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Research on the Impact of Atmospheric Particulate Matter (PM2.5) on Urban Heat Island Effect

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Abstract: With the rapid development of urbanization, PM2.5 pollution and urban heat island effects have become two major environmental problems that constrain the sustainable development of cities. PM2.5 is one of the important pollutants in the atmosphere, and its influence on the urban thermal environment is still insufficiently clarified. The study establishes an urban thermal environment-PM2.5 interaction model to examine the relationship between these two. The study selected a typical urban agglomeration as the research area, through the use of remote sensing monitoring and ground observation methods to obtain the PM2.5 concentration and urban temperature distribution data from 2018 to 2022. Using machine learning algorithm and thermal balance model analysis, it can be seen that PM2.5 can significantly enhance the heat island intensity by changing the urban atmospheric radiation transmission characteristics. When the PM2.5 concentration is between 75–150 $\mu g/m^3$, the urban heat island intensity increases by about 0.8-1.2 °C, but when the concentration is higher than 200 $\mu g/m^3$, the heat island effect will decrease due to the increased solar radiation scattering. The urban building density and green coverage are the main factors that play a regulatory role in this relationship. This paper provides a scientific basis for the comprehensive management of the urban environment, and also has important reference value for the optimization of urban planning and the formulation of air pollution prevention and control strategies.

Keywords: Atmospheric particulate matter PM2.5; Urban heat island effect; Radiation balance; Urban planning; Environmental management

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1. Introduction

1.1. Research background and significance

In recent years, with the rapid advancement of industrialization and urbanization, atmospheric particulate matter (PM2.5) pollution has become a common environmental problem worldwide, especially in densely populated cities. Because PM2.5 particles are small, have a large specific surface area and strong adsorption capacity, they can float in the atmosphere for a long time and can be spread far away by air currents, so they not only affect the urban landscape, but also pose a great threat to human health. At the same time, the urban heat island effect is also an important urban environmental problem, and it is becoming increasingly serious worldwide. There is a close connection and mutual influence between the two.

The connection between PM2.5 and the urban heat island effect is reflected in several aspects: In the near-Earth surface, the accumulation of PM2.5 particles leads to an increase in the intensity of the urban heat island effect, which indicates the interaction between pollutants and the thermal environment. By altering the radiative transport characteristics of the urban atmosphere, it causes changes in processes such as absorption, scattering, and reflection of solar radiation by the urban atmosphere, thereby altering the energy balance on the urban surface. The larger the building complex, the stronger the effect, and thus some scholars refer to this phenomenon as the superposition of the "pollution island effect" and the "heat island effect" [1].

Studying the relationship between PM2.5 and the urban heat island effect will not only further improve the theoretical system of urban climatology, but also provide an effective basis for the comprehensive management of the urban environment. On this basis, the quantitative relationship and mechanism of action between the two can be analyzed. This will help with urban planning and layout, air pollution prevention and control, urban climate work, improve the quality of the urban ecological environment, and promote the sustainable development of the city.

1.2. Research objectives and research questions

For the interrelationship between atmospheric particulate matter and the urban heat island effect, it is necessary to break the single dimension of traditional environmental research and establish a more complete and systematic research framework from multiple aspects. By exploring the influence of PM2.5 on the urban atmospheric radiation transfer characteristics, its moderating effect on the urban heat island effect is discussed. Analyze the differences in the effects of particulate matter on urban temperature fields under different concentration gradients, and on this basis establish an interaction model of urban thermal environment and PM2.5, quantitatively describe the nonlinear correlation between the two, and enrich and improve the existing theoretical system.

Based on the questions raised in the research, this paper first explores the mechanism by which PM2.5 affects the urban thermal environment through the radiation balance pathway; Subsequently, the harmonizing effect of urban building density and green space coverage on the urban heat island is analyzed; Finally, the spatial differentiation characteristics of the coupling between PM2.5 and heat island intensity under different meteorological conditions and different urban forms are explored as the main thread throughout the entire process from theoretical analysis to empirical research in this paper.

By integrating data from remote sensing monitoring and ground observation, and using machine learning algorithms and thermal balance models to analyze and process the data, this paper can provide a certain scientific basis for the comprehensive prevention and control of the urban environment, help people to have a clearer understanding of the complex pollution of the urban environment, and on this basis put forward reasonable suggestions to improve the urban planning and design scheme, improve air pollution prevention and control measures and promote the healthy development of urban ecosystems [2].

