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Temporal dynamics of urban heat island correlated with the socio-economic development over the past half-century in Seoul, Korea[☆]

Je-Woo Hong [a], Jinkyu Hong [a, *], Eilhann E. Kwon [b], D.K. Yoon [c]

[a] *Ecosystem-Atmosphere Process Laboratory, Department of Atmospheric Sciences, Yonsei University, Seoul, South Korea*
[b] *Department of Environment and Energy, Sejong University, Seoul, South Korea*
[c] *Department of Urban Planning and Engineering, Yonsei University, Seoul, South Korea*

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ABSTRACT

Urban heat island (UHI), an iconic consequence of anthropogenic activities and climate condition, affects air pollution, energy use, and health. Therefore, better understanding of the temporal dynamics of UHI is required for sustainable urban planning to mitigate air pollution under a changing climate. Here, we present the evolution of UHI intensity (UHIi) and its controlling factors in the Seoul metropolitan area, Korea, over the last 56 years (1962–2017), which has experienced unique compressed economic growth and urban transformation under monsoon climate. The analysis demonstrated an inverted U-shape long-term variation of UHIi with the progress of urban transformation and economic climate which has not been reported in Asian cities before. Meanwhile, short-term variations in UHIi are related to both diurnal temperature range and duration after rainfall event unlike previous studies, and the UHIi was exacerbated by heat waves. Our findings suggest that the UHIi will exhibit different temporal dynamics with future changes in the monsoon climate, and heat waves in the urban area will be reinforced if current rapid urbanization continues without a shift toward sustainable and equitable development. Asian cities that are likely to face the similar urbanization trajectory and the implications are that urban (re) development strategy considers changes in rainfall magnitude and timing due to monsoon system variation under changing climate and plans to mitigate synergy between heat wave and UHI in this area.

1. Introduction

Microclimate changes due to a city have a long history since the industrial revolution (Howard, 2006; Arnfield, 2003) and urban heat island (UHI) is the most important example induced by anthropogenic activity in a city. As global rapid urbanization progresses in global warming, it is critical to understand the interaction between global warming and urbanization for our sustainable urban management (Karl and Jones, 1989; Jones et al., 1990, 2008; Kataoka et al., 2009; Fujibe, 2011; Park et al., 2017). It is challenging to evaluate effectiveness of urban management on mitigating heat stress, air pollution and energy consumption in the global warming epoch (Ma et al., 2018). The effectiveness of urban management depends on urban structure and function as well as background climate conditions. As urbanization is progressing, surface energy balance changes together: (*i*) Bowen ratio decreases, (*ii*) fraction of heat storage increases, and (*iii*) anthropogenic heat emission is added to available energy (Oke, 1982). Since UHI intensity (UHIi) depends on urban developmental level making changes in building structure and function, the UHIi shows complex pattern of temporal dynamics.

A lot of megacities have emerged in East Asia since 1980 with rapid economic growth and substantial increases of UHIi have been reported in Asian cities until early 2000s (e.g., Kataoka et al., 2009). Particularly, there has been substantial urbanization and suburbanization as rapid industrialization since the beginning of a 5-year plan for economic development in 1962. After the intensive urbanization around 1970's and 1980's, cities in Korea have been under central business district (CBD) decline and redevelopment since the late 1990's with increases in desire for taller building and three major economic crises of the Asian financial crisis, credit card lending distress and subprime mortgage crisis in the late 1990's, 2003, and late 2000's, respectively (Jun and Ha, 2002; Sohn et al., 2010). It is expected that such redevelopment and abrupt change

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[*] Corresponding author. Ecosystem-Atmosphere Process Laboratory, Department of Atmospheric Sciences, Yonsei University, Yonsei-ro 50, Seodaemun-gu, Seoul, 03722, South Korea.

E-mail address: jhong@yonsei.ac.kr (J. Hong).

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in economic climate are in other cities of developing countries in the near future, but there has not been extensive study to assess impacts of urbanization and economic climate on UHI and heat wave in the monsoon Asia. It is an urgent scientific issue to properly understand impacts of such urban redevelopment and economic activities on microclimate and environment accordingly. To properly understand effects of urbanization on sustainable urban management plans, it is demanding to do extensive analysis of UHIi based on long-term monitoring data in urban area as different urbanization management progresses because urban transformation and economic growth have long time scales of >30 years. Most of previous studies noted short-term meteorological impacts on UHI mainly with wind speed and humidity (Arnfield, 2003 and references therein), or remote sensed UHI without the calibration for complex building surfaces and their emissivity from brightness temperature (e.g., Liu and Zhang, 2011; Choi et al., 2014). Importantly, long-term data is necessary to capture urban transformation cycles and its relationship with urban development.

It is also expected that extreme weather such as heat wave (HW) will be frequent, long-lasting, and intensified by climate change (Hartmann et al., 2013; Dosio et al., 2018). HW is critical to human health and ecosystem, and our better understanding of the HW and UHI with urbanization and urban transformation requires intensive study based on long-term observation data accordingly. A consensus exists for the fact that UHI becomes stronger with progress of urbanization, but its regional scale impact and interaction with HW are currently disagreeing. Urbanization contributed to long-term warming record of air temperature in Asia substantially (Kataoka et al., 2009; Fujibe, 2011; Park et al., 2017; Ren et al., 2008) but such strong contribution has not been reported in Europe possibly because of the doughnut effect which refers that the city center becomes hollow or empty as businesses and inhabitants move into the outskirt of the city (Terjung and O'Rourke, 1980; Jones et al., 1990, 2008; Pallagst, 2008). In perspective of heat wave and urbanization, Zhao et al. (2018) reported synergy effects between UHI and HW based on cities in the US. On the other hand, Scott et al. (2018) found that UHI became weaker in case of HW events in North America. Most of previous studies were conducted over North America and the lack of long-term observation data in other climate region hinders us from our better understanding of the interaction between UHI and HW.

