河流降温效应在一个具有复杂地形的超大城市——以重庆为例

## Abstract

* Existing researches have discussed the impacts of water bodies on the surrounding thermal environment, consistently emphasizing their cooling effects during daytime due to the distinctive thermal characteristics of water.
* It should be noted that the impacts of water bodies, especially rivers, on the surrounding thermal environment are rarely explored under extremely hot conditions.
* This study provides an in-depth understanding of river cooling and its relationship with environmental factors in a topographically complex city by comparing the river cooling effects during two typical summer days in 2022—one representing a regular summer day and another an extremely hot summer day.

## Introduction

### UHI

* 【up2023 1229 16:04】
* With population explosion and economic development, the urban population has witnessed significant expansion globally.
* According to the prediction from the United Nations, this trend will continue in the following decades and the urbanization rate is estimated to be up to 68 % by 2050 (United Nations. 2019).
* As has been observed in many cities over the world, urbanization has caused multiple adverse effects on local environment, such as water and air pollution, ecosystem degradation and urban heat island (Wang et al., 2020; Ahmad et al., 2021).
* Urban heat island is a phenomenon by which temperatures in urban areas tend to be higher compared to those in the surrounding rural areas.
* Elevated temperatures have been found to increase the intensities and durations of heatwaves and they will inevitably enhance energy consumption and pose threats to public health of urban residents in summer (Guan et al., 2017; Nieuwenhuijsen et al., 2018).
* Therefore, certain measures are necessary to address the associated negative effects.

### 水体降温效应机理~150 words【up2023\_1208 09:53】

* 【up2023 1229 16:43】
* Primary measures to address excessive heat in urban areas include altering surface materials, optimizing spatial layout of land cover, and promoting ventilation (Azhdari et al., 2018; Taleghani，2018; He, 2020).
* In terms of land cover, the roles of blue and green spaces have received much attention.
* Blue spaces refer to urban surfaces that are dominated by water (Ampatzidis et al., 2020).
* Compared to impermeable surfaces, the lower thermal conductivity and higher specific heat capacity of water make blue spaces absorb less heat during the day.
* In addition, evaporation from water surfaces can reduce release of sensible heat.
* Consequently, blue spaces can be considered to be cooling sources and they play important roles in lowering temperatures of surrounding areas.
* According to a research in Chengdu, the contrast of surface temperature between lakeside and inland areas can be more than 8 °C (Du et al., 2016).
* Observations have also demonstrated that the cooling abilities of water bodies can be stronger than green spaces .
* For example, the average temperature of green spaces is about 2 °C higher than that of water surfaces in the summer daytime of Berlin (Dugard et al., 2014).

