at each measurement point for subsequent analysis. Each route had 50 measurement points, resulting in a total of 300 measurement points across the study area. All measurement points were located away from street trees and other shaded areas to minimize the influence of vegetation shading. The sampling time for each route was 50 minutes.
* Considering the inconsistency in measurement times at different points, we set up two fixed reference points near the six routes. These reference points were located approximately 500 meters away from the park and were minimally affected by the park. In the subsequent analysis, we used the start time of each measurement period as the baseline. By calculating the differences in meteorological data between each measurement time and the baseline at the reference points, we adjusted the data from the mobile measurement points, allowing all datasets to be compared on a common time basis.
* 设备与测量方法：我们使用 TESTO 175H1 数据记录仪测量气象数据，包括气温和相对湿度。该设备具有较高的测量精度，气温误差为 ±0.1°C，相对湿度误差为 ±0.1%，并且响应时间迅速。测量时，数据记录仪被固定在约 1.5 米的高度，并用百叶箱遮挡，以避免辐射等外界因素的干扰。本研究中，记录仪每 60 秒记录一次数据。
* 地理位置信息获取：此外，我们使用 GPS 记录仪获取每个测量点的经纬度等地理位置信息。
* 设备安装与移动方式：所有设备均安装在一个可移动的竖杆上，固定高度为 1.5 米。在测量过程中，竖杆被绑在手推车上，每位志愿者推着手推车缓慢移动。

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* We used a TESTO 175H1 data logger to measure meteorological data, including air temperature and relative humidity. The device has a high measurement accuracy of ±0.1°C for temperature and ±0.1% for relative humidity, with a quick response time. During the measurements, the data logger was fixed at a height of approximately 1.5 meters and shielded with a louvered screen to avoid interference from external factors such as radiation. In this study, the logger recorded data every 60 seconds.
* Additionally, we used a GPS logger to obtain geographic information, such as the latitude and longitude of each measurement point.
* All equipment was mounted on a movable vertical pole, fixed at a height of 1.5 meters. During the measurements, the pole was attached to a cart, which each volunteer pushed slowly along the measurement path.

### 2.4 降温指标的定义

* 绿地对气温的影响：通常认为，绿地周围的气温会呈现渐进变化的趋势。对于气温等气象变量，随着与绿地距离的增加，气温会逐渐上升，直到某一距离后停止上升，进入相对稳定的状态。同样，对于随着距离增加而波动下降的气象变量（如相对湿度），这种下降趋势也会在某一距离停止。我们将这种趋势终止的点称为该变量的转折点。图1以气温为例展示了其随距离变化的格局，其中点P1即为转折点。
* 转折点的定义：在本研究中，对于随着距离增加而值上升的变量（如气温），当某一点的值大于其后连续5个点的值时，该点被定义为转折点。相反，对于随着距离增加而值下降的变量（如相对湿度），当某一点的值小于其后连续5个点的值时，该点即为转折点。
* 渗透距离与影响强度：起始点与转折点之间的距离被定义为渗透距离，而这两个点对应气象变量的差值则被定义为影响强度。对于气温、相对湿度和不舒适指数（DI），渗透距离分别被称为"停车降温距离"、"公园降温距离"和"公园缓解不适距离"；其影响强度则分别被定义为"停车降温强度"、"公园降温强度"和"公园缓解不适强度"。

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It is generally believed that air temperature around green spaces shows a gradual variation trend. For meteorological variables such as temperature, the values tend to fluctuate upward as the distance from the green space increases, until a certain distance where the upward trend ceases and becomes relatively stable. Similarly, for variables like relative humidity, which tend to fluctuate downward with increasing distance from the green space, the downward trend will also stop at some point along the route. This point where the trend halts is referred to as the turning point of the variable. Figure 1 illustrates the gradual variation in temperature with increasing distance from the park, where point P1 can be considered the turning point.

In this study, for variables that increase with distance (e.g., temperature), a point is defined as the turning point when its value is higher than the subsequent five consecutive points. Conversely, for variables that decrease with distance (e.g., relative humidity), a point is considered a turning point when its value is lower than the next five consecutive points.

The distance between the starting point and the turning point is defined as the penetration distance, while the difference in meteorological variables between these two points is referred to as the impact intensity. For temperature, relative humidity, and discomfort index (DI), the penetration distances are defined as parking cooling distance, park cooling distance, and park relieving discomfort distance, respectively, while their corresponding impact intensities are termed parking cooling intensity, park cooling intensity, and park relieving discomfort intensity.

### 2.3 数据

* 遥感影像数据：GF-2高分辨率遥感影像被用于本研究中的土地覆盖分类分析。
* 影像特点：该影像具有1米的空间分辨率，拍摄时间为2023年5月24日，并通过中国遥感卫星数据共享服务平台获取。
* 土地覆盖分类方法：我们采用监督分类的方法，将研究区域划分为3种主要的土地覆盖类型，分别为植被、不透水地表（如道路和广场）以及其他类型（如水体或裸地）。
* 建筑信息来源与处理：所有的建筑信息（包括位置、足迹、楼层数）均采集自高德地图。根据重庆市住宅楼的实际情况，我们将建筑层数乘以3，以估算实际的建筑高度信息，用于计算建筑相关的环境指标。

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* GF-2 high-resolution remote sensing imagery was used for land cover classification analysis in this study.
* The imagery has a spatial resolution of 1 meter, captured on May 24, 2023, and obtained from the China Remote Sensing Satellite Data Sharing Service Platform.
* We employed a supervised classification approach to divide the study area into three main land cover types: vegetation, impervious surfaces (such as roads and plazas), and other types (such as water bodies or bare land).
* All building information, including location, footprint, and number of floors, was collected from Amap. To estimate the actual building height, we multiplied the number of floors by 3, based on the typical residential building conditions in Chongqing, for calculating building-related environmental metrics.

