Postprint: Study on the Interaction between Urban Heat Island Effect and Pollution Island Effect in Xi’ an

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Abstract

The Surface/Canopy Urban Heat Island (SUHI/CUHI) effects and the Atmospheric/Near-surface Urban Pollution Island (AUPI/NSUPI) effects interact and mutually influence each other, posing significant threats to urban ecological and environmental security. Utilizing land surface temperature, air temperature, aerosol optical depth, and PM2.5 data, and based on spatial coupling analysis and attribution quantitative estimation methods, this study investigates the relationships between AUPI’ s impact on SUHI under radiative effects and CUHI’ s impact on NSUPI under turbulent mixing in Xi’ an from 2003 to 2020. The results indicate that: (1) Due to diurnal differences in aerosol radiative effects during winter, the SUHI intensity is less than -0.2 K during winter daytime, with strong aerosol radiative cooling effects resulting in low urban land surface temperatures that make urban areas colder than rural areas; whereas at night, the SUHI intensity exceeds 2.2 K, with enhanced aerosol longwave radiative effects, and pollutant particles suspended in urban space act as an “insulating layer” for the city. (2) When CUHI continuously intensifies during spring and summer, enhanced turbulent mixing facilitates the diffusion of near-surface pollutant particles, leading to reductions in both urban PM2.5 concentration and NSUPI intensity; during autumn and winter, atmospheric temperature inversion layers hinder the upward turbulent air motion driven by CUHI effects, causing PM2.5 particles to accumulate and build up in the near-surface region, thereby strengthening NSUPI. (3) Attribution analysis of haze’ s contribution to the surface heat island reveals that nighttime aerosol optical depth (AOD) is significantly negatively correlated with SUHI, with correlation coefficients of -0.431 and -0.386, respectively; haze primarily exerts a radiative cooling effect on the nighttime surface thermal environment, while its weakening or enhancing effect on the local climate of the urban heat island is mainly attributed to the positive or negative difference in AOD between urban and rural areas. The variations in urban heat island effects and pollution

island effects are inseparable; therefore, promoting comprehensive research on urban climate and urban pollution is of great significance for constructing a green urban ecological environment.

Full Text

Exploring the Interaction between the Heat Island Effect and Pollution Island Effect in Xi’ an, China

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Abstract: Surface/Canopy Urban Heat Island (SUHI/CUHI) effect and Atmospheric/Near-surface Urban Pollution Island (AUPI/NSUPI) effect interact and influence each other, posing a significant threat to urban ecological environment security. Using land surface temperature, air temperature, aerosol optical depth (AOD), and PM2.5 data, this study employs spatial coupling analysis and attribution quantitative estimation methods to investigate the interactions between AUPI and SUHI under radiation effects and between CUHI and NSUPI under turbulent mixing in Xi’ an from 2003 to 2020. The results indicate: (1) Due to diurnal differences in aerosol radiation effects during winter, winter daytime SUHI intensity is less than 0.2 K. The strong aerosol radiation cooling effect leads to lower ground temperatures in urban areas, making cities cooler than rural areas. At night, when SUHI intensity exceeds 2.2 K, the long-wave radiation effect of aerosols is enhanced, and pollutant particles suspended in urban space form an “insulation layer” for the city. (2) Significant CUHI in spring and summer enhances atmospheric turbulent mixing, causing diffusion of near-surface pollutant particles in urban areas, with corresponding decreases in PM2.5 concentration and NSUPI intensity. In autumn and winter, the atmospheric inversion layer obstructs upward turbulent air movement driven by the CUHI effect, leading to aggregation and accumulation of PM2.5 particles in near-surface urban areas and enhanced NSUPI. (3) Attribution analysis reveals that the contribution of haze to surface heat islands shows significant negative correlations between nighttime AOD (both urban and rural) and SUHI, with correlation coefficients of -0.386 and -0.386, respectively. This suggests that the primary radiation effect of haze on the nighttime surface thermal environment is cooling. The weakening or strengthening effect of haze on the local climate of urban heat islands is mainly attributed to the positive or negative difference in AOD between urban and rural areas. The UHI and UPI effects are inseparable, making comprehensive

research on urban climate and pollution crucial for constructing green urban ecological environments.

