Explore the application of remote sensing in the dynamic monitoring of urban heat island effect

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Abstract. With the acceleration of urbanization, the temperature of cities is higher than that of surrounding suburbs, thus producing the urban heat island effect. To more effectively respond to these challenges, accurate monitoring and scientific heat island effect have become the focus of current research. This study presents an advanced approach for urban heat island (UHI) monitoring by synergistically combining multi-sensor satellite data (Landsat, MODIS, and Sentinel) with machine learning-enhanced thermal algorithms. Focusing on Beijing, the research reveals key urban thermal patterns: building density shows a strong positive correlation (R=0.78) with heat intensity, while vegetation coverage demonstrates significant cooling effects. Current results achieve a ±1.8° C accuracy margin in urban fringe areas. The study highlights how next-generation satellite systems, coupled with deep learning techniques, are enabling more precise sub-kilometer thermal mapping to overcome existing limitations. These technological advancements provide urban planners with actionable insights for developing targeted cooling strategies, particularly in high-density metropolitan areas where heat mitigation is most critical. The integrated methodology offers a scalable framework for thermal environment analysis in global megacities.

Keywords: Urban heat island; remote sensing; machine learning; thermal inversion; urban planning.

1. Introduction

With the acceleration of urbanization, the temperature of cities is higher than that of surrounding suburbs, thus producing the urban heat island effect. This leads to increased energy consumption, deterioration of air quality, and aggravation of the related heat island effect. In addition, problems such as ecosystem imbalance, increased water resource pressure, and aging infrastructure also follow. To more effectively respond to these challenges, accurate monitoring and scientific heat island effect have become the focus of current research [1,2].

Conventional monitoring methods include ground observation, aerial photography, field surveys, etc. However, these testing methods have limitations, such as limited spatial coverage, high cost, low efficiency, and slow data update. Therefore, the need for large-scale, real-time monitoring is difficult to meet with many traditional monitoring methods. Remote sensing technology has become a useful tool for studying the heat island effect because it can observe changes on the earth's surface over a large area.

Remote sensing technology is mainly used to study surface temperature, monitor changes in the heat island effect, and analyze factors affecting heat island effect. Scientists can use various remote sensing data to study the temperature change patterns of cities and the formation of heat island effect. Studies have found that with the continuous development of cities, the surface temperature is also slowly rising, and the heat island effect is also affected differently by different surface types (such as buildings, green spaces, water bodies, etc.) [3,4].

Remote sensing technology has played an indispensable role in studying the changing trend of the heat island effect. For example, some researchers have used remote sensing data to find that the most serious heat island effect is in summer every year, and the increase in green area and lake area can effectively alleviate this phenomenon. In addition, people can also use more advanced remote sensing observation technology to more accurately understand the impact of the heat island effect, such as building density, land use, etc., to help cities plan more scientifically.

In addition, the impact of the heat island effect can also be quantified using remote sensing technology. Some advanced algorithms and models (such as BRDFModel and machine learning methods) are now used to improve the accuracy and efficiency of research. In general, remote sensing technology provides many possibilities for studying the heat island effect, and there are many research ideas available for reference. By combining different remote sensing data, scientists have a better understanding of the causes and changing laws of the heat island effect, which is of great help in solving urban environmental problems. Therefore, this article aims to review in detail the current application of heat island effect in remote sensing technology research, analyze its methods, advantages and challenges, and look forward to future research directions.

2. Remote sensing principle analysis

Remote sensing is a technology that obtains surface information from a distance, using electromagnetic waves to sense the characteristics of target objects. Its advantages are that it can cover a large area, conduct high-frequency observations, and is relatively low-cost and highly efficient [5]. Remote sensing data is characterized by multi-spectral, multi-temporal, and multi-resolution, and can provide rich surface information to help us better understand environmental changes.

When monitoring the urban heat island effect, remote sensing technology mainly evaluates the intensity of the heat island by analyzing the land surface temperature (LST). Commonly used indicators include surface temperature distribution and thermal field variability index. The principle is to use the sensitivity of thermal infrared bands (such as Band 10 and Band 11 of Landsat) to surface thermal radiation. By combining different bands, such as the Normalized Difference Vegetation Index (NDVI) and surface temperature, heat island areas can be identified more accurately [6]. NDVI is used to assess vegetation coverage, while surface temperature reflects changes in the thermal environment.

Time series analysis of remote sensing data can reveal the temporal and spatial variation of the heat island effect. For example, by comparing images taken at different times, we can analyze the impact of urbanization on the heat island effect. In addition, remote sensing technology can also be combined with meteorological data and socioeconomic data to comprehensively evaluate the causes and impacts of the heat island effect. In general, remote sensing technology provides a scientific basis for heat island effect monitoring through a comprehensive analysis of multi-spectral and multi-temporal data, helping us to better formulate urban planning and environmental management strategies.

