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Daily maximum urban heat island intensity in large cities of Korea

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With 8 Figures

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Summary

This study investigates the characteristics of the daily maximum urban heat island (UHI) intensity in the six largest cities of South Korea (Seoul, Incheon, Daejeon, Daegu, Gwangju, and Busan) during the period 1973–2001. The annually-averaged daily maximum UHI intensity in all cities tends to increase with time, but the rate of increase differs. It is found that the average annual daily maximum UHI intensity tends to be smaller in coastal cities (Incheon and Busan) than in inland cities (Daejeon, Daegu, and Gwangju), even if a coastal city is larger than an inland city.

A spectral analysis shows a prominent diurnal cycle in the UHI intensity in all cities and a prominent annual cycle in coastal cities. A multiple linear regression analysis is undertaken in order to relate the daily maximum UHI intensity to the maximum UHI intensity on the previous day (PER), wind speed (WS), cloudiness (CL), and relative humidity (RH). In all cities, the PER variable is positively correlated with the daily maximum UHI intensity, while WS, CL, and RH variables are negatively correlated with it. The most important variable in all cities is PER, but the relative importance of the other three variables differs depending on city. The total variance explained by the multiple linear regression equation ranges from 29.9% in Daejeon to 44.7% in Seoul. A multidimensional scaling analysis performed with a correlation matrix obtained using the daily maximum UHI intensity data appears to distinguish three city groups. These groupings are closely connected with distances between cities. A multidimensional scaling analysis undertaken using the normalized regression coefficients obtained from the multiple linear regression analysis distinguishes three city groups. Notably, Incheon and Busan form one group, whose points in the two-dimensional space are very close. The results of a cluster analysis performed using the multivariate data of PER, WS, RH, and CL are consistent with those of the multidimensional scaling analysis. The analysis results in this study indicate that the characteristics of the UHI intensity in a coastal city are in several aspects different from those in an inland city.

1. Introduction

One of the most known phenomena associated with inadvertent climate change is the urban heat island (UHI), in which the air temperature in the urban canopy is higher than that in the surrounding rural area. The UHI intensity varies with urban size, urban surface characteristics, anthropogenic heat release, topography, and meteorological conditions (e.g. Landsberg, 1981; Oke, 1987). Many observational studies indicate that the UHI is prominent on calm, clear nights and its intensity can exhibit diurnal and seasonal cycles (e.g. Ackerman, 1985; Jauregui, 1997; Montavez et al., 2000). The UHI intensity is influenced by synoptic and mesoscale circulations (Yague et al., 1991; Yoshikado, 1994; Runnalls and Oke, 2000; Gedzelman et al., 2003). For example, in coastal cities under the influence of sea breeze circulation, the UHI intensity might be reduced by the intrusion of relatively cold air into the land and/or the enhanced wind speed due to the sea breeze. Many investigators showed that the maximum UHI intensity is well correlated with the population (e.g. Oke, 1973; Park, 1986). Also, it has shown that a strong relationship exists between the maximum UHI intensity and urban parameters such as sky view factor and built-up ratio (e.g. Park, 1986; Bottyan and Unger, 2003).

In a recent study, Kim and Baik (2002) investigated the daily maximum UHI intensity in Seoul, Korea using data measured at two meteorological observatories (an urban site and a rural site) during the period 1973–1996. Their results show that the average daily maximum UHI is weakest in summer and strong in autumn and winter. Similar to previous studies for other cities of the world, the daily maximum UHI intensity is more frequently observed in the nighttime than in the daytime, decreases as the wind speed increases, and is pronounced with clear skies. A multiple linear regression analysis was undertaken to relate the daily maximum UHI intensity to the meteorological elements of maximum UHI intensity on the previous day, wind speed, cloudiness, and relative humidity. The analysis results show that among those four elements the maximum UHI intensity on the previous day is the most important and that the relative importance among the elements varies depending on time of day and season.

This study extends our previous work (Kim and Baik, 2002) to characterize the daily maximum UHI intensity in the six largest cities of Korea and find its characteristic similarities and differences among the cities. In particular, we focus on characteristic differences in the UHI intensity between coastal and inland cities. For this, spectral analysis, multiple linear regression analysis, multidimensional scaling analysis, and cluster analysis are performed using observed data. In Section 2, data used and analysis method are described. In Section 3, analysis results are presented. Finally, a summary and conclusions are given in Section 4.

2. Data and analysis method

The data used in this study are from the archives of the Korea Meteorological Administration (KMA). The data contain near-surface air temperature ($z = 1.2 \sim 1.5$ m, z: height from the ground), wind speed, cloudiness, and relative humidity measured at meteorological observatories in the six largest cities of Korea (Seoul, Incheon, Daejeon, Daegu, Gwangju, and Busan) and surface air temperature at nearby meteorological observatories (Yangpyong, Ganghwa, Geumsan, Yeongcheon, Suncheon, and Geoje, respectively). The data used span the years from 1973 to 2001 and are at 6-h intervals (03, 09, 15, and 21 local times). In this study, the daily maximum UHI intensity of a city is defined as the maximum temperature difference between the city and its nearby observatories during a day. Figure 1 shows the locations of the six paired observatories. These pairs were chosen in previous studies on UHIs in Korea (Kim et al., 2000; Kim and Baik, 2002).

Table 1 lists the climatological values of meteorological elements during the period 1971–2000 in the six cities, together with the locations of observatories. Also, the populations of years 1973 and 2001 are listed. Korea belongs to a temperate climate zone with four distinct seasons. It is warm/hot and humid in summer with precipitation being concentrated in this season, and cold

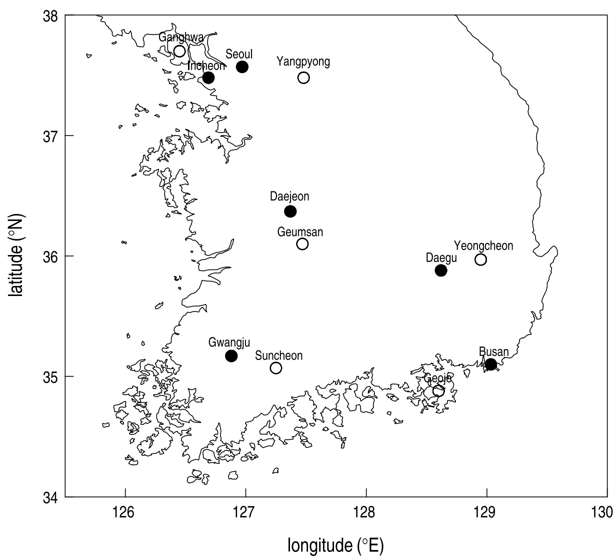

Fig. 1. The locations of meteorological observatories selected for this study. The distance between Seoul and Yangpyong observatories is 60 km, Incheon and Gwanghwa 33 km, Daejeon and Guemsan 32 km, Daegu and Yeongcheon 38 km, Gwangju and Suncheon 41 km, and Busan and Geoje 54 km

Table 1. The latitudes, longitudes, and elevations (above sea level) of meteorological observatories and the climatological values of meteorological elements from 1971 to 2000 in the six largest cities of Korea (KMA, 2001). The populations of 1973 and 2001 are listed in the last two rows. The cloudiness is expressed in values of 0–10, where 0 represents no clouds and 10 represents overcast skies