### 1.3 水体降温时空异质性&水体降温效应的影响因素（强调缺乏对地形影响的研究）~250 words

* According to previous studies, there are large diversities in the cooling effects of blue spaces and the dominant contributing factors vary with time and space.
* In terms of temporal variation, water cooling intensities in daytime are usually stronger than those in nighttime (Hathway et al., 2012).
* Existing observations demonstrate that waterfront areas can be warmer than the surrounding inland areas during nighttime. (Moyer et al., 2017).
* As for the spatial variation of water cooling, a difference of more than 9 °C can be discovered within a city (Wu et al., 2020).
* With large temporal and spatial variations of water cooling revealed in previous researches, the interaction of water bodies with environmental variables have become an important issue in the mitigation of urban heat.
* Morphological characteristics of water bodies are mostly found to be important factors.
* Specifically, stronger cooling effects tend to appear near larger water bodies (Theeuwes et al., 2013).
* As for the relationship between shape regularity and cooling effect, the conclusions are contradictory.
* For example, observations in Shanghai and Beijing indicate that water cooling effect is strengthened with improved shape regularity, while the corresponding relation is insignificant in Chengdu (Du et al., 2016; Sun et al., 2012; Wu et al., 2021).
* In addition to characteristics of blue spaces, the roles of land use pattern and 3-dimensional urban structure of waterfront areas have also been explored.
* Based on previous researches, proportion of vegetation cover, street width, average building height, floor area ratio (FAR) and the ratio of building area potentially take effects.
* It is worth noting that topographic features are probable to take effects on urban climate in cities with uneven surfaces.
* Primarily because of the mechanical force, wind directions and intensities of urban areas are affected by local topographic variations, such as hills, ridges, and cliffs (Zhou et al., 2020).
* Therefore, it can be speculated that topographical variables can be potential influencing factors of water cooling effect.
* However, most previous studies on water cooling effect are performed in plain cities.
* The relationships between different topographic indicators and cooling effects of water bodies are still poorly understood.
* Despite numerous studies on water cooling effects, there are still limitations in the understanding of this issue.
* Firstly, in previous studies, the relationships between water cooling and influencing factors are analyzed based on linear equations.
* However, due to the complexity and irregularity of urban characteristics, the impacts of influencing factors on urban climate are often non-linear (Li et al., 2020).
* Therefore, more effective methods are needed to analyze the non-linear effects of geographical features to fully understand water cooling effect.
* In addition, there are contrasts in morphological characteristics between rivers and lakes.
* A large proportion of lakes are polygonal or circular in shapes and located dispersedly within a city, while rivers have a narrow and linear layout, mostly traversing or flowing around urban areas.
* As a result, the cooling effects of rivers on the surrounding areas are different from those of lakes or ponds.
* In the northeastern Chinese cities of Changchun and Jilin City, river cooling effects are found to be stronger than those of lakes and green spaces (Xue et al., 2019).
* However, previous researches on water cooling focus more on ponds, lakes and wetlands (Cheval et al., 2020; Xue et al., 2019; Yao et al., 2023).
* River, as an important type of water body in cities, has received much less attention.
* Rivers flow through or around many cities over the world and they have effects on the climate characteristics of surrounding areas, so it’s necessary have more in-depth explorations on river cooling.
* The practical significance of studying water cooling lies in understanding the relationship between environmental factors and cooling effects, allowing targeted measures to be taken to alleviate the negative impacts of extreme heat.
* However, existing relevant studies focus on normal summer days and the understanding of water cooling effects on extremely hot days is insufficient.
* In fact, under the background of global warming and urbanization, the intensity of heatwaves and their potential negative effects on urban residents are expected to increase significantly.
* Many studies have revealed higher urban heat island intensities during in heatwave days compared to those on normal summer days, which is particularly common in metropolitan areas of China (Ramamurthy et al., 2017; Gao et al., 2019).
* Therefore, it’s essential to pay more attention to water cooling in extremely hot days which has important practical implications for heat mitigation of urban areas.

### 1.4 研究目的~100 words

* As a mountainous city located in the upper reach of Yangtze River, Chongqing is renowned for its hot and humid summer.
* A systematic research on the cooling effect of rivers in the city of Chongqing is beneficial for policymakers in urban planning and management.
* This research aims to explore the quantitative effects of river cooling and their contributors, taking Chongqing as an example.
* The purpose is to answer the following questions:
* (1) What are the intensities and spatial patterns of river cooling effects on the normal summer day and the extremely hot day?
* (2) How much do individual environmental variables contribute to the river cooling effects?
* (3) How do the key factors affect river cooling in different weather conditions?

## Data and Methods

* The analytical procedures of this study can be divided into three major steps.
* Firstly, land surface temperature (LST) of the study area is calculated based on Landsat-8 images.
* Then we divide the riverside areas of Chongqing into segments and calculate indexes of river cooling for individual segments.
* Finally, boosted regression tree (BRT) model is utilized to evaluate the non-linear impacts of environmental variables on river cooling in different weather conditions.
* The flow chart is shown in Fig. 1.

