

Urbanization-associated summer warming and temperature–moisture changes in the Beijing–Tianjin–Hebei region

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Short Report

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Abstract

Summer temperature changes are closely linked to surface thermal conditions and atmospheric moisture availability, but their coupling characteristics under specific regional climate backgrounds remain insufficiently understood. This study investigates summer temperature and moisture variations in the Beijing–Tianjin–Hebei (BTH) region during 1981–2025 using ERA5 reanalysis data and Global Human Settlement Layer (GHSL) built-up fraction data. Trends in maximum temperature ($T_{\max}$), minimum temperature ($T_{\min}$), diurnal temperature range (DTR), and dew-point temperature (T_d) were analyzed, and their relationships with continuous urbanization intensity were examined. Results show that the BTH region experienced significant summer warming, with $T_{\max}$ exhibiting a stronger increasing trend than $T_{\min}$. Both $T_{\max}$ and $T_{\min}$ trends were positively correlated with built-up fraction, whereas no significant relationship was found between DTR and urbanization intensity. In contrast, T_d trends showed a significant negative correlation with built-up fraction, indicating relatively weaker atmospheric moisture increases in highly urbanized areas. These results suggest that urbanization is associated with enhanced thermal conditions and altered temperature–moisture relationships in the moisture-sensitive BTH region. The findings highlight the importance of considering regional moisture conditions when assessing urbanization-related climate responses.

1 Introduction

Urbanization has become an important factor influencing regional climate by modifying land surface properties and land–atmosphere exchanges. The expansion of impervious surfaces changes surface radiation, heat storage, vegetation coverage, and moisture availability, thereby affecting surface energy partitioning and near-surface climate conditions (Oke 1982; Arnfield 2003). These processes contribute to urban thermal anomalies and modify local climate characteristics, but their impacts are strongly regulated by regional climate backgrounds and surface moisture conditions (Grimmond 2007; Manoli et al. 2019). Therefore, understanding urbanization-related climate responses requires consideration of both thermal conditions and atmospheric moisture variations.

Urbanization-induced changes in surface energy balance can influence temperature characteristics differently during daytime and nighttime. Previous studies have reported widespread asymmetric changes in maximum and minimum temperatures, with nighttime warming often exceeding daytime warming at global and continental scales (Karl et al. 1991; Easterling et al. 1997; Vose et al. 2005). However, the relative contributions of daytime and nighttime warming vary among regions due to differences in climate background, land surface characteristics, and moisture availability (Manoli et al. 2019). In regions where surface moisture availability limits evaporative cooling, changes in land surface properties associated with urbanization may alter the balance between sensible and latent heat fluxes, potentially affecting daytime thermal responses.

Atmospheric moisture provides an important perspective for investigating urbanization-related climate changes. Dew-point temperature (T_d) directly reflects atmospheric moisture conditions and is suitable

for examining long-term moisture variations. Urban expansion can influence atmospheric moisture through changes in vegetation, surface water availability, and land–atmosphere interactions (Grimm et al. 2008). However, temperature and moisture responses do not necessarily change synchronously because urbanization modifies both energy and water exchange processes. Investigating temperature–moisture coupling therefore provides additional information for understanding regional urban climate responses beyond temperature changes alone.

The Beijing–Tianjin–Hebei (BTH) region in northern China is an ideal area for examining these interactions. As one of the most rapidly urbanizing regions in China, BTH has experienced substantial expansion of built-up areas and significant land surface changes over recent decades (Ren et al. 2008). Previous studies have shown that urban thermal environments in China are influenced by both urbanization processes and regional climate conditions (Zhao et al. 2014). Meanwhile, BTH is characterized by warm summers and relatively limited surface moisture availability, suggesting that changes in land surface properties may influence thermal and moisture responses through altered surface energy partitioning.