Keywords: Xi’an; surface/canopy urban heat island; atmospheric/near-surface pollution island; spatial coupling analysis; attribution method

1 Introduction

Urban Heat Island (UHI) effect refers to the phenomenon where urban areas exhibit higher temperatures than surrounding rural areas, caused by human impacts on the Earth’ s environment [1]. Differences in surface radiative thermal properties and solar radiation absorption between urban and rural areas create the UHI phenomenon [2]. Under current global warming, the global average daytime surface UHI intensity of 0.85°C is increasing at approximately 0.03$±$0.02°C annually [3]. UHI intensity (UHII) can be characterized using both surface temperature and air temperature parameters, resulting in two forms: Surface Urban Heat Island (SUHI) and Canopy Urban Heat Island (CUHI). The CUHI effect is defined as the air temperature difference between urban areas and surrounding environments, measured through meteorological stations or mobile observations [4].

Urban Pollution Island (UPI) refers to the phenomenon where pollutant concentrations differ between urban and rural areas due to urban characteristics and activities [5], with Urban Pollution Island Intensity (UPII) defined by the difference in pollution levels between urban and rural regions [6]. Air pollution levels are commonly characterized using Aerosol Optical Depth (AOD) and surface fine particulate matter (PM2.5) concentration. AOD represents the vertical integration of the extinction coefficient of atmospheric aerosol particles, describing the radiative effect of solar radiation attenuation caused by aerosol scattering and absorption, and serves as a proxy indicator for particulate concentration and air pollution degree in the atmospheric column. The primary sources of near-surface PM2.5 are fossil fuel combustion and pollutants emitted from production and daily activities [7]. These fine particles, such as PM2.5, are primary pollutants affecting air quality and represent an important indicator for atmospheric quality monitoring and assessment [8].

Based on these definitions, urban pollution can be divided into Atmospheric Urban Pollution Island (AUPI) and Near-surface Urban Pollution Island (NSUPI). Urban pollution islands exist within the atmospheric dome and participate in surface aerodynamic, turbulent motion, and other dynamic processes within the urban atmospheric dome.

Research indicates that aerosol pollution is one of the controlling factors for nighttime UHI [9]. Conversely, the UHI effect can enhance turbulent mixing intensity, increase urban boundary layer height, and facilitate upward diffusion of aerosol particles [10], while urban cool islands reduce turbulent mixing rates and mixing layer height [11], leading to increased near-surface pollutant accumulation. For example, Zhong et al. [12] found a significant two-way feedback mechanism between deteriorating weather conditions and cumulative aerosol pollution during cold, heavily polluted periods in Xi’ an. Additionally, the mutual influence between UHI and UPI exhibits significant seasonal effects. Ngarambe et al. [13] found statistically significant interactions between air pollution concentration and UHI in Seoul, Korea, with the strongest correlation between pollutant particle concentration and UHI in autumn and winter, and weaker correlation in spring and summer. Li et al. [14] also noted that seasonal variations in air pollution are a reason for the seasonal impact of the UHI phenomenon.

Since the implementation of the Western Development Strategy in 2000, northwestern Chinese cities have experienced surges in population, motor vehicles, and industrial pollution emissions, warranting further analysis of potential interactions between UHI and air pollution in this region. Xi’ an, located in the central Guanzhong Basin, experiences pollutant accumulation due to its trumpet-shaped topography [15], facing unprecedented pressures from thermal and air pollution. Existing studies on UHI and UPI effects typically use single parameters to characterize these effects, rarely employing multiple parameters to deeply explore the relationship between SUHI/CUHI and AUPI/NSUPI from both radiative transfer and turbulent mixing perspectives. Moreover, due to uncertainties in aerosol radiative effects, the interaction between UHI and UPI varies significantly across different urban regions and background climates. Therefore, the interaction mechanism between SUHI/CUHI and AUPI/NSUPI in Xi’ an requires in-depth analysis. This study investigates the interaction and mutual influence between SUHI/CUHI and AUPI/NSUPI effects in Xi’ an at seasonal scales from 2003 to 2020.