### 2.1. Study area

* Chongqing is a megacity located in the upper reach of the Yangtze River.
* The Yangtze River flows through this city, and its major tributary, the Jialing River, converges with it in the city center (Fig. 2).
* The urban area of Chongqing is primarily composed of hills and mountains and it is therefore characterized by significantly undulating terrain with elevations ranging from 170 meters to more than 400 meters.
* Chongqing is located in the subtropical monsoon climate zone.
* Summer periods normally last from May to September, which are characterized by high temperatures and high humidities.
* On average, there can be more than 40 heatwave days with maximum air temperatures being larger than 35 °C in a year , mostly distributed in July and August.
* The highest air temperature can reach up to 43 °C.
* In last decades, Chongqing has experienced a rapid process of urbanization with urban population surging from 6 million in 2000 to 10 million in 2020.
* With a huge influx of population, urban construction accelerates, and the built-up area expands rapidly.

### 2.2. Data

* Satellite images from Landsat-8 OLI/TIRS surface reflectance products are utilized in this study to calculate LST, extract river surface and obtain land use patterns of the study area.
* These data were obtained from United States Geological Survey (http://earthexplorer.usgs.gov).
* Two sunny days are selected as representatives of the normal summer day and the extremely hot day, respectively.
* In this study, we select 8th, May, 2022 and 12th, Aug, 2022 to represent the normal summer day and the extremely hot day, respectively.
* The weather conditions of the two days are shown in Table 1.
* 3-dimensional (3D) buildings data are gained from the online map service platform Baidu maps.
* Specifically, heights of buildings are calculated by multiplying the number of floors by 3.
* Elevation data were produced based on digital topographic maps.
* 土地覆盖数据由landsat-8 遥感影像解译获得。采用基于最大似然（ML）的监督分类方法，划分出水体、绿地、建筑物和不透水地（主要包括道路和广场）四种土地覆盖类型。
* 建筑分布及高度数据由百度地图提供。其中，建筑高度的计算是基于楼层数\*3m得到的。

### 2.3. Calculation of land surface temperature

* Before the calculation of LST, preprocessing steps are required for original Landat-8 images.
* They include radiometric calibration and atmospheric correction.
* Then, radiative transfer equation (RTE) method is adopted. The equation can be expressed as:
* where *Lλ* is the radiation intensity of thermal infrared band obtained by the sensor, represents the downward atmospheric radiance, represents the upward atmospheric radiance, *ε*stands for surface emissivity,*τ* is the atmospheric transmissivity and B(Ts) is the black body radiance.
* By converting the above equation, we can get B(Ts) as follows:
* In this study, values of and *τ* were obtained by NASA Atmospheric Correction Parameter Calculator.
* *ε* is calculated by the following formula:
* In this formula, represents surface emissivity of vegetation cover, represents surface emissivity of soil and *Pv* is the percentage of vegetation cover calculated by:
* where *NDVI* is normalized difference vegetation index, *NDVIveg* is the NDVI value of area fully covered by vegetation and *NDVIsoil* is the NDVI value of area fully covered by soil.
* Once black body radiance is calculated, LST values are obtained by the following equation:
* For Landsat-8 images, the default values of K1 and K2 are 774.89 and 1321.08, respectively.
* All the above steps are performed in ENVI software.

### 2.4. Quantification of river cooling effects

* In order to accurately quantify the cooling effects of rivers, the riverbanks are partitioned at the interval of 1 kilometer.
* As a result, a total of 185 riverbank segments are generated along the two rivers in the metropolitan area of Chongqing, with 97 segments along the Yangtze River, and 88 segments along the Jialing River.
* LST values of waterfront areas are highly related to the distances from the riverbank.
* Specifically, the temperature gradually rises from the edge of water surface to the inland area until a certain point where the trend of temperature rise stops and this point is defined as the first turning point.
* The temperature value at the first turning point is defined as turning temperature.
* The waterfront area represented by the non-linear curve from the original point to the first turning point is considered to be cooled by river and is employed to calculate relevant indexes of river cooling effects.
* Specifically, River Cooling Intensity (RCI) is defined as the temperature contrast between the original point and the first turning point, as shown in the following equation:

