Analysis of the Impact of Urbanization on Climate Change in Korean Cities

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Abstract

Understanding the rise in urban temperatures by distinguishing between the effects of urbanization and global warming is essential for preparing for future urban climate changes. The purpose of this study is to quantitatively analyze the impact of urbanization by calculating the urban bias of urban temperatures. To achieve this, we analyzed the pixels of nearby urban areas based on land use maps for 66 synoptic weather stations nationwide, categorizing them into metropolitan areas, small and medium-sized cities, and rural areas. Using the average temperature values measured at the weather stations from 1991 to 2020, we conducted a time series analysis of temperatures by city category and extracted urban bias and urban bias trends. The results of estimating the contribution of urbanization for each group indicated that the urban bias was positive for all, meaning that metropolitan areas have higher temperatures than small and medium-sized cities and rural areas. On the other hand, urban bias trends were negative under almost all conditions, indicating that the changes in annual and seasonal average temperatures in rural areas are greater than those in metropolitan and small and medium-sized cities.

Key words: climate change, urban temperature, contribution of urbanization, land use map

I. Introduction

The increase in the frequency and intensity of extreme weather events such as droughts, floods, heatwaves, and cold waves today has been found to be deeply related to climate change (Alexander, 2016). Among these, extreme heat caused by rising temperatures is one of the severe phenomena that significantly affects human health (Dosio et al., 2018). It is predicted that heat-related phenomena will continue to worsen in the future (Sherwood & Huber, 2010; Perkins et al., 2013).

The impact of warming is particularly intensified in urban areas. The frequency and damage of heatwaves in cities worldwide are increasing (Lee et al., 2020), and most major cities in the United States are warming at twice the rate of the global average (Stone, 2012). Urban areas experience the urban heat island effect, where temperatures are higher than surrounding areas due to factors such as land cover like asphalt roads, dense high-rise buildings, artificial heat from energy consumption, and land use changes (Kim et al., 2011; Hong et al., 2015). Urban population and area are expected to continue increasing in the future (Seto et al., 2012; Chapman et al., 2017), leading to enhanced urban heat islands, increased heat stress (Oleson et al., 2015), and health threats (Mora et al., 2017; Heaviside et al., 2017).

The changes in the urban thermal environment are an overlap of the urban heat island phenomenon, which trends toward warming, and climate change. Therefore, climate data from urbanized areas cannot be said to purely reflect climate change due to the influence of the urban heat island. To understand and prepare for changes in the urban thermal environment due to future climate change, it is necessary to analyze these changes separately by the impacts of urbanization and climate change. Quantifying the size of the urbanization impact can provide ideas for rational urban development that can adapt to climate change and monitor the long-term trends of ongoing climate change to predict the future.

Efforts to distinguish the impact of urbanization from the climate of urbanized areas have been varied (Choi et al., 2003; Chung et al., 2004; Hua et al., 2008; Fujibe, 2009; Adachi & Kimura, 2010; Wickham et al., 2013; Higashino & Stefan, 2014; Park et al., 2017; Lee et al., 2018). These studies identify the influence of urbanization and regional climate change on urban temperature changes by comparing time series trends of temperature changes based on weather data from urban and rural areas. Thus, setting criteria to distinguish between urban and rural areas is crucial to quantify urban bias.

Previous studies have mainly used demographics to distinguish between urban and rural areas, such as population density (Choi et al., 2003), population number (Hua et al., 2008; Park et al., 2017), or considering both population density and growth rate (Chung et al., 2004). Although urbanization patterns may vary depending on policies and environments, overall trends in population demographics and urban size change have been useful metrics to distinguish urban and rural areas. This is because past urbanization trends have been characterized by urban decentralization, settlement expansion, and suburban growth due to residential area expansion (Halbac-Cotoara-Zamfir et al., 2020). However, recent urban changes show population decline in urban areas, re-urbanization, recovery of central areas, and a slowdown in suburban growth (Kurek et al., 2015), making it difficult to adequately reflect recent urbanization using existing demographic criteria.