	Seoul	Incheon	Daejeon	Daegu	Gwangju	Busan
latitude (°N)	37°34′	37°28′	36°22′	35°53′	35°10′	35°06′
longitude (°E)	126°58′	126°38′	127°22′	128°37′	126°54′	129°09′
elevation (m)	85.5	68.9	68.3	57.6	70.5	69.2
mean temperature (°C)	12.2	11.7	12.3	13.7	13.5	14.4
maximum temperature (°C)	16.9	15.9	18.0	19.2	18.8	18.7
minimum temperature (°C)	8.2	8.3	7.5	9.0	9.1	11.1
wind speed ($m\,s^{-1}$)	2.4	3.3	1.7	2.9	2.2	4.0
relative humidity (%)	66.9	70.3	71.3	64.1	72.0	66.2
cloudiness	5.1	4.8	5.1	4.9	5.6	5.0
precipitation (mm)	1344	1152	1354	1028	1368	1492
population (1973, millions)	6.47	0.91	0.61	1.45	0.71	2.39
population (2001, millions)	10.06	2.56	1.42	2.54	1.40	3.72

and dry in winter. Seoul, the largest city in Korea, is located in the western part of the Korean peninsula and is close to the Yellow Sea. In Seoul, the annual mean temperature is 12.2 °C and the annual precipitation amount is 1344 mm. Incheon is a coastal city located west of Seoul. It is interesting to observe that the annual precipitation amount in Incheon (1152 mm) is 192 mm less than that in Seoul, considering that the distance between Seoul and Incheon observatories is only 39 km. Daejeon is an inland city located in the central western part of South Korea. The annual mean wind in Deajeon ($1.7\,m\,s^{-1}$) is weakest among the six cities. Daegu is an inland-basin city, which is located in the southeastern part of the peninsula. Daegu exhibits the highest annual mean maximum temperature (19.2 °C), the lowest annual mean relative humidity (64.1%), and the smallest annual precipitation amount (1028 mm). Gwangju is located in the southwestern part of the peninsula and has the highest annual mean relative humidity (72.0%) and cloudiness (5.6). Busan, the second largest city in South Korea, is a coastal city located in the southeastern tip of the peninsula. The wind speed in Busan ($4.0\,m\,s^{-1}$) is highest among the six cities. It should be noticed in Table 1 that the wind speed at the coastal cities (Incheon and Busan) is higher than that at the inland cities (Daejeon and Daegu) mainly due to the influence of the sea/land breeze circulation.

In order to characterize UHI intensity in the six cities, spectral analysis and relevant multivariate statistical analyses (multiple linear regression analysis, multidimensional scaling analysis, and cluster analysis) are performed with the UHI intensity data. A spectral analysis allows us to examine dominant periods in the time series data of UHI intensity. Following Kim and Baik (2002), the daily maximum UHI intensity of each city is related to meteorological elements through a multiple linear regression analysis. In the regression analysis, the dependent variable is the daily maximum UHI intensity and the independent variables are the maximum UHI intensity on the previous day, wind speed, cloudiness, and relative humidity. Before the multiple linear regression analysis is undertaken, each of the dependent and independent variables is subtracted from the mean and then divided by the standard deviation. This normalization makes it possible to compare regression coefficients for different variables.

A multidimensional scaling analysis is to compute coordinates for a set of points (or objects) in a small number of dimensions in such a way that the distances between pairs of the points match as closely as possible to measured dissimilarities between a corresponding set of objects. By scaling the points in two dimensions, we can obtain a spatial configuration of different cities grouped together depending on the similarities of the maximum UHI intensity. For this analysis, the degree of correlation among the temporal data of the daily maximum UHI intensity in the six cities is first estimated in the Pearson's product-moment correlation coefficient and from this calculation a correlation matrix is produced. With this correlation matrix, a multidimensional scaling analysis is performed in order to find similar city groups in the daily maximum UHI intensity data. Also, a multidimensional scaling analysis is performed with regression coefficients obtained through the multiple linear regression analysis. Finally, a cluster analysis based upon the Ward's minimum-variance method (Huh, 2002) is undertaken in order to find similar city groups in the multivariate data of the maximum UHI intensity on the previous day, wind speed, cloudiness, and relative humidity.

3. Analysis results

3.1 Observed daily maximum UHI intensity

Figure 2 shows the time series of annually-averaged daily maximum UHI intensity in the six cities, together with linearly fitted regression lines. The average annual daily maximum UHI intensity over the 29-year period is also shown in parentheses. In all cities, an increasing temporal trend in the daily maximum UHI intensity is observed, but the rate of increase differs city by city. Also, interannual variability is observed in the time series. The increasing temporal trend is essentially due to increasing urbanization. As expected, the average annual daily maximum