1.1 Study Area Overview

The study area encompasses Xi’ an city and its surrounding regions [Figure 1: see original paper], including Xincheng, Beilin, Lianhu, Yanta, and Weiyang districts in Xi’an; Weicheng, Qindu, Xingping, Jingyang, Liquan, Sanyuan counties in Xianyang; as well as Huyi, Chang’ an, Lantian, Baqiao, Lintong, Gaoling, and Yanliang districts in Xi’ an. Geographically located between 108°27 58 -109°19 18 E and 33°55 47 -34°40 39 N, the region features the Guanzhong Plain in its center at 350-700 m elevation, with elevations exceeding 750 m in both southern (Qinling Mountains) and northern (Loess Plateau) areas. The climate is warm temperate semi-humid continental monsoon with distinct seasons.

Land use data show eight categories: cultivated land, forest, grassland, water bodies, urban land, rural residential areas, other construction land, and unused land. Urban agglomerations were defined as urban areas, with a 25 km buffer generated outside urban boundaries [16]. Within this buffer, pixels with elevation differences >$±$100 m from urban areas, water pixels, other small urban land clusters, rural residential areas, and other construction land were excluded, with remaining areas defined as rural zones.

1.2 Data Sources and Processing

Land Surface Temperature Data: MODIS MYD11A2 data products were used with 1 km spatial resolution and 8-day temporal resolution. Surface temperature was calculated from LST_{Day}*{1km} and LST*{Night}_{1km} sub-datasets acquired by MODIS during 2003-2020 (orbit tiles h27v05 and h26v05). Data from NASA' s LAADS website (https://ladsweb.modaps.eosdis.nasa.gov/search/) were processed including sinusoidal projection conversion to WGS84, mosaicking, clipping, and quality control, all implemented through ENVI IDL and ARCPY batch processing tools.

Aerosol Product Data: MCD19A2 dataset from MODIS Terra/Aqua combined Multi-Angle Implementation of Atmospheric Correction (MAIAC) provides 1 km AOD data. Cloud removal, reprojection, mosaicking, and clipping were completed using the Google Earth Engine cloud platform.

Air Temperature Data: The China 1 km resolution monthly mean air temperature dataset from the National Earth System Science Data Center was used. Based on monthly data from Chinese meteorological stations and using DEM data as covariates, the dataset was generated via spline interpolation with threshold validation against station observations in NetCDF format.

PM2.5 Concentration Data: The China High Air Pollutants dataset from the University of Maryland Atmospheric Environment Remote Sensing team [17] provides 1 km resolution data (https://weijing-rs.github.io/product.html). Integrating MODIS AOD data with ground observations, satellite data, reanalysis, and model simulations, this dataset reconstructs high-resolution, high-quality PM2.5 data for mainland China (ChinaHighPM2.5).

Land Use Data: Obtained from the Geographic Monitoring Cloud Platform (http://www.dsac.cn) with three classification levels. Average classification accuracy for cultivated land and urban/industrial/residential land exceeds 95%, meeting research requirements.

1.3 Research Methods

Calculation of UHII. SUHII and CUHII were calculated using land surface temperature and air temperature data, respectively. The specific calculation method for MODIS MYD11A2 data is as follows [18]:

For each pixel i in urban areas, let Tcity represent daytime surface temperature, nighttime surface temperature, or air temperature; Trural represent the corresponding mean values in rural areas. Then:

$$UHII_i = T_{city} - \bar{T}_{rural}$$

$$UHII = \frac{1}{n}\sum_{i=1}^{N_{city}} UHII_i$$

where n is the number of pixels. SUHIIday, SUHInight, and CUHII represent overall daytime surface UHI intensity, nighttime surface UHI intensity, and canopy UHI intensity, respectively.

Calculation of UPII. AUPII and NSUPII represent urban-rural differences in AOD and near-surface PM2.5 concentration, respectively. For each urban pixel i:

$$UPII_i = N_{city} - \bar{N}_{rural}$$

$$UPII = \frac{1}{n}\sum_{i=1}^{N_{city}} UPII_i$$

where Ncity represents AOD or PM2.5 concentration at pixel i, and Nrural represents the mean value in rural areas.