The objectives of this study are to report temporal dynamics of UHIi with the different stages of urbanization (i.e., invigoration, decline, and redevelopment) and changes in urban spatial structure and economic growth in Seoul, Korea and to assess its relationship with HW. This study focuses on how the urban sprawl and economic conditions in Seoul make impact on UHIi. Because of the rapid urbanization and dramatic economic development in Korea, cities in Korea provides unique information on the interplay between urbanization and economic climate with climate changes. Based on about half century observational data, we analyze the observed long-term air temperature in Seoul over the last 56 years (1962–2017). Particularly, our analysis focuses on temporal variability of UHIi along urban development trajectory, economic activity, and climate conditions (i.e., precipitation and HW) together. Then, this study further compares results on this long-term data with those reported in other studies and then discuss implication of our findings in perspectives of the urban redevelopment and interaction between UHIi and HW.

2. Materials and methods

2.1. Seoul observatory

In the Seoul metropolitan area of Korea, two stations have more than 50 years of measurement history: Seoul observatory and Kimpo airport observatory (Fig. 1A). The Seoul observatory (SO, 37.5714°N 126.9658°E) is a synoptic station and is located at the central area of Seoul. Annual air temperature at the SO is nearly as same as the spatial average of 34 automatic weather stations in Seoul. Around the SO, high-density residential area has been a typical land cover, but the density of residential buildings has been changed dramatically during the study period: compact low-rise until 1980, compact mid-rise between 1980 and 2015, and open high-rise after 2015 (Fig. 1B–E). According to the Local Climate Zones classification (Stewart and Oke, 2012), these built types during each period correspond to LCZ_3, LCZ_2, and LCZ_4, respectively. Therefore, the observed data at the SO is useful for evaluating and tracking the changes in micro-climatic environment of Seoul with progress of urbanization and economic growth.

There has been significant CBD decline in Seoul since the 1980s, and CBD and subcenters have been moving outward from the old districts because of higher land prices in the old CBD, similarly to cities in the developed countries (Figs. 2and3) (Jun and Ha, 2002). From about 2000, the southeastern areas of Seoul have been rapidly developed, and economic, educational, and residential development has been concentrated in the southern part of Seoul (Fig. 3), leading to imbalance between the north and south of Seoul (Sohn et al., 2010). Accordingly, there has been gradual decline of urban area around the SO in the northern part of Seoul (Fig. 2A), and this inner-city decline was reinforced by the Asian financial crisis (Yim and Lee, 2002; Lee and Choi, 2010; Lee et al., 2018) (Fig. 2B).

Apart from the rapid economic growth, there were relatively short-term economic slowdowns due to the oil shock in the mid and late 1970s and economic crises after 1990s. In the late 1990's, the Asian financial crisis was a trigger for strengthening such spatial polarization between the North and South region by making urban decline around the SO in northern Seoul. Moreover, the global financial crisis of 2007–2009 slowed the town redevelopment. Various social indices (e.g., population and its structure, wage income, real estate, land prices, number of subway station) show that the town around the SO has lost its vitality for the past 15 years.

2.2. Kimpo airport observatory

The Kimpo airport observatory (KAO, 37.5722°N 126.7751°E) is an aerodrome meteorological observation station, and measurement data is available from 1961. The KAO is in the western border of Seoul and thus about 14 km west of the SO. There is a grassland within a radius of 500 m around the observatory, and outside of the grassland is surrounded by rice paddy and cropland up to 1.0 km from grassland (LCZ_D). Because of the limited development district around the airport, the meteorological instrument in the KAO has not been exposed to anthropogenic sources, indicating that major thermal source is natural surface. Additionally, since dominant wind direction is westerly, the KAO is influenced by the same synoptic weather conditions as Seoul in general rather than urban areas in Seoul.

2.3. Quantification of urban heat island intensity

Our study calculated the UHIi in the urban canopy layer by using 1.5 m air temperature from both sites (Stewart and Oke, 2012). Other meteorological data include relative humidity, solar duration, wind speed, precipitation, and cloudiness. Quality-controlled measurement data and metadata are opened through the National Climate Data Portal of Korea Meteorological Administration (KMA) (http://data.kma.go.kr/). The UHIi is quantified as the temperature difference between urban and rural sites typically. This