### 2.4影响因素

* 城市气候特征与缓冲区设置：城市气候特征是由多种因素共同作用的结果。为了计算这些环境变量并分析其与气象变量之间的关系，我们设置了半径为100米的缓冲扇区。该缓冲区大小是通过比较不同缓冲区尺寸下环境因素与气象变量之间的关系，并选择相关性最大的尺寸来确定的。
* 环境变量的选择：本研究选取了XX个环境变量，从土地覆盖特征、城市形态特征以及相对位置等多个维度，探讨城市绿地对周边热环境的影响。
* 土地覆盖特征：在这一方面，我们考虑了建筑面积比和绿地面积比。
* 城市形态特征：我们分析了平均建筑高度、天空视角因子（SVF）和街道宽度对绿地周边气象变量的影响。值得注意的是，由于研究区主要为住宅区，不同类型的建筑沿东西走向的道路排列，因此建筑朝向趋于一致，本研究不考虑建筑朝向的影响。
* 街道宽度的定义：街道宽度由对应街道两侧建筑物之间的最近距离表征，对于每条街道，这一宽度保持不变。本研究中，6条街道的宽度在XX-XX米之间。
* 平均建筑高度和天空视角因子：平均建筑高度是指场地范围内各建筑按建筑面积加权的高度均值。天空视角因子表示各位置的可视天空面积与总天空面积之比，这一指标可能影响该位置日照被遮挡的程度。
* 绿地距离的影响：此外，绿地与测量点之间的距离也作为一个重要因素，分析其对绿地效应的影响。

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Urban climate characteristics are the result of multiple interacting factors. To calculate these environmental variables and analyze their relationships with meteorological variables, we established a buffer sector with a radius of 100 meters. The buffer size was determined by comparing the relationships between environmental factors and meteorological variables at different buffer sizes, selecting the one with the strongest correlation.

This study selected XX environmental variables, exploring the influence of urban green spaces on the surrounding thermal environment from various dimensions, including land cover characteristics, urban morphology, and relative location.

In this aspect, we considered the building area ratio and green space area ratio.

We analyzed the effects of average building height, Sky View Factor (SVF), and street width on meteorological variables around green spaces. It is noteworthy that the study area mainly consists of residential zones, with different types of buildings arranged along east-west oriented roads. Therefore, building orientation was not considered in this study due to its uniformity.

Street width was characterized by the shortest distance between buildings on both sides of the corresponding street. This width remained constant for each street. In this study, the widths of the six streets ranged from XX to XX meters.

Average building height refers to the mean height of buildings within the area, weighted by building area. The Sky View Factor represents the ratio of visible sky area to total sky area at each location, potentially influencing the degree of sunlight obstruction.

Additionally, the distance between green spaces and measurement points was analyzed as a key factor influencing the green space effect.

### 2.5 研究框架

* 数据处理与分析：在完成实地测量后，我们首先基于气温和相对湿度计算了不舒适指数（Discomfort Index）。接着，对所有测量日中各街道的气象变量（气温、相对湿度和不舒适指数）与环境变量进行皮尔逊相关分析，以探讨环境因素对气象变量的影响。鉴于气温、相对湿度及不舒适指数等气象变量在逐日间存在显著变化，我们使用所有测量日的均值进行相关分析。
* 公园影响的量化：此外，我们计算了公园对周围环境气象变量影响的强度和距离，并量化其与环境变量的相关性。所有数据分析均在R 4.3中完成。

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After completing the field measurements, we first calculated the Discomfort Index based on temperature and relative humidity. Then, we conducted Pearson correlation analysis between meteorological variables (temperature, relative humidity, and Discomfort Index) and environmental variables for each street across all measurement days, to explore the impact of environmental factors on the meteorological variables. Considering that these meteorological variables exhibited significant variations from day to day, we used the averages of all measurement days for the correlation analysis.

Additionally, we calculated the intensity and distance of the park's influence on surrounding meteorological variables and quantified their correlations with environmental variables. All data analyses were conducted using R version 4.3.