Recent advances in environmental datasets provide new opportunities to investigate urbanization-related climate variations. The ERA5 reanalysis dataset provides long-term consistent atmospheric and land surface variables, while the Global Human Settlement Layer (GHSL) enables urbanization intensity to be quantified using continuous built-up fraction rather than simple urban–rural classifications (Hersbach et al. 2020; Pesaresi et al. 2016). These datasets allow investigation of climate responses along urbanization gradients and provide a basis for evaluating regional temperature–moisture interactions.

In this study, we investigate summer temperature and moisture changes in the BTH region during 1981–2025 using ERA5 reanalysis and GHSL built-up fraction data. The objectives are to (1) characterize spatial patterns of summer Tmax, Tmin, DTR, and Td trends; (2) examine relationships between urbanization intensity and thermal–moisture changes; and (3) explore temperature–moisture responses under different urbanization conditions. By focusing on a moisture-sensitive urbanized region, this study aims to improve understanding of how regional climate backgrounds regulate urbanization-associated summer climate responses. Unlike previous studies mainly focusing on urban warming intensity, this study examines whether thermal and moisture responses exhibit consistent changes along urbanization gradients under a moisture-sensitive regional climate background.

2 Data and Method

2.1 Study area

The Beijing–Tianjin–Hebei (BTH) region is located in northern China and represents one of the most rapidly urbanizing regions in the country (Fig. 1a). The region has experienced substantial expansion of built-up areas during recent decades, accompanied by significant changes in land surface

characteristics. BTH has a warm summer climate with relatively limited surface moisture availability, making it suitable for investigating interactions between urbanization, thermal conditions, and atmospheric moisture responses.

2.2 Data

Monthly maximum temperature (Tmax), minimum temperature (Tmin), and dew-point temperature (Td) from 1981 to 2025 were obtained from the fifth-generation European Centre for Medium-Range Weather Forecasts reanalysis dataset (ERA5) (Hersbach et al. 2020). ERA5 provides long-term and spatially consistent atmospheric and land surface variables, which have been widely used in regional climate studies.

Urbanization intensity was represented by built-up fraction data from the Global Human Settlement Layer (GHSL) (Pesaresi et al. 2016). The built-up fraction provides continuous information on the proportion of constructed surfaces and was used to characterize spatial variations in urbanization intensity rather than applying a simple urban–rural classification. The spatial distribution of built-up fraction and urbanization categories used in this study are shown in Fig. 1b–c.

The analysis focused on the warm season (June–August) because summer is the period when thermal conditions and surface moisture availability strongly interact in the BTH region. Seasonal mean values of Tmax, Tmin, and Td were calculated for each year, and the diurnal temperature range (DTR) was calculated as:

$$\text{DTR} = T_{\max} - T_{\min}$$

All climate variables were resampled to a common spatial resolution before spatial analysis.

2.3 Trend and statistical analysis

Temporal trends of summer Tmax, Tmin, DTR, and Td during 1981–2025 were estimated using linear regression. The significance of trends was evaluated using the Mann–Kendall test at the 95% confidence level. The slope of each trend was calculated to represent the rate of change over the study period.

To examine the relationship between urbanization intensity and climate responses, Pearson correlation coefficients were calculated between built-up fraction and the trends of Tmax, Tmin, DTR, and Td. Correlation analyses were conducted using grid cells within the BTH region to investigate spatial variations along continuous urbanization gradients.

3 Results

3.1 Spatial patterns of summer temperature and moisture trends

The BTH region experienced significant summer warming during 1981–2025, but the magnitude of warming varied spatially among different climate variables (Fig. 2). $T_{\max}$ showed widespread increasing trends across most of the region, with stronger warming occurring in highly urbanized areas, particularly around the Beijing–Tianjin–Hebei metropolitan core. $T_{\min}$ also exhibited significant increases over large parts of the region, indicating a consistent background warming during summer. However, the increasing rate of $T_{\max}$ was generally higher than that of $T_{\min}$, resulting in a weak decreasing tendency of DTR in some areas.