2. Literature review

2.1. Research status of PM2.5 pollution

Atmospheric fine particulate matter (PM2.5) has become one of the key pollutants in urban environmental governance today, expanding from the study of the characteristics of a single pollutant to the stage of the interaction of multiple environmental effects; Long-term observational data show that PM2.5 has seasonal and regional differences in temporal and spatial distribution, and there is a complex mutual feedback relationship between it and the built urban environment. Taking the University town in Nanshan District, Shenzhen City as an example, a high-frequency (once every 2 hours) observation for one consecutive year revealed a significant positive correlation between urban heat island intensity (UHII) and PM2.5 concentration. The diurnal variation pattern of UHII and the basic concentration of PM2.5 both showed periodic variation patterns. This provides a basis for quantitative analysis of the coordinated prevention and control of urban thermal environment and air pollution.

In response to PM2.5 pollution control, there is growing emphasis on the regulatory function of ecosystems. Urban forests are an important component of urban ecosystems and have a significant role in purifying atmospheric particulate matter. In terms of purifying fine particulate matter in Shanghai, different vegetation types have different adsorption capacities for PM2.5. Evergreen trees have an average annual reduction efficiency about 30% higher than deciduous trees, and the more complex the forest stand structure, the better the particulate matter interception effect. Therefore, starting from the urban forest ecosystem for PM2.5 control can combine pollution control and thermal environment regulation and promote them simultaneously, which will help to create a more coordinated urban environmental governance system [3].

2.2. Research progress on urban heat island effect

The urban heat island effect is a typical climate phenomenon that accompanies urbanization, referring to the phenomenon where the temperature in a local area of a city, such as the urban area, is higher than that in the surrounding suburbs or rural areas. Its causes are mainly due to changes in the characteristics of the underlying surface of the city, including various aspects such as the thermophysical properties of urban materials, urban geometry, and heat dissipation from human activities. The study found that the impermeable cover of the urban surface allows more solar radiation to be absorbed and reduces the evaporative cooling effect, thereby causing a significant change in the energy balance of the urban area.

From the perspective of energy balance, the mechanism of the urban heat island effect is as follows: the built-up area of the city has a large heat capacity and high thermal conductivity, resulting in high daytime temperatures, storing a large amount of heat that cannot be dissipated quickly at night, causing heat accumulation; The height of the atmospheric boundary layer in the Beijing-Tianjin-Hebei region has a distinct seasonal variation pattern. In summer, a large boundary layer height is conducive to heat dissipation and the dilution and diffusion of pollutants. In winter, a small boundary layer height is prone to the accumulation of heat and pollutants. Coupled with the special three-dimensional structure of the city, a “street valley effect” is formed, which hinders urban ventilation and thus makes the heat in the city more likely to be retained.

At present, the research methods for the heat island effect have shifted from fixed-point observation to multi-source data fusion analysis. Remote sensing technology is used for large-scale thermal environment monitoring, and numerical simulation methods are employed to study the heat island mechanism. Meanwhile, urban heat islands interact with multi-scale atmospheric circulation such as sea-land winds and valley winds to influence the urban microclimate system. Further research should be conducted on the interaction mechanism between urban heat islands and atmospheric pollutants, and the impact of PM2.5 on urban radiation balance under different meteorological conditions should be explored to provide more precise scientific basis for urban planning and environmental governance [4].

3. Research methods and data

3.1. Study area selection and data sources

In this study, typical urban agglomerations were selected based on the degree of urbanization, climatic conditions, and characteristics of air pollution. The selection criteria were the scale of urban built-up areas, the diversity of urban forms, the completeness of historical meteorological data, and the coverage density of the PM2.5 monitoring network. Finally, three representative urban agglomerations in the Bohai Rim Economic Circle, the Yangtze River Delta, and the Pearl River Delta were determined. It can better reflect the diurnal variation characteristics of the surface properties of typical urban agglomerations in different climate zones in China, and has strong representativeness and universality.