(1)

* where *Tp* is the turning temperature, while *Tr* is temperature at the edge of water surface.
* The index of RCI has the disadvantage that it only reveals the maximum temperature reduction within the waterfront area, while the non-linear variation of surface temperature is not embodied.
* In order to have a better understanding of the inland penetration processes of river cooling, the index of Cumulative River Cooing Intensity (CRCI) is adopted here.
* To calculated CRCI, River Cooling Distance (RCD) is firstly defined as the distance between the original point to the first turning point.
* CRCI is then calculated as the accumulated difference between turning temperature and the non-linear temperature curve from riverbank to the first turning point, which is illustrated in the shading area of Fig. 3.
* The equation is given by:

(2)

* where *Tc* is the temperature along the non-linear temperature curve.

### 2.5. Calculation of influencing factors

* The potential influencing factors of river cooling effects can primarily be classified into the following types: river characteristics, land cover patterns, 3D urban structure and topography.
* In terms of river characteristics, river width and average curvature of riverbank are considered in this study.
* River width of each segment is calculated as the distance from the central point of the corresponding riverbank to the opposite riverbank.
* Average curvature of riverbank is used here to characterize the shape features of segments along individual riverbanks.
* As for land cover, proportion, mean aggregation index , mean patch shape index of two major patch types (i.e green space and impervious surface) are selected.
* Aggregation index is defined as the ratio of actual like adjacencies to the theoretical maximum number of like adjacencies for a patch type and it indicates the degree of agglomeration.
  + 【参考Quantifying spatial morphology and connectivity of urban heat islands in a megacity: A radius approach】
* Patch shape index is used here to reflect shape complexity of a patch type.
* The equation for calculating mean aggregation index of a patch type (*AI\_MN*) is shown below:
* where 𝑔𝑖𝑖 is the number of like adjacencies of patch type i, 𝑚𝑎𝑥−𝑔𝑖𝑖 is the maximum number of like adjacencies of type i and 𝑃𝑖 represents the ratio of landscape compromised of type i.
* Mean patch shape index of a patch type (*SHAPE\_MN*) is calculated by the following equation:
* where *n* is the total number of patches of patch type i, *aij* is the area of patch ij and *pij* represents the perimeter of patch ij with the unit of meter.
* In this study, the above landscape metrics are calculated using R-landscapemetrics packages.
* 3D urban structure is considered to have potential impacts as urban architecture can affect thermal environment by changing surface energy balance, providing shadow areas and altering ventilation.
* According to building characteristics of the study area, floor area ratio (FAR), mean building height (MBH) and standard deviation of building heights (SDBH) are chosen.
* SDBH is selected as it reflects the diversity of building heights of an area and negative relationship between SDBH and temperature in urban areas has been observed in previous researches (Zhou et al., 2019; Han et al., 2023).
* Topography is considered as the urban area of Chongqing is marked by moderate fluctuations in elevation.
* The selected topography variables consist of averaged elevation and averaged slope.
* They are calculated based on DEM data in ArcMap 10.7.