The stronger $T_{\max}$ increase suggests enhanced daytime thermal responses in the BTH region during summer. Previous studies have shown that nighttime warming often dominates at global and continental scales due to enhanced longwave radiation effects and increased atmospheric moisture (Karl et al. 1991; Easterling et al. 1997). However, regional warming characteristics can vary depending on climate background, land surface properties, and moisture availability (Vose et al. 2005). In the BTH region, relatively limited surface moisture availability during summer may constrain evaporative cooling, allowing changes in surface energy partitioning to influence daytime temperature responses.

T_d also showed increasing trends over most of the BTH region, indicating an overall increase in atmospheric moisture during summer (Fig. 2). However, the spatial pattern of T_d trends differed from temperature trends, suggesting that thermal and moisture responses were not spatially identical. Regions with stronger warming did not necessarily experience stronger increases in atmospheric moisture, implying that temperature–moisture coupling may vary along urbanization gradients.

These results indicate that summer climate changes in BTH involve both thermal and moisture variations. The spatial differences among $T_{\max}$, $T_{\min}$, and T_d highlight the importance of considering regional moisture conditions when interpreting urbanization-related warming characteristics.

3.2 Relationship between urbanization intensity and summer climate changes

To examine how urbanization intensity is associated with summer climate responses, the relationships between built-up fraction (BUFRAC) and climate trends were analyzed (Fig. 3). Significant positive correlations were found between BUFRAC and $T_{\max}$ trends, indicating that highly urbanized areas generally experienced stronger daytime warming. BUFRAC was also positively correlated with $T_{\min}$ trends, although the relationship was weaker than that for $T_{\max}$.

The stronger association between BUFRAC and $T_{\max}$ suggests that urbanization-related surface changes may influence daytime thermal conditions in BTH. Urban expansion modifies surface characteristics by increasing impervious surfaces and reducing vegetation coverage, which can affect surface energy partitioning and evaporative cooling processes (Arnfield 2003; Grimmond and Oke 1999). Under relatively limited moisture conditions, reduced evaporative cooling may contribute to enhanced sensible heat accumulation during daytime.

In contrast, no significant relationship was identified between BUFRAC and DTR trends, suggesting that urbanization intensity was not strongly associated with changes in the difference between daytime and nighttime warming rates. This indicates that urbanization-related warming responses involve coordinated changes in $T_{\max}$ and $T_{\min}$ rather than simply altering diurnal temperature differences.

A different response was observed for T_d . The correlation between BUFRAC and T_d trends was significantly negative, suggesting that highly urbanized areas experienced weaker increases in atmospheric moisture compared with less urbanized areas (Fig. 3). This pattern indicates that urbanization may influence temperature–moisture coupling by modifying surface water and energy exchange processes.

Overall, these results suggest that urbanization intensity is associated with both thermal and moisture variations during summer in BTH. The contrasting relationships between BUFRAC–temperature and BUFRAC– T_d highlight the importance of considering water availability when evaluating urbanization-related climate responses.

3.3 Possible mechanisms regulating urbanization-associated climate responses

The observed relationships between urbanization intensity and summer climate changes may be related to modifications in surface energy and moisture exchanges. Urban expansion increases impervious surfaces and reduces vegetation-related evapotranspiration, which may alter the partitioning between sensible and latent heat fluxes (Oke 1982; Arnfield 2003). Under moisture-sensitive conditions in BTH, such changes may contribute to stronger daytime thermal responses and weaker atmospheric moisture increases in highly urbanized areas.

However, the present study focuses on statistical relationships between urbanization intensity and climate trends. Detailed physical processes involving vegetation changes, soil moisture variations, and boundary-layer responses require further investigation using additional observations and modeling approaches.

4 Discussion

This study demonstrates that urbanization-associated summer climate responses in the Beijing–Tianjin–Hebei region are not limited to thermal changes but also involve modifications in temperature–moisture relationships. Although enhanced warming in highly urbanized areas is consistent with previous understanding of urban climate effects, the different responses of temperature and dew-point temperature indicate that urbanization impacts are strongly regulated by regional moisture conditions. In the moisture-sensitive BTH region, changes in surface characteristics associated with urban expansion may alter the balance between sensible and latent heat exchanges, leading to distinct thermal and moisture responses along urbanization gradients.

