TREND ANALYSIS OF URBAN HEAT ISLAND INTENSITY ACCORDING TO URBAN AREA CHANGE IN ASIAN MEGA CITIES

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ABSTRACT: As the urbanization progresses, the green space in the city decreases and the heat absorption surface such as concrete and asphalt pavement increases, and local urban warming occurs. As urban warming becomes stronger, the temperature difference with the suburban area appears, which is called Urban Heat Island (UHI) phenomenon. UHI is a phenomenon occurring in cities all over the world, and thus there is a possibility of causing global scale climate change. Therefore, there is an increasing need for studies on the difference in UHI intensity and long-term trends according to macroscopic characteristics related to urbanization

In this study, for Asian mega cities, we conducted a correlation analysis between urban area size and UHI intensity for each Asian mega city and season during 1992-2012, and time series analysis was also performed to check the increase trends of UHI intensities. The differences according to the characteristics were compared and analyzed.

Our results suggested that There is a difference in the correlation between urban area size and UHI intensity according to the season and most cities showed a significant correlation in summer, with the least correlation in winter. According to characteristics such as urban area size and economic situation of each city, there was a difference in correlation between urban area size and UHI intensity, and it seems that the influence of topography and development direction also exist. UHI intensity across the city is increased by a combination of urban area size, economic situation and population number. This is the macroscale study that analyzed the effects of urban area size and impact on UHI intensity change and based on this, future studies are required.

1. INTRODUCTION

Urban Heat Island(UHI) is a commonly observed phenomenon worldwide, describing an elevated temperature of urban areas compared to their surroundings, and it causes problems such as changes in relative humidity in urban areas, increase of energy consumption, and human thermal stress (Douglas, 1981; Oke, 1982; Fujibe, 2009; Santamouris, 2013). UHI effect arises from the anthropogenic modification of natural landscapes and the consequent atmospheric and thermophysical changes in the urban boundary layer (Oke, 1987). The formation of UHI can be mainly ascribed to an increased absorption and trapping of solar radiation in built-up urban fabrics and other factors including population density, built-up density and vegetation fractions (Zhou et al., 2016). Especially built-up areas of cities differ considerably in albedo, thermal capacity, and roughness which can significantly modify the surface energy budget (Arnfield, 2003). In addition, urban areas are the major sources of anthropogenic carbon dioxide emissions from the burning of fossil fuels for heating and cooling; from industrial processes; from transportation of people and goods, and so forth (Grimmond, 2007). In this regard, the size of urban area could be a main factor in the UHI development, as explained by Oke (1973). However, the characteristics of such correlation are poorly understood.

UHI studies can be roughly categorized in two domains. One is case study work focusing on one or a few cities and assessing the UHI characteristics with a high level of details. On the other hand, ensemble or cross-sectional studies investigate several cities with an aim of achieving an understanding of common characteristics or fundamental differences arising among them. The availability of remote sensing with global coverage has given a rise to a number of systematic empirical studies of the latter type (Zhou et al., 2017), and our study also falls in this domain. Many studies have indicated that continuing urbanization gradually increases the UHI, and Several demonstrated that the urban impact could have an effect on recent warming trends (Dienst et al, 2019; Hamdi, 2010; Zhou et al., 2004). Hence, comparative studies of UHI changes among cities with different climatic and socio-economic settings and urban characteristics have progressively become more important for researchers and decision makers (Grimmond, 2007; Jones et al., 1990; Tran et al, 2006; Wang and Ge, 2012; Yang et al., 2011).

Several existing studies dealing with UHI at a macroscopic level were examined. Karl et al., (1988) classified urbanization in cities of the United States by population and performed a time-series analysis on temperature differences between urban and suburban areas with regards to the degree of urbanization using monthly temperature data from 1901 to 1984, obtained from 1219 observation stations of the Historical Climatology Network (HCN). Although differences in urbanization and seasonality were confirmed as a result of the study, there were limitations in that variability according to the location and the degree of constructed data was not taken into consideration. Jones et al., (1990) attempted to identify the effect of temperature increase due to urbanization using rural-station temperature series for the three regions of the West Soviet Union, Eastern Australia, and Eastern China. However, there was a limitation due to the varying numbers of observation stations and analysis periods, and significant trends were not observed in all regions. Hua et al., (2008) conducted a time-series analysis on temperature differences between urban and suburban areas in China between 1961 and 2000, using urban station data. As a result of the analysis, the difference of UHI effects according to the degree of urbanization and latitude as well as the positive correlation between population size and UHI were confirmed, but there was an absence of quantitative analysis. Jin et al., (2005) used MODIS images to identify the differences in surface temperature between urban and suburban areas of Beijing, New York, and Phoenix, but were unable to identify trends in UHI changes due to a single year analysis performed instead of a long-term analysis. In the study of Asian mega cities by Tran et al., (2006) and the study of Northern West Siberia (NWS) by Miles & Esau (2017), the change of UHI intensity according to the season and the correlation with related variables were verified by using MODIS image. The study of Zhou et al., (2017) analyzed the difference in UHI intensity according to the area of each city by using MODIS image. However, for all three studies above (Tran et al, 2006; Miles and Esau, 2017; Zhou et al,2017), images from different periods were used for each city and the trend of long-term change was not confirmed. For the UHI intensity comparison analysis of various cities, it is necessary to use the temperature data constructed according to unified conditions and periods rather than the temperature data constructed independently for each city. And in the case of a study using remotely sensed datasets, only a short-term analysis was made due to the limitation of temporal resolution (Grimmond, 2007).