Therefore, this study aims to distinguish between urban and rural areas based on land cover types. Lee et al. (2018) concluded that among various urban variables such as population, nighttime light, and Normalized Difference Vegetation Index (NDVI), the variable most significantly affecting urban temperature change was NDVI, a variable related to urban land cover. Additionally, land cover identification using satellite images has been used as a useful method to distinguish between urban and rural areas in several previous studies (Klok et al., 2012; Wang et al., 2021; Guchhait et al., 2023). Thus, this study aims to quantify the impact of urbanization on long-term urban temperature trends by distinguishing between urban and rural areas based on land cover types and using the temperature differences between these areas.

II. Data and Analysis Methods

1. Temperature Measurement Data of the Korean Peninsula

Long-term observation data is essential for analyzing long-term temperature changes and the effects of urbanization in cities. For this study, we selected 66 out of 97 Automated Synoptic Observing System (ASOS) stations operated by the Korea Meteorological Administration, which have been providing data continuously from 1991 to the present without long-distance relocations. The selected ASOS stations are shown in Figure 1. Although some of these stations experienced nearby relocations or equipment changes, their impact on average temperature trends is considered minimal (Park & Choi, 2011). This study utilizes daily average temperature data from January 1, 1991, to December 31, 2020, measured at each selected ASOS station.

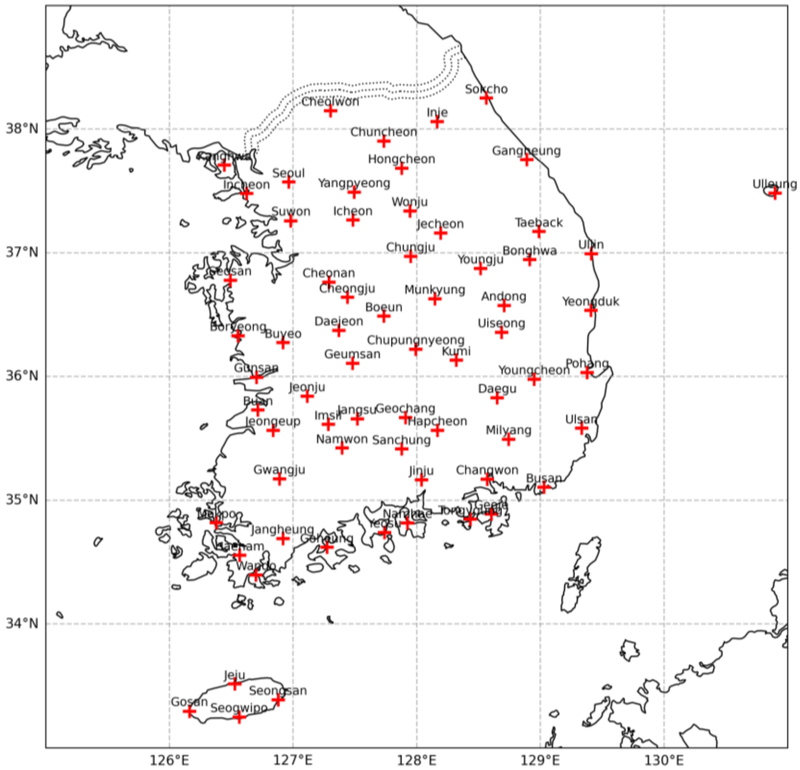

Figure 1. Station map

2. Method of Classifying Meteorological Observing Stations in Metropolis, Medium-sized City, and Rural

In this study, meteorological observing stations are classified into urban and rural categories based on the types of land cover around the stations. Since the measurements reflect the local climate around the stations rather than the broader city scale, the land cover types within a 10km radius of each station were used to distinguish between urban and rural areas.