These findings highlight the importance of considering regional climate backgrounds when interpreting urbanization-related climate changes. Rather than representing a uniform urban warming signal, urbanization effects may vary among climate variables depending on local water availability and land–atmosphere interactions. Further investigations combining observations and modeling approaches are needed to better quantify the physical mechanisms linking urban development, surface processes, and atmospheric responses.

Declarations

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

H.S. conducted the research, performed the analysis, prepared the figures, and wrote the manuscript. C.M. contributed to data analysis and discussion of the results. L.L. supervised the research, reviewed and revised the manuscript, and provided scientific guidance. All authors read and approved the final manuscript.

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Figures

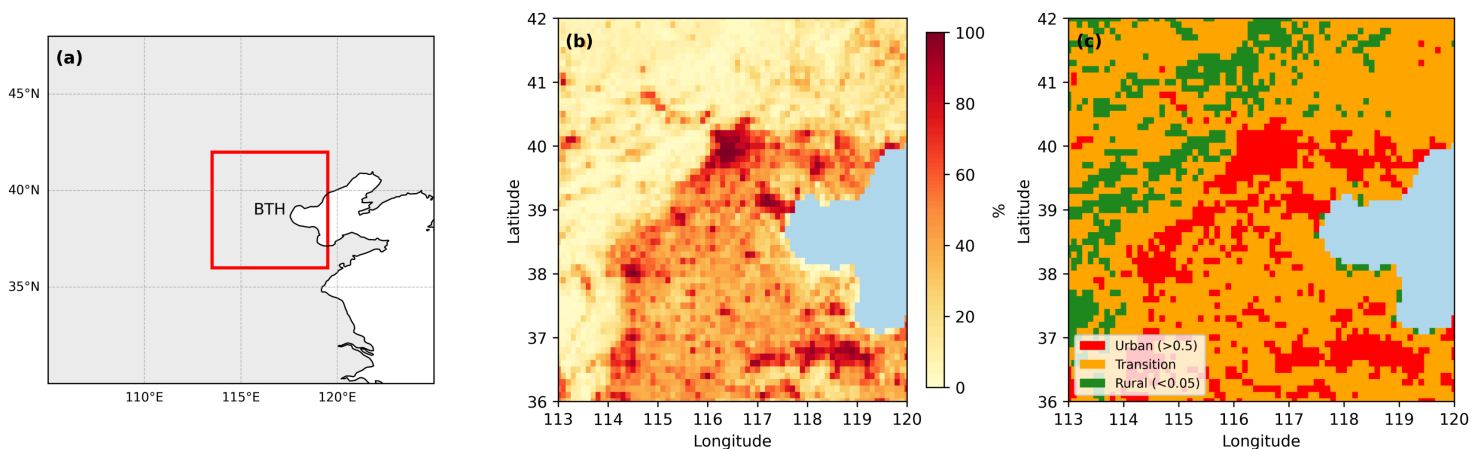


Figure 1

Location of the Beijing–Tianjin–Hebei region and spatial distribution of urbanization intensity. (a) Geographic location of the BTH region in North China; (b) spatial distribution of built-up fraction derived from GHSL data; (c) classification of urbanization intensity into urban, transition, and rural areas.