Spatial Coupling Analysis. Coupling coordination degree M between SUHI/CUHI and AUPI/NSUPI was calculated to analyze interaction intensity [19]. The coupling coordination degree comprises coupling degree C and coordination degree T:

$$M = \sqrt{C \times T}$$

$$C = 2\sqrt{\frac{A \times B}{(A+B)^2}}$$

$$T = aA + bB$$

where A and B represent standardized SUHIIday/SUHIInight/CUHII and AUPII/NSUPII, respectively; a and b are parameters (both set to 0.5 based on previous studies), indicating equal importance of temperature and PM2.5.

Attribution Method for Quantifying Haze Impact on SUHI. Following Li et al. [20], surface energy balance was used to calculate contributions of various factors (radiation, sensible heat convection efficiency, evaporation, heat storage, and anthropogenic heat) to surface temperature changes. Haze pollution is represented by AOD data, and its contribution to SUHI intensity change is calculated as:

$$\Delta SUHI_{AOD} = \text{Sen} \times \Delta\text{AOD}$$

where Sen represents local climate sensitivity ($0.2\ \text{K} \cdot {\tau_0}^2$); f is energy allocation coefficient (3.0$±$1.8 for humid regions like Xi' an); $\lambda_0 = 1/4\sigma$; and ΔAOD is the urban-rural AOD difference.

2 Results and Analysis

2.1 Annual and Seasonal Variation Characteristics of UHI and UPI

Temporal Trends. SUHIIday decreased annually at a rate of $0.038\ \text{K} \cdot \text{a}^{-1}$, while SUHIInight increased at $0.061\ \text{K} \cdot \text{a}^{-1}$. Xi' an' s daytime surface UHI effect gradually weakened from 2003–2020, with urban and rural surface temperatures converging, whereas nighttime surface UHI intensified, making urban areas increasingly warmer than rural areas—consistent with Liang et al. [21]. CUHII remained stable with minimal annual variation ($0.007\ \text{K} \cdot \text{a}^{-1}$). AUPII decreased at $0.223\ \ \text{g} \cdot \text{m}^{-3} \cdot \text{a}^{-1}$, and NSUPII decreased at $1.394\ \ \text{g} \cdot \text{m}^{-3} \cdot \text{a}^{-1}$, indicating narrowing urban-rural gaps in atmospheric and near-surface pollution and weakening AUPI and NSUPI effects.

Seasonal Variations. SUHIIday showed annual mean of 1.66 K, while SUHIInight exhibited stronger nighttime effects (3.078 K). Nighttime UHI is primarily driven by release of daytime solar radiation energy stored in urban surfaces and anthropogenic heat emissions [22], with greater heat storage and more heat sources in central urban areas creating pronounced nighttime UHI. Significant diurnal differences in surface UHI occurred in winter, with intensities of -0.767 K (daytime cold island) and 3.38 K (nighttime strong UHI). This daytime cold island and nighttime strong UHI phenomenon likely results from combined effects of surface thermal radiation, anthropogenic heat, and atmospheric thermal radiation under air pollution. CUHII annual mean (0.723 K) was significantly smaller than SUHIIday and SUHIInight, as differences in urban-rural evapotranspiration cooling create smaller air temperature differences than surface temperature differences [23].

AUPII seasonal means were: spring (0.7-1.3 K), summer (0.8 K), autumn (0.7 K), and winter (0.5 K), with stronger effects in summer/autumn than spring/winter. Natural factors include: (1) Higher atmospheric humidity in summer/autumn in Xi' an enlarges hygroscopic aerosol particle diameters, increasing atmospheric extinction coefficients and aerosol formation capacity; (2) Enhanced summer solar radiation and vigorous atmospheric vertical transport strengthen aerosol vertical transport, increasing atmospheric aerosol content [24]. Spring/winter feature dry-cold weather, strong winds, and inversion layers that prevent high-altitude pollutant accumulation [25].

NSUPII showed strongest intensity in winter ($3.015\ \ \text{g} \cdot \text{m}^{-3}$), followed by spring/autumn (2.274 and $1.666\ \ \text{g} \cdot \text{m}^{-3}$), and weakest in summer (-1.260 g ·

m^{-3}). Seasonal NSUPI differences are determined by urban-rural PM2.5 differences, with vehicle emissions being a continuous annual source and seasonal variations from coal burning and other factors causing seasonal differences. During winter heating seasons, urban coal and biomass burning increase urban-rural PM2.5 concentration gaps. Spring dust storms and autumn straw burning create secondary peaks [26]. Summer’ s negative NSUPII results from urban thermal effects enhancing air turbulence and diffusion.

