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Characteristics of the Urban Heat Island in a High-Altitude Metropolitan City, Ulaanbaatar, Mongolia

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Abstract: Ulaanbaatar, the capital city of Mongolia, with a population of 1.1 million is located at an altitude of about 1350 m and in a valley. This study is the first to document the characteristics of the urban heat island (UHI) in Ulaanbaatar. Data from two meteorological stations, an urban site and a rural site, for the 31-year period 1980-2010 are used for UHI analysis. The average UHI intensity is 1.6°C. The UHI intensity exhibits a large seasonal dependence, being strongest in winter (3.3°C) and weakest in summer (0.3°C). The average daily maximum UHI intensity is 4.3°C. The strongest daily maximum UHI intensity occurs in winter with an average intensity of 6.4°C, and the weakest one occurs in summer with an average intensity of 2.5°C. The occurrence frequency of the daily maximum UHI intensity in the nighttime is 5.6 times that in the daytime. A multiple linear regression analysis is undertaken to examine the relative importance of meteorological parameters (previous-day maximum UHI intensity, wind speed, cloudiness, and relative humidity) that affect the daily maximum UHI intensity. The half of the variance (49.8%) is explained by the multiple linear regression model. The previous-day maximum UHI intensity is the most important parameter and is positively correlated with the daily maximum UHI intensity. Cloudiness is the second most important parameter and is negatively correlated with the daily maximum UHI intensity. When the data are classified into daytime/nighttime and season, the relative importance of the meteorological parameters changes. The most important parameter in spring and summer is cloudiness, while in autumn and winter it is the previous-day maximum UHI intensity.

Key words: Urban heat island, Ulaanbaatar, daily maximum urban heat island intensity, multiple linear regression model

1. Introduction

The near-surface air temperature is higher in an urban area than in its surrounding rural area. This phenomenon is known as the urban heat island (UHI). The causative factors for the UHI are well known. These include anthropogenic heat, impervious surfaces, and three-dimensional urban geometry (Ryu and Baik, 2012). Anthropogenic heat is an important causative factor, especially in the nighttime (Fan and Sailor, 2005). Artificial surfaces such as paved roads and buildings lead to a surface energy balance different from the surface energy balance for natural rural surfaces (Oke, 1982; Taha, 1997). Owing to the high heat storage capacity of urban surfaces and the low surface moisture availability of less vegetated urban surfaces, the sensible heat flux is larger and the latent heat flux is smaller in urban areas than in rural areas.

Meteorology affects UHIs. A number of studies have investigated the relationships between meteorological parameters/weather conditions and UHI intensity (e.g., Unger, 1996; Kim and Baik, 2002; Hinkel *et al*., 2003; Lee and Baik, 2010). An ideal meteorological condition for UHI development is a stable, calm, and clear sky condition (Oke, 1982). Under clear nighttime skies, rural surfaces tend to cool off faster than urban surfaces. Clouds and strong winds reduce the UHI intensity (Figuerola and Mazzeo, 1998; Morris *et al*., 2001).

The UHI intensity depends on the time of day and the season. The UHI intensity is stronger in the nighttime than in the daytime (e.g., Magee *et al*., 1999; Boo and Oh, 2000; Liu *et al*., 2007). In many cities around the world, a strong UHI intensity appears frequently in winter (e.g., Jauregui *et al*., 1992; Figuerola and Mazzeo, 1998; Montávez *et al*., 2000; Kim and Baik, 2002; Liu *et al*., 2007). For example, in Fairbanks, Alaska, U. S. A., stronger UHIs occurred in winter than in other seasons under calm and clear sky conditions (Magee *et al*., 1999). However, some cities do not experience the strongest UHI intensity in winter. For example, in Lodz, Poland, favorable conditions for UHI development occurred more frequently in summer and hence the strongest UHIs occurred on summer nights (Klysik and Fortuniak, 1999).

The near-surface air temperature in urban areas is at times or often lower than that of surrounding rural areas. This phenomenon is called the urban cool island. Granada, Spain, often experiences a lower air temperature in the urban area than in its surroundings, and the city's urban cool island intensity was reported to reach up to 2°C (Montávez *et al*., 2000). Kim and Baik (2004) reported daytime urban cool islands in Seoul, South Korea.