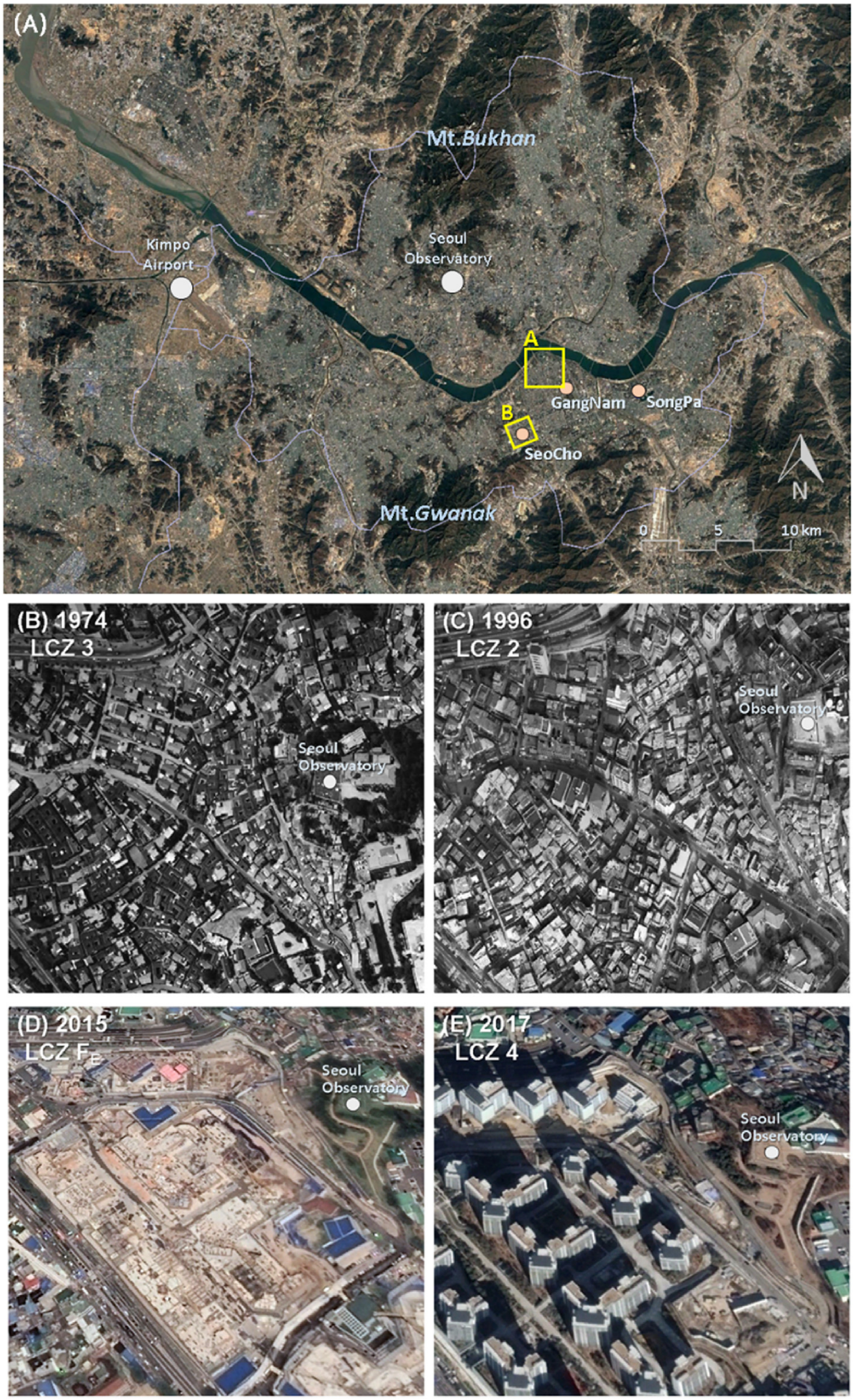

Fig. 1. Location of surface stations in Seoul and aerial photographs around Seoul observatory (B) in 1974, (C) 1996, (D) 2015, and (E) 2017 (modified from map data ©2018 Google). Rectangles of A and B in (A) refer to the new business districts in Fig. 3.

study used the SO (LCZ_4 from LCZ_3 through LCZ_2) as urban site and the KAO (LCZ_D) as rural standard. Accordingly, UHIi is estimated with 3-h mean air temperature at the SO and KAO, and the daily maximum of UHIi is used for our analysis. To investigate relationship of UHIi with HWs conditions, the KMA guideline is used for HWs definition: HW is defined if daily maximum air temperature at SO lasts more than 33 °C for two or more consecutive days, then from second day (http://www.weather.go.kr).

3. Results and discussion

3.1. Long-term trends of air temperature

Fig. 4 shows time-series of mean annual air temperature and its

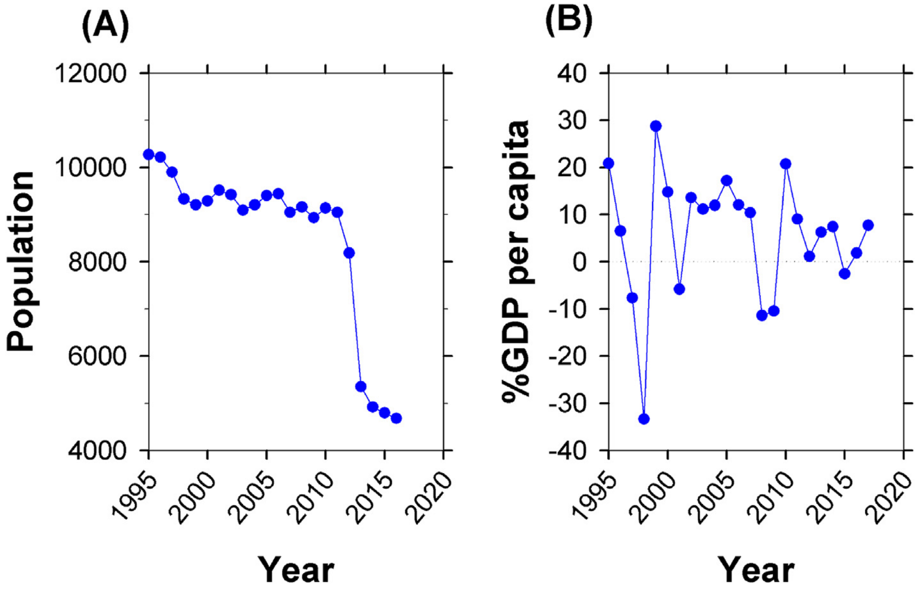

Fig. 2. (A) Population of Gyonam-dong (Seoul Metropolitan Government), the town around Seoul Observatory (seen in Fig. 1B–E) and (B) percentile changes of GDP per capita from 1995 to 2017 (source: the World Bank).

