## 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，位于长江流域的上游。在过去的二十多年里，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；夏季则在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，日最高气温可达到43°C。
* **中央公园概述**：中央公园位于重庆市区北部，占地面积约1.6平方公里，呈长方形布局，南北长约2公里，东西宽约0.8公里。公园周围主要是新建住宅区，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 megacity in southwestern China, located in the upper reaches of the Yangtze River. Over the past two decades, Chongqing's urban population has grown rapidly, increasing from 6 million in 2000 to 10 million in 2020.
* Chongqing has a subtropical monsoon climate, with winter primarily occurring from December to January, characterized by cold and humid weather. The summer season, from May to September, is marked by frequent high temperatures, with more than 40 days per year exceeding 35°C, and daily maximum temperatures reaching up to 43°C.
* Central Park is located in the northern part of Chongqing’s urban area, covering approximately 1.6 square kilometers. The park has a rectangular layout, extending about 2 kilometers from north to south and 0.8 kilometers from east to west. The surrounding area consists mainly of newly built residential districts, including high-rise tower buildings, low-rise slab buildings, and villas.
* Since this area is a newly developed urban district with low pedestrian and vehicle traffic, the impact of human activity on the local thermal environment can be considered negligible.
* This study aims to conduct field measurements and research on the cooling effects of Central Park and its impact on the surrounding areas.

### 2.2 测量

* **研究期间与条件**：重庆的夏季从5月至9月，其中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。为减少阴雨天气对区域热环境的影响，我们特意选取了6个少云且晴朗的日子。
* **测量时间安排**：在这几天中，我们每天在三个时间段进行测量，分别是10:00、15:00和20:00，对应上午、下午和夜间。其中，下午是一天中最热的时段。附近标准气象站的监测数据显示，这6天中15:00的气温在28.5°C至36.8°C之间。

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* Chongqing’s summer season extends from May to September, with August being the hottest month. In this study, we conducted meteorological measurements in August 2023. To minimize the impact of cloudy or rainy weather on the local thermal environment, we specifically selected six days with clear skies and minimal cloud cover.
* On these selected days, we conducted measurements at three time intervals: 10:00, 15:00, and 20:00, representing morning, afternoon, and nighttime, respectively. The afternoon is typically the hottest part of the day. Data from nearby standard meteorological stations showed that, during these six days, temperatures at 15:00 ranged between 28.5°C and 36.8°C.
* **测量方法**：为了对研究区域进行精细尺度的气象测量，我们采用了移动测量的方法来收集数据。
* **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。每条路线的测量长度为500米，如图XX所示。
* **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两次数据，取其均值作为该点的最终数据，用于后续分析。每条路线共设置50个测量点，整个研究区域共包含300个测量点，涵盖了高层塔式建筑、低层板式建筑和别墅等主要建筑形态。所有测量点均避开行道树，以最大程度地减少树木遮阴的影响。
* **参考点设置**：同时，我们在6条路线附近设置了一个固定参考点。该参考点距离公园约500米，几乎不受绿地影响。
* 在后续分析中，我们将每个时间段开始测量的时间作为基准时间点。通过计算移动测量点与固定参考点在该时间点的气象数据差值，对移动测量点的数据进行调整。

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* To conduct fine-scale meteorological measurements in the study area, we employed a mobile measurement approach to collect data.
* During the field measurements, we selected six parallel routes, all running east-west and perpendicular to Central Park. Each route was 500 meters in length, as shown in Figure XX.
* Six surveyors conducted measurements simultaneously along their respective routes, advancing 10 meters every minute. At each measurement point, data was collected twice, and the average was taken as the final value for subsequent analysis. Each route had 50 measurement points, resulting in a total of 300 data points across the entire study area, covering major building types such as high-rise tower buildings, low-rise slab buildings, and villas. All measurement points were positioned away from roadside trees to minimize the impact of shading from the trees.
* Each route had 50 measurement points, resulting in a total of 300 data points across the entire study area.
* Additionally, we established a fixed reference point near the six routes. This reference point was located approximately 500 meters from the park and was minimally influenced by the green space.
* In the subsequent analysis, the starting time of each measurement period was used as the reference time point. The meteorological data at each mobile measurement point was adjusted by calculating the difference between the mobile measurement point and the fixed reference point at that time.
* 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。该设备的测量精度为气温±0.1°C，相对湿度±0.1%。在测量过程中，数据记录仪固定在约1.5米的高度，并用百叶箱遮蔽，以避免辐射和其他外界因素的干扰。在本研究中，记录仪每5秒记录一次数据。
* 此外，使用GPS记录仪获取每个测量点的经纬度等地理位置信息。
* 所有设备均安装在可移动竖杆上，固定高度为1.5米。