In this study, we investigate the characteristics of the UHI in Ulaanbaatar, the capital of Mongolia. The present study is motivated by the absence of research on the Ulaanbaatar UHI. The study area is characterized by unique geographical features and weather conditions. In section 2, the study area and the

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data used are described. In section 3, analysis results are presented. The summary and conclusions are given in section 4.

2. Study area and data

Mongolia is laid on the area between the permafrost to the north and desert lands to the south. Ulaanbaatar is the economic, social, political, cultural, and educational center of Mongolia. The city is located at an altitude of about 1350 m and in a valley between the northern foot of the Bogd Khan mountain with a maximum height of about 2200 m and the southern foot of branches of the Khentiin Nuruu mountain range with a maximum height of about 2800 m (Fig. 1a). The area belongs to a cold semi-arid climate (Bsk) according to the Köppen-Geiger climate classification (Kottek *et al*., 2006). Ulaanbaatar is known as the coldest capital city in the world because of its geographic features such as high altitude and landlocked location and the effects of wintertime Siberian high. Spring is dry and windy; summer is short; and winter is long and cold. The monthly average temperature for each month from October to March is below 0^{o}C, and the average temperature in winter is −19^{o}C. The annual precipitation amount is about 270 mm, and most precipitation occurs in summer. The population of Ulaanbaatar reached 0.8 (at the end of 1999) and 1.1 million (at the end of 2009), constituting 32% and 41% of the total population of Mongolia, respectively, and the increase is mostly because of rural-to-urban migration. The city area has almost doubled since 1974 (Amarsaikhan *et al*., 2009).

Ulaanbaatar station, located in a residential area that consists of ger-houses (traditional living houses known as yurts) and apartment buildings, represents an urban station. Buyant-Ukhaa airport station, located to the southwest of the city, represents a rural station. The Ulaanbaatar and Buyant-Ukhaa airport stations are chosen in this study because the other urban station has a gap in the measurement period and the other meteorological stations/posts outside the city have short data records. The distance between Ulaanbaatar station and Buyant-Ukhaa station is 10 km. Figures 1b and 1c show the surroundings of Ulaanbaatar and Buyant-Ukhaa stations, respectively. The altitudes of Ulaanbaatar and Buyant-Ukhaa stations are 1306 and 1286 m, respectively. The altitude difference between the two stations is very small. Thus, the altitude difference would have very little influence on the difference in air temperature between the two stations. The UHI intensity is defined as the difference in air temperature between Ulaanbaatar and Buyant-Ukhaa stations.

Data recorded in 3-h intervals from 1980 to 2010 are used in this study. Data are obtained from the State Archive and Database Center of the National Agency for Meteorology and Environmental Monitoring (NAMEM), Mongolia. Only 85% of the original data are used for UHI analysis; the rest of the original data (15%) are not used because of missing data and/or poor decoding.

3. Analysis results

a. Characteristics of the UHI

Figure 2a shows the time series of annually averaged daily mean temperature at Ulaanbaatar (urban) and Buyant-Ukhaa (rural) stations. Both time series exhibit a similar fluctuation pattern with an increasing temperature trend. It is clearly seen that the annually averaged daily mean temperature at Ulaanbaatar station is higher than that at Buyant-Ukhaa station. The difference in annually averaged daily mean temperature between the two stations, that is, the average UHI intensity, is 1.6^{o}C for the period of 1980-2010. Figure 2b depicts the time series of annually averaged daily minimum temperature at the two stations. The difference in annually averaged daily minimum temperature between the two stations is 3.2^{o}C for the period of 1980-2010. The linear increasing trend of the annually averaged daily minimum temperature at Ulaanbaatar station (0.6^{o}C per decade) is larger than that at Buyant-Ukhaa station (0.5^{o}C per decade). That is, the annually averaged daily minimum temperature has increased more at the urban station than at the rural station. The time series of annually averaged daily maximum temperature at Ulaanbaatar and Buyant-Ukhaa stations were also examined. The annually averaged daily maximum temperature at Ulaanbaatar station is similar to that at Buyant-Ukhaa station in its magnitude and its fluctuation

Fig. 1. (a) Locations of Ulaanbaatar and Buyant-Ukhaa stations that are marked by circle and triangle (also marked in (b) and (c)), respectively, and topography. The topographic elevation is derived from the Shuttle Radar Topography Mission (SRTM) database with a spatial resolution of 90 m (Jarvis *et al*., 2008). The solid line indicates the Ulaanbaatar city boundary. Surroundings of (b) Ulaanbaatar and (c) Buyant-Ukhaa stations from Google Inc. (2011).