In this study, global climate modelling data combining observation data and remote sensing data were used to perform a time-series analysis for seasonal UHI intensity from the periods of 1992 to 2012 for eight Asian mega cities (Beijing, Chongqing, Dhaka, Karachi, Manila, Mumbai, Seoul, Tokyo) and to compare and analyze the correlation with urban area and urban characteristics. As a global climate modelling data, Climatologies at High Resolution for the Earth's Land Surface Areas (CHELSA) data were used with a main goal of providing long-term trends of UHI intensity for each city under unified condition and understanding climate effects by urbanization.

2. MATERIALS AND METHODS

2.1 Study Area

In Asia, urbanization rates increased from 17% in 1950 to 45% in 2010, mainly led by Japan, China, and Korea. In 2014, Asia's urban population was the largest in the world, with 2.1 billion people. Developing countries are also steadily urbanizing, with an average urbanization rate of about 2% (Song, 2014). Asian cities continue to rapidly grow in both population and physical size because of urbanization, but resulting from the varying characteristics of topography, population and economic level, differences in UHI intensity values according to urban area and changing trends are expected to be observed. With consideration of existing reports and researches, geography, population, GDP and climate were examined for each megacity, where GDP growth rate refers to the projected average real GDP growth rates between 2008 and 2025 (table 1) (Habitat, U.N.,&ESCAP, U., 2015; PricewaterhouseCoopers, U. K., 2009).

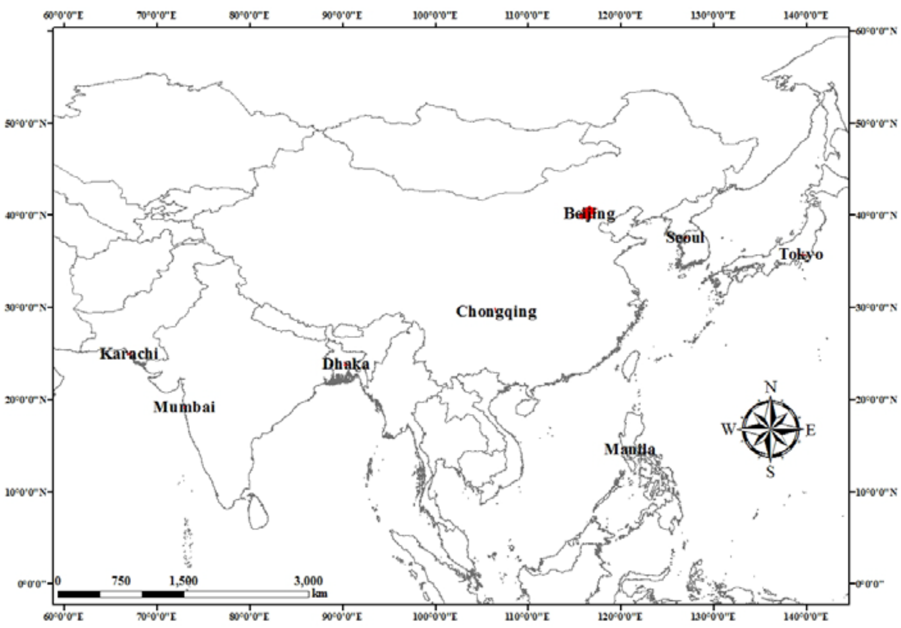

Figure 1. Study Area, Asian Mega Cities

Table 1. Information of Each City

City	Major geography of city	Population in 2010 (thousands)	Urban area size in 2010 (km^2)	GDP in 2008 ($bn at PPPs)	GDP growth rate (% pa: 2008-25)	Köppen Climate
Beijing	inland, plain	16,190	2992.90	166	1.8	humid continental
Chongqing	plateau, basin topography	11,244	311.16	57	5.6	humid subtropical
Dhaka	near Ganges Delta (flat & close to sea level)	14,731	214.73	78	6.5	tropical savanna
Karachi	coastal, plain	14,081	322.83	78	4.1	arid
Manila	coastal area	11,891	506.10	149	1.8	tropical savanna
Mumbai	coastal area	19,422	405.08	209	6.3	tropical
Seoul	inland, basin topography	9,796	450.16	291	2.3	humid subtropical
Tokyo	coastal area	36,834	1084.79	1,479	1.7	humid subtropical