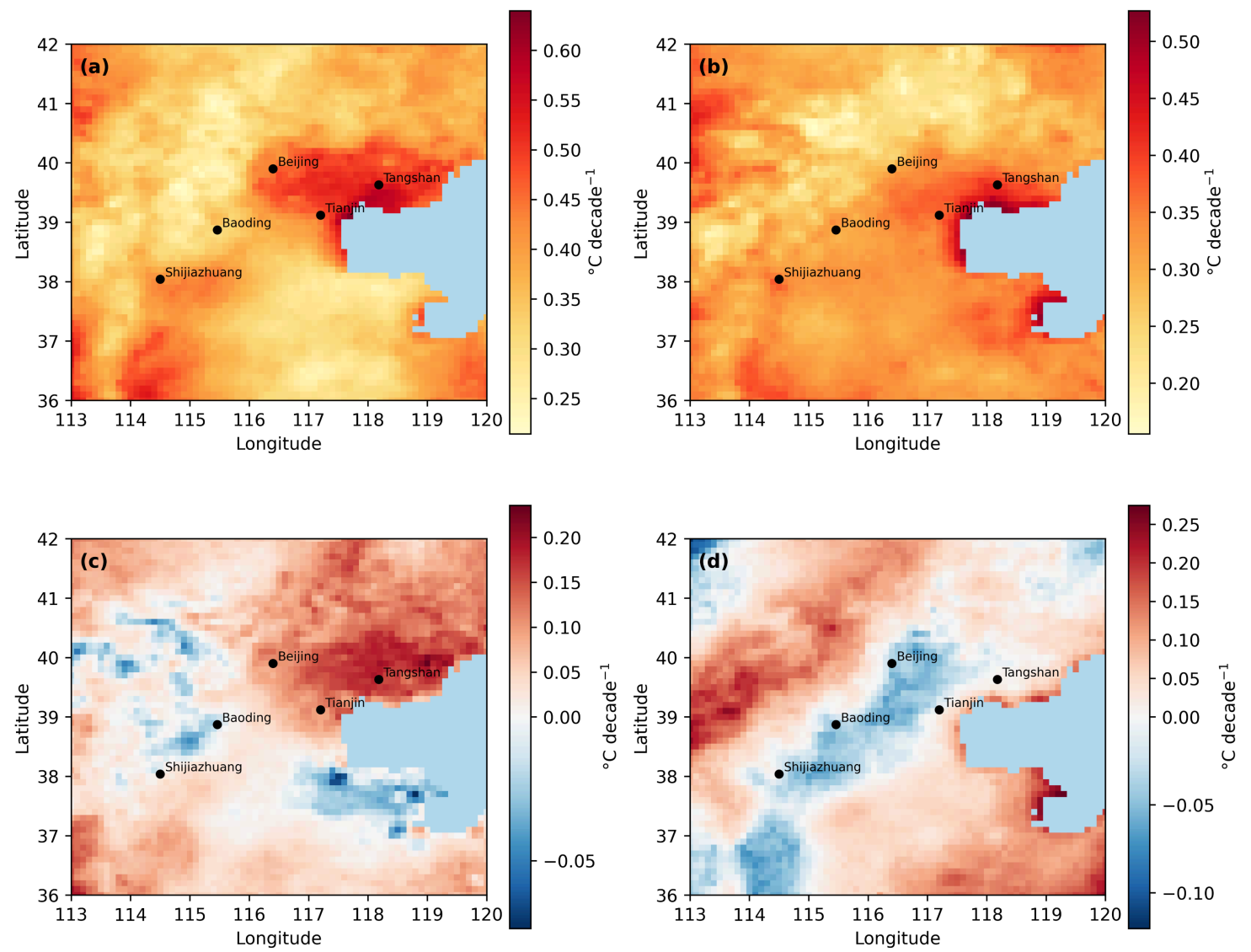


Figure 2

Spatial distributions of summer climate trends in the Beijing–Tianjin–Hebei region during 1981–2025. (a) Maximum temperature (Tmax) trend. (b) Minimum temperature (Tmin) trend. (c) Diurnal temperature range (DTR) trend. (d) Dew-point temperature (Td) trend. Trends are expressed as °C decade⁻¹.