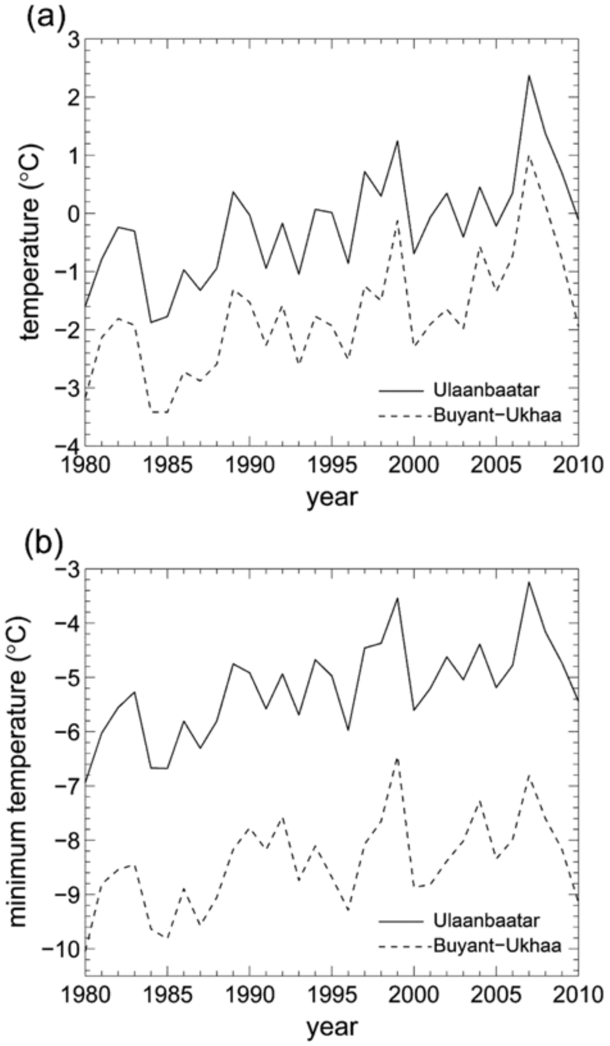

Fig. 2. Time series of (a) annually averaged daily mean temperature and (b) annually averaged daily minimum temperature at Ulaanbaatar and Buyant-Ukhaa stations.

pattern with an increasing temperature trend. Our results indicate that the difference in daily minimum temperature between the urban and rural stations is pronounced compared to that in daily maximum temperature.

Figure 3a shows the monthly variation of the UHI intensity. The UHI intensity is strongest in winter (3.3°C) and weakest in summer (0.3°C). The UHI intensity in winter in Ulaanbaatar is stronger than that (2.2°C) in Barrow, Alaska, U. S. A. (Hinkel *et al*., 2003). As pointed out by Goldreich (1984), the stronger UHI intensity is expected in high-altitude cities owing to inevitable space heating demand under cold conditions. The diurnal variation of the UHI intensity is depicted in Fig. 3b. The UHI intensity is stronger in the nighttime than in the daytime. This is a typical feature observed in cities (e.g., Magee *et al*., 1999). The UHI intensity is shown to be strongest at 0500 LST (2.9°C). Note that in this study the data at 0200, 0500, 2000, and 2300 LST are used as nighttime data and the data at 0800, 1100, 1400, and 1700 LST are used as daytime data. Around