2.2 Data

Our research makes use of three major data sets, (i) land cover information, (ii) surface-air temperature, and (iii) city boundary information. For the land cover information, Climate Change Initiative (CCI) Annual Land Cover maps (from the European Space Agency (ESA)) were used for identifying and comparing changes in land cover. The CCI-LC maps deliver consistent global LC at 300m spatial resolution on an annual basis from 1992 to 2015. This unique dataset was produced by reprocessing and interpretation of different satellite missions (MERIS, FR/RR, AVHRR, SPOT-VGT, PROBA-V). As a result, the set of annual maps are not produced independently and the key aspect is their consistency over time (Arino & Ramoino, 2017). The data created by the ESA CCI are publicly available. In this study, we used the maps for 1992 and 2012 to check the change in urban area size. Urban area in CCI-LC consists of Global Human Settlement Layer and Global Urban Footprint (Arino & Ramoino, 2017). Table 2 provides an overview of the LC classes.

For LST data, Climatologies at high resolution for the earth’s land surface areas (CHELSA) mean temperature time series data from 1992 to 2012 were used. CHELSA data is the data of downscaled model output temperature and precipitation estimates of the ERA-Interim climatic reanalysis to a high resolution of 30 arc sec (~1km). ERA-Interim (developed at the European Centre for Medium-Range Weather Forecast, ECMWF), simulates six-hourly large-scale atmospheric fields for 60 pressure levels between 1,000 and 1hPa globally with a horizontal resolution of 0.75° lat/long. Since the ERA-Interim reanalysis combines modelling results with ground and radiosonde observations as well as remote sensing data using a data assimilation system, the free-atmospheric and surface fields can be considered as the best approximation of the current large-scale atmospheric situation for every time step. Several studies show that ERA-Interim adequately captures the variability of relevant free-air meteorological parameters, even over complex terrain (Karger et al., 2017).

For boundaries of cities, we used the GADM data. GADM, the Database of Global Administrative Areas is a database of the location of the world’s administrative areas (boundaries). Administrative areas in this database are countries and lower level subdivisions such as provinces, departments. GADM describes where these administrative areas are, and for each area it provides some attributes, foremost being the name and in some cases variant names (see https://gadm.org/data.html).

Table 2. Legend of the Global CCI-LC Maps

Value	Label
10	Cropland, rainfed
20	Cropland, irrigated or post-flooding
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover)
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)
50	Tree cover, broadleaved, evergreen, closed to open (>15%)
60	Tree cover, broadleaved, deciduous, closed to open (>15%)
70	Tree cover, needle leaved, evergreen, closed to open (>15%)
80	Tree cover, needle leaved, deciduous, closed to open (>15%)
90	Tree cover, mixed leaf type (broadleaved and needle leaved)
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)
110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)
120	Shrubland
130	Grassland
140	Lichens and mosses
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)

160	Tree cover, flooded, fresh or brakish water
170	Tree cover, flooded saline water
180	Shrub or herbaceous cover, flooded, fresh/ saline/brakish water
190	Urban areas
200	Bare areas
210	Water bodies
220	Permanent snow and ice

2.3 Method

With a reference to Zhou et al., (2013), we defined the UHI intensity as the difference of temperature between urban area in city boundary and that of surroundings, $\Delta T = Tu - Ts$, where Tu and Ts are mean temperatures of the urban area and the surrounding area. We excluded water body for calculating UHI intensity as it can significantly influence the temperature (Miles & Esau, 2017).

