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How do urban buildings impact summer air temperature? The effects of building configurations in space and time

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A B S T R A C T

The urban building plays an important role that dominates the urban thermal environment by altering the heat exchange. In this study, we coupled GIS techniques with statistical methods to investigate the variance of Air Temperature (AT) and how it is influenced by urban buildings in Wuhan (China). The objectives of this study are to: 1) explore the dynamic relationships of building indicators and AT at varying geographic scales, so as to determine the calculation scale for spatial configuration; 2) examine how the relationships change with time; 3) investigate the combined and individual effects of these building indicators. The indicators were chosen from the perspective of urban planning, including Floor Area Ratio (FAR), Building Density (BD), the local Moran's I of Building (MB) and Building Height (BH). Results show that an area extent of 200 m is optimal for examining the AT-building relationships. The AT-building relationships are evidenced to be significant during nighttime but negligible during daytime, and reach the strongest level at different time depending on the day's temperature levels. Results of ridge regression analyses demonstrate that, for hot days, urban buildings can jointly explain as high as 48.9% of the AT variance during summer nighttime, and the explanatory level can reach 53.4% at 1:00 a.m. Spatial configuration was proved to effectively impact on AT, which is always neglected by urban planners and decision-makers. Our findings suggest that optimizing building patterns at an appropriate scale can achieve more significant effects on mitigating nighttime UHI. The insights gained from our study have significant implications for sustainable urban development.

1. Introduction

1.1. The Urban Heat Island

The Urban Heat Island (UHI) is the result of urbanization due to the alterations of land use and the impacts of human activities [1–5]. It has negative effects on ecosystems, energy and water demands, human well-being. The UHI not only decreases the outdoor air quality inside the city, and even impacts regional atmospheric pollution [6]. The growing demands for energy to cool the indoor temperature [7] and the increasing needs for water to irrigate urban vegetation [8] lead to consuming more earth's resources. Furthermore, its impacts on local meteorology (e. g. local wind patterns, humidity, cloud forming) influence human comfort and health directly [9]. Heat-related illness and death are elevating, and the situation will be even worse in the future because of the intensifying urbanization [10–12]. It's an urgent task to take actions for improving human well-being and achieving the sustainability target. The urban management can be a practical approach if the mitigating strategies are incorporated into the urban planning and design stage. According to the study framework proposed by Oke [13], once the phenomenon is determined, linking it with other factors and studying the process of causing the phenomenon are important. It's the basis to construct the 'Phenomenon-Formation mechanism' relationship and find effective strategies.

1.2. The dynamics of the relationships

Landscape pattern is scale-dependent [14], the knowledge and

Abbreviations: AT, Air Temperature; BD, Building Density; BH, Building Height; MB, local Moran's I of Buildings; FAR, Floor Area Ratio.

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findings also can be dynamic at different scales [15]. The association of the phenomenon-factors may be strongest at a certain scale, and generally, the desirable scale varies in regions due to the land surface characteristics in particular areas. This scale-dependence is well considered in the Land Surface Temperature (LST) studies. The relationship between the LST and vegetation fraction was found to be strongest at the pixel scale around 120 m in Indianapolis [16], the optimal scale for measuring the relationships between landscape compositions and LST is around 660 m and 720 m in Beijing [17], and the operational scale of the LST-land surface relationship is 500–650 m in Wuhan, China [15]. Recently, this scale-dependent consideration is also involved in Air Temperature (AT) studies, for instance, an area extent of 200 m was proved to be optimal for examining the vegetation-AT relationship in Phoenix [18]. Noticing the issues of scale, deliberating the scaling effects can not only obtain more reliable findings, but can clear about the operational scale for implementing mitigation strategies as well.

The time-dependence is the other issue worthy of consideration. Although early studies reported that man-made features (including urban buildings, squares, roads, parking lots) are the major contributors to the UHI effect, temporal patterns of the effects were not well-investigated because these studies rely on remote sensing images [16,19,20], which are time-static images that hardly obtain hourly continuous data. In contrast, the hourly AT data obtained from weather stations makes it possible to study the dynamic building-AT relationships. What's more, the impacts of urban buildings are far more complicated than just amplifying the urban temperature. Numerous studies manifested that, during daytime, building shading is an important factor to improve outdoor thermal comfort [21–24], due to the lower temperature caused by the lower intensity of direct solar irradiation. As for nighttime, urban buildings releases the heat energy, which is absorbed and stored during daytime [5]. That's why lower sky view factor always leads to lower daytime temperature and higher night time temperature [25–28]. Since the AT changes all the time, and the impacts of urban buildings vary in time as well, the dynamic building-AT relationships are worth being further investigated.

