An Investigation of Urban Heat Island Effect and Environmental Livability based on Remote Sensing Methods

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Abstract. Rapid urbanization has led to an increase in the urban heat island (UHI) effect. The UHI effect leads to localized high temperatures, reduced air quality, increased risk of heat stress and other diseases among residents. At the same time, it also reduces socialization among residents. Remote sensing technology, with its advantages of quantification, automation and real-time, can be used to analyze the UHI effect and further assess the livability of cities. In this paper, based on remote sensing image processing methods, the indexes of land surface temperature (LST), normalized vegetation index (NDVI), normalized difference build-up index (NDBI), and urban heat island intensity (UHII) were selected to analyze the scope of influence of UHI and urban livability. The important index of urban livability is human comfort, while UHI affects human comfort by influencing temperature and humidity. This paper concludes that the UHI effect is mainly reflected in the significant decrease in NDVI value and the significant increase in NDBI value. Meanwhile, there is a linear regression relationship between UHI and urban livability. In addition, UHI increases urban energy consumption and decreases environmental quality, destroying livability. This paper has proposed green city programs such as green roofs and cool sidewalks to improve the urban spatial structure. However, such programs still have the limitations of lower efficiency and higher cost. Therefore, in the future, UHI will be mitigated at the source by directly reducing solar radiation.

Keywords: Remote sensing, Urbanization, urban heat islands, Correlation, Vegetation cover.

1. Introduction

In recent decades, scientific technology and economic development have accelerated the development of urbanization, which is most directly characterized by a significant increase in urban population and urban sprawl. Urbanization has largely changed the demographic structure, vegetation and industrial spatial patterns, thus affecting the urban heat island (UHI) effect and, to some extent, destroying the livability of urban areas.

The city has changed dramatically horizontally and vertically, and the surface structure of the city has changed from vegetation to extensive concrete and asphalt. These changes affect the evaporation and transpiration of the vegetation, altering the rate of heat absorption and release from the urban surface and thus exacerbating the UHI. In addition, the high level of industrial activity and energy consumption are also important factors contributing to urban warming, accelerating the formation and expansion of the UHI effect. At the same time, this increases the risk of environmental pollution, which further affects the city's livability, for example, by increasing the probability of disasters such as flooding [1].

To further improve the living comfort of residents and mitigate the UHI effect, the relevant authorities have adopted many measures to control building density and increase the percentage of vegetation and water bodies. However, this can only change the local urban structure and cannot show the influence factors and change trends of UHI well. In this case, remote sensing technology shows an indispensable side. Remote sensing plays an important role in monitoring the quality of the environment for better urban planning. Venkatraman S et al. revealed that the Remote Sensing (RS) technique can understand the temperature changes of the whole city, which means that remote sensing can be used for monitoring on a large scale and large area [2]. In addition, it can also understand the long-term diurnal and seasonal changes in the city through spatio-temporal fusion (STF). Based on the data obtained from remote sensing, environmental and ecological quality and social economy can be analyzed comprehensively to determine the factors influencing the city's livability and give planning suggestions [3]. Therefore, remote sensing technology is of great significance in studying urban heat island effects, especially for those large cities with rapid urbanization, drastic changes in land use and energy consumption, and more complex environmental problems. Using RS technology, the temporal and spatial patterns of the urban heat island effect can be more clearly grasped to meet the needs of urban environmental management and planning.

This paper uses remote sensing data to explore the relationship between UHI and urban livability. First, the paper introduces remote sensing data sources and common indices to analyze UHI and urban livability. Next, the changes in LST and land use under the influence of UHI are specifically explored, and the links between the indices are described. Finally, the obtained data can be used to clearly and intuitively reflect the changes in UHI and the impact on urban livability.

2. Description of Commonly Used Remote Sensing Data Sources

2.1. Sources of Remote Sensing Data

The Landsat series of satellites (Landsat7, Landsat8, etc.) and MODIS satellites have disclosed many remote sensing image data. NASA owns both Landsat and MODIS, and Landsat can operate the Land Imager and the Thermal Infrared Imager through two multispectral sensors. As shown in Table 1, compared with MODIS, Landsat has the advantage of high resolution and can be used for land planning and environmental monitoring applications. While MODIS has a slightly poorer resolution, it has a faster update rate and is easier to monitor dynamic changes in physical information [4].