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* The TESTO 175H1 data logger was used to measure meteorological data, including temperature and relative humidity. The device's measurement accuracy is ±0.1°C for temperature and ±0.1% for relative humidity. During measurement, the data logger was mounted at a height of approximately 1.5 meters and enclosed in a radiation shield to prevent interference from radiation and other external factors. In this study, the logger recorded data every 5 seconds.
* Additionally, a GPS recorder was used to capture the geographic coordinates, including latitude and longitude, of each measurement point.
* All devices were mounted at a height of 1.5 meters on movable poles.

### 2.4 降温指标的定义

* 通常认为，绿地周围的气温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，其值会呈现波动上升的趋势。直至某一距离，这种上升趋势停止，转为相对稳定的状态。同样，对于随着与绿地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路线上的某一距离停止。我们将这一趋势终止的点称为该变量的转折点。
* **转折点定义**：对于气温等随着距离增加而值上升的变量，当某一点的值大于其后连续5个点的值时，该点即定义为转折点。相反，对于相对湿度等随着距离增加而值下降的变量，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定义为渗透距离，而两个点对应气象变量的差值则定义为影响强度。

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* It is generally accepted that the meteorological variables around green spaces exhibit gradual changes. For meteorological variables such as temperature, as the distance from the green space increases, the values tend to fluctuate upward. At a certain point, this upward trend stops and the temperature stabilizes. Similarly, for variables like relative humidity, which decrease with distance from the green space, the downward trend also ends at a certain point along the route. This point where the upward or downward trend halts is defined as the inflection point for the respective variable.
* For variables such as temperature that increase with distance, the inflection point is defined as the location where the value is greater than that of the next five consecutive points. Conversely, for variables like relative humidity that decrease with distance, the inflection point is where the value is lower than that of the following five points.
* The distance between the starting point and the inflection point is defined as the penetration distance, and the difference in meteorological variable values between these two points is referred to as the impact intensity.

### 2.3 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。
* 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。
* 采用监督分类的方法，我们将研究区域划分为四种主要的土地覆盖类型，分别为植被、建筑物、不透水地表（如道路和广场）以及其他类型（如水体或裸地）。
* 除此之外，所有的建筑高度信息均采集于百度地图。

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* The 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, was captured on May 24, 2023, and was obtained from the China Remote Sensing Satellite Data Sharing Service Platform.
* Using a supervised classification method, we categorized the study area into four main land cover types: vegetation, buildings, impervious surfaces (such as roads and plazas), and other types (such as water bodies or bare land).
* Additionally, all building height information was obtained from the Baidu Map.

### 2.4影响因素

* 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。
* 本研究选取了XX个环境变量，从二维景观特征、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。
* 在二维景观特征方面，我们考虑了建筑面积比、绿地面积比以及景观形状指数（landscape shape index）。
* 对于城市形态特征，我们分析了街道宽度、平均建筑高度和容积率等潜在影响绿地周边气象变量的因素。值得注意的是，由于研究区主要为住宅区，不同类型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。
* 平均建筑高度指的是场地范围内各建筑按建筑面积加权的高度均值，容积率则表示建筑总面积与场地面积的比例。
* 此外，绿地与测量点之间的距离也被作为影响绿地效应的重要因素进行分析。
* 具体环境变量的详细信息见表XX。

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* Urban climate characteristics result from the combined effects of multiple factors in the urban environment. To calculate these environmental variables and analyze their relationship with meteorological variables, we established a 100-meter radius buffer zone.
* In this study, we selected XX environmental variables to explore the impact of urban green spaces on the surrounding thermal environment from several dimensions, including two-dimensional landscape features, urban morphology, and relative location.
* For two-dimensional landscape features, we considered the building area ratio, green space area ratio, and landscape shape index.
* Regarding urban morphology, we analyzed street width, average building height, and floor area ratio as potential factors influencing the meteorological variables around green spaces. It is important to note that the study area primarily consists of residential zones where different building types are aligned along east-west oriented roads, resulting in consistent building orientation. Therefore, the influence of building orientation was not included in this study.
* Average building height refers to the height-weighted mean of buildings based on their area, while floor area ratio represents the ratio of total building area to the site area.
* Additionally, the distance from green spaces was also considered as a significant factor affecting the thermal environment around green spaces.
* Detailed information on the environmental variables is provided in Table XX.