### 2.6 Discomfort Index

### 中文版

为了评估空气温度和湿度对人体热舒适的综合作用，我们采用了不适指数（Discomfort Index，DI）。该指数由Thom提出，目前已被广泛应用于城市热舒适度的相关评估。其计算公式如下：

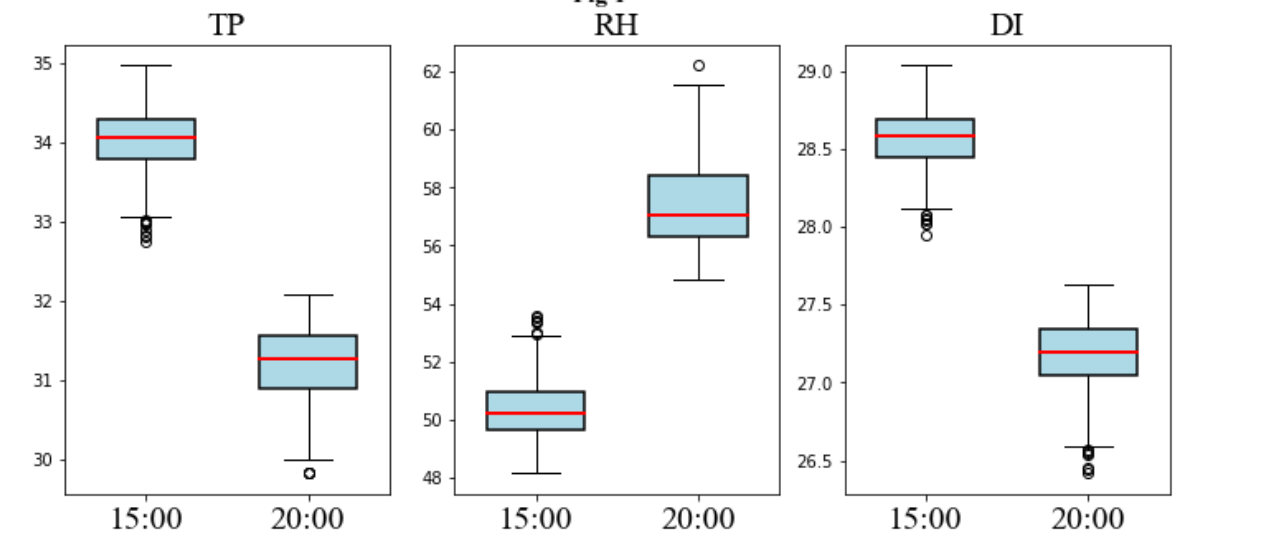
DI = Ta - (0.55 - 0.0055 \* RH) \*(Ta - 14.5)

其中，\( Ta \) 为环境干球温度（℃），\( RH \) 为相对湿度（%）。

* To assess the combined effect of air temperature and humidity on human thermal comfort, we used the Discomfort Index (DI). This index, proposed by Thom, has been widely applied in the evaluation of urban thermal comfort. The calculation formula is as follows:
* DI = Ta - (0.55 - 0.0055 \* RH) \*(Ta - 14.5)
* Where Ta is the ambient dry-bulb temperature (°C), and RH is the relative humidity (%).