Table 1. Comparison of Landsat and MODIS Partial Differences

Properties \ Type	Landsat	MODIS
Spatial Resolution	30 meters	250 meters, 500 meters or 1 kilometer
Temporal resolution	16 days	12 hours
Number of bands	9-11	Usually 36
Range	Small range, detailed feature characterization	Large range, suitable for large scale monitoring
Application	Landsat series 7&8 Land use, environmental monitoring, etc.	MODIS Terra&Aqua Climate change, vegetation cover monitoring, ocean change, etc.

2.2. Methods for Analyzing Tthe Urban Heat Island Effect and Urban Livability

Remote sensing applications have become more widely used in recent years, with an increased demand for land-based remote sensing and sensors with higher accuracy, low power consumption and high radiation resistance. Remote sensing image preprocessing is also an important and indispensable step due to the defects of the sensors and the relative motion of the satellite platforms to the Earth, which can lead to the appearance of inhomogeneous radiometric brightness streaks and distorted regions in the images [5].

Due to the significant climate change and rapid urbanization in recent years, the UHI effect has gradually entered the human vision. Xiang et al. also revealed that UHI directly or indirectly affects the thermal comfort and well-being of urban residents [6], so more and more scholars have begun to use UHI to assess and improve the urban environment.

Currently, the indicators commonly used for UHI assessment include land surface temperature (LST), surface air temperature (SAT), normalized difference vegetation index (NDVI), and normalized difference build-up index (NDBI). Table 2 demonstrates the computational formulas primarily used for monitoring. Among them, LST and SAT are UHI's two main temperature indicators. These two temperature indicators can be used to calculate the urban heat island intensity (UHII). In addition, as the green vegetation in the city influences the ecosystem to a certain extent, it maintains the ecological environment [7]. NDBI can reflect the influence of urbanization degree and building density on UHI, while NDVI can reflect the mitigation effect of vegetation cover on UHI. By comparing the spatial distribution and correlation of NDBI and NDVI, a more comprehensive understanding of the formation mechanisms and influencing factors of UHI can be obtained. NDVI is usually used to monitor vegetation cover and reflect the vegetation growth pattern, and the larger the value, the higher the vegetation cover is when the NDVI is positive [8]. NDBI is similar to NDVI, with positive values for more man-made cover and negative values for more vegetation cover.

Yu et al. found that dryness and water humidity indicate wet and dry conditions in the environment and can also help more effective urban planning, constructed urban landscapes and wetlands to balance wet and dry. Analyzing land use changes can determine land suitability in time for more rational use [4]. It can be seen that urban livability is judged by the urban environment, in addition to the monitoring of temperature and vegetation cover, it is also necessary to consider the normalized difference bare soil index (NDBSI), normalized difference water index (NDWI), Aerosol optical depth (AOD), and comprehensive analysis of the integrated atmosphere, hydrology, and soil. As shown in Fig. 1, the basic process of remote sensing data to study UHI and urban livability is demonstrated.

Fig. 1 illustrates the basic flow of remote sensing data to study UHI and urban livability. Remote sensing image preprocessing aims to eliminate image noise through radiometric correction, atmospheric correction and other methods to improve the quality and availability of the picture. The features can be visualized through spatial analysis, temporal and spatial fusion, etc., and then analyzed and processed using some parameters to reflect UHI and urban livability. Table 2 demonstrates the calculation formulas mainly used for monitoring. The relationship between livability and these parameters will be discussed in detail below.