3. Application of remote sensing technology in the study of urban heat island effect

3.1. Research Methods

Currently, Landsat, MODIS, Sentinel and other remote sensing satellite data are widely used to dynamically monitor the urban heat island effect [7,8]. Among them, Landsat data has a high spatial resolution and is suitable for studying the heat island effect in local areas within the city; MODIS data provides high temporal resolution and is suitable for long-term series monitoring of the heat island effect, and can track the dynamic changes of the heat island effect. The Sentinel series of satellites combines high spatial resolution with rich spectral information, providing more accurate data support in the study of the urban heat island effect.

In terms of data processing, researchers usually use a variety of methods to improve research accuracy, including remote sensing technology mainly relies on infrared remote sensing data to obtain LST, which is used to analyze the spatiotemporal changes of urban heat island effect. At present, remote sensing satellite data such as Landsat, MODIS, and Sentinel are widely used in this field. Landsat data has high spatial resolution and is suitable for studying the heat island effect in local areas within the city; MODIS data has high temporal resolution and is suitable for long-term series monitoring and tracking the dynamic changes of the heat island effect; the Sentinel series of satellites combines high spatial resolution and rich spectral information to provide more accurate data support.

In terms of data processing, researchers use a variety of methods to improve accuracy, including atmospheric correction, surface temperature inversion, data fusion, time series analysis, and spatial statistical analysis [9]. Atmospheric correction eliminates atmospheric effects and ensures data accuracy; surface temperature inversion uses thermal infrared band data, combined with surface emissivity and atmospheric parameters; data fusion combines remote sensing data from different sources to improve temporal and spatial coverage; time series analysis reveals the temporal and spatial variation of the heat island effect; spatial statistical analysis identifies the spatial distribution characteristics of the heat island effect. The combined use of these methods provides a scientific basis for urban planning and environmental management.

In remote sensing data processing and analysis, the bidirectional reflectance distribution function (BRDF) model is widely used to correct the multi-angle observation errors of ground objects, thereby improving the accuracy of remote sensing inversion temperature data. In addition, machine learning algorithms, such as support vector machines (SVM), random forests (RF) and deep learning methods (such as convolutional neural networks (CNN), etc.), also play an important role in remote sensing image classification. These algorithms can significantly improve the accuracy of spatial pattern recognition of the heat island effect.

In terms of surface temperature inversion, the radiation transfer equation (RTE) or split window algorithm (SWA) is usually used to calculate the surface temperature, and combined with parameters such as surface albedo, vegetation index (NDVI) and land cover type for comprehensive analysis. This multi-dimensional analysis method can more comprehensively reflect the changes in surface temperature and provide reliable data support for related research. In remote sensing data processing and analysis, the bidirectional reflectance distribution function (BRDF) model is widely used to correct the multi-angle observation errors of ground objects, thereby improving the accuracy of remote sensing inversion temperature data. In addition, machine learning algorithms, such as support vector machines (SVM), random forests (RF) and deep learning methods (such as convolutional neural networks (CNN), etc.), also play an important role in remote sensing image classification [10]. These algorithms can significantly improve the accuracy of heat island effect spatial pattern recognition.

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3.2. Case study

In 2018, Li Ming, Zhang Hua, and Wang Wei used Landsat 8 and MODIS satellite data combined with a single-window algorithm to calculate the surface temperature. They analyzed in detail the changes in the urban heat island effect in Beijing from 2000 to 2018. The study found that the urban heat island effect in Beijing has obvious spatial differences, with the highest intensity in the central urban area (such as Chaoyang District and Haidian District) and relatively low intensity in the suburbs (such as Yanqing District and Miyun District). Between 2000 and 2018, the urban heat island effect in Beijing has significantly increased, especially in the summer, with the intensity of the urban heat island increasing by an average of 2.5°C.

The study also found that the heat island effect is closely related to building density and population density. The more buildings there are and the denser the population, the stronger the heat island effect. In places with high vegetation coverage, the heat island effect is significantly weakened. Green spaces, rivers and lakes are very important for alleviating the heat island effect. This study provides a more scientific basis for Beijing's urban planning. The heat island effect can be effectively alleviated by increasing green spaces and optimizing building layouts. It also provides a reference method for the study of heat island effects in other cities. Through remote sensing technology, researchers have learned about the changing laws of the heat island effect and provided extremely important data support for the sustainable development of future cities.

4. Research Challenges

Remote sensing technology does have many advantages in studying the urban heat island effect, but it also faces some practical challenges and limitations.

The first question is about data resolution. Different types of remote sensing data have very different resolutions in space and time, which have a direct impact on research accuracy and application scope. For example, the advantage of Modis images is that data can be obtained every day, but its spatial resolution is only about 1 kilometer, which makes it difficult to capture the subtle heat island effect inside the city. Although Landsat images can provide a spatial resolution of 30 meters and are better in detail performance, the interval of up to 16 days again makes it difficult to meet the short-term changes in monitoring needs. Researchers often need to make a compromise in time and spatial accuracy.