## 3. 结果

### 3.1 气象变量的时空格局



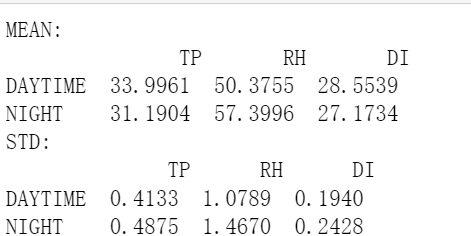
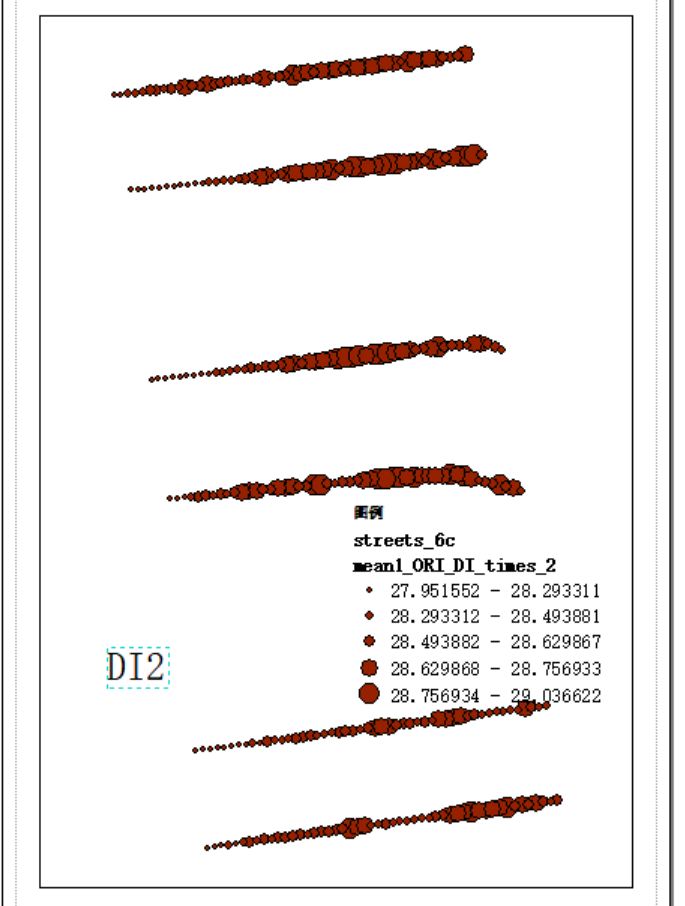
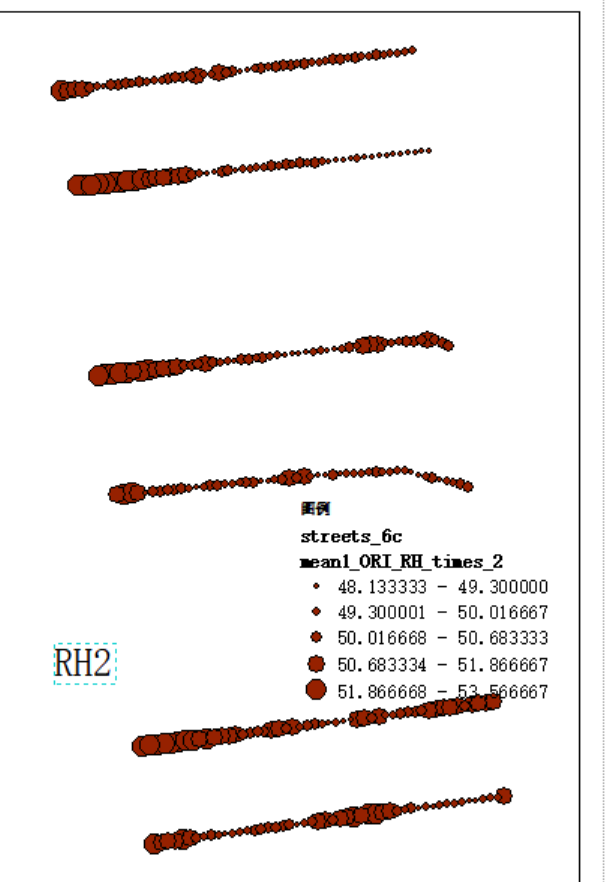
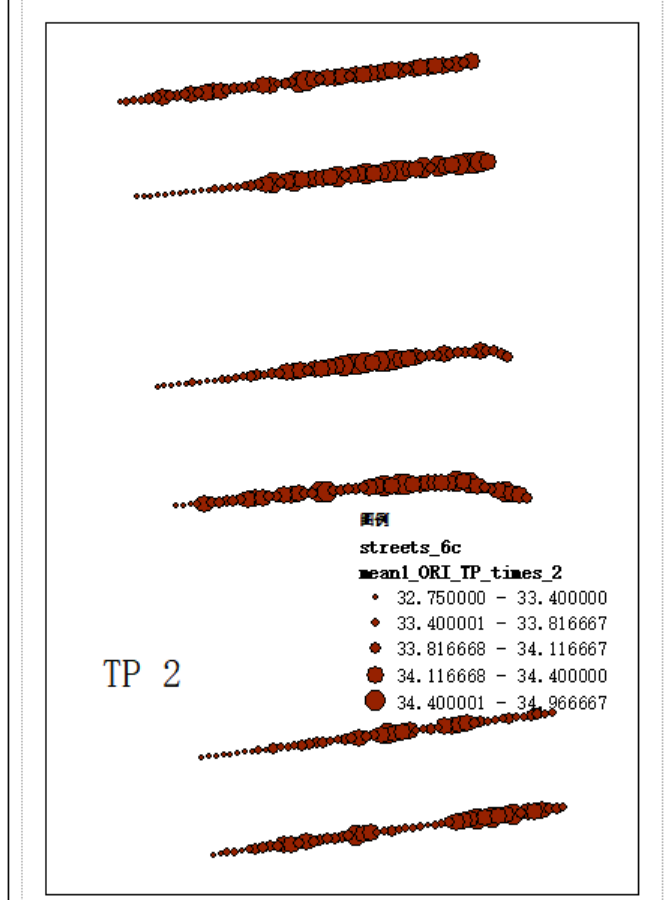


图1展示了所有测量点白天和夜间的日均温度、相对湿度和不适指数的分布箱线图。可以清楚地看出，相较于白天，夜间气温降低，而相对湿度增加。在气温和相对湿度的共同作用下，不适指数仍然显著下降。根据表1中列出的这三个气象变量的均值，从白天到夜间，气温的平均值从34.0℃降至31.2℃，相对湿度的平均值从50.4%升至57.4%。相应地，不适指数从28.6℃下降至27.2℃。这表明，尽管相对湿度有所上升，绿地的降温作用仍能降低热不适感，使周围环境更为舒适，尽管热不适感的下降幅度低于气温的降低。此外，该图还显示，夜间不同测量点之间的这三个气象指标的标准差比白天更大。根据表1中列出的标准差数据，气温、相对湿度和不适指数的标准差分别从白天的0.41℃、1.1%和0.19℃增加到夜间的0.49℃、1.5%和0.24℃。

The boxplots in Figure 1 illustrate the distribution of daily average temperature, relative humidity, and discomfort index for all measurement points during the day and at night. It is clearly observed that, compared to daytime, nighttime temperatures decrease while relative humidity increases. Due to the combined effects of temperature and relative humidity, the discomfort index still significantly decreases. According to the averages of these three meteorological variables in Table 1, from day to night, the average temperature drops from 34.0°C to 31.2°C, and the average relative humidity rises from 50.4% to 57.4%. Consequently, the discomfort index decreases from 28.6°C to 27.2°C. This indicates that despite the increase in relative humidity, the cooling effect of green spaces can still reduce thermal discomfort, making the surrounding environment more comfortable, although the decrease in thermal discomfort is less pronounced than the reduction in temperature. Additionally, the figure shows that at night, the standard deviations of these three meteorological indicators are larger across different measurement points compared to daytime. According to the standard deviations of the three variables listed in Table 1, the temperature, relative humidity, and discomfort index increase from 0.41°C, 1.1%, and 0.19°C during the day to 0.49°C, 1.5%, and 0.24°C at night, respectively.