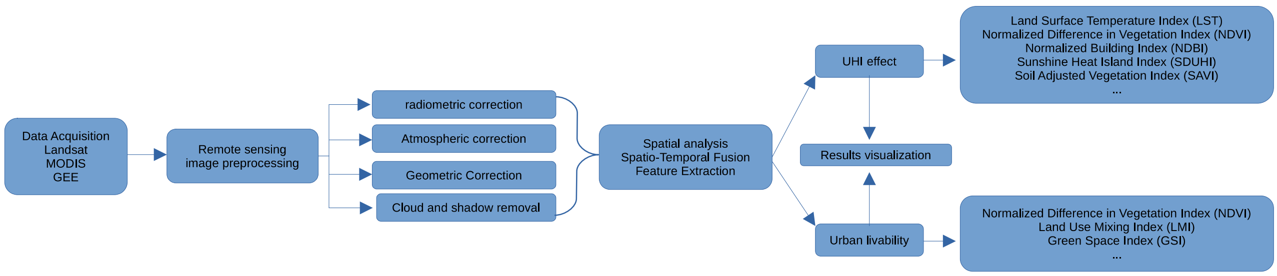

Figure 1. Remote sensing image preprocessing methods and judgment parameters

Table 2. Formulas for calculation of some parameter indicators

Parameter	Formula
Land Surface Temperature (LST)	$LST = \frac{K2}{\ln\left(\frac{K1}{DN} + 1\right)}$
Normalized Difference Vegetation Index (NDVI)	$NDVI = \frac{NIR - Red}{NIR + Red}$
Urban Heat Island Intensity (UHII)	$UHII = SAT_{urban} - SAT_{suburb}$ $SUHII = LST_{urban} - LST_{suburb}$
Normalized Difference Water Index (NDWI)	$NDWI = \frac{\rho_{Green} - \rho_{NIR}}{\rho_{Green} + \rho_{NIR}}$
Normalized Difference Bare Soil Index (NDBSI)	$NDBSI = \frac{IBI + SI}{2}$

3. Applications of Remotely Sensed Data for Monitoring the Urban Thermal Environment

3.1. Analysis of Surface Temperature Changes

Based on the analysis of remotely sensed data, the Copernicus study indicates that the global surface temperature (LST) has risen by 1.2 degrees Celsius compared to the pre-industrial era, as shown in Fig. 2 [9]. The surface temperature in Europe has risen by 2.2 degrees Celsius, almost twice the average global warming [8]. In addition, urban surface temperatures are rising faster than in rural areas, which is closely related to human activities. Rashid et al. found that much of the agriculture and vegetation has been converted to building land due to urban sprawl, leading to localized temperature increases [9]. As a result of the land use change, the soil becomes infertile, the water content decreases, and the soil becomes less capable of conducting and storing heat. In addition, the reduced water content weakens soil evaporation and prevents it from carrying away heat from the surface, which leads to an increase in LST. Therefore, land use and land change (LULC) are also important factors influencing the change of LST [10]. Under the influence of multiple factors such as human activities and LULC, the difference between urban LST and rural LST increases, and by analyzing the trend of LST, we can understand the intensity and evolution of UHI, which will be specifically analyzed below.

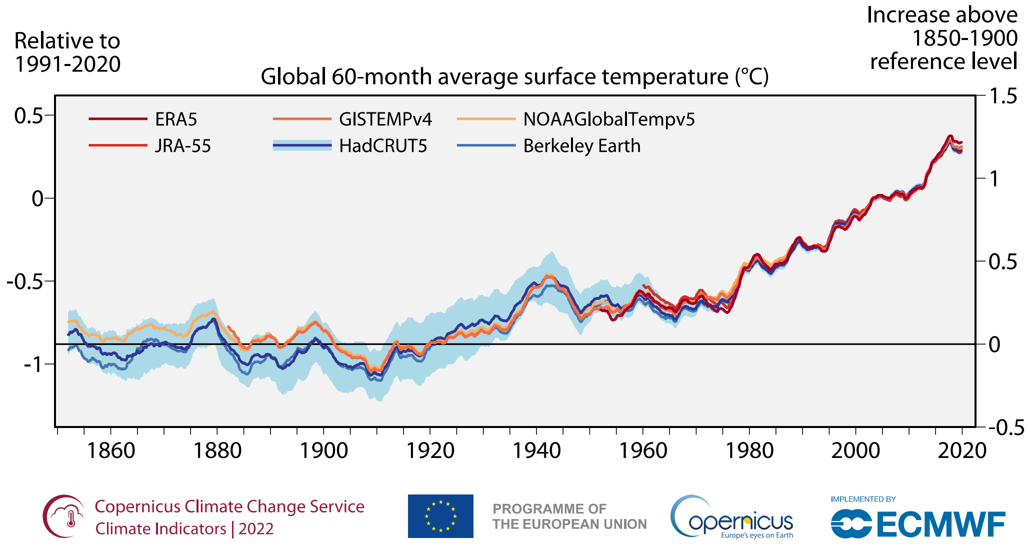

Figure 2. Global 60-month average surface temperature (℃) [8]