For the calculation of seasonal average temperature, spring was defined as the period from March to May, summer from June to August, autumn from September to November, and winter from December to the following February (Hua et al, 2008; McKinnon et al, 2016). The equation to derive seasonal average temperature (℃) using CHELSA data is as following, where T_1, T_2, T_3 each refer to the months belonging to each season.

$$T_{average}(℃) = (T_1 + T_2 + T_3)/30 - 273 \tag{1}$$

By extracting urban area shape and surrounding area shape during the period of 21 years (1992-2012) for each city, average temperature was calculated for each year and season to derive UHI intensity. Using the UHI intensity derived, time series analysis for the 21-year-period was performed and the tendency of UHI intensity change was identified through the trend line. The Pearson correlation analysis by season and city was performed between the UHI intensity and urban area size to confirm the quantitative correlation. In order to calculate the urban area, Universal Transverse Mercator (UTM) zone for each megacity was identified to transform coordinate systems. Using the Pearson correlation analysis, it was analyzed that a significant correlation appeared when the p-value was less than 0.05. Through the analysis, the difference in the value of UHI intensity and the change trend of each city was confirmed (Gogtay & Thatte, 2017). All GIS and remote-sensing data were processed using ArcGIS 10.3 software and correlation analysis was performed using the SPSS24 program and time series analysis was performed using excel program. An example of a LC map, surface-air temperature around the Seoul city, is shown in Figure 2.

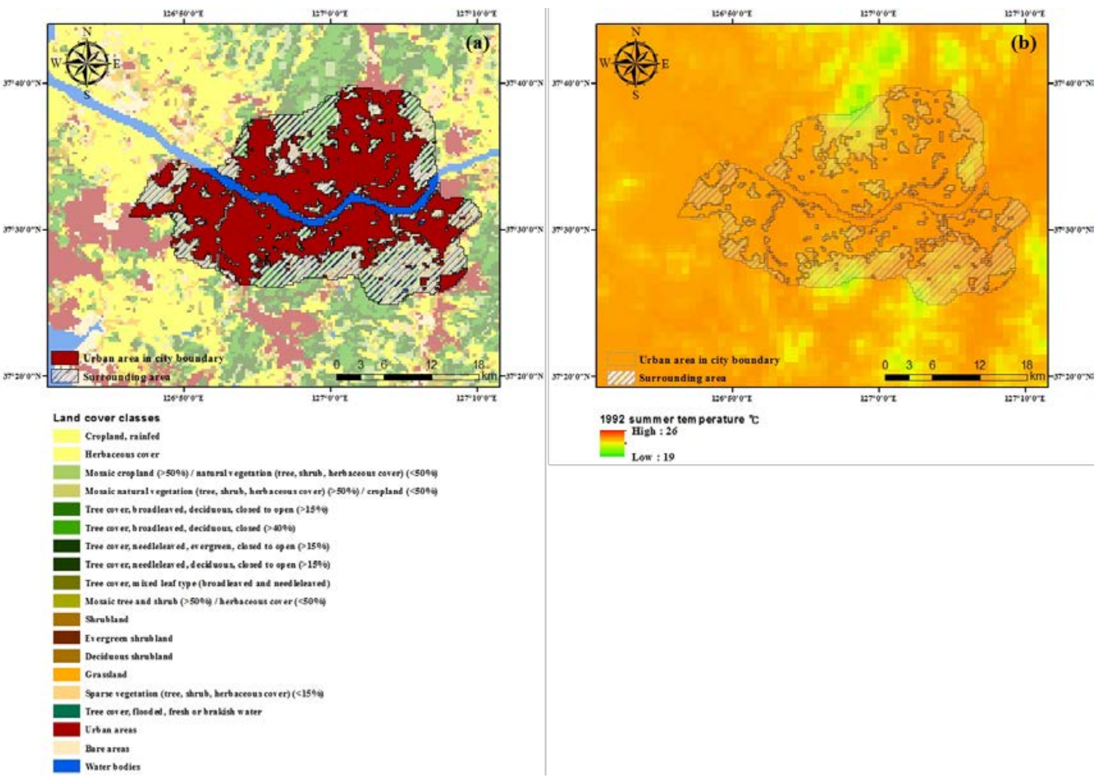

Figure 2. Example of Seoul City Polygon and Land Cover and Summer Surface-Air Temperature Pattern in 1992. (a) Urban Area in City Boundary and Surrounding Area and Land Cover Climate Change Initiative (LC CCI). (b) Surface-Air Temperature for the Same Area as in Figure (a) on the basis of Climatologies at High Resolution for the Earth's Land Surface Areas (CHELSA) Time Series Data.

3. RESULTS AND DISCUSSION

3.1 Correlation Analysis

We tried to find the potential relations between UHI intensity and urban area size. UHI intensities are affected by numerous factors – spatially (the density of the built environment, lake proximity and topographic relief) and temporally (wind speed, cloud cover, and relative humidity). Hence, UHI intensities tend to be higher during the warmer summer months and lower during the colder winter months (Schatz and Kucharik, 2014). The analysis results of this research also showed that the most significant positive correlation was found in the summer season, and the least significant one was found in the winter season.