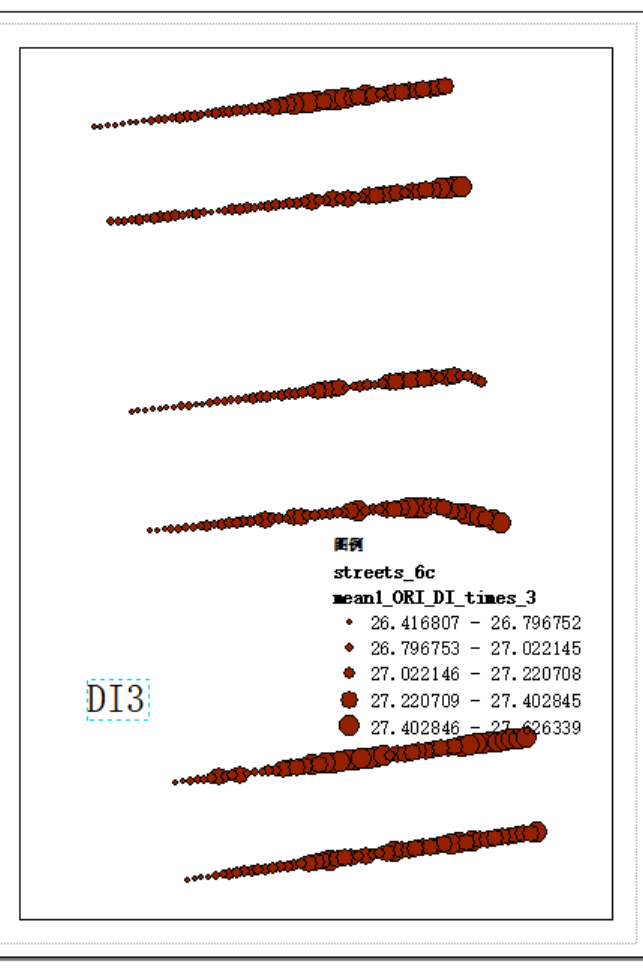
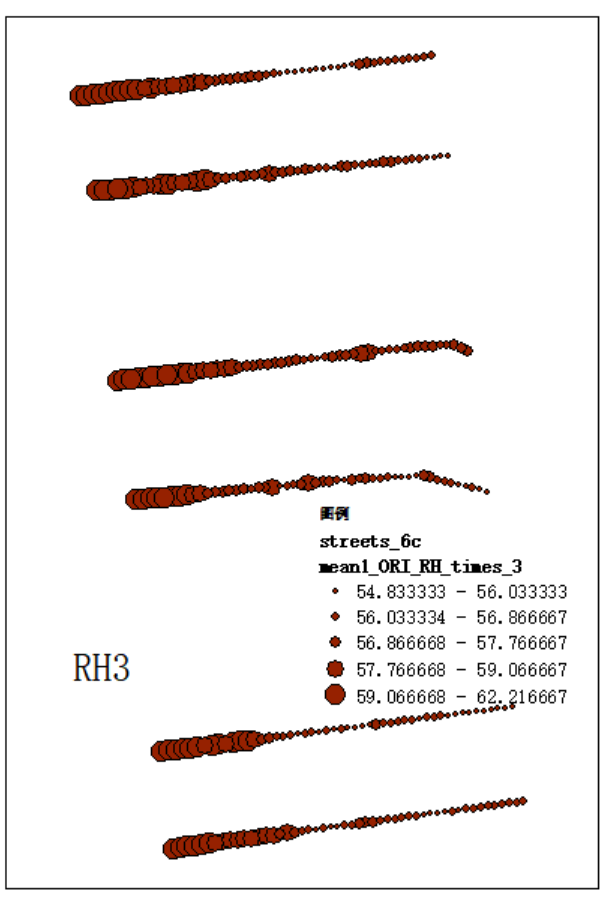
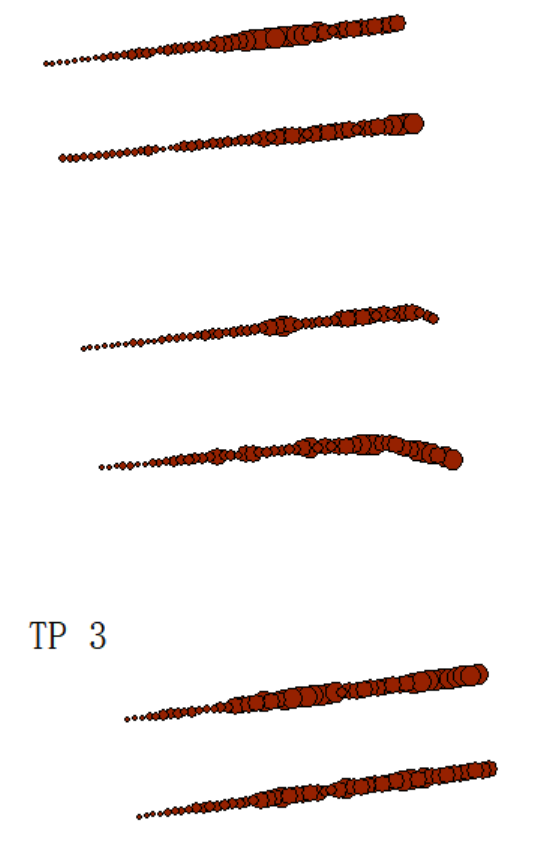