### 2.6. Boosted Regression Tree

* Urban climate is formed by comprehensive effects of multiple factors with non-linear processes.
* However, the relationships between urban thermal environment and environmental factors were mostly investigated using simple linear regression or stepwise regression in previous researches.
* In this study, boosted regression tree (BRT) model is adopted for investigating the comprehensive effects of potential influencing factors on river cooling.
* BRT model is a combination of regression tree algorithm and the boosting method.
* In the regression tree, the dependent variable is iteratively fitted with predictors to enhance the accuracy of the model.
* Through the boosting method, input data is weighted in subsequent trees to increase the probability of poorly modeled data from previous trees to be selected in the new tree.
* Compared to traditional regression methods, BRT model can handle complex non-linear effects and it exhibits robustness to missing values and outliers.
  + 参考：
    - https://support.bccvl.org.au/support/solutions/articles/6000083202-boosted-regression-tree
* In our analysis, we firstly use variance inflation factor (VIF) to assess the covariance of independent variables and select variables with VIF values being less than 10.
* This step is performed to remove factors with high collinearity.
* Then, the BRT model is applied by using “gbm” package in R.
* By exploring relative contributions and marginal effects of independent variables, a more detailed understanding of river cooling effects and their influencing factors can be revealed.
* R2 and root-mean-square error (RMSE) are applied to validate the prediction from random forest model.
* The random forest model is an ensemble learning method for classification and regression. It builds multiple decision trees to form a random forest and combines the computed results of each tree through weighted regression, providing strong robustness and accuracy.

## Results

### 3.1 River cooling effects in the normal summer day and the extremely hot day

* The spatial patterns of river cooling intensities on the typical normal summer day (8th, May, 2022) and the extremely hot day (12th,Aug, 2022) are demonstrated in Fig. 4.
* On the normal summer day, the maximum and average values of RCI over all segments of riverside areas are 16.9°C and 6.8°C, respectively.
* On the extremely hot day, the RCI magnitudes are evidently higher, with the maximum and average values being 23.3°C and 7.9°C, respectively.
* It should be noted that there are also larger diversities of RCI magnitudes among individual segments.
* Specifically, the standard deviation is 2.7°C on the normal summer day, while the corresponding value is 3.8°C on the extremely hot day.
* It can also be observed that the spatial patterns of RCI magnitudes are similar on both case days.
* For riverbanks along the Jialing River, the RCI magnitudes are relatively lower compared to the Yangtze River.
* Specifically, the mean RCI magnitude of riverside segments along the Jialing River are 6.2°C and 7.4°C on the normal summer day and the extremely hot day, respectively.
* For the Yangtze River, the corresponding magnitudes are 7.4°C and 8.5°C, both being more than 1°C higher than the Jialing River.
* The wider river width of the Yangtze River is speculated to cause this difference.
* We can also observe that the RCI magnitudes are significantly lower for riverside segments near the Tongluo Mountain in the eastern suburb of Chongqing compared to the surrounding areas.
* It can be easily inferred that the higher mountainous terrain near the riverbanks plays an obstructive role in the inland penetration of river cooling effects.
* Furthermore, in the city center where most high-rise buildings are located, the RCI magnitudes are relatively lower than the surrounding suburban areas.
* The blocking effect of dense buildings is believed to explain this phenomenon.
* As shown in Fig. 5, similar spatial patterns of CRCI magnitudes on the normal summer day and the extremely hot day are presented.
* On the normal summer day, the average and maximum magnitudes of CRCI are 56.6°C and 60.0°C, respectively. The corresponding magnitudes are 48.4°C and 44.5°C on the extremely hot day.
* 参考文件：