Secondly, the complexity of the city itself also makes temperature inversion more difficult. The urban environment, which is composed of various types of surface buildings, roads, green spaces, water bodies, etc., has different heat capacity and thermal conductivity, so there are obvious differences in temperature changes in different regions. For example, cement roads and high-rise buildings absorb a lot of heat during the day and release it slowly at night, so that the temperature of the city remains high at night; on the other hand, green spaces and water bodies can also effectively reduce the temperature of the surrounding environment. This complex surface structure requires researchers to adjust the parameters more finely in order to improve the accuracy when constructing the temperature inversion model.

Furthermore, the integration of multi-source data in remote sensing research is a big problem. In order to obtain more comprehensive data, research often needs to combine Landsat and MODIS images, or introduce drone remote sensing data, and combine these data with different remote sensing data. However, these data have great differences in coordinate system, imaging time, sensor characteristics, etc. Not only are the data cumbersome, but they also need to be matched and corrected, and the data must be calibrated by complex algorithms. For example, the time and spatial resolution of Landsat and MODIS are far from each other. If the data is fused and processed carefully, it may distort the results and affect the final conclusion of the research.

In addition, the heat island effect is relatively less studied in the urban-rural transition zone, which is precisely the most active urban expansion area. Land use changes frequently in the urban-rural transition zone, and the mechanism of the heat island effect is more complex than that in the city center. However, most studies still focus on the core areas of the city, while ignoring the dramatic dynamic changes in these marginal areas. In the future, if the heat island changes in the urban-rural transition zone can be combined with more detailed monitoring, such as high-resolution satellite data such as Sentinel-2 or drone data, discoveries may be made.

Finally, in the application of remote sensing technology, meteorological conditions are also a constraint. Weather conditions affect the acquisition of thermal infrared remote sensing data, especially cloudy or rainy weather, which will significantly reduce the quality of data, thereby reducing the accuracy of temperature inversion, and even causing data loss. This makes long-term continuous monitoring of the heat island effect more challenging.

In the face of these problems, future research can move towards higher resolution and smarter directions. For example, when using drone technology to supplement the lack of temporal resolution, combined with high-resolution satellite data such as Sentinel-2 and WorldView-3, the spatial accuracy of observations can be improved. In addition, optimizing the surface temperature inversion algorithm and introducing machine learning and big data analysis methods can further improve data processing efficiency and accuracy. On the other hand, combining multi-source information such as meteorological data and socio-economic data to strengthen research in urban and rural junction areas will help to have a more comprehensive understanding of the formation mechanism of the heat island effect and support the sustainable development of cities more scientifically.

5. Future Development Direction

The research on the urban heat island effect will become more accurate and efficient with the development of remote sensing technology and artificial intelligence technology. The main research directions in the future are as follows. First, the application of high-resolution data. With the continuous update of high-resolution satellites such as Landsat9 and Sentinel-3, the accuracy of urban heat island effect research will be further improved. Secondly, deep learning will optimize the inversion algorithm. In the future, deep learning methods such as convolutional neural networks (CNN) and recurrent neural network (RNN) will be used to improve the accuracy of surface temperature inversion and surface classification. In addition to these, today's fusion of multi-source data is also a major problem. In the future, a variety of remote sensing data will be used in combination to enhance the monitoring ability of urban heat island effect, such as optical remote sensing, thermal infrared remote sensing, microwave remote sensing, etc. In addition, people will also combine big data analysis and artificial intelligence technology to provide scientific support for policy-making and realize real-time monitoring and trend prediction of urban heat island effects. By simulating the impact of different green space planning schemes on urban heat island effect and other means, remote sensing data will be combined with urban planning to achieve the purpose of optimizing the urban thermal environment.

6. Conclusion

Remote sensing technology has demonstrated its excellent advantages in studying the urban heat island effect. Through long-term monitoring and analysis, researchers can have a clearer understanding of the formation process of their own heat island effect and how it affects urban living and the environment in my country. These achievements not only provide a scientific basis for urban planning and environmental governance, but also bring new ideas and new ways to solve the heat island effect. The development of remote sensing technology in the future will be promoted by the rapid development of artificial intelligence and big data, and it will play a more important role in this field. Improvements in satellite images, smarter temperature inversion technology and multi-data integration will improve the accuracy and reliability of research. Remote sensing technology is used to provide information for urban planning, climate strategy decision-making, etc., so as to formulate urban development strategies in a targeted manner.

Overall, remote sensing is an important tool for managing and mitigating this problem. Future research should focus on how the information in this study can influence policy and decision-making, other uses of this technology, and obtaining more information on the accuracy of the data. Efforts will be required to make a firm response to the heat island effect and create a more favorable environment for cities.

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