The above information is based on the data obtained from 2018 to 2022 using multi-source fusion data collection methods, remote sensing monitoring and ground observation means; PM2.5 concentration is mainly based on hourly mean observations from the national atmospheric environment monitoring network, supplemented by high-density block-scale data collected by mobile monitoring vehicles; Urban temperature distribution was obtained using surface temperature products retrieved from the thermal infrared band of the Landsat8 satellite and measured temperatures at meteorological stations. High-resolution remote sensing images were used to extract urban spatial morphological parameters, including building density, height, green space coverage, etc. CFD simulation technology was applied to build an optimization scheme for building arrays and road orientations to select urban spatial parameters, and to study the relevant description of the influence of building layout on the spatial distribution of PM2.5 concentration [5].

The collected raw data are first processed for quality control, outlier detection and spatio-temporal consistency correction to establish data sets of meteorological elements, pollutant concentrations and urban morphological parameters; Then, GIS spatial analysis technology was used to interpolate the point monitoring data to generate a continuous distribution area, with the aim of providing data support for future quantitative analysis of the spatial coupling between the urban heat island effect and PM2.5 concentration.

3.2. Research indicators and analysis methods

Based on references to relevant literature, this paper establishes a system with PM2.5 concentration and urban heat island intensity as the core indicators, and uses quantitative methods to analyze the interaction mechanism between the two. Among them, PM2.5 concentration uses the 24-hour moving average, combined with the daily maximum value and seasonal variation trend to show the atmospheric particulate matter pollution status; Urban heat island intensity is represented by the value of higher temperatures in urban areas than in suburban areas, and the heat island intensity index (UHII) is used to measure the differences in the thermal environment among different urban areas. In addition, auxiliary indicators such as building density, green space coverage, and urban underfloor are set to form the right half of the evaluation system.

This paper uses multiple statistical regression and machine learning methods to establish a correlation model between PM2.5 and the heat island effect, applies principal component analysis (PCA) to reduce multicollinearity among variables, and uses random forest (RF) algorithm to screen out the main influencing factors. In numerical simulation, the WRF/CALPUFF coupling model was used to simulate the impact of different concentrations of PM2.5 on the urban radiation balance. In the simulation of severe smoggy pollution weather in Harbin, the PM2.5 mass concentration distribution caused by the heat island effect was well simulated, thus verifying the suitability of this method for the research of this subject.

The data processing procedure includes preprocessing methods such as outlier detection, missing value interpolation and spatio-temporal interpolation to make the analysis results more scientific and reasonable; And creatively using the radiative transport model to incorporate the influence values of PM2.5 in different concentration intervals on solar shortwave radiation and surface long-wave radiation, and explaining the mechanism of particulate matter on the heat island effect, that is, the duality of particulate matter, through energy balance, this methodological system can perfectly combine fixed-point monitoring data with remote sensing data. This makes the research results more accurate and reliable [6].

3.3. Study the technical route

This technical route ensures the scientific and rigorous nature of the entire research work by constructing a complete and systematic technical route from multi-source data collection to data preprocessing, multi-model coupling prediction, and optimization plan formulation. First, use a satellite remote sensing platform to obtain images of urban surface temperature distribution and collect real-time PM2.5 concentration data from ground monitoring stations, as well as auxiliary data such as urban building density and green space coverage rate; Secondly, in the process of data preprocessing, the spatio-temporal consistency correction method is used to remove the influence of clouds in the remote sensing data, and the Kriging interpolation algorithm is used for the spatial continuous processing of monitoring station data to create a complete urban PM2.5 concentration distribution map.

For the development of the urban thermal environment-PM2.5 interaction model, in this stage of the urban thermal environment-PM2.5 interaction model, the radiative transfer equation and the principle of thermal equilibrium are combined to represent the influence of different mass concentrations of PM2.5 on the radiation characteristics of the urban atmosphere, At the same time, feature parameters of the urban underlying surface were added during the model calculation process, and machine learning algorithms were used to quantitatively describe the relationship between PM2.5 and heat island intensity under complex urban conditions. Finally, cross-validation was used to verify the differences between the model's predicted values and independent observation datasets, and root mean square error and correlation coefficient were calculated to assess the accuracy and stability of the model's predictions.

From this technical route, it can be seen that this study can effectively reveal the pattern of the influence of changes in PM2.5 concentration on the urban heat island effect, so as to provide a reference method for future related research. At the same time, this study combines air pollution monitoring with urban thermal environment research, and uses multi-dimensional data and optimization models to increase the accuracy of correlation analysis between PM2.5 and the heat island effect in complex urban environments, thereby providing a more solid theoretical basis for the comprehensive management and governance of the urban environment in the future [7].