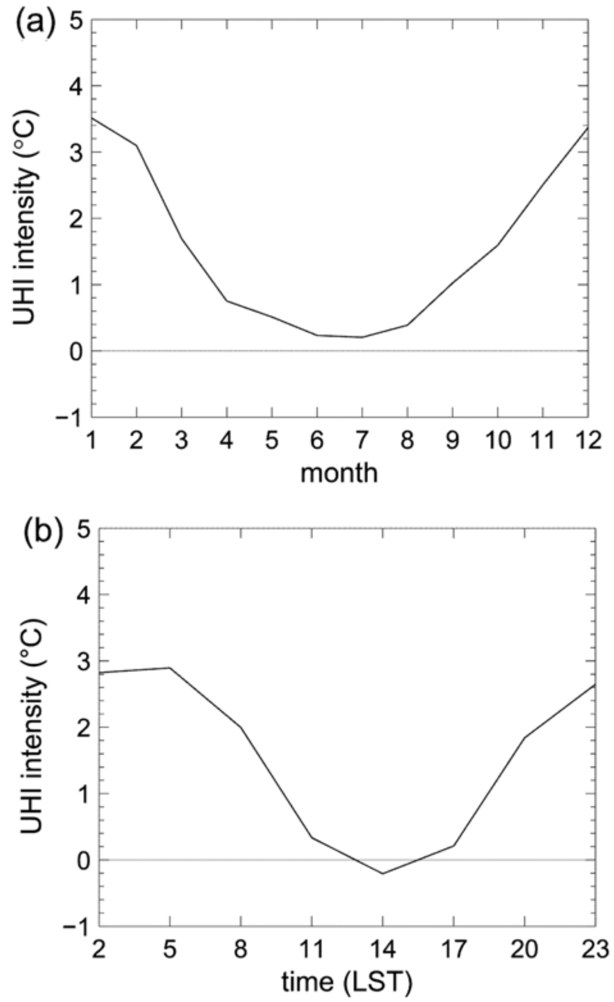

Fig. 3. (a) Monthly and (b) diurnal variations of the UHI intensity.

1400 LST, the temperature at the urban station is lower by 0.2°C than that at the rural station. In other words, the urban cool island appears. However, the urban cool island intensity is weak.

The air temperature in urban areas can be lower than that in surroundings. One of the possible reasons for the lower temperature in urban areas is the large thermal inertia of urban surface materials. Because of the large thermal inertia, urban surface materials store a large amount of heat and hence urban areas can warm up more slowly than rural areas do, resulting in a lower temperature in urban areas (Oke, 1987; Giovannini *et al.*, 2011). This can lead to the urban cool island.

Figure 4 shows the diurnal variation of the UHI intensity in each season. The average UHI intensity is strongest in winter and weakest in summer throughout a whole day. The average UHI intensity is 1°C in spring, 0.3°C in summer, 1.7°C in autumn, and 3.3°C in winter. In the daytime, the urban cool island occurs more frequently for more extended times with stronger intensity in summer than in spring and autumn. The average intensity of the urban cool island in summer is 0.4°C. Similarly, the urban cool island with an average intensity of

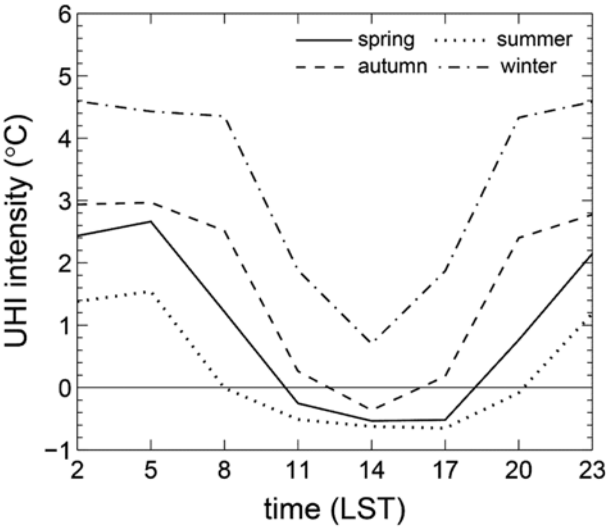

Fig. 4. Diurnal variation of the UHI intensity in each season.

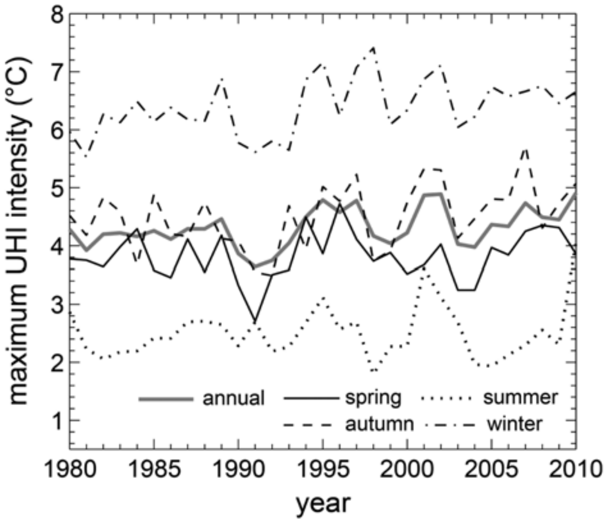

Fig. 5. Time series of annually and seasonally averaged daily maximum UHI intensities.