Land cover maps were obtained from the Ministry of Environment's Environmental Spatial Information Service, using the most recent map from December 2022. These maps were converted into raster files with a resolution of 3" × 3". Pixels within a 10km radius of each station were extracted. The Sokcho station was excluded due to the unavailability of a land cover map.

The number of land cover pixels within the 10km radius was approximately 46,100. These pixels were categorized by land cover codes and summed accordingly. Built-up areas (residential, industrial, commercial, cultural facilities, transportation, and public facilities) were combined, and their pixel counts were calculated. The remaining areas were categorized separately by their land cover codes.

Based on the pixel counts of built-up areas, stations were classified into three types: more than 8000 pixels, between 2000 and 3000 pixels, and fewer than 1000 pixels. Stations in Jeju Island and Ulleung Island were excluded due to specific latitude and climate considerations. The results of this classification are shown in Table 1. The locations of the selected stations are spread across inland and coastal areas, minimizing geographical effects.

Table 1. Distinction between metropolis, medium-sized city, and rural areas

	Built-up area pixel	Station name
Metropolis	More than 8000	Seoul, Incheon, Gwangju, Suwon, Daejeon, Busan, Daegu, Ulsan, Cheongju, Jeonju
Medium-sized city	2000 or more but 3000 or less	Gangneung, Yeosu, Geoje, Chungju, Yeongcheon, Jeongeup, Jecheon, Andong, Seosan, Namwon, Milyang, Cheonan, Boryeong, Mungyeong, Buyeo
Rural	Less than 1000	Ganghwa, Cheolwon, Inje, Bonghwa, Yeongdeok, Jangsu, Uljin, Wando, Chupungnyeong, Uiseong, Sancheong, Hongcheon, Namhae, Hapcheon, Yeongju

3. Method for Estimating Urbanization Effect

To quantify the effect of urbanization on temperature trends, a common method used in previous studies is comparing the temperature trends between urban and rural areas (Lee & Kang, 1997; Chung & Yoon, 1999; Ha et al., 2004). This approach allows for a relatively simple and intuitive estimation of the urbanization effect. However, preliminary analysis in this study showed that the temperature trend in rural areas was greater than that in urban areas, making it difficult to apply this method. Therefore, we adopted the method used by Choi et al. (2003) and Park et al. (2017), which estimates the urbanization effect using the temperature difference between urban and rural areas (Eq. 1).

$$T_i' = T_i - \overline{T}_{u-r} + \left[(\Delta T_{u-r}/N)\left(i - i_{sy}\right)\right] \qquad (1)$$

Here, N is the number of years analyzed, i represents the years from 1991 to 2020, and i_{sy} is the initial study year, 1991. The urban bias magnitude ($\overline{T}_{u-r}$) was calculated by averaging the annual differences between metropolis, medium-sized city, and rural observing stations for the period 1991-2020. The urban bias trend (ΔT_{u-r}) was calculated by doubling the difference between the mean annual estimates for two 15-year periods: 1991-2005 and 2006-2020. Finally, the contribution of urbanization to temperature trends for each urban station group was estimated by comparing the original and adjusted trends using Eq. 1.

III. Results

1. Spatiotemporal Analysis of Temperature Changes on the Korean Peninsula

To analyze the temperature changes on the Korean Peninsula over the 30 years from 1990 to 2020, seasonal temperature anomalies were calculated. The anomalies were determined by the difference between the seasonal average temperatures over the 30-year period and the seasonal average temperatures from 1990 to 2020 (Figure 2). Overall, the temperature increased across all seasons, with varying rates of increase. The rates of increase were highest in summer, followed by spring, autumn, and winter. Specifically, the rate of increase in summer was 0.044 ± 0.015 °C/year ($p<.01$), in spring 0.041 ± 0.014 °C/year ($p<.01$), in autumn 0.032 ± 0.013 °C/year ($p<.05$), and in winter 0.011 ± 0.021 °C/year. All seasons showed considerable variability.