In the case of Beijing, an insignificant correlation between summer UHI intensity and urban area size was observed, which could be ascribed to the relatively rapid increase in urban area size (1,623.28km^2→3,085km^2) leading to modification of urban form and reduction of compactness ratio of urban land (Qiao et al, 2014). There is an existing study which identified that the winter UHI intensity of construction area in Beijing was at its highest for potential reasons including anthropogenically generated heat in urban area and major geography being a plain terrain (Liu et al, 29007). However, additional research is required to identify the major contributing factor.

In the cases of Dhaka and Karachi, neither seasonal UHI intensity nor the correlation with urban area size were found. According to Spence et al (2008), urbanization is related to city growth as in per capita income and urban-based industry and services. In developed countries, urbanization rates and growth moved together, and per capita income expanded much more rapidly when urbanization reached close to 60 percent. However, urbanization has not been pulled by productive industrialization in developing countries such as Bangladesh. As a result, cities experiencing relatively lower economic achievement failed to structurally shift from rural activities to urban-based industry, possibly being the reason for the phenomenon where UHI intensity did not increase proportionally with urban area size.

On the other hand, despite the relatively low economic achievement, Chongqing showed the significant and strong correlation for the spring and summer UHI intensity and relatively significant correlation for the autumn UHI intensity. Industrial output value of Chongqing ranked eleventh among the 35 biggest city economies in China in 2000 and had attracted much greater foreign investment during the reform era of China, allowing substantial industrialization in the region (Sigurdson & Palonka, 2008). And basin topography could make an ascending thermal airflow in a basin city enveloped by the foul air to lead hot air sinking along with the mountain in the basin edge barrier, thereby affecting UHI temperature rise compared to other cities (Chang, 2016).

In Manila and Mumbai, the correlation between summer UHI intensity and urban area size was found to be significant and strong, and that with Autumn UHI intensity was found to be relatively significant. In the case of Manila, a previous study reported that urbanization resulted in increasing tendency of sensible heat flux and summer rainfall (Oliveros, 2019). It is examined that population growth led to increase in urban area and intensification of urban materials that absorb more solar radiation, which can collectively influence UHI intensity. As Mumbai is also one of the largest metropolises of South Asia, modification of the land surface by urban development was induced (Srivastava et al, 2016).

In both cases of Seoul and Tokyo, significant and strong correlations for summer UHI intensity were observed. Additionally, in Tokyo, significant correlations were also observed for spring and autumn UHI intensity. As Seoul and Tokyo represent developed megacities of East Asia, a previous study done by Choi et al. (2014) also identified that summer season had the highest UHI effect on temperature.

Table 3. Results of Correlation Analysis between Urban Area Size and UHI intensity for Each City and Season During 1992-2012

City	Spring		Summer		Autumn		Winter	
	R	P-value	R	P-value	R	P-value	R	P-value
Beijing	0.298	0.189	0.261	0.254	0.127	0.585	0.645**	0.002
Chongqing	0.873**	0.00	0.862**	0.00	0.545*	0.011	0.14	0.546
Dhaka	-0.058	0.804	-0.024	0.918	0.196	0.395	-0.173	0.453
Karachi	0.120	0.604	-0.056	0.810	-0.274	0.230	0.025	0.913
Manila	0.395	0.076	0.937**	0.00	0.468*	0.033	0.414	0.062
Mumbai	0.244	0.287	0.930**	0.00	0.523*	0.015	0.222	0.333

Seoul	-0.073	0.755	0.854**	0.00	0.279	0.220	0.304	0.180
Tokyo	0.468*	0.033	0.627**	0.002	0.477*	0.029	0.188	0.414

*P<0.05, **P<0.01

3.2 Time Series Analysis of UHI intensity

The trends of UHI intensity for the period from 1992 to 2012 are depicted through Figs. 3-10, describing annual and seasonal UHI intensity of average temperature for each mega city. As results of time series analysis, the increasing trend of UHI intensity was most visibly observed during the summer season. Chongqing showed the summer UHI intensity increase rate of about 0.07˚C/decade. Manila and Mumbai showed significant increase rates of 0.015˚C/decade and 0.036˚C/decade. Increase rates of about 0.02˚C/decade and 0.085˚C/decade were found in Seoul and Japan, respectively.

For the cases of other seasons, the increase rates varied for each city. However, Beijing showed insignificant changing trend of determination coefficient (R^2) of lower than 0.1 in all seasons except winter. For the winter UHI intensity increase rate (˚C/decade), determination coefficient was 0.373, reflecting an increase by a rate of 0.18˚C/decade.