1.3. The perspective of urban planning

A large number of studies investigated the impacts of urban factors on the urban thermal environment, many of these urban factors are geographic or morphological indicators, such as Normalized Difference Vegetation Index (NDVI) for vegetation abundance [16,29], Normalized Difference Built-up Index (NDBI) for built environment [19], Sky View Factor (SVF) for street geometry [30], Impervious Surface Fraction (ISF) for land cover [15]. However, it's recognized that climate issues still have limited impacts on urban planning process [31,32], and it is partly because of the knowledge gap between urban planners and climatologists [31]. To help urban planners and decision-makers better understand and use the research findings, linking the climate issues to planning parameters can be more helpful than geographic or morphological parameters.

From the perspective of urban planning, it's both the composition and configuration of urban land surface influence the urban temperature. The land surface composition is given higher priority actually. Higher building density was demonstrated to cause higher temperature [33,34], increasing the fraction of vegetation is a practical way to mitigating UHI effects [18,33,35]. In contrast, the impacts of spatial configuration received lower research attention respectively, only a few relevant researches on LST [18,36–39]. Clustered arrangements of anthropogenic land cover amplify LST [36,37], the spatial configuration of urban vegetation was demonstrated to has strong negative correlations with LST, implying that clustered vegetation lowers surface temperatures more effectively [36], and the relationships were evidenced to be strongest during summer daytime and lowest during winter nighttime [18]. However, the impacts of spatial arrangement on AT were not well-investigated, relevant researches on AT is quite necessary.

1.4. This research

Given the above background, this study aims at examining the dynamic relationships between urban buildings and AT from the view of urban planning, especially the spatial configuration of urban buildings, so as to provide insights on AT mitigation for urban planners and managers. Several planning indicators are involved. The aims of this study are to: 1) explore the dynamic relationships of building indicators and AT at varying geographic scales, so as to determine the calculation scale for spatial configuration; 2) examine how the relationships change with time; 3) investigate the combined and individual effects of these building indicators.

2. Materials and methods

2.1. Study area

The city of Wuhan is the capital of Hubei province, located in central China (Fig. 1). It is the fifth most populous city in the nation. It is characterized by a subtropical monsoon climate with extremely hot summer, known as one of the Chinese "stove cities". The extent of the study area is 45 × 36 km, which covers the entire downtown Wuhan and reaches into the rural surroundings. The upper-left and lower-right coordinates are 114°5′32″E, 30°43′50″N, and 114°33′37″E, 30°24′17″N. There are 30 weather stations inside this area. Three rings were formed with the development of Wuhan city, which generally, represents the building intensity level (i.e., the 1st Ring has the highest building intensity, and followed by the 2nd Ring then 3rd Ring).

2.2. Air temperature

The AT was obtained from the 30 weather stations, hourly AT was recorded. The data used in this study was collected during the summer of 2012, from July to August. In order to exclude the impacts of wind and humidity, only the calm (wind speed <2 m/s) days which without rain before and after one day were chosen in this study. Excepting the days with damaged data, there are 8 days (including July 16th,17th,19th,23rd,24th, 25th, and August 22nd,23rd, labeled as D0716, D0717 and the like) with valid data in total. For each day, the daily average air temperature was calculated for each station, and the results were symbolized in the ArcGIS system to analyze the spatial variance of AT. Meanwhile, associating the AT with building environment preliminary according to the three rings.

2.3. Building indicators

The principle for selecting indicators are as follows: 1) the potential effects on air temperature; 2) from the perspective of urban planning, easily understood by planners; 3) fully describing the characteristics of the urban building, including the characteristics of three dimensions and spatial arrangement of urban building. The Floor Area Ratio (FAR) was chosen as a comprehensive indicator, Building Density (BD) and Building Height (BH) were used to describe the ground information and vertical information respectively, the spatial arrangement was measured by local Moran's I of Building (MB).

The computations of FAR, BD and BH were based on ArcGIS