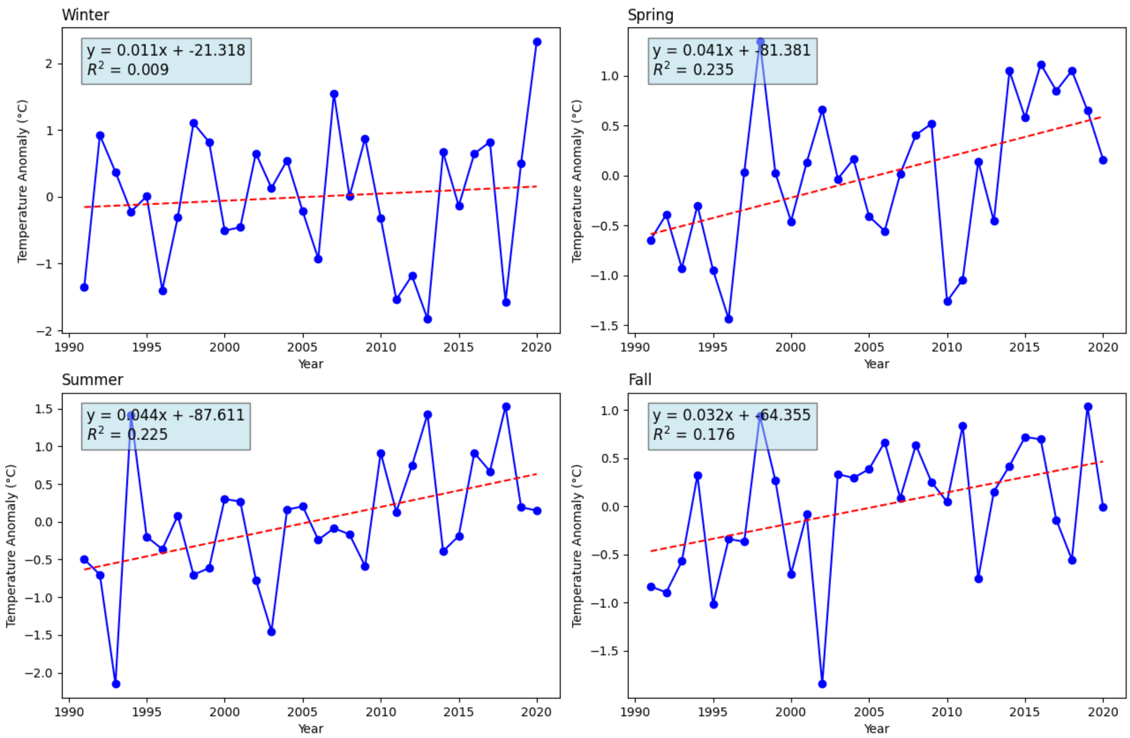

Figure 2. Seasonal average temperature anomalies from 1990 to 2020 in South Korea

To analyze the spatial distribution of temperature changes on the Korean Peninsula over the 30 years from 1990 to 2020, annual average temperature data from each meteorological observing station were divided into the recent 15 years (2006-2020) and the previous 15 years (1991-2005), and the differences were calculated (Figure 3). Most observing stations showed an overall increase in temperature in the recent 15 years compared to the previous 15 years.

Warming trends were observed in most regions, with strong warming trends in Hongcheon (1.04°C), Uiseong (0.92°C), Wonju (0.90°C), Cheongju (0.82°C), and Jangheung (0.80°C). A weak cooling trend was noted in Changwon (-0.27°C), while Mokpo (0.01°C) and Haenam (0.05°C) showed minimal temperature differences. These results indicate that the overall temperature on the Korean Peninsula has increased compared to the past, with no distinct trends related to geographical or spatial features such as inland, marine, or latitude differences (Park et al., 2017).