0.6°C occurred in summer in Birmingham, U. K. (Unwin, 1980).

In each season, the UHI is stronger in the nighttime than in the daytime. According to Ryu and Baik (2012), in the nighttime anthropogenic heat contributes greatly to the UHI intensity. In the nighttime, coal and wood burning in the traditional ger-houses for heating and cooking purposes likely contributes to increasing temperature in the urban area, especially in cold months.

b. Characteristics of the daily maximum UHI intensity

Figure 5 shows the time series of annually and seasonally averaged daily maximum UHI intensities. The annually averaged daily maximum UHI intensity exhibits an increasing trend for the period of 1980-2010. The increasing trend seems closely related to urbanization. Such an increasing trend in daily maximum UHI intensity was also observed in the six largest cities of South Korea (Kim and Baik, 2004) but with different rates because of the differences in the degree of urbanization and local geographical features. The average daily maximum UHI intensity for the period of 1980-2010 is 4.3°C, 2.7 times the average UHI intensity for the same period (1.6°C). The strongest daily maximum UHI intensity occurs in winter with an average intensity of 6.4°C, and the weakest daily maximum UHI intensity occurs in summer with an average intensity of 2.5°C. The average daily maximum UHI intensity is 3.8°C in spring and 4.5°C in autumn. The increasing rate of the daily maximum UHI intensity is larger in autumn and winter than in spring and summer.

Figure 6 shows the histogram of the frequency distribution of the daily maximum UHI intensity as a function of the time of day in each season. The frequency distribution is represented in fraction. In spring and summer, the occurrence frequency in

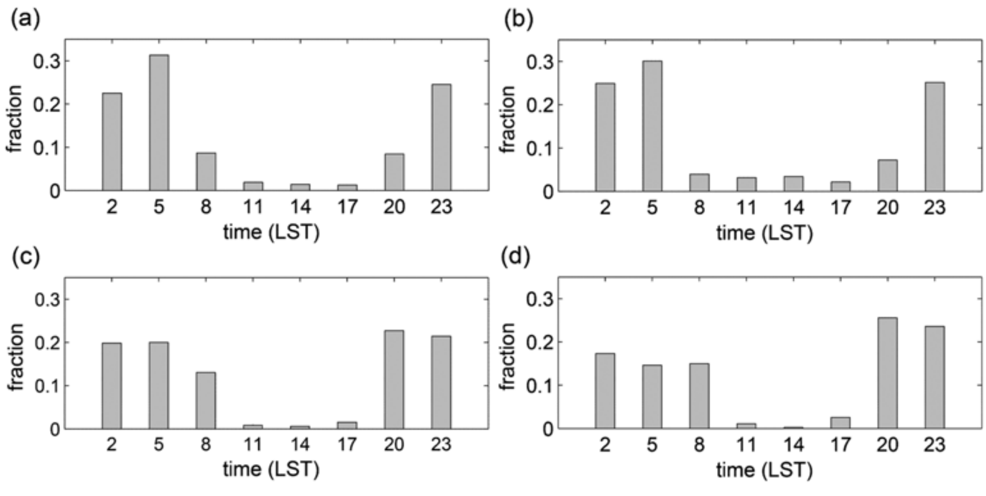

Fig. 6. Histogram of the frequency distribution (in fraction) of the daily maximum UHI intensity as a function of the time of day in (a) spring, (b) summer, (c) autumn, and (d) winter.

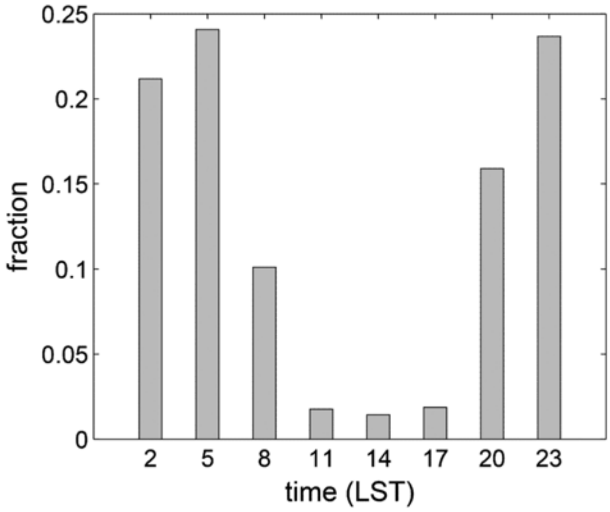

Fig. 7. Histogram of the frequency distribution (in fraction) of the daily maximum UHI intensity as a function of the time of day.