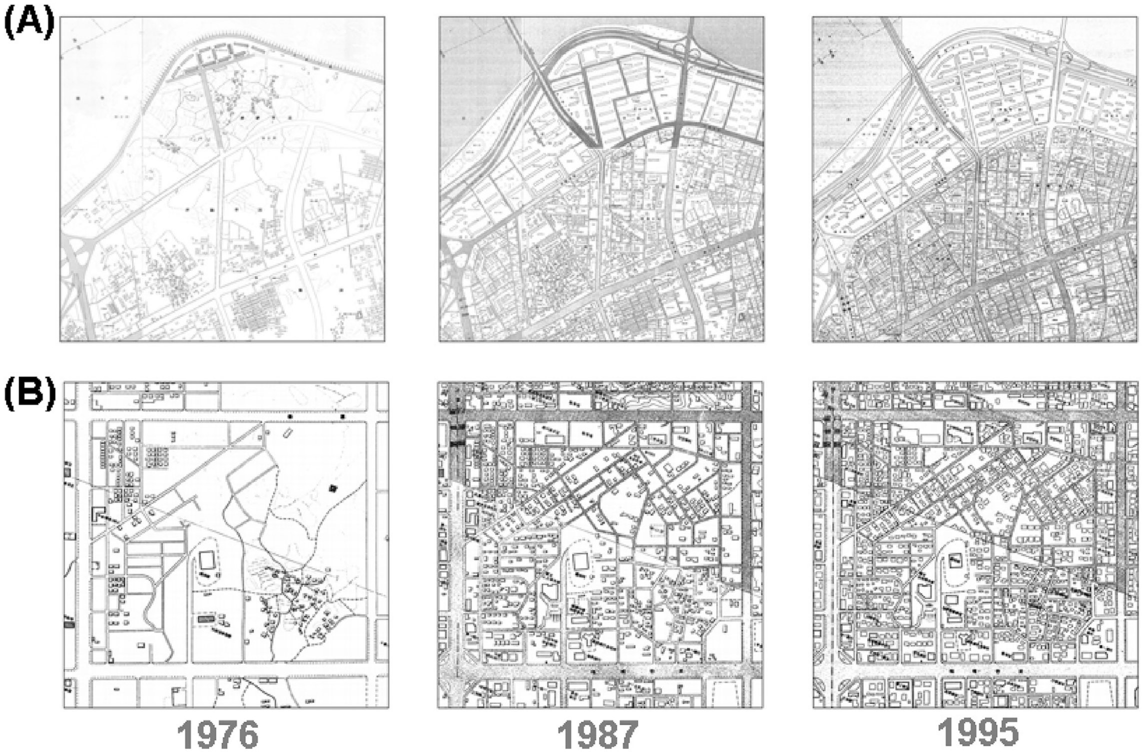

Fig. 3. Aerial photographs of New CBD areas in 1976 (left), 1987 (center), and 1995 (right): (A) and (B) indicate (A) and (B) in Fig. 1, respectively. Reference of photographs is 'Urban form study of Seoul (Seoul Development Institute, 2009)'.

linear trends at the SO and KAO during the last 56 years (1962–2017). Our results indicate typical pattern of the second phase of urbanization in Seoul by showing unprecedented increase of UHIi in both amplitude and speediness (Oke et al., 2017). During this period, air temperature has increased about 1.7 °C and 0.9 °C in the SO and KAO, respectively. It is obvious that the warming trend in the city center (SO) is larger than the adjacent rural area (KAO). These warming trends correspond to 3.0 °C century^{-1} for SO and 1.7 °C century^{-1} for KAO. The warming rate of KAO is similar to the global warming trend over land of about +0.9 °C during 1962–2017 (Hansen et al., 2010). SO in the urban area shows about 1.8 times higher than this global warming trend over land. This finding indicates that urbanization has a significant impact on regional warming trend in the Seoul metropolitan area by accounting for 43% of the urban warming trend. This result is comparable with previous studies for short-term nationwide scale in Korea

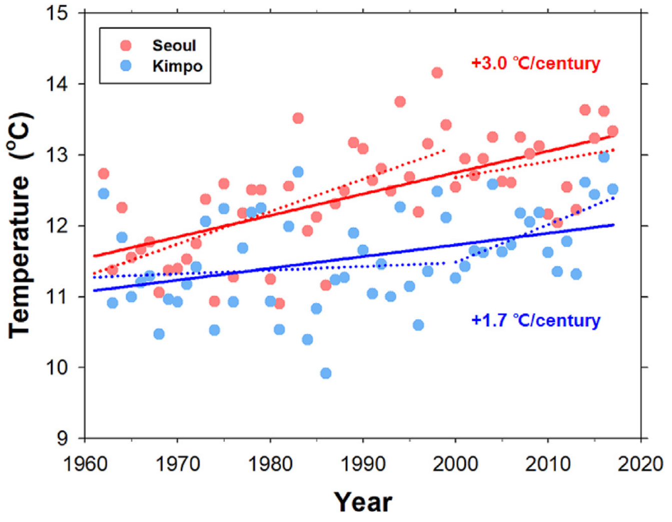

Fig. 4. Time series of annual temperature and its linear trends of Seoul (red) and Kimpo (blue) airport observatory over the last 56 years (1962–2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(+1.8–2.4 °C century^{-1} of warming trend with 25–50% of urbanization effect; Park et al., 2017), Japan (+2.1–3.3 °C century^{-1} and 29–46%; Fujibe, 2011), and China (+1.1 °C century^{-1} and 38%; Ren et al., 2008). Such substantial contribution of urbanization to air temperature has not been reported in developed countries.