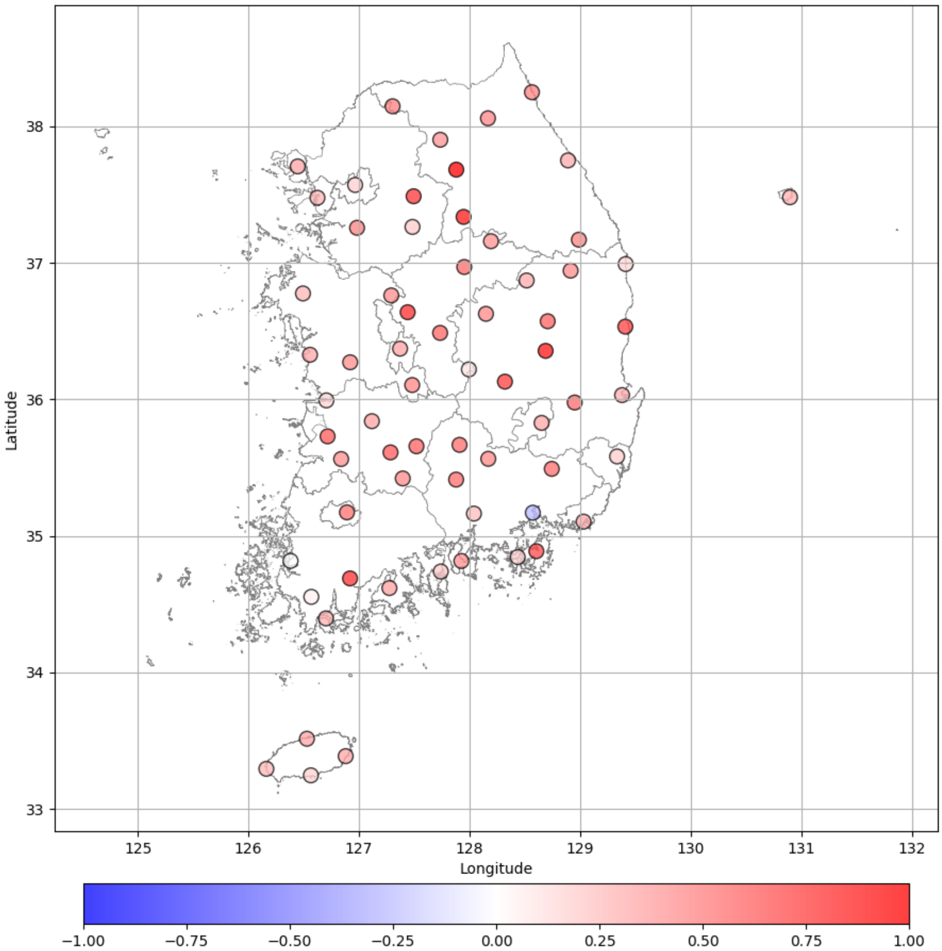

Figure 3. Differences in station-based daily average temperatures between the most recent 15 years (2006-2020) and the previous 15 years (1991-2005)

2. Analysis of the Urbanization Effect on Urban Temperature Changes

To analyze the temperature increase trends based on city classification, the annual and seasonal average temperatures of metropolis, medium-sized city, and rural meteorological observing station groups over the 30 years from 1991 to 2020 were graphed (Figure 4). The annual and seasonal average temperatures were highest in metropolises, followed by medium-sized cities and rural areas, showing similar patterns of temperature variation annually and seasonally.

Table 2 presents the trends of annual and seasonal temperature changes by city classification. All groups showed an increasing trend in both annual and seasonal temperatures. The increase was greatest in summer, followed by spring, autumn, and winter in all groups. Additionally, rural meteorological observing stations exhibited a larger increase trend in annual, summer, and spring temperatures compared to metropolises and medium-sized cities. The metropolis stations showed a smaller increase in both annual and seasonal average temperatures compared to other city classifications.