2.2 Spatial Coupling Analysis of UHI and UPI

SUHIIday and AUPII Coupling. Coupling coordination degree M values indicate interaction strength. Figure 3 shows spatial coupling distributions across seasons. Table 2 presents mean coupling values for urban and rural areas and their differences. Seasonally, coupling is weaker in spring but similar and stronger in summer, autumn, and winter. Spatially, nighttime coupling distributions oppose daytime patterns, with high-value zones concentrated in central urban districts (Lianhu, Xincheng, Beilin, Yanta), decreasing with distance from city center. Nighttime urban-rural coupling differences exceed daytime values, especially in autumn (difference = 0.15), indicating stronger aerosol radiative effects in urban areas under stable meteorological conditions, potentially leading to mutual enhancement.

SUHIInight and AUPII Coupling. Figure 4 shows spatial coupling coordination distributions. Seasonally, autumn and winter coupling exceeds spring and summer, indicating stronger surface temperature-haze interactions in cold seasons. Spatially, high-coupling zones in spring, summer, and autumn show northeast-southwest trends, while winter exhibits higher coupling in eastern (Lintong, Gaoling, Baqiao), northern (Weiyang), and southern Chang’ an districts than central urban areas. Urban-rural coupling differences are positive in spring, summer, and autumn (highest in summer at 0.08) but negative in winter (-0.03), indicating opposite interaction mechanisms in winter daytime.

CUHII and NSUPII Coupling. Figure 5 shows spatial coupling coordination distributions. NSUPI coupling is higher than AUPI coupling across all seasons, with closer ties and stronger coordination. Seasonally, summer and autumn coupling exceeds spring and winter. Spatially, summer’ s widespread high-coupling regions result in minimal urban-rural differences (0.01), indicating weaker mutual feedback than other seasons.

2.3 Effects under Radiation and Turbulence

2.3.1 Radiation Effect Impact on SUHI. Figure 6 shows the relationship between AUPII and SUHII. Spring and autumn SUHI characteristics are complex due to meteorological interference. In summer, SUHII and AUPII show similar trends—seasonal effects. Winter SUHI variation is primarily driven by aerosol radiative effects: daytime aerosol radiative cooling reduces surface solar radiation, causing urban surface cooling [27]; nighttime aerosol long-wave radiation acts as an urban "insulation layer," enhancing warming [28].

2.3.2 Turbulence Effect Impact on NSUPI. Figure 7 shows the relationship between CUHII and NSUPII. When CUHII is 0.7–1.3 K in spring, both CUHII and NSUPII increase (by 0.6 K and 3.655 $g \cdot m^{-3}$, respectively, in summer). This results from simultaneous increases in traffic "pollution emissions" (vehicle exhaust, dust) and "heat emissions" raising urban PM2.5 concentrations. However, when CUHII exceeds 0.8 K, NSUPII decreases in spring and summer (by 0.7 K and 4.344 $g \cdot m^{-3}$) because enhanced turbulence from strong heat islands diffuses near-surface particulates [29].

In autumn and winter, when CUHII is below 0.5 K, NSUPII increases slowly (by 0.248 and 1.806 $g \cdot m^{-3}$). As CUHII exceeds 0.7 K, NSUPII continues increasing (by 5.473 $g \cdot m^{-3}$ in autumn). The high-temperature effect of urban canopy heat islands enhances NSUPII, opposite to spring/summer trends. Turbulent mixing from strong CUHII fails to reduce urban PM2.5 because inversion layers create "warm-above-cool-below" structures that suppress upward air movement [30]. Pollutant particles become trapped near the surface, gradually accumulating and increasing urban PM2.5 concentrations and urban-rural concentration differences, thereby strengthening NSUPII. Inversion also causes atmospheric pollutants to circulate counter-current to rural areas under wind action.