### 2.5 研究框架

* 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。
* 此外，我们基于各气象变量计算了绿地对其影响的强度和距离，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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* We first calculated the Discomfort Index based on temperature and relative humidity. Then, we conducted Pearson correlation analysis between the 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 meteorological variables. Given the significant day-to-day variation in temperature, relative humidity, and the Discomfort Index, we used the mean values of all measurement days for the correlation analysis.
* In addition, we calculated the intensity and distance of green space influence on the meteorological variables and quantified their correlation with environmental variables. All data analyses were conducted using R 4.3.

### 2.6 Discomfort Index

### River cooling effects on the normal summer day and the extremely hot day

Fig. 4 The spatial patterns of average RCI of individual river segments on the normal summer day (a) and the extremely hot day (b), respectively. The widths of river segments represent the corresponding RCD.

Fig. 5 The spatial patterns of average RCD of individual river segments on the normal summer day (a) and the extremely hot day (b), respectively.

Fig. 6 The spatial patterns of average CRCI of individual river segments on the normal summer day (a) and the extremely hot day (b), respectively.

The spatial patterns of RCI are illustrated in Fig. 4. On the normal summer day, RCI exhibited maximum and average values of 12.2 °C and 5.5 °C across all river segments. On the extremely hot day, the cooling intensities became notably higher, with maximum and average values reaching 15.5 °C and 6.4 °C, respectively. Notably, there were considerable variations in RCI values among individual segments on both case days. Specifically, the standard deviation was 2.4 °C on the normal summer day and it increased to 3.1 °C on the extremely hot day.

Additionally, it can be observed that the spatial patterns of RCI remained similar on both case days. Along the Jialing River, RCI values were comparatively lower than those along the Yangtze River. Specifically, the mean RCI values for river segments along the Jialing River were 4.8 °C and 5.9 °C on the normal summer day and the extremely hot day, respectively. In contrast, for the Yangtze River, the corresponding values became 6.1 °C and 6.9 °C, approximately 1 °C higher. This difference was speculated to be resulted from the wider river width of the Yangtze River. Additionally, the cooling intensities on the left banks of rivers were significantly higher than those on the right banks. Specifically, the average RCI on the left banks were 5.8°C and 6.8°C on the 2 case days. The corresponding magnitudes became 5.1°C and 6.0°C for the right banks.

RCI values were notably lower for river segments near the Tongluo Mountain in the eastern suburb of Chongqing compared to the surrounding areas. The higher mountainous terrain near the riverbanks was inferred to obstruct the inland penetration of river cooling. In the city center where numerous high-rise buildings were concentrated, RCI values were relatively lower than those in the surrounding suburban areas. This observation can be attributed to the obstructive effect of dense buildings on river cooling.

As for RCD, the values varied from 60 to 720 meters with average distances of 225.8 meters on the normal summer day and 222.2 meters on the extremely hot day (Fig. 5). Similar spatial patterns of CRCI values on the 2 case days are presented in Fig. 6. On the normal summer day, the average CRCI value was 505.9 °C·m and it increased to 587.0 °C·m on the extremely hot day. The spatial diversity were also more pronounced in hotter ambient weather conditions with the standard deviation rising from 461.7 °C·m to 565.5 °C·m. River segments exhibiting CRCI values below 400 °C·m were predominantly concentrated in the city center and near the Tongluo Mountain, which were characterized by dense buildings or rugged topography.

### 3.2. Model performance

Table 3 Performances of the BRT model in modelling river cooling effects on the 2 case days.

|  |  |  |  |
| --- | --- | --- | --- |
| Index | Weather condition | R2 | RMSE |
| RCI | Normal summer day | 0.60 | 0.8 (°C) |
| Extremely hot day | 0.57 | 1.3 (°C) |
| RCD | Normal summer day | 0.69 | 46.3 (m) |
| Extremely hot day | 0.75 | 40.7 (m) |
| CRCI | Normal summer day | 0.72 | 169.0 (°C·m) |
| Extremely hot day | 0.64 | 208.5 (°C·m) |

The validation results of the BRT model are shown in Table 3. The R2 values of the RCI simulations were 0.60 on the normal summer day and 0.57 on the extreme hot day, with the RMSE values being 0.8 °C and 1.3 °C, respectively. In comparison to RCI, the explanatory powers of environmental factors were relatively higher for RCD and CRCI. Specifically, the corresponding R2 values were 0.69 and 0.75 for the RCD simulations, with the corresponding RMSE values being 46.3 m and 40.7 m. For the CRCI simulations, the corresponding R2 values were 0.72 and 0.64, with the RMSE values being 169.0 °C·m and 208.5 °C·m, respectively.