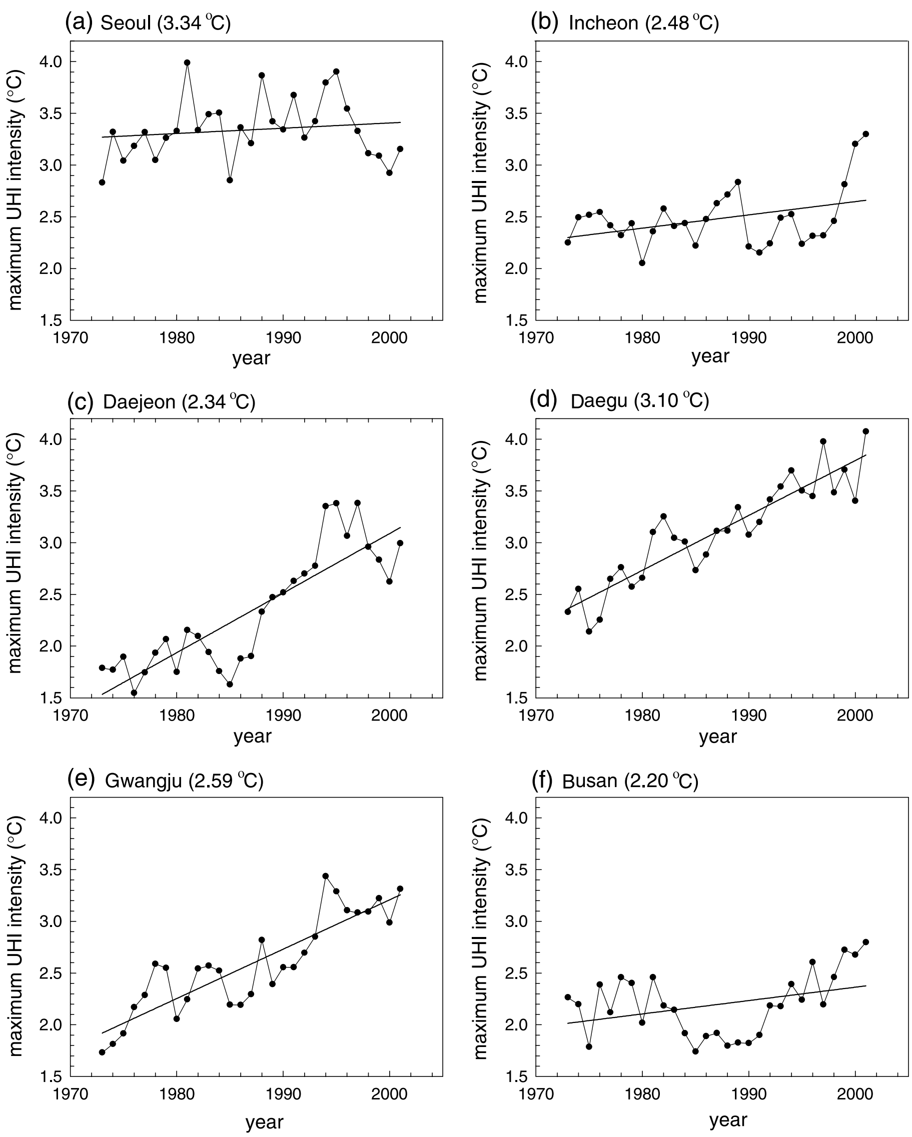

Fig. 2. The time series of annually-averaged daily maximum urban heat island (UHI) intensity in (**a**) Seoul, (**b**) Incheon, (**c**) Daejeon, (**d**) Daegu, (**e**) Gwangju, and (**f**) Busan. In each figure, the linear regression line is drawn and the average annual daily maximum UHI intensity over the 29-year period is shown in parentheses

UHI intensity is strongest in Seoul (3.34 °C). Although Busan is the second largest city, the average annual daily maximum UHI intensity is weakest (2.20 °C) due to oceanic influences such as sea/land breezes. This agrees qualitatively with the finding that sea breezes commonly reduce and delay UHI, as documented for the New York City region by Gedzelman et al. (2003). The wind speed in Busan is highest among the six cities (Table 1). It is well known that UHI intensity decreases as wind speed increases (e.g. Oke, 1987), so this can be a reason for the weakest daily maximum UHI intensity in Busan. Based upon the linear regression line, the rate of increase in the daily maximum UHI intensity in Seoul, Incheon, Daejeon, Daegu, Gwangju, and Busan over the 29-year period is 0.15, 0.38, 1.68, 1.54, 1.38, and 0.38 °C, respectively. Seoul experienced the smallest rate of increase in the daily maximum UHI intensity because Seoul had been rapidly urbanized before 1973. The daily maximum UHI intensity in Daejeon, Daegu, and Gwangju exhibits a more rapid rate of increase than that in the other cities. This is consistent with the fact that those three cities have been rapidly urbanized during the past three decades. Incheon also has been rapidly urbanized, but the increase rate is small (0.38 °C per 29 years, the same value as in Busan) due to oceanic influences.

All of the data for the daily maximum UHI intensity for each city were stratified into daytime/nighttime and season in order to examine their diurnal and seasonal characteristics. Also, the daily maximum UHI intensity for each city was related to each of wind speed and cloudiness. The analysis results showed that the daily maximum UHI intensity in all six cities more frequently occurs in the nighttime than in the daytime, decreases with increasing wind speed, and is more prominent with clear skies. These results are similar to those observed in many other cities (e.g. Yague et al., 1991; Klysik and Fortuniak, 1999; Montavez et al., 2000). The analysis results also showed that the average daily maximum UHI intensity is weakest in summer and strongest in autumn. This feature is common to all six cities. The average daily maximum UHI intensity in summer is 2.05 °C in Seoul, 1.73 °C in Incheon, 1.94 °C in Daejeon, 2.50 °C in Daegu, 2.08 °C in Gwangju, and 1.11 °C in Busan. The average daily maximum UHI intensity in autumn is 4.21 °C in Seoul, 3.26 °C in Incheon, 2.73 °C in Daejeon, 3.43 °C in Daegu, 3.19 °C in Gwangju, and 2.78 °C in Busan. The range in the average maximum UHI intensity between autumn and summer is largest in Seoul (2.16 °C) and smallest in Daejeon (0.79 °C).

Among the above-mentioned analysis results, the relation between the daily maximum UHI intensity and wind speed is presented in some detail with Fig. 3, which shows the frequency (in number) distribution of the daily maximum UHI intensity as a function of wind speed. In all cities, the frequency of the daily maximum UHI intensity is high in calm or weak wind conditions. In Seoul, a prominent peak in frequency is observed at a wind speed of about 1.3 m s^{-1} and a daily maximum UHI intensity of 4.4 °C. Note that for Seoul the intervals in UHI intensity and wind speed are finer in Fig. 3a of the present study than in Fig. 6a of Kim and Baik (2002). Because of this, the highest frequencies appear to be lower for the period 1973–2001 (this study) than for the period 1973–1996 (Kim and Baik, 2002). In Incheon, the range of the daily maximum UHI intensity is smallest for calm and weak winds among the six cities. In Daejeon where the mean wind is weakest among the six cities (Table 1), the highest frequency is observed in calm wind conditions and the daily maximum UHI intensity rapidly weakens as the wind speed increases. In Busan where the mean wind is strongest, high peak frequencies are observed in a broader range of wind speeds ($0 \sim 5$ m s^{-1}) compared with those in the other cities.

For very strong winds, the thermal contrast between a city and its nearby observatories disappears, suggesting that there can be a critical wind speed above which the UHI is not noticeable. As in Kim and Baik (2002), if the cases with a daily maximum UHI intensity of less than 0.3 °C are considered as the cases of the near-absence of UHIs, the critical wind speed is 6.9 m s^{-1} in Seoul, 12.1 m s^{-1} in Incheon, 6.4 m s^{-1} in Daejeon, 9.4 m s^{-1} in Daegu, 7.0 m s^{-1} in Gwangju, and 10.9 m s^{-1} in Busan.

As mentioned above, the average annual daily maximum UHI intensity over the 29 years is strongest in Seoul. However, in the last 10 years the average annual daily maximum UHI intensity