2.4 Quantitative Estimation of Haze Impact on SUHI

AOD and SUHI show significant negative correlations at night (correlation coefficients: -0.386 for urban AOD, -0.386 for rural AOD), indicating haze's primary nighttime radiation effect is cooling. Daytime correlations are insignificant (coefficients < 0.1) due to aerosols both scattering solar radiation and trapping long-wave radiation, creating complex impacts.

Attribution analysis shows haze's contribution to SUHI is negative, particularly in 2013 (-0.235 K) and 2016 (-0.179 K). The weakening or strengthening effect depends on urban-rural AOD differences. When rural AOD exceeds urban AOD, rural cooling exceeds urban cooling, relatively strengthening the UHI effect (by 0.039 K). When urban and rural AOD differences are small (-0.05 to 0.05 K), haze impact on UHI becomes negligible.

3 Discussion

Analysis of long-term MODIS land surface temperature, MYD04 aerosol data, air temperature datasets, and ChinaHighPM2.5 data reveals seasonal-scale interactions between SUHI/CUHI and AUPI/NSUPI in Xi' an. The study shows complex aerosol effects on SUHI in spring, summer, and autumn, while winter aerosol radiative effects are clear: daytime cooling and nighttime warming, weakening daytime UHI and enhancing nighttime UHI. This occurs because local circulation transports pollutants and changes atmospheric humidity during rainfall and wind events, altering aerosol radiative effects and local circulation. For canopy heat island turbulence effects, northwestern valley cities like Lanzhou share similar mechanisms with Xi' an—winter strong inversions inhibit turbulence [31]. However, complex boundary layer structures and local circulation create intricate relationships between UHI and aerosol pollution. In southern and coastal cities with high humidity and sea breezes, local circulation involves combined effects of urban winds, sea breezes, and land breezes requiring case-specific analysis. Urban pollution heat island circulation, horizontal transport, and vertical mixing are influenced by dominant wind directions and topography.

Limitations include the long-term seasonal perspective ignoring specific local climate and circulation impacts. Future research should examine winter heavy haze episodes with detailed meteorological and radiation data to explore AOD-SUHI mechanisms. Precise relationships between pollutant concentrations and UHI intensity require consideration of terrain, meteorology, and anthropogenic emissions.

4 Conclusions

This study investigated interactions between SUHI/CUHI and AUPI/NSUPI in Xi' an from 2003-2020, revealing:

1. **Temporal Trends:** SUHIIday decreased at 0.038 $K \cdot a^{-1}$ while SUHIInight increased at 0.061 $K \cdot a^{-1}$, with stronger nighttime (3.078 K) than daytime (1.66 K) effects. CUHII remained stable (0.723 K). AUPII and NSUPII decreased at 0.223 and 1.394 $g \cdot m^{-3} \cdot a^{-1}$, respectively, indicating weakening pollution island effects.
2. **Spatial Coupling:** SUHIIday-AUPII coupling coordination exceeded 0.5 across most regions, with urban-rural differences positive in spring, summer, and autumn but negative in winter. Nighttime urban-rural coupling differences were positive across all seasons. SUHIInight-AUPII coupling was stronger in autumn/winter. NSUPI showed higher coupling than AUPI, with summer/autumn coupling exceeding spring/winter.
3. **Radiation Effects:** Winter SUHI variation was driven by aerosol radiative effects—daytime cooling (-0.2 K) and nighttime warming (2.2 K). Spring/autumn effects were complex due to meteorological interference. Summer SUHII and AUPII trends aligned due to seasonal factors.
4. **Turbulence Effects:** Spring/summer CUHII enhancement (0.7-1.3 K) increased turbulent mixing, reducing NSUPII. Autumn/winter inversion layers obstructed upward transport, causing PM2.5 accumulation and NSUPII enhancement.
5. **Attribution:** Nighttime AOD-SUHI correlations were significantly negative (-0.386), showing haze' s cooling effect. Haze contributions to SUHI were negative, especially in 2013 (-0.235 K) and 2016 (-0.179 K). Effects depended on urban-rural AOD differences, with rural AOD > urban AOD strengthening UHI by 0.039 K.

Comprehensive study of urban climate and pollution interactions is essential for green urban ecological environment construction.

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