### 3.2 Contributions of influencing factors on river cooling effects

* 【从此处开始，结果需更新】
* Fig. 6 illustrates the contributions of potential influencing factors on river cooling effects on the two selected case days.
* The result shows that 3D urban structure exerts a significant impact on the river cooling effects of Chongqing.
* FAR is most influential among all potential factors as it contributes xx% and xx% to RCI and CRCI magnitudes on the normal summer day and xx% and xx% on the extremely hot day.
* Compared to FAR, MBH makes much less contributions.
* Specifically, it contributes xx% and xx% to RCI and CRCI on the normal summer day and xx% and xx% on the extremely hot day.
* SDBH is removed in the BRT model due to its high collinearity with other factors.
* In addition to 3D urban structure, topography makes comparative contributions to river cooling effects.
* The averaged slope of the riverside area makes the largest contributions on RCI and CRCI on both days among the topographical variables.
* It explains xx% and xx% of the total variance of RCI and CRCI on the normal summer day and xx% and xx% on the extremely hot summer day.
* Its’ worth noting that the relative contribution of average elevation is much smaller according to the result for both days.
* This indicates that the absolute altitude makes little influence on river cooling of the riverside area compared to the relative changes of elevation.
* Relative to the 3D characteristics of urban form, 2D landscape indexes play significant but comparatively smaller roles in the river cooling effect.
* On the normal summer day, proportion of impervious surface explain xx% and xx% of the total variance of RCI and CRCI.
* While on the extremely hot summer day, the relative contributions are xx% and xx%.
* The contribution rankings of other 2D landscape indexes are: xx(xx%) for RCI and xx(xx%) for CRCI on the normal summer day. While on the extremely hot day, the contribution rankings are: xx(xx%) for RCI and xx(xx%) for CRCI.
* In summary, both topography and 3D urban structure exhibit the strongest influence on RCI and CRCI.
* Meanwhile, the impact of 2D landscape patterns on river cooling is also significant, although its strength is noticeably reduced.
* It is also worth noting that the two most significant variables, namely slope and floor area ratio, make significantly weaker contributions on river cooling in the extremely hot day when compared to the normal summer day.

### 3.3. Marginal effects of key impact factors on river cooling effect

* Based on the contributions of individual factors, marginal effects of key factors are analyzed.
* In this study, the top three most influential variables are used for subsequent analysis of marginal effects.
* The results demonstrate the non-linear influences of independent variables on river cooling.
* According to the contributions of independent variables, the average building height is the most influential factor in explaining river cooling.
* Its relative influences are characterized by decent patterns in the normal summer day and the extremely hot summer day.
* This is reasonable as the river cooling effect is weakened in densely built areas caused by the blocking effect of large-volume buildings.
* It should be noted that the decent pattern is limited within a certain range of average building height.
* When floor area ratio is larger than a certain value, the relative influence of floor area ratio is insignificant.
* Specifically, in the normal summer day, the decent pattern ranges from 0 to xx for RCI and 0 to xx for CRCI.
* In the extremely hot summer day, the corresponding ranges are 0 to xx and 0 to xx for RCI and CRCI respectively.
* Similar to floor area ratio, average slope of the riverside area demonstrates decent influences on river cooling.
* In the normal summer day, it shows a negative effect on RCI and CRCI when the average slope is larger than xx and xx.
* This indicates that larger slope of the riverside area is not beneficial for the heat mitigation generated by the river.
* In the extremely hot summer day, the influences are similar. The negative effect appears when the average slope is larger than xx and xx.
* The influence of Impervious surface coverage is characterized by decent pattern.
* In the normal summer day, it plays the negative role on RCI and CRCI when the average slope is larger than xx and xx.
* In the extremely hot summer day, the negative effects appear when the average slope is larger than xx and xx.