In Chongqing, UHI intensity increase rate was observed to be about 0.07˚C/decade in spring, about 0.05˚C/decade in autumn, and insignificant in winter. For the cases of Dhaka and Karachi, determination coefficient was lower than 0.1 in all seasons demonstrating insignificant changing trend.

When considering average UHI intensity for each city with respect to intercept value, UHI intensity was higher than 2˚C for all seasons in Beijing and Tokyo, and less than 0.5˚C in all other cities. Such increases in UHI intensity value in Beijing and Tokyo were examined to be results of the relatively high urban area size in Beijing and urban area size, economic situation and population in Tokyo.

In Dhaka and Karachi, urban heat sink effect was also observed, which is a phenomenon occurring in subtropical desert cities where urban area has lower temperature than surrounding bare land due to large amount of urban vegetation and incomplete development (Fan et al, 2017). Other differences resulting from climate were not apparent.

The UHI intensity increase rate derived from this study may be different from previous studies due to differences in target time and spatial scale, and the UHI intensity value is the average value of the whole city and may be different from the UHI intensity value of smaller administrative units in the city (Lee et al., 2017).

Table 4. Results of Time Series Analysis of UHI intensity for Each City and Each Season During 1992-2012

City	Spring		Summer		Autumn		Winter	
	Function (y)	**R^2**	**Function (y)**	**R^2**	**Function (y)**	**R^2**	**Function (y)**	**R^2**
Beijing	0.0076x+2.4156	0.098	0.0039x+2.2554	0.07	0.0023x+2.3311	0.019	0.0183x+2.0819	0.373
Chongqing	0.0068x+0.4622	0.673	0.0066x+0.4669	0.614	0.0046x+0.4844	0.278	0.0016x+0.4214	0.042
Dhaka	0.0003x-0.0032	0.002	-8E-05x-0.0592	0.002	0.0005x+0.0011	0.006	-0.0061x+0.1532	0.056
Karachi	0.0024x-0.1233	0.007	-0.0007x-0.0823	0.019	-0.0039x+0.0638	0.051	0.001x+0.0739	0.002
Manila	0.0056x+0.0447	0.195	0.0015x+0.0702	0.803	0.0061x+0.0216	0.159	0.005x+0.0307	0.158
Mumbai	0.0045x+0.4106	0.059	0.0036x+0.3941	0.792	0.015x+0.3368	0.240	0.0044x+0.4594	0.031
Seoul	-0.0028x+0.4164	0.025	0.0018x+0.3636	0.398	0.0039x+0.2954	0.046	0.0002x+0.3619	0.000
Tokyo	0.0067x+2.6582	0.104	0.0085x+2.2644	0.291	0.006x+2.6296	0.083	-0.0009x+2.8896	0.004

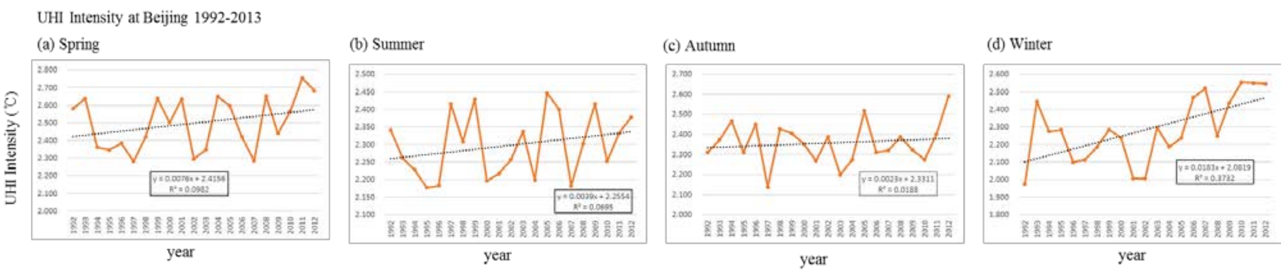

Figure 3. Annual UHI intensity Changes in Beijing for Each Season During 1992-2012. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