图2展示了三个气象变量日均值的空间分布格局。可以清晰地看出，在距绿地不同距离的位置，这些气象变量存在显著差异。具体而言，距离绿地较近的区域气温较低，相对湿度较高，这表明绿地具有降温和增湿的作用。在气温和相对湿度的共同影响下，不适指数（DI）也有所降低，夜间的效果尤为显著。

夜间，日均气温低于33℃的区域主要集中在距绿地约200米以内，而这些区域的相对湿度均值大多高于54%，不适指数低于27%。此外，我们还发现，与夜间相比，白天绿地对周围区域的降温、增湿和降低不适指数的效果较为有限。同时，在某些街道上，绿地的影响范围也相对较小，仅延伸至绿地以外的数十米。因此，白天三个变量从绿地边缘向外的变化趋势较弱。

具体来说，气温的降幅从夜间的约2℃减少至白天的约1℃，相对湿度的升幅从夜间的约4%下降至2%，不适指数的降幅也从2℃降低为1℃。这可以解释为什么夜间的日均温度分布范围显著大于白天。

Figure 2 illustrates the spatial distribution patterns of the daily averages of three meteorological variables. It is evident that there are significant differences in these variables at varying distances from the green space. Specifically, areas closer to the green space tend to have lower temperatures and higher relative humidity, demonstrating the cooling and humidifying effects of green spaces. As a result of the combined impact of temperature and relative humidity, the discomfort index (DI) also decreases, especially during the night.

At night, regions with daily average temperatures below 33°C are primarily located within approximately 200 meters of the green space, and these areas generally show relative humidity averages above 54% and DI values below 27%. Additionally, it is observed that, compared to nighttime, the cooling, humidifying, and DI-reducing effects of green spaces near the surrounding areas are more limited during the daytime. In some streets, the influence of green spaces is also relatively confined, extending only a few dozen meters beyond the green space. Consequently, the trends in the three variables from the edge of the green space outward are less pronounced during the day.

Specifically, the temperature reduction due to green spaces decreases from around 2°C at night to about 1°C during the day. Similarly, the increase in relative humidity drops from around 4% at night to 2% during the day, while the effect on DI is reduced from 2°C to 1°C. This also explains why the range of daily average temperatures is significantly larger at night compared to the daytime.

### 3.2 气象变量的影响因素

随着距绿地距离的增加，绿地的影响逐渐减弱，其他环境因素的影响则相应变化。因此，本研究将研究区域按距绿地的距离分为5个区段，分别为0-100米、100-200米、200-300米、300-400米和400-500米。针对每个区段，量化分析环境因素与气象变量之间的关系。