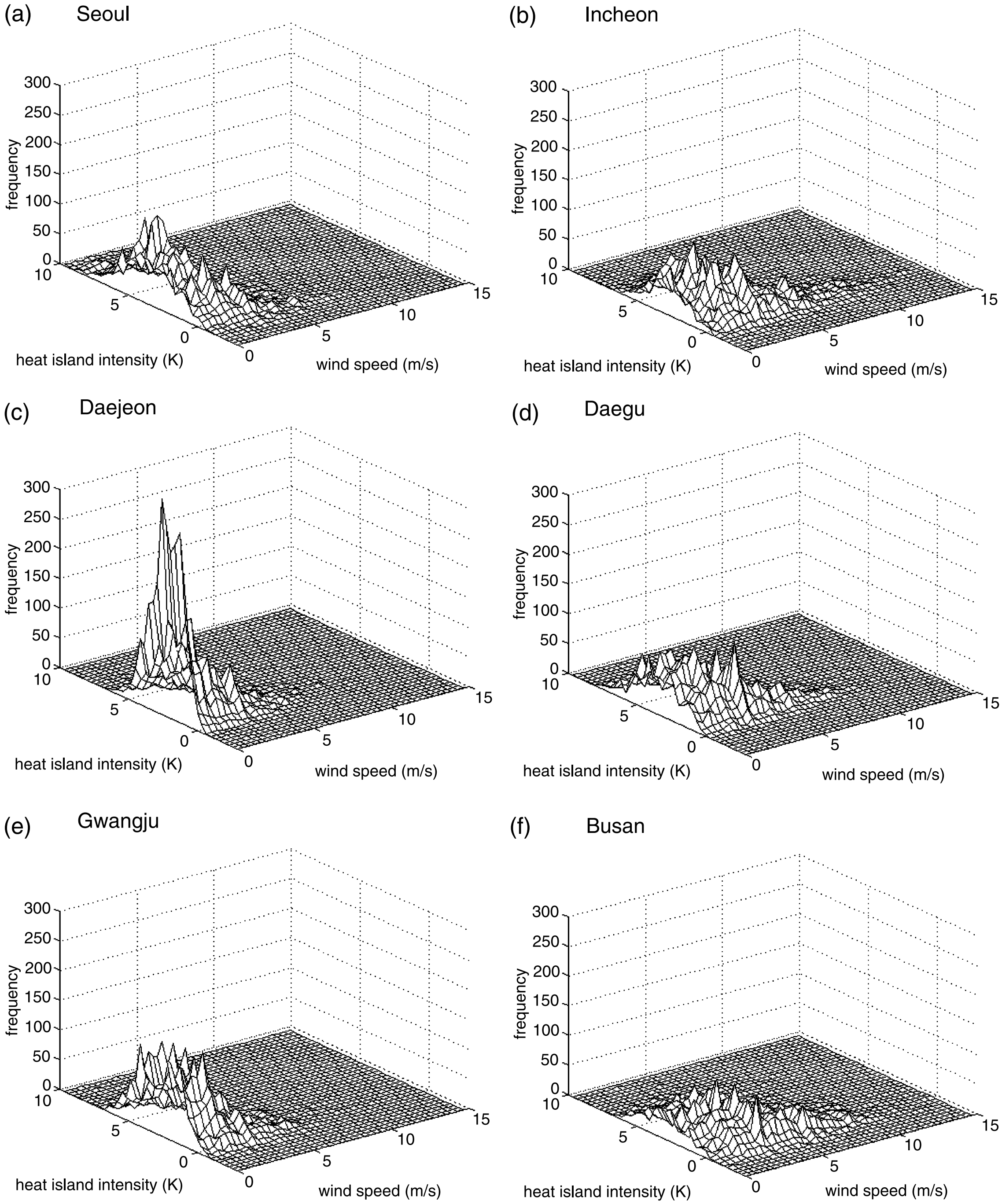

Fig. 3. The frequency distribution of the daily maximum UHI intensity as a function of wind speed in (**a**) Seoul, (**b**) Incheon, (**c**) Daejeon, (**d**) Daegu, (**e**) Gwangju, and (**f**) Busan

is stronger in Daegu than in Seoul, even though Daegu has 4 times smaller population (Table 1). Busan has the second largest population, but the daily maximum UHI intensity is weakest. Our analysis results for the six largest cities of Korea indicate that the population alone cannot be a sufficient factor to explain observed UHI intensity. In a study of examining a relationship between UHI intensity and population, one needs to take into account the rate of urbanization, the geographic location of city, and environment conditions around city observatory (street aspect ratio, sky view factor, etc.) as well as the climatology of wind, cloud, and humidity.

Following a study of the estimation of urban warming amounts due to urbanization in Korea (Kim et al., 1999), we calculated the population increase rate in %/year using population data of years 1973 and 2001. The population increase rate is 5.4%/year in Seoul, 9.7%/year in Incheon, 8.0%/year in Daejeon, 6.0%/year in Daegu, 6.8%/year in Gwangju, and 5.4%/year

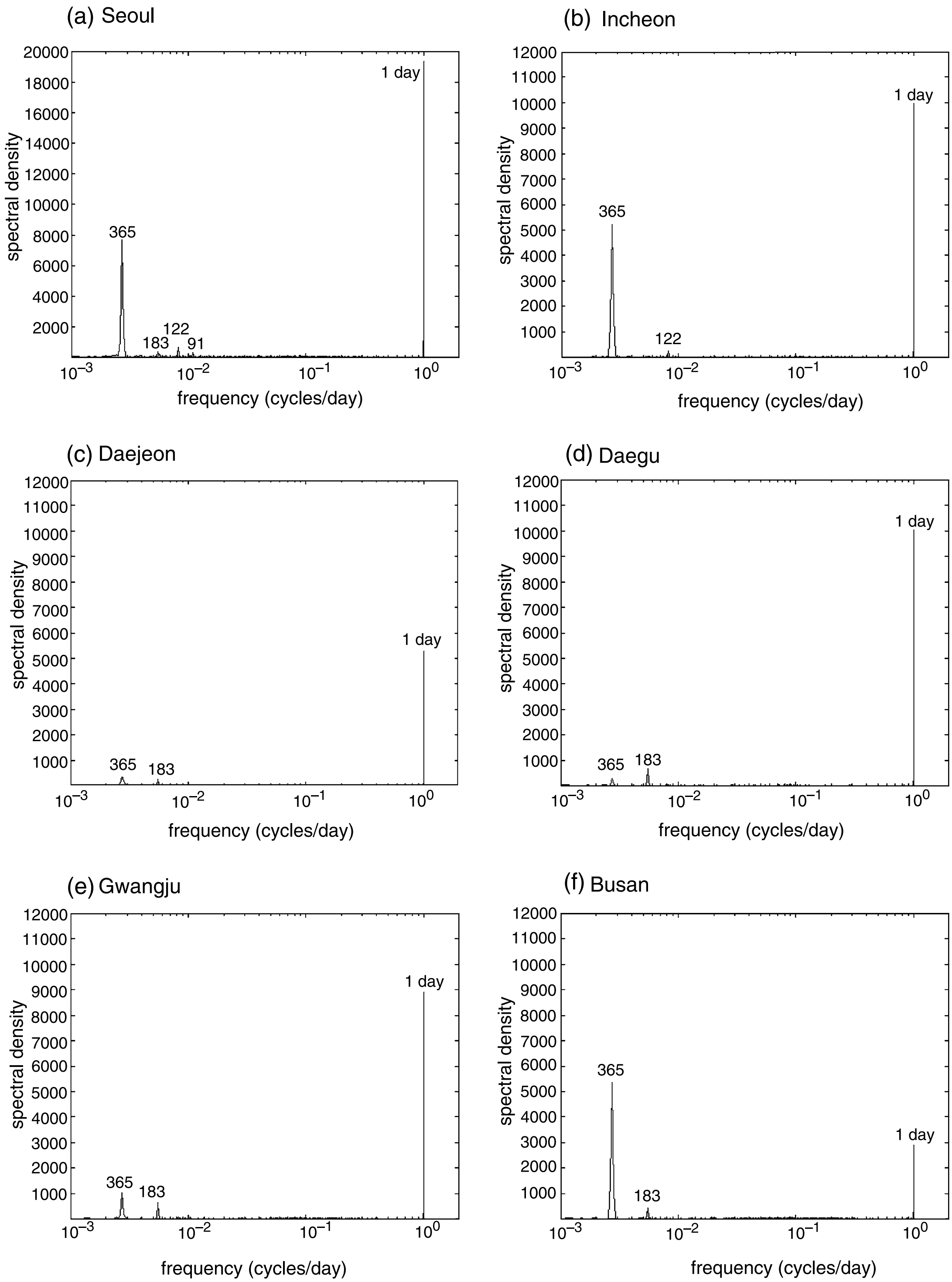

Fig. 4. The power spectrum of UHI intensity in (**a**) Seoul, (**b**) Incheon, (**c**) Daejeon, (**d**) Daegu, (**e**) Gwangju, and (**f**) Busan. The horizontal axis (frequency in cycles per day) is on a logarithmic scale and the vertical axis is on a linear scale. The dominant periods are shown

in Busan. The large increase rate of the average annual daily maximum UHI intensity in Daejeon, Daegu, and Gwangju over the 29 years (Fig. 2) is connected with the relatively large population increase rate. In Incheon, the increase rate of the average annual daily maximum UHI intensity is small due to oceanic influences, although the population increase rate is largest.