In general, urban structure has not changed significantly in cities of Europe and US compared to East Asian cities that developed shortly in the late 20th century. Accordingly, there are smaller urbanization effects (<+0.05 °C century^{-1}) on long-term trend of surface air temperature in cities of Europe and North America (Jones et al., 1990, 2008). Notably, it is also observed that the rapid increase of UHIi has decreased significantly with a few substantial drops since the late 1990's (dotted line in Fig. 4). Our finding suggests that the urbanization has been moving towards a different phase with completion of urban structure.

3.2. *Temporal dynamics of urban heat island*

Fig. 5 shows annual and seasonal mean of the daily maximum UHIi of Seoul during 1962–2017. UHIi is a constant of about 1.5 °C until 1980, then increased up to 3.0–3.5 °C and declined after the late 1990's, which is consistent with Kim and Baik (2002). These overall trends of UHIi are accordance with rapid progress of urbanization around the SO since the 1980s and decrease of energy consumption due to the inner-city decline since the late 1990's around the SO (Fig. 1B–E). Such decline of UHIi after the late 1990's has not been reported in the southeastern sub-centers of Seoul which experienced no substantial inner-city decline and are the new CBD of Seoul. The mean annual UHIi does not change at the new CBD region (GN, SC, and SP stations; red circles in Fig. 1A) during 1996–2017 (Fig. 6). It is also notable that abrupt drops of UHIi coincide with the events of economic crisis described in section 2.1 (Fig. 2B).

Until 1980, dominant residential housing form was a slate-roofed single-story house (Fig. 1B) for several decades, implying LCZ$_3$ of compact low-rise. Before 1980, asphalt pavement was only applied in major road and minor roads were commonly covered by hard-packed bare-soil or concrete with small stone aggregate. Such long LCZ$_3$ changed around 1980 with a rapid influx of population into Seoul. For about a decade after 1980, housing form has changed

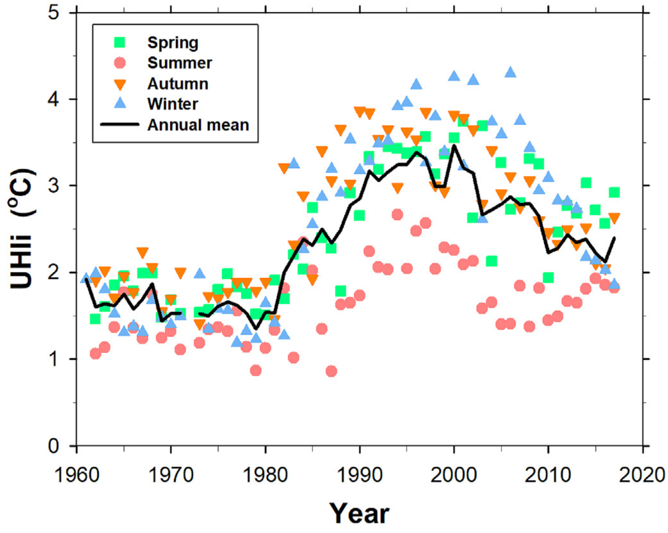

Fig. 5. Annual and seasonal mean of daily maximum UHI intensity (UHIi) in Seoul over the last 56 years (1962–2017).

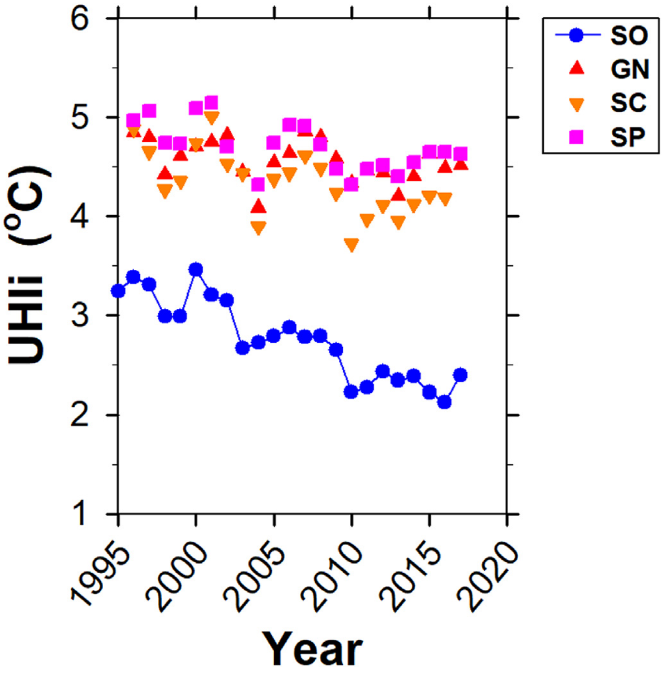

Fig. 6. Annual mean UHIi at Seoul observatory (SO; blue circle) and 3 weather stations in southern part of Seoul: GangNam (GN; red triangle), SeoCho (SC; orange triangle), and SongPa (SP; pink square). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

to cement middle-stories (3–5 stories) and LCZ changed to LCZ$_2$ (compact mid-rise) accordingly (Fig. 1C). Moreover, asphalt road fraction around the SO increased and asphalt pavement was also applied to minor roads after 1980. These changes indicate that urban heat capacity by a building and road has increased substantially since the 1980s.

Along with the rapid economic growth and industrialization in the late 20th century, energy consumption in Korea increased dramatically, leading to significant increases in anthropogenic heat emission and heat storage. National energy consumption of household was increased from 13.4 million toe (tonne of oil equivalent) in 1983 to 21.4 million toe in 1995, and energy consumption per capita of household also increased from 0.334 to 0.474 toe (Korea Energy Economics Institute, 2014). However, due to the financial crises in 1997 and 2007–2009, energy consumption of household has not changed much after 1995 (22.1 million toe in 2013), and the energy consumption per capita of household decreased to 0.440 toe in 2013. Electricity consumption and greenhouse gas emission also decreased during these economic crises.