图3展示了不同距绿地区段下白天和夜间气温与距离的散点图。

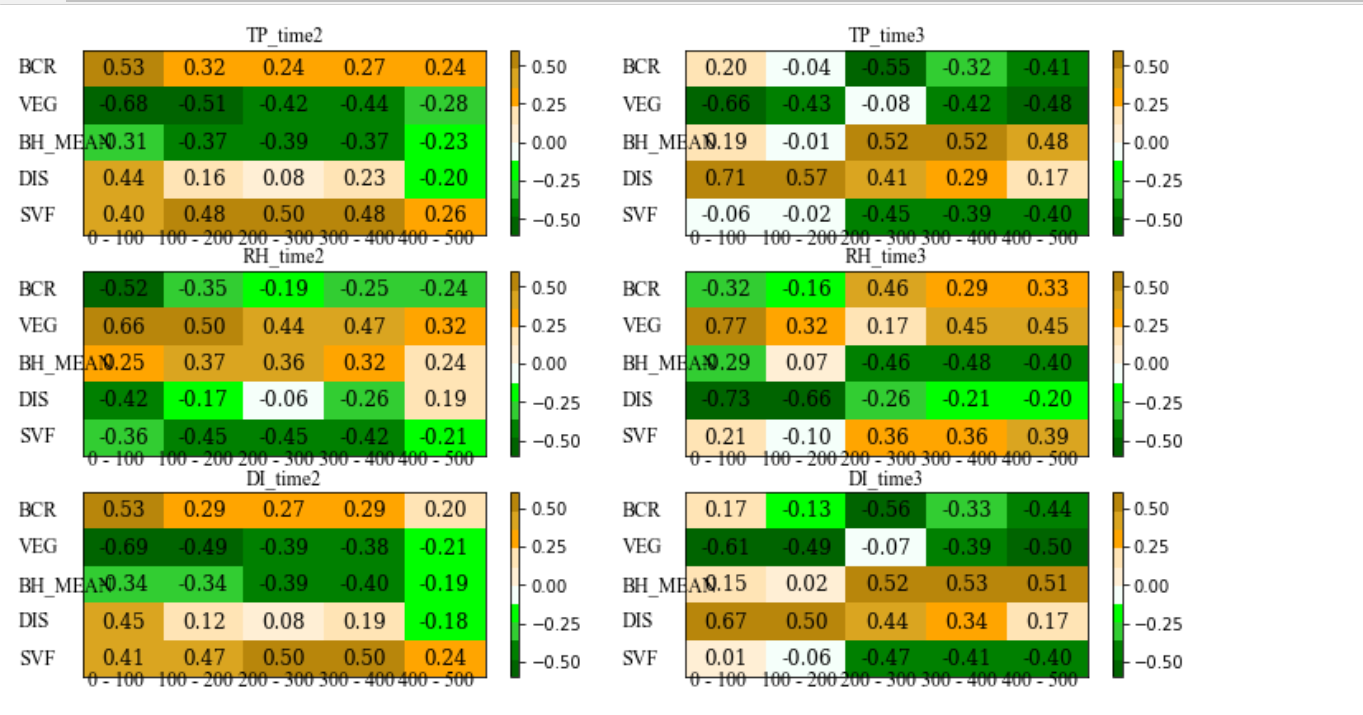
【昼夜比较】可以看出，在夜间，气温与距离之间的关系在距绿地300米以内较为显著。具体而言，在0-100米范围内，二者的相关系数为0.71；在100-200米和200-300米范围内，相关系数分别下降至0.57和0.41。在300-500米的两个区段内，气温与距离的相关性均小于0.3。白天时，气温与距离的相关性明显减弱。在0-100米范围内，相关系数为0.44，而在100-500米的四个区段中，相关性均显著低于0.2。这表明白天绿地对100米以外区域的影响较弱。类似的情况也出现在相对湿度（RH）与距离的相关性分析中。夜间，在0-100米和100-200米范围内，相关系数分别为0.76和0.66，而白天仅在0-100米区间内相关系数为0.42，其余区段均小于0.3。对于不适指数（DI）与距离的相关性，夜间在五个区段内的相关系数依次从0-100米的0.67降低至400-500米的0.17，而白天仅在0-100米区间的相关系数大于0.3。

总体来看，随着距绿地距离的增加，影响程度显著减弱，直到特定距离后几乎消失。影响的范围在一天的不同时间段内也存在显著差异。夜间，绿地对周围气象变量的影响可达200-300米，而白天的影响范围则一般在100米左右。

As the distance from the green space increases, the influence of the green space gradually weakens, while other environmental factors change accordingly. Therefore, this study divided the study area into five segments based on the distance from the green space: 0-100 meters, 100-200 meters, 200-300 meters, 300-400 meters, and 400-500 meters. A quantitative analysis was conducted to examine the relationship between environmental factors and meteorological variables for each segment.

Figure 3 shows scatter plots of temperature versus distance from the green space for different segments during the day and night. It can be seen that at night, the relationship between temperature and distance is more pronounced within 300 meters of the green space. Specifically, the correlation coefficient is 0.71 within 0-100 meters, but it decreases to 0.57 and 0.41 in the 100-200 meter and 200-300 meter ranges, respectively. In the 300-500 meter segments, the correlation between temperature and distance is less than 0.3. During the day, the correlation between temperature and distance weakens significantly. In the 0-100 meter range, the correlation coefficient is 0.44, while in the 100-500 meter segments, it is significantly below 0.2. This indicates that during the day, the influence of the green space is weaker beyond 100 meters. A similar pattern can be observed in the correlation analysis of relative humidity (RH) with distance. At night, the correlation coefficients for the 0-100 meter and 100-200 meter ranges are 0.76 and 0.66, respectively. However, during the day, only the 0-100 meter range shows a correlation coefficient of 0.42, with all other segments below 0.3. For the discomfort index (DI), the correlation coefficients at night decrease across the five segments, from 0.67 in the 0-100 meter range to 0.17 in the 400-500 meter range, while during the day, only the 0-100 meter segment has a correlation coefficient greater than 0.3.

Overall, as the distance from the green space increases, the degree of influence significantly weakens and almost disappears beyond a certain distance. The range of influence also varies considerably between different times of the day. At night, the green space's impact on surrounding meteorological variables extends up to 200-300 meters, while during the day, the influence is generally limited to around 100 meters.