3.2 Spectral analysis

Figure 4 shows the power spectrum of UHI intensity for each city. The data used for the spectral analysis are the UHI intensity data at 6-h intervals. The spectral density peaks are strongest in Seoul (note that the vertical axis scale in Seoul is 1.7 times larger than that in the other cities). In all cities, a period of one day (diurnal cycle) in the power spectrum is prominent. The analysis indicated that the UHI intensity is strong in the nighttime and weak in the daytime, thus exhibiting its diurnal cycle. A period of one year (annual cycle) is prominent in Seoul and coastal cities (Incheon and Busan) and less prominent in Gwangju. Seasonally, the UHI intensity is strong in autumn and winter and weak in spring and summer, thus exhibiting its annual cycle. Note that the UHI intensity is expected to be weaker in spring and summer partly because those seasons are when sea/land breezes are most likely. In Daejeon and Daegu (inland cities), a one-year period is observed, but its signal is very weak. The diurnal and annual cycles of the UHI intensity are well documented in many previous studies (e.g. Runnalls and Oke, 2000). A period of 6-month, but with very weak signals, is observed in all cities except in Incheon where a period of 4-month is observed, although its signal is very weak.

3.3 Multiple linear regression analysis

Following the pioneering work of Sundborg (1950), the multiple linear regression analysis is performed to relate UHI intensity to meteorological elements. Our regression analysis differs from that of previous studies (e.g. Sundborg, 1950; Morris et al., 2001) in that each of the dependent and independent variables is properly normalized, as mentioned in Section 2, thus making it possible to compare regression coefficients for different variables. Figure 5 shows normalized regression coefficients for the four meteorological variables (PER: maximum UHI intensity on the previous day, WS: wind speed, CL: cloudiness, RH: relative humidity) for each city. The value in parentheses is the percent of total variance explained by the multiple linear regression equation. The sample size of each variable is 10592 over the 29-year period.

In all cities, the PER variable is positively correlated with the daily maximum UHI intensity, meaning that the daily maximum UHI intensity tends to be strong (weak) if the maximum UHI intensity on the previous day was strong (weak). WS, CL, and RH variables are negatively correlated with the daily maximum UHI intensity. These negative correlations are physically consistent, as explained in Kim and Baik (2002). The fact that UHI intensity becomes weaker as wind speed and amount of cloud cover become larger found in numerous cities of the world [e.g. Uppsala, Sweden (Sundborg, 1950); Seoul, Korea (Park, 1986); Lodz, Poland (Klysik and Fortuniak, 1999); Vancouver, Canada (Runnalls and Oke, 2000); Melbourne, Australia (Morris et al., 2001); New York, U.S.A. (Gedzelman et al., 2003)]. The most important variable in all cities is PER. The PER variable is meteorologically a persistent one and is dependent upon the duration of certain types of weather. The relative importance of the other three variables differs according to city. In Seoul, Incheon, and Daegu, the second most important variable is WS and the least important variable is RH. In Seoul, the normalized regression coefficient of WS (-0.24) is slightly larger in magnitude than that of CL (-0.21). In Deajeon, the contribution of CL to the daily maximum UHI intensity is much larger than WS or RH. This is a peculiar feature compared with the other cities. The stronger contribution of CL on the maximum UHI intensity in Daejeon might be due to light winds (Table 1). In Gwangju, each of WS, CL, and RH similarly contributes to the daily maximum UHI intensity. In Busan, the magnitude of normalized regression coefficient of CL is slightly larger than that of WS.

Although the cloudiness data used in this study do not contain information on cloud types, it is worthwhile to mention that for UHIs low-level cloudiness is more important than high-level

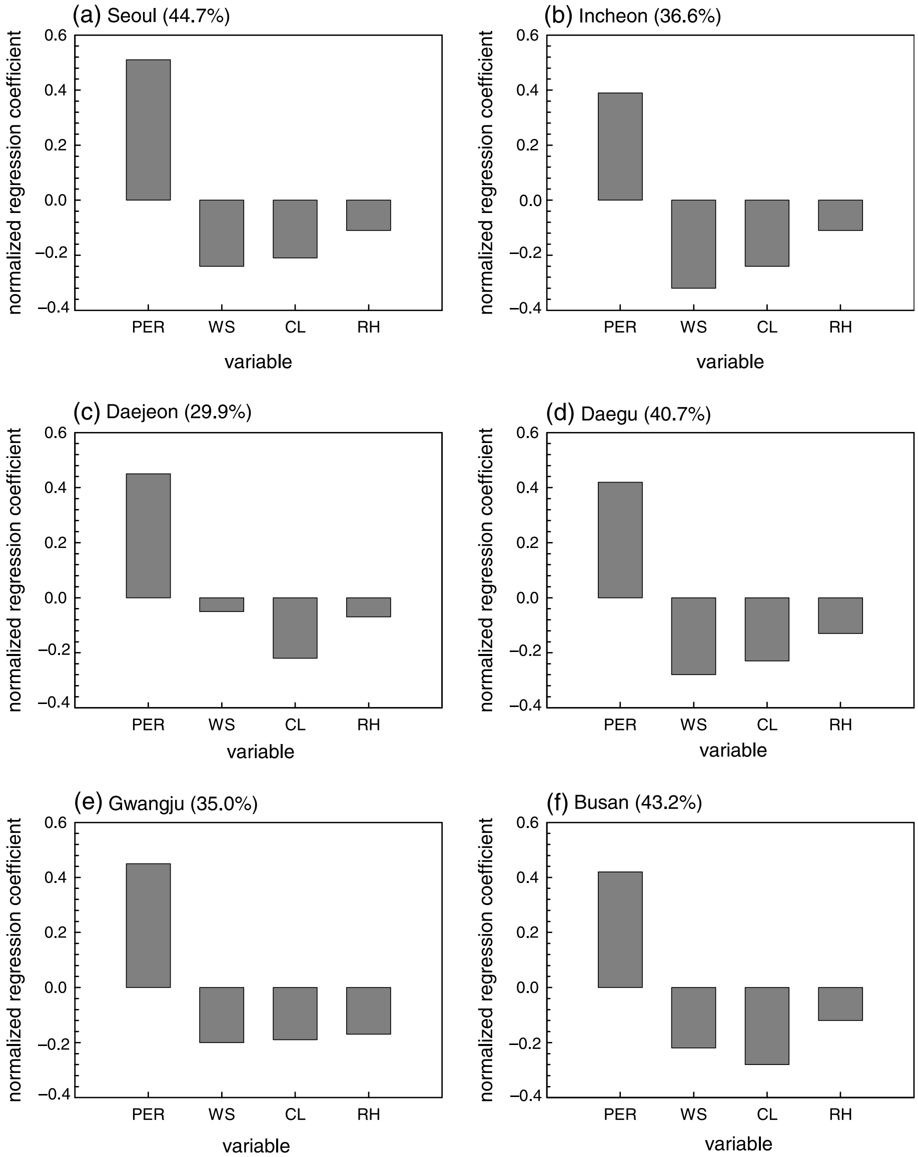

Fig. 5. Normalized regression coefficients of the four meteorological variables (PER: maximum UHI intensity on the previous day, WS: wind speed, CL: cloudiness, RH: relative humidity) for each city. All regression coefficients are statistically significant at the 95% confidence level. The percent of total variance explained by the multiple linear regression equation is shown in parentheses

cirrus clouds because cirrus clouds emit less infrared radiation. Therefore, the influence of cloudiness on the UHI intensity can be weakened if many cloudy days have only cirrus clouds.