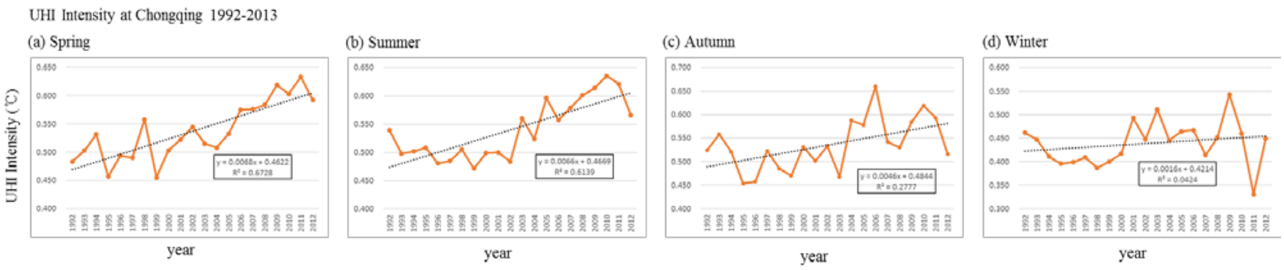

Figure 4. Annual UHI intensity Changes in Chongqing for Each Season During 1992-2012. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

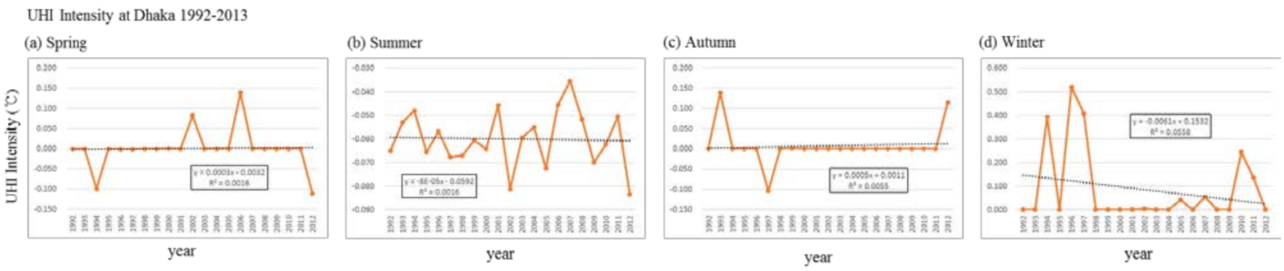

Figure 5. Annual UHI intensity Changes in Dhaka for Each Season During 1992-2012. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

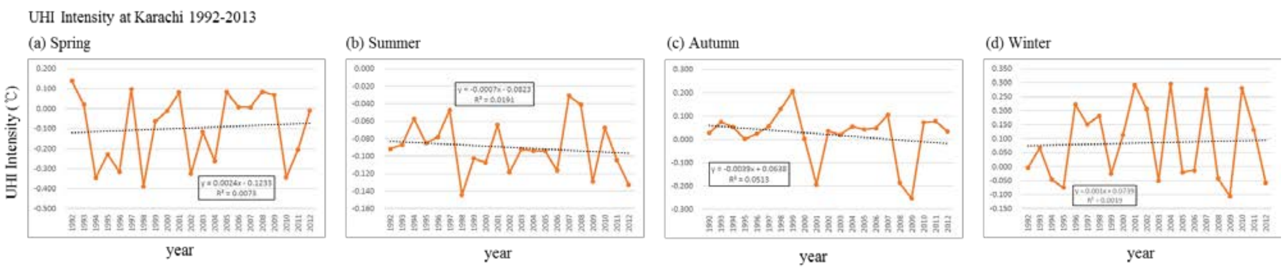

Figure 6. Annual UHI intensity Changes in Karachi for Each Season During 1992-2012. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

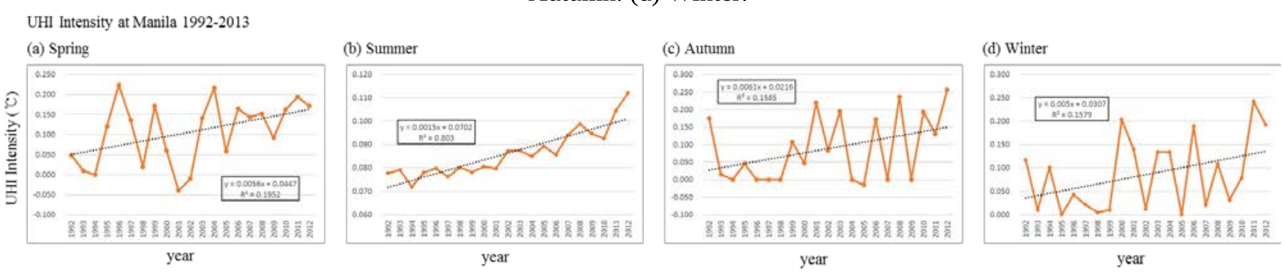

Figure 7. Annual UHI intensity Changes in Manila for Each Season During 1992-2012. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