### 3.3. Relative importance of influencing factors

Fig. 7 Relative importance of influencing factors for RCI, RCD and CRCI on the normal summer day and the extremely hot day, respectively.

Fig. 7 illustrates the relative importance of influencing factors for river cooling effects during the 2 case days. Our results highlight the substantial impacts of topography in the metropolitan area of Chongqing, the city characterized by undulating terrain. Regarding RCI, average slope emerged as the most influential factor among all potential contributors on the normal summer day, constituting 16.5%. The contribution of average elevation was smaller, accounting for 11.0%. On the extremely hot day, average elevation emerged as the most influential factor with the relative importance being 16.1%.

In terms of land cover characteristics, the findings distinctly highlight that the configuration of land cover played a more pivotal role than the composition in explaining the variations of RCI. On the normal summer day, PD was the most important land cover characteristic with a contribution rate of 10.7%, followed by AI\_I (9.9%), AI\_V (4.9%), PLAND\_I (4.9%) and PLAND\_V (4.4%). On the extremely hot day, PD (11.4%) also contributed most, followed by AI\_V (7.3%), PLAND\_I (7.1%), AI\_I (6.5%) and PLAND\_V (6.0%). Regarding 3D building characteristics, the contributions of MBH were 5.7% and 6.1% on the 2 case days, which were significantly higher than those of FAR and BCR. This implies that height played a larger role in affecting river cooling intensity compared to density or volume of buildings.

As has been mentioned in Sect. 3.1, the impacts of river characteristics cannot be overlooked. Our results show that river width made the contributions of 11.6% and 7.8% on the normal summer day and the extremely hot day, ranking second and fourth among all the selected environmental variables. The roles of rotation angle and orientation of river decreased successively, accounting for 6.7% and 6.2% on the normal summer day. On the extremely hot day, the proportions were further decreased to 6.3% and 5.6%.

Similar to RCI, RCD was also significantly influenced by topography. As the most influential factor, average elevation contributed 37.5% and 34.0% to RCD on the 2 case days. The ratios were much higher than those to RCI. In addition, the factors ranked from second to fourth in relative importance were SLP (19.3%), PD (15.1%) and AI\_I (4.4%) on the normal summer day and PD (20.6%), SLP (15.0%) and PLAND\_V (5.6%) on the extremely hot day. As for CRCI, the top 4 most influential factors in sequence were ELE (34.9%), SLP (12.1%), PD (10.3%) and RW (7.0%) on the normal summer day and ELE (32.2%), PD (16.5%), SLP (12.3%) and RW (5.7%) on the extremely hot day.

The results also reveal that there were obvious differences in the contributions of environmental variables on river cooling effects between the 2 case days. Specifically, in comparison to the normal summer day, the relative importance of patch density was increased, while the role of river width was decreased.on the extremely hot day.

### 3.4. Marginal effects of key influencing factors on river cooling effects

Fig. 8 Marginal effects of the top 4 most influential factors on RCI on the 2 case days.

The top 4 most influential factors were selected for the subsequent analysis of the marginal effects on the 2 case days. The results unveil the non-linear effects of environmental variables on river cooling. As the most influential factor in explaining RCI on the normal summer day, average slope manifested a descent pattern. When it increased from 9.2° to 23.3 °, the average cooling intensity induced by the rivers decreased, indicating that larger slope of riverside area was not conducive to the enhanced heat mitigation provided by the nearby river. It should be noted that when SLP was greater than 23.3 °, the RCI value remained relatively stable. In contrast to SLP, the effects of RW and ELE demonstrated ascent patterns with fluctuations. RCI demonstrated an increase when RW ranged from 246.7 to 623.8 meters or ELE fell within the range of 174.6 - 222.0 meters. Beyond these specific ranges, the RCI value remained relatively stable. The positive relation between river width and RCI revealed here aligned with the higher RCI for river segments of the Yangtze River compared to the Jialing River, as discussed in Sect. 3.1. The influence of patch density exhibited a relatively complicated pattern. As PD increased within the range of 18.2/100ha - 30.2/100ha, RCI showed a fluctuating upward trend. Subsequently, PD gradually decreased until it reached 66.1/100ha. As a whole, the increased patch density was associated with the corresponding reduced RCI.