The total variance explained by the multiple linear regression equation is 44.7% in Seoul, 36.6% in Incheon, 29.9% in Daejeon, 40.7% in Daegu, 35.0% in Gwangju, and 43.2% in Busan. The difference in the total variance between Seoul and Daejeon is 14.8%. This relatively large difference implies that the controlling effects of the four meteorological variables (PER, WS, CL, and RH) on the daily maximum UHI intensity are relatively much stronger in Seoul than in Daejeon. That the total variance is less than 50% in all cities implies that other relevant variables such as synoptic variables should be taken into account in order to increase the variance explained.

In addition to synoptic variables, a nonlinear regression equation might increase the total variance explained. This issue is addressed in Kim and Baik (2002). In that study, we performed multiple nonlinear regression analyses (power and quadratic regression models) and compared the performance of each model with that of a multiple linear regression model in predicting the maximum UHI intensity in Seoul. The results indicate that the total variance explained by the power regression equation is smaller than that explained by the multiple linear regression equation and that the prediction error from the power regression model is larger than that from the multiple linear regression model. On the other hand, the total variance explained by the quadratic regression equation is slightly larger than that explained by the multiple linear regression equation and the prediction error from the quadratic regression model is slightly smaller than that from the multiple linear regression model. As stated in Kim and Baik (2002), these results suggest that a multiple nonlinear regression model can improve upon a multiple linear regression model if a nonlinear functional relationship between dependent and independent variables is well chosen.

Since the PER variable is related to the persistence of meteorological elements, it is associated with the other variables WS, CL, and RH on the previous day. We performed a multiple linear regression analysis in which the PER variable was omitted. The analysis results show that WS, CL, and RH variables are, as expected, negatively correlated with the daily maximum UHI intensity and that the magnitude of normalized regression coefficient for each variable at each city is (slightly) larger than that in Fig. 5. For example, in Seoul, normalized regression coefficients for WS, CL, and RH are −0.30 (−0.24), −0.24 (−0.21), and −0.15 (−0.11), respectively, when the PER variable is omitted (included) in the regression analysis. However, the total variance explained by the multiple linear regression equation is much smaller when the PER variable is omitted; 19.2% in Seoul, 21.7% in Incheon, 9.8% in Daejeon, 23.5% in Daegu, 15.1% in Gwangju, and 26.6% in Busan. The inclusion of the PER variable greatly increases the total variance.

3.4 Multidimensional scaling analysis

A multidimensional scaling analysis was previously employed to produce an automatic grouped systemization of temperature variation trends in Spain (Onate and Pou, 1996). Here, a multidimensional scaling analysis is performed with the correlation matrix produced using the daily maximum UHI intensity data in the six cities. The scaling technique used in this study is based upon the work by Kruskal (1964a, 1964b). The analysis result is plotted in Fig. 6. The badness-of-fit criterion representing stress (a numerical measure of closeness) in a two-dimensional configuration is 0.49%. This indicates that

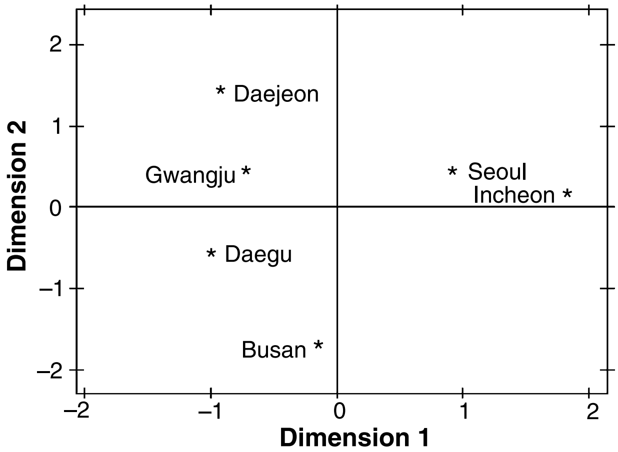

Fig. 6. A representation of the six cities in two dimensions through a multidimensional scaling analysis. The multidimensional scaling analysis is performed with the correlation matrix produced using the daily maximum UHI intensity data in the six cities

a representation of the cities in two dimensions is reasonable. Three city groups appear. Seoul and Incheon form one group, Daejeon and Gwangju form another, and Daegu and Busan form the last. These three groups essentially appear according to distances between cities (Fig. 1). If two cities are close to each other, meteorological conditions (including mesoscale and synoptic conditions) that affect UHI intensity are also similar. Thus, the temporal trend of the daily maximum UHI intensity of a city is more similar to that of a nearby city than to that of a distant city. This is reflected in Fig. 6.

From the multiple linear regression analysis, a linear combination of the four variables (PER, WS, CL, and RH) for the daily maximum UHI intensity of each city is obtained. For the linear system $Z = CX$ ($\mathrm{UHI}_i = c_{i1}\mathrm{PER} + c_{i2}\mathrm{WS} + c_{i3}\mathrm{CL} + c_{i4}\mathrm{RH}$, where c_{ij} are normalized regression coefficients and subscripts i and j denote the city and variable, respectively), a variance–covariance matrix of X is obtained. With this variance–covariance matrix, a multidimensional scaling analysis is undertaken in order to find city groups based upon the normalized regression coefficients obtained from the multiple linear regression analysis. The analysis result is plotted in Fig. 7. The badness-of-fit criterion in a two-dimensional configuration is 3.4%. Therefore, a representation of the cities in two dimensions is reasonable. Incheon and Busan

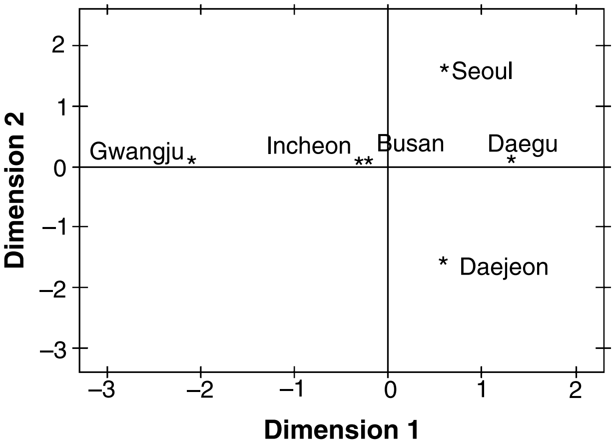

Fig. 7. A representation of the six cities in two dimensions through a multidimensional scaling analysis. The multidimensional scaling analysis is performed with the variance–covariance matrix produced using the normalized regression coefficients in the six cities obtained from the multiple linear regression analysis