Table 2. Trends(□/year) in annual and seasonal average temperature time series by group

	Annual	Winter	Spring	Summer	Fall
Metropolis	0.029	0.008	0.039	0.041	0.034
Medium-sized city	0.032	0.014	0.040	0.043	0.035
Rural	0.033	0.010	0.045	0.048	0.033

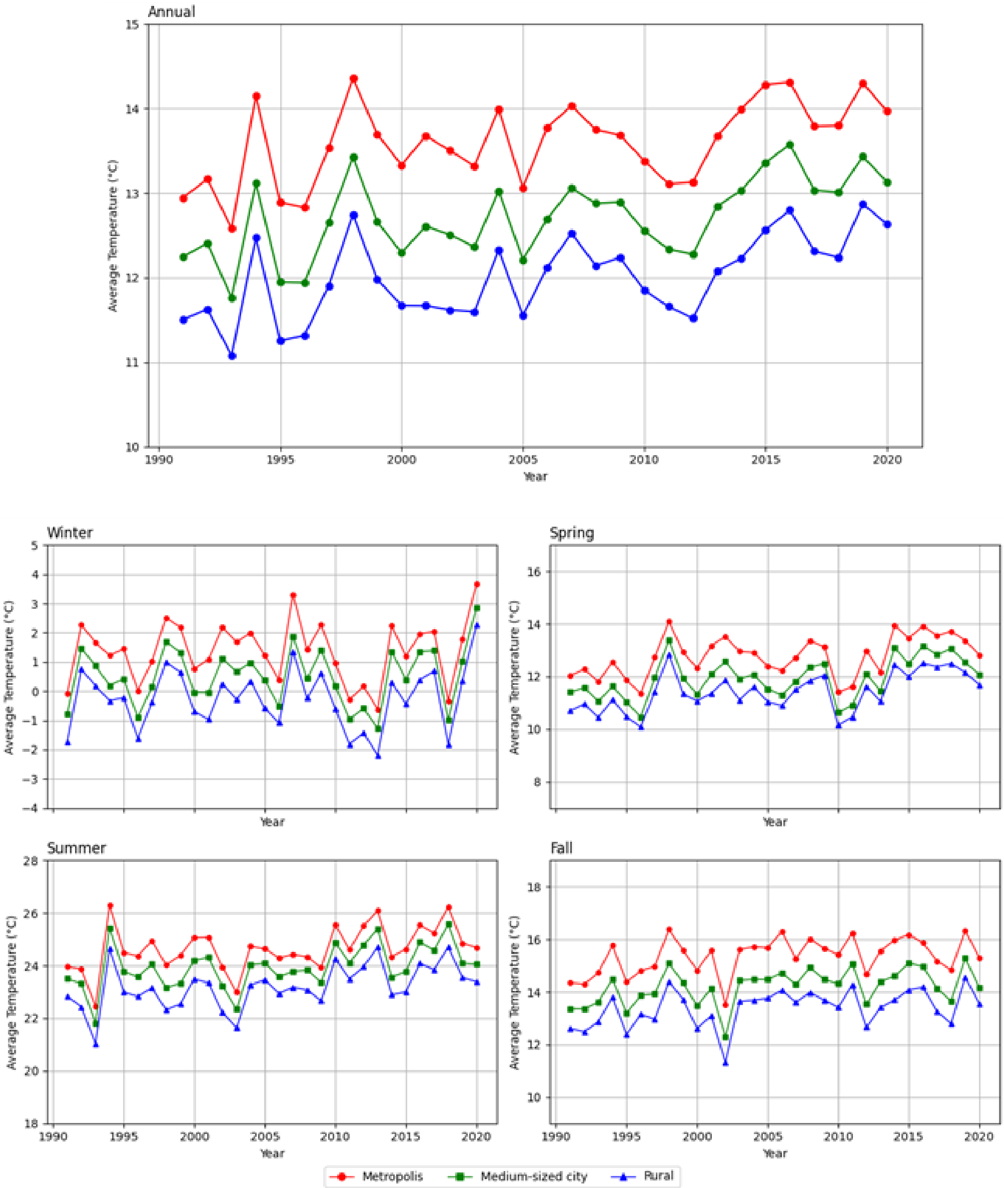

Figure 4. Annual, seasonal average temperature time series graphs for metropolis, medium-sized city and rural from 1991 to 2020

To analyze the temperature differences based on city classification, paired T-tests were used to compare the annual and seasonal average temperatures among various pairs of groups over the 30 years from 1990 to 2020 (Table 3). The annual average temperature at metropolis meteorological stations was 1.598°C higher than that in rural areas and 0.892°C higher than in medium-sized cities, with the differences being statistically significant.