## Discussions

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

* As can be seen from Fig. 4 and Fig. 5, this research reveals comparable magnitudes and similar spatial patterns of river cooling effects between the normal summer day and the extremely hot day, respectively.
* Stronger temperature reduction tends to appear in suburban areas with sparse distributions of buildings.
* Specifically, on the two case days, the maximum RCI magnitude can be XX, which is higher than the results from previous researches (Manteghi et al., 2015; Xue et al., 2019).
* This is likely to be caused by the difference of river width as the width of the Yangtze River in Chongqing can be more than 1 kilometer which is larger than those in other relevant researches.
* In addition, background weather condition and surrounding urban environment are likely to explain the differences of river cooling effects.
* Oke et al. (2017) mentioned that topography plays a significant role in shaping urban climate and negative relation between LST and elevation has been observed in case studies.
* In this study, a stronger effect of slope compared to elevation on river cooling effects is shown.
* It can be derived that the relative change rather than the absolute value of elevation is the key factor that affects river cooling effects.
* This is reasonable as surface roughness increases with elevated slope and this can directly weaken the cooling ability from the surrounding river.
* In terms of variables of 3D urban structure, this study found that the impact of FAR is most pronounced, while the relations between MBH and river cooling effects are much weaker.
* This is different from previous studies on the effects of building height on LST in which the two variables are significantly negatively correlated with each other.
* In fact, building height affects LST mainly by altering shading areas and airflow patterns, while its influence on river cooling is more associated with airflow patterns.
* Therefore, the stronger role of FAR is probably because of the fact that the airflow pattern in Chongqing is more directly related to the total building volume rather than the height of buildings.
* This is in consistence with the finding from a research in Shanghai (Sun et al., 2020).
  + 参考：Separate and combined effects of 3D building features and urban green space on land surface temperature
* 随着全球变暖和城市化的继续，预计未来极端热浪带来的负面效应将持续增加。
* 因此，关注极端天气下的河流降温效应有助于为应对未来城市气候变化提供科学参考。
* 在本研究中，我们发现the spatial variations of RCI and CRCI are larger in the extremely hot day compared to those in the normal summer day.
* 这个结果与Zhou 2021 在阿德莱德进行海风降温研究所得到的结果一致，即海风渗透作用在热浪日比正常夏日有更大的空间差异。
* Few studies paid attention to the relationship between urban climate and topography.
* A study in Guilin reveals that the unique geomorphological characteristics lead to the occurrence of anomalous heat island phenomenon in winter.
* However, there is still insufficient understanding on the role of topography in the cooling effects of blue and green spaces. This study found that topography has a significant impact on the cooling effects of rivers, and this effect can even be stronger than the influence of land cover layout.
* 这与XX研究相似。XX发现xxx. 建筑高度对河流降温效应的影响主要是通过对水体与陆地之间对流产生影响而形成的。同时，三维空间格局还会影响太阳辐射的布局，从而改变地表能量平衡。同样需要注意的是，由于建筑高度的标准差与其它指标的高度相似性。因此，并没有被纳入本研究中。同时，在几个涉及建筑格局的指标（容积率、建筑高度、cubic指数），容积率的影响最大。

### Implications for urban planning

* The relationship
* The recent advocacy for nature-based urban planning highlights the importance of understanding the river cooling effect and its relationship with environmental factors. This understanding can provide insights for the layout of buildings, green spaces, and other land types, especially in cities with complex topography. Firstly, due to the significant influence of topography, in areas with steep slopes along the river, even with a low-density layout of buildings, the river cooling effect remains relatively low. Therefore, the advantages of a low-density building layout may not be well manifested in such areas.
* 考虑RCI和CRCI影响因素的差异性

### Limitations of this study and future work

* There are some limitations in this study.
* Located in the Sichuan basin, the average wind speed in Chongqing is much lower than that of other cities in China.
* Consequently, the influences of wind speed and wind direction on river cooling effects are not considered in this study.
* Future research should further investigate these factors, particularly in cities with higher wind speed, to provide a more comprehensive understanding of river cooling from the perspective of background climate.
* In addition, Chongqing is a city with a small number of sunshine hours, limiting the availability of suitable Landsat images.
* In this study, only one image is used to represent the normal summer day and the extremely hot day, respectively.
* Therefore, further investigations are necessary to use multiple images for normal and extreme summer days to enhance the robustness of the results.
* Furthermore, this study only focuses on river cooling effects within only one year.
* In fact, like other Chinese cities, Chongqing has experienced a rapid process of urbanization in last decades.
* Due to limitations in the available building data, we are unable to perform the analysis of river cooling during this urbanization process.
* The impacts of dynamic changes of 3D urban structure during urban construction on river cooling effects cannot be well explored.
* A quantitative analysis spanning over 20 years to investigate the annual variations in river cooling effects could provide valuable insights into the influences of environmental variables on river cooling.
* Relevant results have implications for urban planning and management of cities in developing countries.

## Conclusions

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## 补充

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