4. The influence mechanism of PM2.5 on the urban heat island effect

4.1. The effect of PM2.5 on urban heat radiation

The effect of atmospheric particulate matter (PM2.5) on urban heat radiation is a very complex physical explanation, and aerosols are achieved by altering the urban atmospheric radiation balance. The optical properties of aerosols enable them to absorb and scatter short-wave solar radiation, while also altering the transmission of long-wave radiation on the surface. When aerosols are at a certain concentration (critical value), in urban areas, aerosols act as a "semi-transparent barrier" to weaken direct solar radiation reaching the surface, but increase the absorption and re-radiation of long-wave radiation emitted from the surface by the atmosphere.

In the urban thermal environment, the interference of PM2.5 particulate matter on radiation transmission is one of the important factors affecting the urban energy balance. According to research, when PM2.5 concentration reaches a certain range (75–150 μg/m^3), it has a stronger insulating effect on the near-surface atmosphere, thereby delaying the rate of urban heat dissipation at night. Observations in the area where pollution sources are concentrated in Xi'an have found that in the near-surface layer, the large accumulation of particulate matter significantly enhances the absorption of long-wave radiation on the urban surface. Moreover, the effect of PM2.5 on urban heat radiation varies in different seasons and at different times of the day, and the pattern of the effect is not the same during the heating season in winter and the high temperature period in summer [8].

The impact of urban underlying surface characteristics on PM2.5 is more complex. Different materials in the city (concrete, asphalt, glass curtain walls) have different radiation characteristics in the context of PM2.5 pollution, and particulate matter attached to the building surface can change the albedo and heat capacity of that material. In turn, it affects the energy distribution and transmission efficiency of the urban three-dimensional space, as well as the temperature field distribution of the city.

4.2. The impact of PM2.5 on urban microclimate

Urban microclimate systems are greatly affected by PM2.5 concentrations. Due to the radiative transport characteristics of the urban atmosphere, when PM2.5 particles float in the air, they scatter and absorb solar radiation, which changes the amount of short-wave radiation received on the surface. At the same time, it also affects the transmission of long-wave radiation. In the urban environment, changes in the corresponding radiation flux can cause changes in surface temperature, thereby affecting the distribution of near-surface air temperature.

Furthermore, PM2.5 also alters the thermodynamic properties of the atmosphere, thereby affecting the urban microscale air flow organization. When the concentration of particulate matter reaches a certain level, it creates a temperature gradient in the vertical direction, thereby altering atmospheric stability. Observational analysis shows significant spatial distribution differences and seasonal variations in the height of the atmospheric boundary layer in the Beijing-Tianjin-Hebei region, which is closely related to the degree of PM2.5 pollution. When the height of the atmospheric boundary layer decreases, it is difficult for pollutants to diffuse vertically, and heat exchange is also affected, making the thermal environment of the city more uneven.

The multi-scale circulation system plays a very important role in the interaction between PM2.5 and the urban microclimate. The sea and land winds, valley winds, and urban heat island circulation within the city together form a complex circulation system, which has a significant impact on the transport and diffusion of atmospheric pollutants. When the concentration of PM2.5 is high, it inhibits the development of vertical convection, reduces the intensity of turbulence near the surface, and causes some heat to be retained in the urban boundary layer, further strengthening the urban heat island effect. Under certain meteorological conditions, microscale circulation can also facilitate the diffusion of pollutants and slow down the accumulation of heat, thereby creating a balance between PM2.5 and the urban microclimate [9].

4.3. The moderating effect of urban form on PM2.5 and the heat island effect

Urban form is a material carrier of the urban environmental system, and the pattern of the city affects the interaction between PM2.5 pollution and the heat island effect. The density and height distribution of buildings in a city determines whether urban ventilation corridors can be formed, thereby influencing the diffusion channels of PM2.5 in the urban space. High-density building areas are prone to the "canyon effect", where air circulation is poor, leading to heat accumulation and pollutant retention, thereby intensifying the heat island effect. It is scientifically and reasonably arranged building clusters that allow for better air circulation and slow down the accumulation of pollutants, thereby reducing the intensity of the heat island effect.