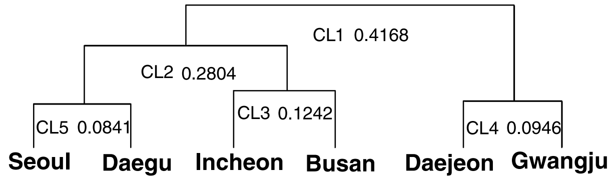

Fig. 8. A dendrogram constructed through a cluster analysis. The cluster analysis is performed using the multivariate data of the maximum previous day UHI intensity, wind speed, cloudiness, and relative humidity. CL means the cluster and the number in each cluster is the value of semi-partial R^2. The semi-partial R^2 is the decrease portion of the coefficient of determination resulting from joining two clusters

form one group, whose points in two-dimensional space are very close. Incheon and Busan have the common feature of being coastal cities, where the combined effects of WS and CL on the daily maximum UHI intensity appear to be relatively large and the effect of PER is relatively small. Seoul and Daegu may form another group or Daejeon and Daegu may form another group. Gwangju is most dissimilar to the other cities. Among the six cities, Gwangju exhibits in magnitude the smallest normalized regression coefficient of WS except for Daejeon, the smallest normalized regression coefficient of CL, and the largest normalized regression coefficient of RH.

3.5 Cluster analysis

In order to classify cities by climatological propensity affecting the daily maximum UHI intensity, a cluster analysis is performed using the multivariate data of the maximum UHI intensity on the previous day, wind speed, cloudiness, and relative humidity. The analysis result is shown in a dendrogram (Fig. 8). As expected from Fig. 7, Incheon and Busan form a cluster (cluster 3), where the daily maximum UHI intensity is weak and the wind speed is strong. These two cities are most similar to each other among the six cities. Seoul and Daegu form a cluster (cluster 5), where the daily maximum UHI intensity is strong. Daejeon and Gwangju form a cluster (cluster 4), where the wind speed is weak and the relative humidity is high. Next, clusters 3 and 5 are combined into a cluster (cluster 2) that includes Seoul, Daegu, Incheon, and Busan. These four cities have strong wind speed and low relative humidity. These cluster analysis results are similar to those of the multidimensional scaling analysis (Fig. 7).

3.6 Some discussions

Several points deserve to be mentioned. First, in practice, almost every definition of the UHI suffers from some degree of ambiguities or uncertainties. Here, we adopted a traditional two-station approach in which the UHI is the difference in near-surface air temperature between an urban observatory and a surrounding rural (or non-urban) observatory. In the present study, this approach was inevitably taken due to the limited number of observatories with long-term meteorological data records. An ideal definition of the (maximum) UHI at any time might be the difference between the maximum near-surface air temperature within a city and an averaged near-surface air temperature over its surrounding rural (or non-urban) stations. However, this definition could be applied only when there are numerous meteorological stations within and around a city.

Second, the temperature data used in the present study are in 6-h intervals (03, 09, 15, and 21 local times). This is because the temporal resolution common to all the 12 observatories over the period 1973–2001 is 6 h. Hence, the magnitude of the daily maximum UHI intensity of a city is understated. This can affect the analysis results to some extent. Since 1988, KMA has installed automatic weather stations (AWSs) over the country, measuring air temperature, wind speed and direction, and precipitation amount, and has operated them in order to provide real-time weather information and make better weather forecasts through data assimilation. Currently, 490 AWSs are in operation and the density of installed AWSs is relatively high in large cities of Korea. Particularly, there are 24 AWSs within Seoul and many AWSs are located on the outskirts of Seoul. The meteorological data at AWSs are saved in one-hour intervals. With these high spatial and temporal resolution data, the first and second problems mentioned above could be greatly resolved. We are now investigating the spatial and temporal structure of the UHI in Seoul using temperature data measured at 31 AWSs in the Seoul Metropolitan area.

Third, data inhomogeneities always raise a problem in UHI research. This issue is well addressed in a recent article by Peterson (2003), which assesses urban versus rural surface temperatures in the contiguous U.S.A. He applied a variety of adjustments to the data in order to remove the inhomogeneities (or biases) caused by differences in elevation, latitude, time of observation, instrumentation, and non-standard siting. He found that there is no statistically significant impact of urbanization in annual temperatures and postulated that this is due to micro- and local-scale impacts dominating over the mesoscale UHI. The data inhomogeneity problem is believed to be not so severe in the present study because of standardization by KMA and small differences in elevation and latitude between an urban observatory and its corresponding nearby observatory. However, during the period 1973–2001, many observatories moved to nearby locations (Yeongcheon in 1986, Ganghwa in 1989, Yangpyong in 1991, Gwangju in 1992, Daejeon in 1995, Geoje in 1995). In a future study of UHIs in the large cities of Korea, the impact of data inhomogeneity due to the observatory move needs to be carefully examined. Also, the impact of data inhomogeneity due to the land use/land cover needs to be studied.

Fourth, the estimation of urban warming caused by urbaninaztion is an important issue in global and regional climate research. Kim et al. (1999) estimated urban and greenhouse warming amounts over 12 stations of Korea for the 40-year period of 1954–1993. In their study, the greenhouse warming mode over Korea was identified with the first empirical orthogonal function (EOF) mode. It was found that the mean warming amount (urban plus greenhouse) over Korea is about 0.6 °C/40 years and the urban warming amount due to urbanization is about 0.4 °C/40 years. The urban warming amount due to urbanization over the 40-year period differs greatly for cities, with 0.68 °C in Seoul, 0.44 °C in Incheon, 0.84 °C in Daegu, 0.40 °C in Gwangju, and 0.45 °C in Busan [Daejeon is not included in Kim et al. (1999)]. The urban warming amount in Seoul and Daegu is meaningfully larger than that in Incheon, Gwangju, and Busan (note that these three cities have similar urban warming amounts). This pattern is consistent with the present result that the mean maximum UHI intensity in Seoul and Daegu is meaningfully stronger than that in the other four cities (see values in Fig. 2). This implies that the methodology used to estimate urban warming amount due to urbanization in Kim et al. (1999) is reasonable to a large extent, although some assumptions are made in their calculation. It is worth stating that research on observed UHI intensity and research on urban warming estimation in the context of global and regional climate is closely connected with and can benefit each other.

4. Summary and conclusions

The daily maximum urban heat island (UHI) intensity in the six largest cities of Korea (Seoul, Incheon, Daejeon, Daegu, Gwangju, and Busan) during the period 1973–2001 was characterized using statistical methods. In all cities, the annually-averaged daily maximum UHI intensity tends to increase with time, but the rate of increase differs city by city. The rate of increase in the annually-averaged daily maximum UHI intensity is closely connected with the urbanization rate for each city. For example, Seoul, the largest city in Korea, exhibits the largest daily maximum UHI intensity among the six cities. However, the rate of increase in the annually-averaged daily maximum UHI intensity is smallest because Seoul had experienced a rapid urbanization before 1973 in a comparative sense. The average annual daily maximum UHI intensity tends to be smaller in coastal cities (Incheon and Busan) than in inland cities (Daejeon, Daegu, and Gwangju), even if a coastal city is larger than an inland city.