3.2. Land-cover Change

Land cover change is divided into area change and type change. The NDVI map can reflect the change in vegetation cover, which is important for analysing the change in local land vegetation cover and urban land use. For example, the city center of São Paulo, Brazil, South America, is more planned with low vegetation, mostly used for urban planning but with insufficient nutrient levels [2]. It is important to note that a high NDVI (0.4-0.5) does not necessarily mean high vegetation cover but may also be a large water body with a high density of mosses [9]. The NDBI maps can differentiate between urban and rural areas. The light yellow in the NDBI maps tends to be in rural areas, while the darker brown indicates built-up areas, which shows the size of the urban area and the direction of urban sprawl through the colours [2]. Due to the change in LULC, the soil properties are changed and the structure is destroyed. Organic carbon, sand, and gravel in the soil increase and clay decreases, affecting infiltration and increasing the risk of natural disasters such as flooding [11]. Areas with high LST may be at risk of ground subsidence [10]. Overall, land cover change seriously affects urban planning, land use, the water cycle, and biodiversity. Therefore, rational planning and utilisation of urban land are particularly important.

3.3. Relationship between NDVI, NDBI and LST

There is a close relationship between NDVI, NDBI and LST. When NDVI shows a negative value and decreases, NDBI increases. This is because different land covers have different albedo patterns, and the density and concentration of land covers vary from region to region [12]. Furthermore, Bagyaraj et al. found that the average LST increased to 152% between 1985 and 2021 [12]. It has been demonstrated that there is a significant simple linear regression relationship between NDVI and LST and NDBI and LST. LST is usually chosen as the dependent variable and NDVI and NDBI are independent variables [13]. As shown in Table 3, NDVI showed a negative correlation with LST. On the contrary, in Table 4, NDBI showed a positive correlation with LST (Enhanced Building and Bare Ground Index; EBBI has the same characteristics of reflecting built-up areas of the city as NDBI) [14]. Rashid et al. found that R^2 was higher in the regression model of NDBI and LST, which implies that the degree of correlation between NDBI and LST is higher [15].

Table 3. Relationship of LST to NDVI and NDBI (R2) [10]

Period	LST-NDVI	LST-NDBI
1990	-0.7849	0.7452
2013	-0.6221	0.6321
2020	-0.4831	0.4906

Table 4. Relationship of LST to NDVI and EBBI [16]

Period	LST-NDVI	LST-EBBI
1990	-0.189	0.199
2000	-0.395	0.484
2010	-0.286	0.411
2020	-0.213	0.585

3.4. Impact Analysis of UHI Effect

UHI is the phenomenon of higher temperatures in the city relative to the surrounding countryside. UHII is the temperature difference between the city and the countryside, which can better reflect the UHI [13]. However, UHII is usually affected by microclimatological influences, such as airports built on the city's outskirts. In addition, NDVI and NDBI can be used as reference indicators of UHI. Reduced vegetation is an important reason for the UHI effect, leading to higher local LST [10]. Florim et al. found that urban built-up areas and bare surfaces are the main cause of SUHI, which is closely related to LST [14]. Halder et al. also proposed an LST-based UHI assessment by comparing built-up areas (in yellow colour) with vegetation-covered areas (in green colour) to plan urban land use [10]. In addition, it has been found that UHI varies significantly across seasons and time scales. The maximum intensity of UHI in a year is usually in summer, and the maximum of the daily cycle of UHII usually occurs in the midday to afternoon hours [15]. This is closely related to solar radiation and atmospheric circulation. Therefore, the study of UHI can provide constructive advice for the rational layout of the city. UHI not only affects the environment but has also been found to affect the urban environment and then affects human health through changes. UHI affects the inner city by influencing the temperature, humidity, and atmospheric circulation. The most important aspect of urban livability is the comfort of its inhabitants. Comfort includes air cleanliness, vegetation coverage, etc. Among them, human thermal comfort is an important indicator. It is a state in which the human body expresses satisfaction with the thermal environment, and two important parameters that affect thermal comfort are air temperature and humidity [17]. Therefore, elevated LST changes the optimal temperature and humidity of the human body, which negatively impacts comfort and human health. The most direct impact of UHI on the human body is the risk of high temperatures, mainly heat waves, which also tend to cause several heat-related illnesses, and the impact is particularly severe on poor, poor areas lacking in materials, which also tends to cause conflicts between the rich and the poor.