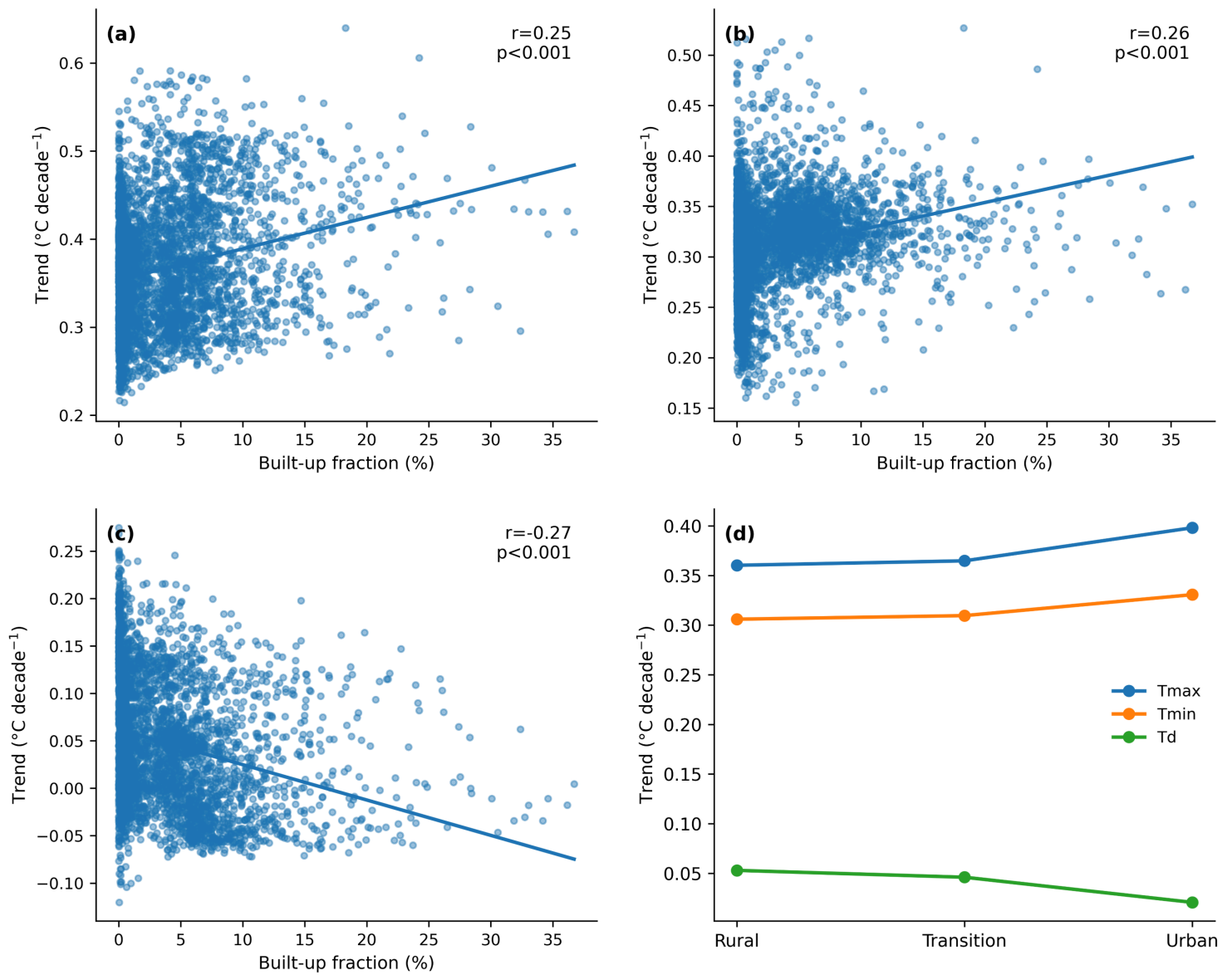


Figure 3

Relationships between urbanization intensity and summer climate trends in the Beijing–Tianjin–Hebei region. (a) Relationship between built-up fraction (BUFRAC) and T_{max} trends. (b) Relationship between BUFRAC and T_{min} trends. (c) Relationship between BUFRAC and T_d trends. (d) Comparison of climate trends among urban, transition, and rural areas.