Seasonally, metropolises were over 1.3°C warmer than rural areas, with the greatest difference in autumn at 1.977°C. Medium-sized cities were over 0.5°C warmer than rural areas in all seasons, with the largest difference in autumn at 0.815°C. These differences were used as estimates for the urban bias magnitude ($\overline{T}_{u-r}$) in the urbanization effect estimation.

Table 3. Results of paired T-test for annual and seasonal average temperatures by group

	Annual	Winter	Spring	Summer	Fall
Metropolis - Rural	1.598***	1.621***	1.356***	1.452***	1.977***
Medium-sized city - Rural	0.706***	0.757**	0.518*	0.748**	0.815***
Metropolis - Medium-sized city	0.892***	0.864**	0.838***	0.704**	1.162***

*p<.05, **p<.01, ***p<.001

Table 4 shows the estimates of the urban bias magnitude ($\overline{T}_{u-r}$) and trend (ΔT_{u-r}) for annual and seasonal average temperatures of meteorological station groups by city classification. $\overline{T}_{u-r}$ was greater than 0 in all conditions, indicating that annual and seasonal average temperatures of metropolis and medium-sized city station groups were higher than those of rural areas. The urban bias magnitude for seasonal temperatures was greatest in autumn for both metropolis and medium-sized city station groups, followed by winter, summer, and spring. Additionally, ΔT_{u-r} was less than 0 in almost all conditions, indicating a decreasing trend in urban bias over time. This suggests that the changes in annual and seasonal average temperatures in rural areas were greater than those in metropolis and medium-sized cities.

Table 4. Estimating average size($\overline{T}_{u-r}$) and trend(ΔT_{u-r}) to assess the impact of urbanization by group

		Annual	Winter	Spring	Summer	Fall
Metropolis	$\overline{T}_{u-r}$	1.598	1.621	1.356	1.452	1.977
	ΔT_{u-r}	-0.203	-0.135	-0.307	-0.338	-0.017
Medium-sized city	$\overline{T}_{u-r}$	0.706	0.757	0.518	0.748	0.815
	ΔT_{u-r}	-0.071	0.066	-0.192	-0.196	0.047

These results differ from the findings of Choi et al. (2003), who analyzed temperature by city classification over 32 years from 1968 to 1999. In their study, both $\overline{T}_{u-r}$ and ΔT_{u-r} were greater than 0. Additionally, the bias magnitude was largest in autumn, followed by spring, winter, and summer. These differences may be due to variations in the analysis period and the methods used for city classification.

In contrast to the findings of Choi et al. (2003) and Park et al. (2017), this study notably found ΔT_{u-r} to be less than 0 in almost all conditions. This can be explained as follows: first, urbanization tends to have a relatively weaker contribution to temperature increases once a certain stage of urbanization saturation is reached (Kug & Ahn, 2013). Therefore, the trend of urbanization in already developed metropolis and medium-sized city appears to be less than in rural area. The temperature changes due to urbanization, such as city expansion and infrastructure development during past industrialization periods, have already been reflected, making it difficult to sensitively capture additional urban warming due to recent urban changes.

Secondly, today's urban characteristics seem to contribute to this difference. Modern urban development considers the urban thermal environment, with infrastructures like city structures for air circulation, artificial ponds, lakes, and urban parks to partially mitigate the heating effect of solar radiation (Hart and Sailor, 2009; Lindén, 2011). Additionally, high-rise buildings and street trees in city centers create shade during the day, reducing heat storage (Roberts et al., 2006). Moreover, aerosols and pollutants in urban areas, which are more prevalent than in rural areas, can temporarily block solar radiation. These various factors are thought to influence urban temperatures.