图XX显示了对于不同的与绿地距离区间，环境因素对气象变量的影响。上图已经表明，随着与绿地距离的增加，距离的影响程度显著削弱直到特定距离后几乎消失。然而对于其它变量，影响的程度也显著变化。

在夜间，可以看到0-200米和200-500米区间段内的气温与环境因素的相关性格局呈现显著的差异性。在200-500米的区间内，SVF/BH/VEG和BCR对气温的影响显著。其中，平均建筑高度对气温呈正相关，而建筑面积与植被面积与气温负相关。植被面积与气温的负相关较易理解，这是因为随着周围植被面积的增加，植被的蒸散作用增强，对气温的下降起到促进作用。而至于建筑高度与气温的正相关可以被解释为增加的周围建筑高度可以增加研究区域的储热。周边面积与气温的负相关可能是由于其与建筑高度的负相关性所导致的。

由上图可以看到，在200-500米的范围内，建筑高度的相关性整体上最强，在3个区间分别为0.52、0.52和0.48.，植被面积、建筑面积、SVF的相对作用相对较弱。这表明建筑高度带来的储热效应对夜间绿地影响较弱区域起最为显著的作用。需要注意的是，在200-300米的区间内，植被对气温的影响较弱，这可能是由于绿地降温对该区域的渗透作用使得该区域不仅受建筑和周边植被影响，还受来自中央公园的降温作用的影响。这使得气温格局更为复杂。

与200米以外的区间不同，在距中央公园200米以内的区域，距绿地的距离的影响显著增加。同时，植被面积的影响同样增加。这可以由以下事实解释：距公园距离越近，植被比例越高。由于公园降温的作用，其它与建筑形态相关的指标对气温的影响可以忽略不计。因此，可以得到以下事实，即对于夜间气温来说，在公园降温效应没起作用的区域，建筑形态起重要作用。而在公园降温效应起作用的区域，公园的降温可以覆盖掉其它因素的影响。

环境因素对相对湿度的影响与对气温的影响正好相反。在200-500米的区间，建筑高度对相对湿度起显著的负效应。而植被比例、建筑比例和SVF对其起显著的正效应，且影响的强度相对较弱。而在0-200米的区间内，与公园的距离和植被覆盖比例的影响较强。其中，与公园的距离的相关系数为0.77、0.6，与植被覆盖的相关系数分别为0.77、0.32.

此外，在气温与相对湿度的综合作用下，环境因素对DI的影响与对气温的影响呈现相似的格局和强度。其中，建筑高度的影响最强，在300-500米的三个区间段的相关系数分别为0.52、0.53和0.51，SVF、BCR和VEG的相关系数相对较弱。因此，相比于相对湿度，气温对DI时空格局及其与环境因素关系影响更为显著。

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在白天，环境因素对气象变量的影响与夜间有显著差异，这很大程度上是由白天和夜间之间气象指标的驱动机制以及来自中央公园的降温效应的差异所导致的。在100-500米的区间范围内，SVF和植被覆盖比例对气温的影响最强，尤其是SVF。这很容易解释，因为SVF越大，太阳直射的面积越大，因此气温就越高。而白天由于日照强烈，因此相对于其它建筑形态变量，SVF对气温的影响起主导作用。此外，受植被蒸散作用等效应的影响，植被对周边环境的降温仍起显著作用。需要注意的是，在白天，建筑形态指标对气温的影响与夜间正好相反。这可能是由于不同时间建筑形态影响气温的机制不同。在夜间，影响气温的主要因素是储热释放，因此过高的建筑会增加储热释放，而在研究区中，建筑高度与SVF和建筑面积呈显著负相关，因此建筑高度与气温呈正相关，而SVF和建筑面积呈负相关。相反在白天，建筑储热的释放起的作用有限，太阳辐射差异是导致气温空间格局的主要影响因素。还需要注意的是，相对于夜间，建筑高度和建筑覆盖比例的影响在白天相对较弱。

在白天，环境因素对相对湿度的影响与对气温的影响趋势相反。需要注意的是，在对相对湿度的影响分析中我们发现，植被覆盖比例的影响程度略微上升，而SVF影响的程度相对下降。这表明日照差异主要影响气温，而植被对相对湿度的影响更为显著。

与夜间相同，相对于相对湿度，DI也更受到气温的影响，与环境因素的相关系数更接近于气温与环境因素的相关分析结果。

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### 3.3 降温指标及其影响因素

图XX显示降温指标的箱线图。可以看到，整体而言，夜间的降温强度和降温距离显著大于白天。对于气温，夜间的降温幅度在XX-XX之间，平均值为XX，而在白天，降温幅度仅为XX-XX，平均值为XX。至于降温距离，夜间（XX-XX）同样大于白天（XX-XX）。

就相对湿度而言，DRH影响距离的范围从白天的XX-XX增加至夜间的XX-XX，平均值则从XX增加至XX。影响强度的平均值则从XX下降至XX。DI的影响强度和渗透距离与TP和RH相似，在夜间均值为XX，而在白天均值则为XX。

对于降温指标，我们选择了街道宽度和建筑高度作为影响因素。结果表明，街道宽度和建筑高度对于降温距离影响显著，然而对降温强度的影响不明显。对于气温的降温距离，SW和BH的影响率为0.18和0.13。而对于RH，两者的影响程度相对下降，为xx和xx。对于DI，这两个指标则分别为xx和xx。

在白天，上述两个因素的影响强度显著低于夜间。对于气温、相对湿度和DI，两者的影响指标分别为XX,XX XX, XX, XX, XX.

总体而言，建筑高度和街道宽度均与降温距离呈负相关。相对于建筑高度、街道宽度对降温效应的影响显著更强。这表明相对较窄的道路更有利于公园降温效应的向内陆渗透。

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