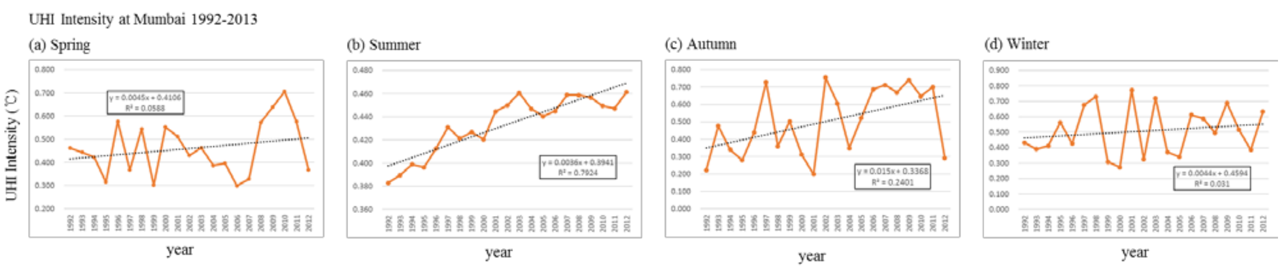

Figure 8. Annual UHI intensity Changes in Mumbai for Each Season During 1992-2012. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

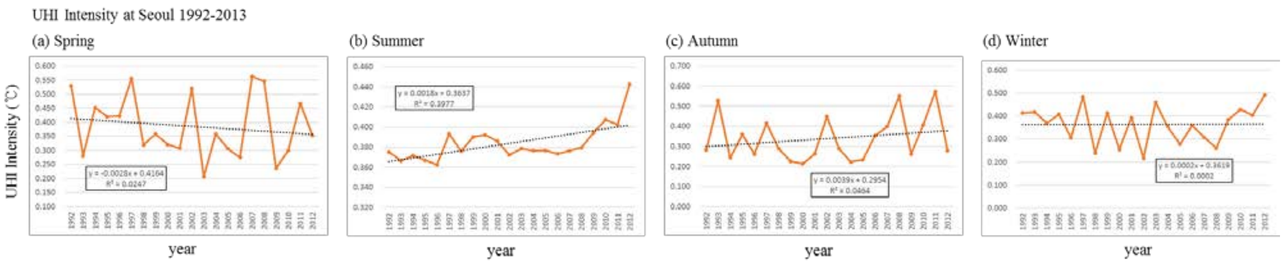

Figure 9. Annual UHI intensity Changes in Seoul for Each Season During 1992-2012. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

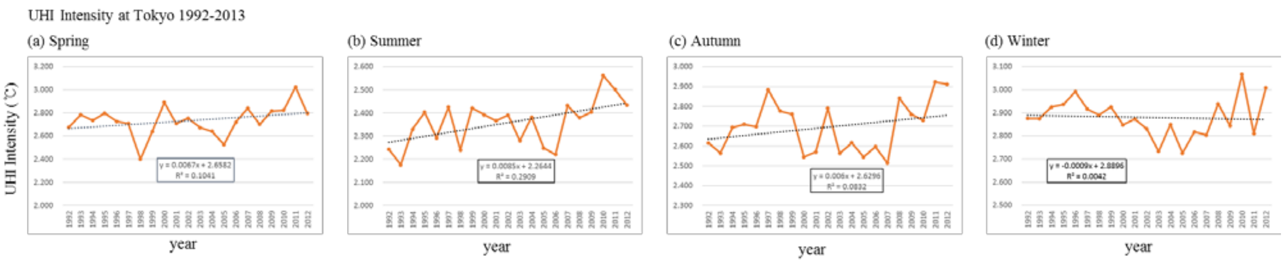

Figure 10. Annual UHI intensity Changes in Tokyo for Each Season During 1992-2012. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

4. CONCLUSION

The present study of UHI intensity trends based on seasonal mean temperature in Asian mega cities lead to the following conclusions:

- There is a difference in the correlation between urban area size and UHI intensity according to the season and most cities showed a significant correlation in summer, with the least correlation in winter.
- According to characteristics such as urban area size and economic situation of each city, there was a difference in correlation between urban area size and UHI intensity, and it seems that the influence of topography and development direction also exist.
- Urbanization only due to urban area increase does not have a significant impact on UHI intensity increase and city growth like urban-based industrialization and increasing in building and road should be done in parallel.
- The UHI intensity increase trend appears to be the best during the summer months and other seasons differed by city.
- UHI intensity across the city is increased by a combination of urban area size, economic situation and population number.
- There was no difference in climate except for the urban heat sink effect in Dhaka and Karachi.
- This is the macroscale study that analyzed the effects of urbanization and impact on UHI intensity change and based on this, future studies are required to study specific urbanization characteristics that affect the increase in UHI intensity or urbanization on global warming.

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