Thirdly, the sensitivity of rural areas to urbanization appears to be greater. As mentioned earlier, metropolises show less change due to urbanization. In contrast, rural areas, being less urbanized, can be significantly affected by even small changes in land use.

Comparing the annual and seasonal average temperature increases from 1991 to 2020, the urbanization effect on temperature increase and the contribution of urbanization for metropolises and medium-sized cities were shown (Table 5). The contribution of urbanization was greater in metropolises than in medium-sized cities. Over 30 years, the urbanization effect on the annual average temperature was estimated at 11.03% for metropolitan station groups and 5.28% for medium-sized city station groups. Additionally, winter showed the highest contribution for both city classifications, with metropolitan station groups at 112.94% and medium-sized city station groups at 11.03%. The contribution of urbanization to seasonal average temperatures was greatest in winter, followed by autumn, spring, and summer.

Table 5. Contribution of urbanization effects by urban classification on annual and seasonal average temperatures over 30 years

	Annual	Winter	Spring	Summer	Fall
Metropolis	1.50℃	1.56℃	1.21℃	1.29℃	1.97℃
	11.03 %	112.94 %	9.45 %	5.23 %	12.81 %
Medium-sized city	0.67℃	1.50℃	0.43℃	0.65℃	0.84℃
	5.28 %	11.03 %	3.56 %	2.73 %	5.90 %

Numerous studies have analyzed the impact of urbanization on temperature changes on the Korean Peninsula. Park et al. (2017) found a 0.6°C increase over 42 years (1973-2014), Choi et al. (2003) reported a 0.76°C increase over 32 years (1968-1999), Ahn et al. (2011) observed a 0.5-1.4°C increase over 35 years (1954-1998), Kim et al. (2011) recorded a 0.77°C increase over 55 years (1954-2008), and Lee et al. (2008) reported a 0.5°C increase over 40 years (1960-2000). These results show significant differences. The variations in urbanization effects are influenced by the period analyzed, the methods used to distinguish urban and rural areas, and the methods used to estimate urbanization effects (Park et al., 2017).

IV. Conclusion

This study analyzed the impact of urbanization using actual temperature data from meteorological observing stations. Instead of demographic data, land cover maps reflecting recent urbanization trends were used to distinguish between urban and rural areas. Over the 30-year period, temperature changes in cities reflected the combined effects of climate change and urbanization. Metropolises had the highest temperatures, followed by medium-sized cities and rural areas, but the rate of temperature increase was greatest in rural areas (0.033°C/year), followed by medium-sized cities (0.032°C/year) and metropolises (0.029°C/year).

The urban bias magnitude ($\overline{T}_{u-r}$) calculated from annual and seasonal average temperatures was largest in autumn, while the urban bias trend (ΔT_{u-r}) was most pronounced in summer. In nearly all conditions, ΔT_{u-r} was less than 0, indicating that long-term temperature changes were greater in rural areas than in metropolises or medium-sized cities. This suggests that urbanization saturation has reduced the temperature increase trend in larger cities, possibly due to urban development that considers the thermal environment.

Furthermore, the sensitivity of rural areas to urbanization is greater. The urbanization contribution to the 30-year annual average temperature was estimated at 11.03% (1.50°C) for metropolises and 5.28% (0.67°C) for medium-sized cities. These results indicate a significant growth bias between urbanized and rural areas. Urbanization, combined with climate change, significantly impacts the urban thermal environment. The high temperatures in metropolises pose health threats, and the temperature increase due to urbanization is also substantial in medium-sized cities and rural areas. To improve the urban thermal environment, it is necessary to reduce the calculated urbanization effect through urban design that considers climate change from the planning stage.

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