3.3. *Impact of weather conditions on urban heat island intensity*

Enhancement of UHIi in calm wind and clear sky conditions have been reported in many studies (Arnfield, 2003 and references therein). Notably, our data demonstrate that urban transformation processes and economic climate explained well the long-term trends (e.g., yearly and decadal scale) of UHIi. Meanwhile, shorter temporal variability (from day-to-day to season-to-season) is well correlated to meteorological conditions (Fig. 7). Our analysis is extended to several meteorological variables and shows consistent explanation on the observed short-term variation of UHIi.

First, UHIi is positively correlated with the diurnal temperature range (DTR). Since DTR is large (small) under dry (humid), clear (cloudy), and calm (windy) conditions in usual, our findings accord with Arnfield (2003) and references therein (i.e., negative relationship of UHIi with wind speed and cloudiness) and explain the observed positive relationship of UHIi with solar radiation. Second, UHIi shows the rectangular hyperbola relationship with atmospheric humidity measures (i.e., relative humidity and day after rainfall). Our analysis on UHIi with the elapsed days after rainfall shows that the UHIi decreases immediately with rain event and it takes about 5 days to regain the magnitude of UHIi during pre-rainfall event. Due to lengthy rain spells during the Asian summer monsoon, on average, 40.9 ± 6.6 days (mean ± standard deviation) of rainy days are recorded during summer, indicating one day of every 2.2 days was a rainy day. It is important to assess UHIi dependence on rainfall events.

Previous studies report that rainfall has significant impacts on urban surface energy balance through the reduction of Bowen ratio and albedo in an urban area but do not clear connection of UHIi with rainfall by discarding the data during rainfall (e.g., Ward et al., 2013; Kotthaus and Grimmond, 2014; Hong and Hong, 2016; Hong et al., 2019). Interestingly, the recovery time of Bowen ratio and albedo after rain events is less than a day, which is shorter than that of UHIi. We speculate that recovery of stored heat inside the buildings and roads is longer than the drying time of surface skin due to evaporation. These observed impacts of rainfall on the UHIi well explain temporal changes of UHIi, such as smaller UHIi in the summer monsoon period compared to other seasons.

3.4. *Synergetic interaction between urban heat island and heat waves*

During the study period (1962–2017), there are 179 days of HW, corresponding mean annual frequency of HW is 3.2 days year^{-1}. There is a clear synergetic interaction between UHI and HW (Fig. 8).