The spectral analysis showed a prominent diurnal cycle in the UHI intensity in all cities, resulting from the fact that the UHI is strong in the nighttime and weak in the daytime. The multiple linear regression analysis was performed in order to relate the daily maximum UHI intensity to the four meteorological variables of maximum UHI intensity on the previous day (PER), wind speed (WS), cloudiness (CL), and relative humidity (RH). In all cities, the PER variable is positively correlated with the daily maximum UHI intensity, while WS, CL, and RH variables are negatively correlated with the daily maximum UHI intensity. These correlations are physically consistent. The PER variable is most important in all cities, but the relative importance of the other three variables is different depending on city. The total variance explained by the multiple linear regression equation ranges from 29.9% in Daejeon to 44.7% in Seoul. This result implies that the overall controlling effects of the four meteorological variables on the daily maximum UHI intensity are different depending on city. It also implies that other relevant variables such as synoptic variables should be taken into account in order to increase the total variance explained. The multidimensional scaling analysis performed with a correlation matrix that is obtained using the daily maximum UHI intensity data appears to distinguish three city groups. These groupings are closely connected with distances between cities. This result reflects the fact that meteorological conditions (including mesoscale and synoptic scale conditions) that affect UHI intensity are similar if two cities are close to each other. The multidimensional scaling analysis performed using the normalized regression coefficients obtained from the multiple linear regression analysis distinguishes three city groups. Notably, Incheon and Busan, coastal cities, form one group, whose points in the two dimensional space are very close. The results of the cluster analysis performed using the multivariate data of the maximum UHI intensity on the previous day, wind speed, cloudiness, and relative humidity are similar to those of the multidimensional scaling analysis.

One of the interesting results found in this study is that the characteristics of the UHI intensity in a coastal city are in several aspects different from those in an inland city. First, the rate of increase in the annually-averaged daily maximum UHI intensity is smaller in a coastal city than in an inland city (Fig. 2). Also, the average daily maximum UHI intensity tends to be weaker in a coastal city than in an inland city (Fig. 2). Second, there appears to be a prominent annual cycle in the UHI intensity in a coastal city, but its signal is very weak in an inland city (Fig. 4). Third, the overall controlling effects of the selected four meteorological variables on the daily maximum UHI intensity are very similar in coastal cities (Figs. 7 and 8). These differences might be closely associated with local atmospheric circulation peculiar to a coastal city, that is, sea/land breeze circulation. It would be interesting to examine whether those differences in the UHI intensity between coastal and inland cities are observed in other countries of the world.

It is well documented that cities affect weather and climate (Changnon, 1981; Cotton and Pielke, 1995). Interestingly, precipitation tends to increase downwind of urban areas (e.g. Changnon et al., 1991; Shepherd et al., 2002). A dynamical link between UHIs and downwind precipitation enhancement has been proposed (Baik et al., 2001). The UHI intensity in large cities of Korea is quite strong (Fig. 3) and the strong UHI can change local weather and climate. An interesting study would be to examine whether precipitation enhancement is observed in the downwind areas of those Korean cities and, if so, to examine how the UHI intensity is quantitatively related to the amount of precipitation enhancement. This will be investigated in the near future.

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References

Ackerman B (1985) Temporal march of the Chicago heat island. J Climate Appl Meteor 24: 547–554

Baik JJ, Kim YH, Chun HY (2001) Dry and moist convection forced by an urban heat island. J Appl Meteor 40: 1462–1475

Bottyan Z, Unger J (2003) A multiple linear statistical model for estimating the mean maximum urban heat island. Theor Appl Climatol 75: 233–243

Changnon SA Jr (1981) METROMEX: A review and summary, Meteorological Monograph No. 40 (Ed.). American Meteorological Society, 181 pp

Changnon SA, Shealy RT, Scott RW (1991) Precipitation changes in fall, winter, and spring caused by St. Louis. J Appl Meteor 30: 126–134

Cotton WR, Pielke RA (1995) Human impacts on weather and climate. Cambridge University Press, 288 pp

Gedzelman SD, Austin S, Cermak R, Stefano N, Partridge S, Quesenberry S, Robinson DA (2003) Mesoscale aspects of the urban heat island around New York City. Theor Appl Climatol 75: 29–42

Huh MH (2002) Multivariate data analysis for social sciences (in Korean). Jayuacademy, 223 pp

Jauregui E (1997) Heat island development in Mexico city. Atmos Environ 22: 3821–3831

Kim KH, Kim BJ, Oh JH, Kwon WT, Baek HJ (2000) Detection of urbanization effect in the air temperature change of Korea (in Korean). J Korean Meteor Soc 36: 519–526

Kim MK, Kang IS, Kwak CH (1999) The estimation of urban warming amounts due to urbanization in Korea for the recent 40 years (in Korean). J Korean Meteor Soc 35: 118–126

Kim YH, Baik JJ (2002) Maximum urban heat island intensity in Seoul. J Appl Meteor 41: 651–659

Klysik K, Fortuniak K (1999) Temporal and spatial characteristics of the urban heat island of Lodz, Poland. Atmos Environ 33: 3885–3895

Korea Meteorological Administration (2001) Climatological Normals of Korea. KMA, 632 pp

Kruskal JB (1964a) Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. Psychometrika 29: 1–27

Kruskal JB (1964b) Nonmetric multidimensional scaling: A numerical method. Psychometrika 29: 115–129

Landsberg HE (1981) The urban climate. Academic Press, 275 pp

Montavez JP, Rodriguez A, Jimenez JI (2000) A study of the urban heat island of Granada. Intl J Climatol 20: 899–911

Morris CJG, Simmonds I, Plummer N (2001) Quantification of the influences of wind and cloud on the nocturnal urban heat island of a large city. J Appl Meteor 40: 169–182

Oke TR (1973) City size and the urban heat island. Atmos Environ 7: 769–779

Oke TR (1987) Boundary layer climate, 2nd edn. Routledge, 435 pp

Onate JJ, Pou A (1996) Temperature variations in Spain since 1901: A preliminary analysis. Intl J Climatol 16: 805–815

Park HS (1986) Features of the heat island in Seoul and its surrounding cities. Atmos Environ 20: 1859–1866

Peterson TC (2003) Assessment of urban versus rural in situ surface temperatures in the contiguous United States: No difference found. J Climate 16: 2941–2959

Runnalls KE, Oke TR (2000) Dynamics and controls of the near-surface heat island of Vancouver, British Columbia. Phys Geogr 21: 283–304

Shepherd JM, Pierce H, Negri AJ (2002) Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. J Appl Meteor 41: 689–701

Sundborg A (1950) Local climatological studies of the temperature conditions in an urban area. Tellus 2: 222–232

Yague C, Zurita E, Martinez A (1991) Statistical analysis of the Madrid urban heat island. Atmos Environ 25B: 327–332

Yoshikado H (1994) Interaction of the sea breeze with urban heat islands of different sizes and locations. J Meteor Soc Japan 72: 139–142

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