4. Recommendation

Remote sensing has thermal infrared sensors (TIRS = 3-14μm) that are prerequisite data for studying LST and SUHI [18]. In this paper, the role of remote sensing data for studying UHI has been specifically addressed. Remote sensing is quantitative, automated and real-time. However, Kim, S. W. et al. found that remote sensing cycles run with limited monitoring hours, making it difficult to match weather data with research measurements. Secondly, due to the complexity of urban surfaces, the transmission time of remote sensing data, image resolution, revisit period, and clouds can impact LST analysis [18].

One of the important methods to reduce the UHI impact and improve the city's livability is to increase the surface albedo. Increasing albedo reduces direct solar radiation and suppresses heat sources at. Vegetation in cities can redistribute heat energy and influence latent heat, thus reducing solar radiation. In addition, low CO2 concentration in areas with dense vegetation cover improves regional environmental atmospheric cleanliness and comfort for urban residents [14]. Evola et al. found that UHI can be mitigated and resident comfort and urban livability can be improved through the use of programs such as green roofs and cool pavements, but the efficiency and cost need to be considered [19]. The principle of this type of program is to change the urban form by changing the surface energy balance in the building space. This type of strategy for integrating green vegetation with urban elements is still improving and provides new ideas for improving urban livability.

The use of remote sensing data to analyse vegetation cover and built-up areas may be inaccurate due to the low quality of spectral index classification. Therefore, the accuracy of developing indices on low-resolution remote sensing images is greatly reduced. Diem et al. found that most of the studies at this stage were for estimating and monitoring UHI and proposed some solutions. We should also focus on the drivers of UHI to radically reduce UHI intensity. In addition, there is a need to further discover the effects of UHI on the human body to rationalise the urban form for livability [20]. Therefore, to perform the analysis more accurately, it is necessary to use machine deep learning and hardware enhancement to discover the correlation between indices and consider the limitations to make multi-dimensional judgments.

5. Conclusion

This paper analysed in depth the factors affecting UHI and the changes in the cities that UHI influences. As UHI directly affects the temperature, the LST increases significantly, and the difference between urban and rural temperatures becomes larger. This paper found that RS technology is important in monitoring urban feature information. It can quantify, automate, capture and analyse real-time information, significantly improving efficiency. Factors contributing to the widening of the UHI effect are the reduction of vegetation cover, the increased energy consumption of urban transport, the increased absorption of heat by building materials, and the difficulty in releasing it. Vegetation affects evaporation and transpiration, resulting in a large accumulation of heat; urban traffic consumes a large amount of energy and releases exhaust gases while generating heat, and most building materials absorb more solar radiation, resulting in higher surface temperatures. The NDVI maps and NDBI maps reveal that the vegetation in the city centre has been rapidly decreasing in recent decades and has been replaced by built-up areas, which greatly affects the local atmospheric circulation and the water cycle. In addition, this paper also found that LST and NDVI and LST and NDBI have some correlation, LST has a negative correlation with NDVI, and LST has a positive correlation with NDBI and the correlation between LST and NDBI is stronger. UHI affects the human body's thermal comfort by influencing the temperature, and the high temperature is prone to cause heat stress and heat-related diseases in human beings, which will increase the burden of medical care in the cities and intensify the conflict between rich and poor to a certain degree. The UHI is a major influence on human thermal comfort through temperature.

Reducing solar radiation is the most direct way to mitigate the impact of UHI on cities, and solutions such as water-permeable floors and green roofs have been used with some success but at a higher cost and with limited diffusion. There are still many challenges in the recent stage, such as limited sensor accuracy of remote sensing equipment, complex ground conditions, and limited research on UHI and, urban livability and human health. With the development of remote sensing technology, remote sensing monitoring will be used in depth to optimise the existing software and hardware deficiencies of remote sensing and monitor UHI in real time, thus contributing to achieving urban sustainability and livability.

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