Green space systems have significant spatial heterogeneity in moderating the relationship between PM2.5 and the heat island effect. From the evaluation results of multi-scale ecosystem services in the Suzhou-Wuxi-Changzhou region, there are significant differences in the effect of different types and sizes of green spaces on the heat island effect. Among them, large contiguized urban parks, due to their transpiration, can lower the surrounding temperature by 2 to 3 °C. Moreover, grassland vegetation has the effect of intercepting PM2.5, which can also reduce PM2.5 by 15 to 20 percent. Scattered small green spaces, although their individual regulating capacity is limited, can form "green island chains" through networked layout, connecting the ecological corridor network for cooling and purifying the air in the city. Therefore, when planning urban green spaces, both the total amount and the spatial distribution of green spaces should be taken into account, so that green spaces can play a better role in coordinating the control of PM2.5 pollution and the heat island effect.

Water bodies and open spaces are also important means of regulating the urban thermal environment. Urban water systems can absorb heat and cool down, reduce the intensity of the urban heat island, and at the same time promote air circulation to a certain extent and dilute the concentration of PM2.5. Therefore, establishing an urban spatial optimization model that considers building form-green space system-water body layout will be beneficial for guiding future urban planning and fulfilling the tasks of pollution control and thermal environment improvement. The technical route of systematic regulation based on urban form is not only a technical route to solve the environmental problems currently faced by urban development, but also a technical path to achieve the goal of resilient urban development [10].

5. Conclusions and recommendations

5.1. Research conclusions

Construct an urban thermal environment-PM2.5 interaction model to explore the mechanism by which atmospheric particulate matter affects the urban heat island. Observations show a nonlinear relationship between PM2.5 and the intensity of the urban heat island. At the medium concentration stage (75–150 $\mu g/m^3$), particulate matter can change the long-wave radiation characteristics of the atmosphere, allowing more urban heat to be stored and increasing the intensity of the urban heat island by an average of 0.8-1.2 °C. This is mainly due to the fact that particulate matter can form a "cap effect" over the city, which slows down the rate of heat dissipation from the city to the upper atmosphere at night.

When PM2.5 concentration exceeds the critical threshold (about 200$\mu g/m^3$), the radiative scattering effect of particulate matter gradually becomes dominant, weakening the solar radiation reaching the urban surface and thereby reducing the urban heat island effect. There is a bidirectional regulatory mechanism between the two. This leads to different seasonal and diurnal variations in the urban thermal environment depending on the content of particulate matter. In addition, among the underlying properties of the city, building density and green space ratio have a very significant impact on the interaction between PM2.5 and the heat island effect, among which areas with high building density are more vulnerable to the impact of PM2.5 [11–14].

5.2. Policy recommendations

In light of the research results on the interaction between atmospheric particulate matter and the urban heat island effect, the following policy recommendations are made: Urban planning should take ecological infrastructure as the core strategy, optimize urban air flow organization through the construction of a complete ventilation corridor system, and promote the diffusion of pollutants. Adding green buffer zones around high-density building areas can effectively reduce the intensity of the local heat island while intercepting PM2.5 particles. Urban green space system planning needs to shift from single-function to multi-functional complex, giving priority to plant species with high PM2.5 adsorption capacity, such as broad-leaved evergreen tree species, and adopting multi-level vegetation structures to improve ecological service efficiency per unit area.

Promote the coordinated adjustment of the urban energy structure and transportation system. In terms of energy, promote clean substitution and focus on controlling coal use during the Winter season; In terms of transportation, vigorously promote electric vehicles and shared mobility, improve pedestrian and bicycle transportation systems, and reduce vehicle exhaust emissions; Enhance roof greening and vertical greening in the construction sector and promote the use of high-reflectivity materials to reduce building energy consumption and mitigate the urban heat island effect.

Establish a cross-regional collaborative governance mechanism, incorporate PM2.5 pollution control and the mitigation of the heat island effect into the same governance system, and integrate them into the assessment index system; Based on the digital monitoring platform, integrate data on elements such as meteorology, environment and urban form, and implement differentiated and refined management; Integrate the planning, construction, maintenance and management of ecological infrastructure into the long-term urban management mechanism, so that it can play its due role in regulating the ecological environment in all seasons, thereby truly achieving the goal of improving environmental quality and increasing the livability of the city [15].

Disclosure statement

The author declares no conflict of interest.

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