Similar to the normal summer day, the impacts of ELE and SLP on RCI on the extremely hot day were characterized by ascent and descent patterns, respectively. An upward trend in RCI was observed as ELE increased within the range from 174.1 to 226.4 meters. Conversely, when SLP was between 6.5° and 20.9°, RCI exhibited a decreasing trend. In addition, the marginal effects of PD and RW on RCI can be described as descent and ascent patterns with fluctuations.

Fig. 9 Marginal effects of the top 4 most influential factors on RCD on the 2 case days.

Fig. 9 illustrates the marginal effects of the top 4 most influential factors on RCD. On both case days, the influences of the 2 topographical variables, namely ELE and SLP, on RCD were characterized by ascent and descent patterns, respectively. RCD exhibited an upward trend when ELE increased from 174.7 to 226.9 meters on the normal summer day and from 175.2 to 230.0 meters on the extremely hot day. Meanwhile, opposing trends in RCD were observed when SLP increased within the ranges of 8.9° to 25.0° and 10.4° to 22.8° on these days. Similar to the effects on RCI, the effects of PD on RCD can be characterized by fluctuating downward trends on the 2 case days. The fourth most influential factor on the normal summer day was AI\_I, which was characterized by a fluctuating ascent pattern within the range of 3.9% - 94.5%. On the extremely hot day, the fourth most influential factor became PLAND\_V. The corresponding effect can be primarily described by an increase followed by a rapid decrease. It can be derived that the effect of vegetation cover ratio on RCD was complicated.

Similar to the influences on RCI, the top 4 most influential factors for CRCI in sequence were ELE, SLP, PD and RW on the normal summer day and ELE, PD, SLP and RW on the extremely hot day. The marginal effects of ELE and SLP were characterized by ascent and descent patterns, respectively. The influences of PD and RW were relatively fluctuating, showing descent and ascent patterns as a whole.

Fig. 10 Marginal effects of the top 4 most influential factors on CRCI on the 2 case days.

## Discussions

### The impacts of influencing factors on river cooling effects

As illustrated in Fig. 4 - 6, this investigation reveals similar spatial patterns of river cooling effects between the normal summer day and the extremely hot day. Notably, greater temperature reductions were observed in suburban areas characterized by sparse architectural layouts. In addition, the average RCI was 5.5 °C on the normal summer day, consistent with findings from prior studies targeting at other types of water bodies (Manteghi et al., 2015). When compared to the cooling intensity of less than 4 °C near the Huangpu River reported in Shanghai, our observed intensity was significantly higher (Du et al., 2016). This contrast can be explained by the difference in river width, as the average river width in Chongqing is larger than that of the Huangpu River. Furthermore, background weather conditions and surrounding urban characteristics were potential contributors to the observed river cooling effects.

As global warming and urbanization continue, the increase in the adverse impacts of future extreme heatwaves becomes inevitable. Consequently, focusing on river cooling effects during extreme weather conditions can offer valuable scientific insights for addressing future urban climate change. This study unveils higher average values of RCI and CRCI on the extremely hot day compared to the normal summer day. This difference can be explained by the mechanism of water cooling on heatwave days, as the larger temperature difference between the land and the nearby water body can lead to a stronger cooling potential for the waterfront area. Due to the significantly higher temperature, the intensity of evaporative cooling from the water surface is also larger. Additionally, it has been found that the spatial variations of river cooling effects were larger on the extremely hot day. This finding is consistent with an observation of cooling from the nearby sea in Adelaide, which demonstrated significantly larger spatial variations in sea breeze cooling capacity under heatwave conditions (Zhou et al., 2020).

Some studies have explored the relationship between urban climate and topography (Oke et al., 2017; Liao et al., 2022; Mo et al., 2024). However, the role of topography in affecting water cooling remains inadequately understood. This study reveals that topography exerted a significant influence on the cooling effects of rivers, surpassing the impact of land cover and 3D building characteristics. This is reasonable as rivers significantly shape the thermal environment of their surroundings through the modulation of inland airflow. Specifically, the irregularity of terrain can alter the direction and intensity of airflow, thus influencing the spatial pattern of the thermal environment. For waterfront area with steep terrain, the inland penetration of water cooling effect is weakened, leading to a reduction in cooling intensity. Additionally, this study identifies a positive correlation between elevation and river cooling, which was likely to be attributed to the temperature decrease caused by the elevated altitude.