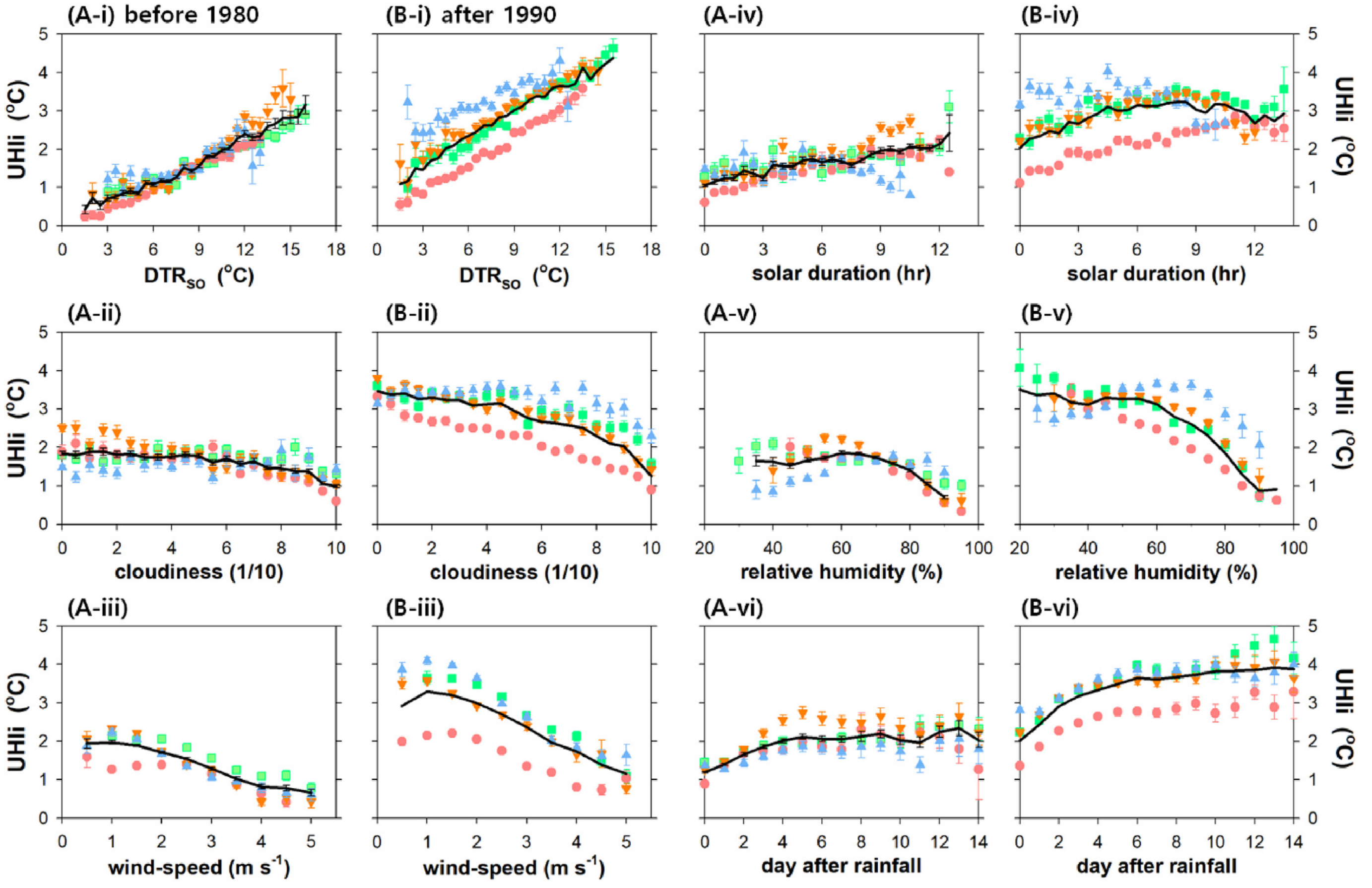

Fig. 7. Relationship between meteorological conditions and UHI intensity (UHIi) (A) before 1980 and (B) after 1990: (*i*) diurnal temperature range (°C), (*ii*) cloudiness (1/10), (*iii*) solar duration (hr d^{-1}), (*iv*) wind-speed (m s^{-1}), (*v*) relative humidity (%), and (*vi*) day after rainfall. Error bar indicates standard error ($\sigma/\sqrt{n}$).

UHIi of HW days is 2.5 ± 0.9 °C which is about 0.9 °C stronger than that of no HW days (1.6 ± 1.1 °C). The enhancement of UHIi in case of HW is consistent during the whole study period. Before 1980, UHIi of HW days is 1.8 ± 0.7 °C which is about 0.5 °C larger than it of no HWs days (1.3 ± 0.9 °C). After 1990, UHIi of HW and no HW days are 2.7 ± 0.9 °C and 1.9 ± 1.1 °C, respectively. Our observational evidence indicates that UHI exacerbates heat stress even more. These results are consistent with results from 21 cities in the US in the temperate climate zone by Zhao et al. (2018), which showed about 0.6 °C intensified nighttime UHIi of HWs during 1975–2004.

This synergetic interaction in temperate climate zone is probably because of the urban-rural difference in latent heat flux is maximized during HW, as the soil moisture of rural in the temperate climate zone remains high even in summer season (Li et al., 2015). Background weather conditions provide plausible explanations of such synergetic interaction between HW and UHIi in this study. Compared with no HW days (4,870 days), all the meteorological conditions on HW days (179 days) are favorable for intensifying the UHIi (Fig. 9). Indeed, HW occurs when the elapsed time of rainfall is large, therefore relative humidity is drier. In addition, HW days are more calm and clear, thus leading to larger DTR than no HW days.

4. Summary and conclusion

Cities in Korea has unique trajectory of urbanization and economic growth compared to other cities in the US and Europe because of compressed growth and dramatic progression of urbanization, and therefore provides unique opportunity to better understand temporal dynamics of UHI. In perspective of different stages of urbanization and economic growth, this study analyzed UHIi of the Seoul metropolitan area over the last 56 years (1962–2017). During the study period, urbanization made significant warming rate of about 1.7 °C increases in air temperature in the city center, the Seoul observatory (SO). This warming rate is about 0.8 °C larger than the adjacent rural area (KAO; +0.9 °C) and about 1.8 times larger than the global land temperature, indicating urbanization has a significant contribution (47%) to warming trend in Seoul.

Our further analysis reveals that evolution of urbanization such as invigoration and decline in urban vitality regulates UHIi with meteorological controls. Since 1960, there have been two major urban transformations around the SO, and the UHIi shows different temporal changes depending on the stages of urbanization: 1980–1990 and after late 1990's. During the first redevelopment in 1980–1990, LCZ surrounding the SO was changed from LCZ_3 (compact low-rise) to LCZ_2 (compact mid-rise) with population increases. In this period, the UHIi increased from around 1.5 °C to 3.0–3.5 °C. However, the UHIi declined after late 1990's with the inner-city decline and a few abrupt changes in UHIi in the financial crises despite change to open-high rise from compact mid-rise residential area in this period. Such decline of UHIi has not been reported in other Asian cities before (e.g., Kim and Baik, 2002; Kataoka et al., 2009). Our findings emphasize that UHIi must be understood not only with meteorological conditions, but also the urban metabolism including financial crisis and urban structure.

While the urban transformation processes and economic climate explained well the long-term trends (e.g., yearly and decadal scale) of UHIi, shorter temporal variability (from day-to-day to season-to-season) was well correlated to meteorological conditions. There was a positive relationship between UHIi and DTR which is consistent with previous studies. The UHIi decreased just after rain events, and it takes 5 days to regain its magnitude before rainfall. Importantly, the UHIi reinforced by ~0.9 °C in case of HW, indicating the positive feedback of HW by UHI through stronger UHIi in warmer background temperature accordingly.