In terms of land cover characteristics, this study observes an intricate correlation between river cooling and the proportion of vegetation area, which can be explained by their complex interactions. On one hand, the lower temperature of green space compared to impervious surface weakens the impact of river cooling. On the other hand, vegetated areas are mostly open areas, which facilitate the inward penetration of cooler airflow from the river. Considering the aforementioned influences, the overall effects of vegetation cover ratio on river cooling are complicated. While some studies indicated an increase in water cooling with expanded vegetation cover, opposite correlations have been discovered elsewhere (Sun et al., 2012; Wu et al., 2020). In Chengdu, no significant correlation was found between the cooling intensity of wetland and the proportion of vegetation cover (Wu et al., 2021). Hence, further investigations are required to gain a better understanding of the relationship between land cover composition and water cooling.

### Implications for urban planning

This study unveils notable spatial variances of river cooling effects influenced by diverse environmental variables. The insights gained from these findings offer valuable references for climate-friendly urban planning to improve residents' living environment. Firstly, because of the negative correlation between slope and river cooling effect found in this study, areas designated for residents' leisure activities should preferably avoid locations with significant changes in topography. Additionally, considering that the configurations of different land cover types can exert stronger influences on river cooling than the compositions, it’s recommended to prioritize the layouts of individual land cover types in urban planning. The result also indicates that patch density demonstrated a negative correlation with river cooling. Hence, it’s advisable to reduce the density of landscape patches to foster a more climate-friendly living environment.

### Limitations of this study and future work

This study has certain limitations. Situated in the Sichuan basin, Chongqing experiences significantly lower average wind speed compared to other cities over the world. As a result, the impacts of wind speed and wind direction on river cooling effects have not been comprehensively addressed in this study. Future research endeavors should consider these factors to offer a more comprehensive understanding of river cooling dynamics from the standpoint of background weather conditions, especially in cities characterized by higher wind speeds. In addition, the city of Chongqing, featured by a relatively low number of sunshine hours, poses constraints on the accessibility of suitable cloud-free Landsat images. In this study, only 2 images were employed to characterize the normal summer day and the extremely hot day. In the future work, additional research endeavors are imperative to incorporate more images for normal and extreme summer days, thereby augmenting the robustness of the finding. Furthermore, like other cities in developing countries, Chongqing has undergone rapid urbanization in the past few decades. However, because of the limitations of available building data, an analysis of river cooling during this urbanization process is unfeasible. Therefore, the impacts of urban structure on river cooling during urban construction remain unexplored. A quantitative analysis spanning over 20 years, investigating annual variations of river cooling effects with dynamic building data, could offer valuable insights. Such findings hold implications for urban planning and management in developing countries.

## Conclusions

This study focuses on the cooling effects of rivers on the surrounding urban environment on normal and extreme summer days, taking the mountainous city of Chongqing as an example. Environmental variables, including river characteristics, land cover characteristics, 3D building characteristics, and topographical characteristics, have been considered. The Boosted Regression Tree model was employed to assess the relative importance of individual influencing factors for RCI, RCD and CRCI and the corresponding marginal effects of the top 4 most influential factors. In contrast to traditional analytical methods such as linear regression, this approach can effectively capture the non-linear effects of influencing factors on river cooling effects.

The conclusions are as follows:

1. The river cooling effects exhibited significant spatial variations with similar spatial patterns. In addition, the average values and spatial variations of RCI and CRCI were higher on the extremely hot day compared to the normal summer day. Specifically, the average values and standard deviations in River Cooling Intensity (RCI) were 5.5°C and 2.4°C on the normal summer day and they increased to 6.4°C and 3.1 °C on the extremely hot day.
2. Explanatory powers of the environmental variables on RCD and CRCI were notably higher compared to RCI for the 2 case days.
3. Topographical characteristics exhibited strong impacts on river cooling effects, with the relative importance of average elevation for RCI being 11.0% and 16.1% on the normal summer day and the extremely hot day, respectively. In comparison to the normal summer day, the relative importance of patch density was increased, while the role of river width was decreased on the extremely hot day.
4. Through the examination of marginal effects, non-linear influences of the top 4 most influential factors on river cooling effects were identified, with most variables exerting their impacts within specific ranges. ELE and SLP exhibited ascent and descent patterns on both summer days, while the impacts of PD and RW were relatively fluctuating, showing descent and ascent patterns as a whole.

These findings provide a scientific understanding of the roles of environmental variables in shaping river cooling effects. They offer guidance for optimizing urban planning and management to improve the thermal environment of riverside areas, especially for cities with uneven surfaces.

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