Urban sprawl will occur rapidly in Asian cities soon and increases the possibility to mitigate UHI. Such changes in urban structure and function, however, make worse energy consumption efficiency by increasing per-capita urban space consumption (Newman and Kenworthy, 1989). Eventually, our findings have important implications for sustainability of urban management and planning to link urbanization with carbon emission, energy consumption, health issues related to heat wave and warming temperature under changing climate. Under projected climate scenarios, there will be changes in precipitation pattern with changes in monsoon system with global warming (Trenberth, 2011) and such change would modify temporal dynamics of UHIi accordingly. Furthermore, frequency of HW is expected to increase in most global land area in the future (Hartmann et al., 2013), and devastating heat wave would occur in urban area if there are no adaptation and mitigation urban development plans to reduce a synergetic interaction between UHIi and HW. Our findings indicate that the synergistic interaction of HW with UHI is closely related to

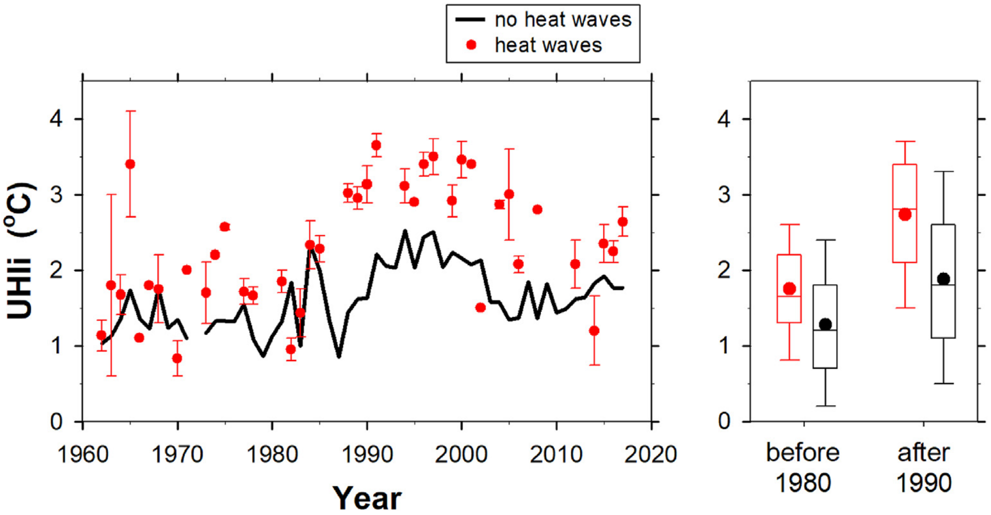

Fig. 8. UHI intensity (UHIi) during and no heat waves days in summer (June–August). Boxplot (right-hand side) indicates median and interquartile (box) with 10th and 90th percentile (whisker), and mean value (circle).

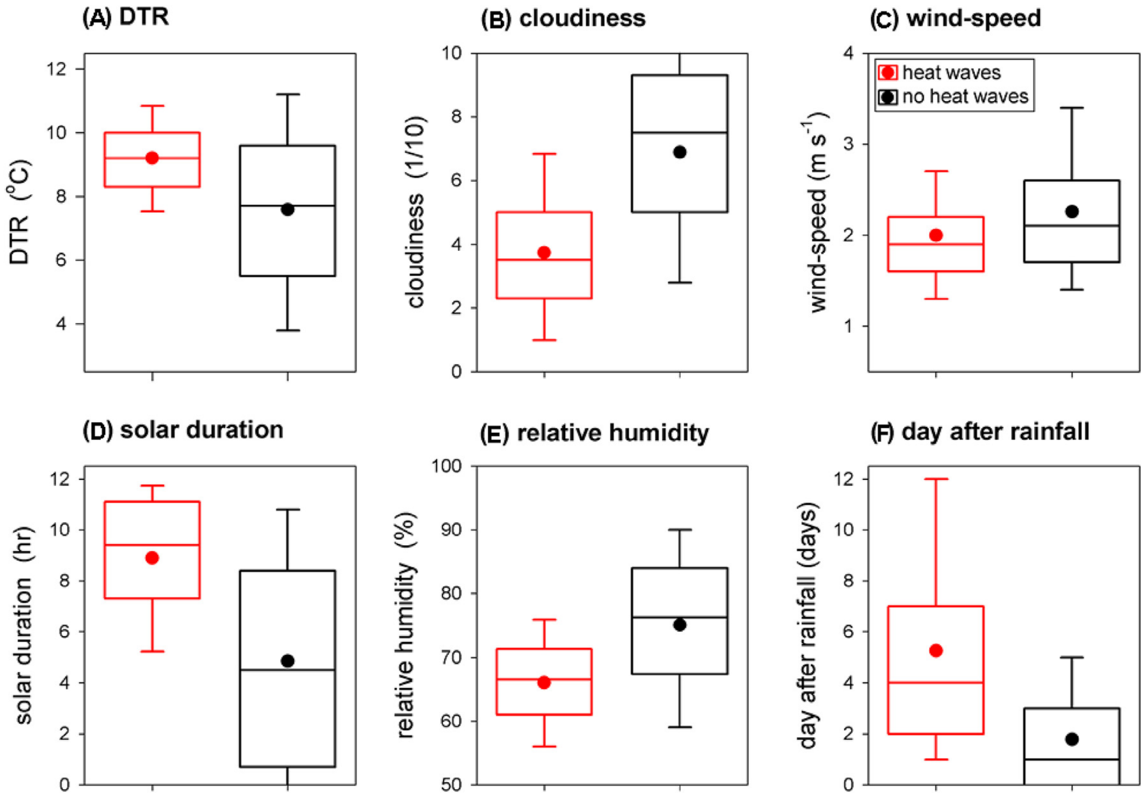

Fig. 9. Meteorological conditions on heat waves days (left; red) and no heat waves days (right; black): (A) diurnal temperature range (DTR), (B) cloudiness, (C) wind-speed, (D) solar duration, (E) relative humidity, and (F) day after rainfall. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

geographic location and monsoon climates as well as building structure and function. Accordingly, in the cities influenced by the monsoon activity, urban development policies consider strategic plans to mitigate harmful effects such as the synergistic interaction between UHI and HW.

Conflicts of interest

None.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.07.102.

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