the nighttime is similar and the highest frequency occurs at 0500 LST. Unlike in spring and summer, the most prominent occurrence frequency of the daily maximum UHI intensity in autumn and winter is found at 2000 LST. The occurrence frequency at 0800 LST in autumn and winter is also greater than that in spring and summer. The increase in occurrence frequency in the morning and evening in autumn and winter is likely associated with increased heating activity in ger-houses in the morning and evening in cold months.

Figure 7 shows the histogram of the frequency distribution of the daily maximum UHI intensity as a function of the time of day. The occurrence frequency of the daily maximum UHI intensity in the nighttime is 5.6 times that in the daytime. This value is larger than the value for Seoul (3.3) (Kim and Baik, 2002).

c. Regression analysis

Following Kim and Baik (2002), a multiple linear regression analysis is performed to examine the relative importance of meteorological parameters that affect the daily maximum UHI intensity. Four meteorological parameters are considered: the maximum UHI intensity for the previous day (PER), wind speed (WS), cloudiness (CL), and relative humidity (RH). The data of wind speed, cloudiness, and relative humidity at Ulaanbaatar station are used for the analysis. The dependent (daily maximum UHI intensity) and independent variables (PER, WS, CL, and RH) are subtracted from the mean and then divided by the standard deviation. This normalization allows us to compare regression coefficients for different parameters and thus understand their relative importance.

The normalized regression coefficients for the four meteorological parameters and the percentage of the total variance explained by the multiple linear regression model are given in Table 1. The analysis is performed using all data and classified

Table 1. Normalized regression coefficients of the four meteorological parameters (PER, maximum UHI intensity for the previous day; WS, wind speed; CL, cloudiness; RH, relative humidity). r^2 is the percentage of the total variance explained by the regression model, and n is the sample size.

	All	Daytime	Night-time	Spring	Summer	Autumn	Winter
PER	0.48	0.48	0.44	0.30	0.20	0.41	0.32
WS	−0.14	−0.11	−0.14	−0.22	−0.14	−0.15	−0.05
CL	−0.34	−0.27	−0.36	−0.36	−0.44	−0.34	−0.26
RH	0.03	0.17	0.01	−0.06	−0.18	−0.02	0.02
r^2 (%)	49.8	55.6	46.6	33.4	33.4	38.1	18.5
n	11272	11272	11272	2845	2847	2818	2762

data in daytime/nighttime and season. All normalized regression coefficients are statistically significant at the 95% confidence level. Half of the variance (49.8%) is explained by the multiple linear regression model. The most important parameter among the four meteorological parameters is PER. The normalized regression coefficient of PER is 0.48. The stronger daily maximum UHI intensity is mostly led by stronger PER. The second most important parameter is CL. CL is negatively correlated with the daily maximum UHI intensity. That is, the daily maximum UHI intensity increases as CL decreases. The third most important parameter is WS. The daily maximum UHI intensity increases as WS decreases. Under calm or weak wind conditions, the daily maximum UHI intensity becomes strong. Magee *et al*. (1999) found that the increase in wind speed reduces the UHI intensity in Fairbanks and noted that the reason for the stronger UHI intensity under weak winds is because weak winds allow heat to accumulate near the surface without extensive mixing. Wind speed and UHI intensity have an inverse relationship, and stronger wind enhances turbulent mixing and advection, resulting in a decrease in the temperature difference between urban and rural areas (Oke, 1982). The importance of RH to the daily maximum UHI intensity is negligible. Kim and Baik (2004) calculated the normalized regression coefficients of the four meteorological parameters for the six largest cities of South Korea (Seoul, Incheon, Daejeon, Daegu, Gwangju, and Busan) and showed that a more important parameter between CL and WS is CL in Daejeon and Busan and WS in Seoul, Incheon, Daegu, and Gwangju. Oke (1982) mentioned that wind and cloud are surrogate parameters that determine the relative roles of turbulent and radiative transfer in producing temperature changes.

The percentage of the total variance explained by the multiple linear regression model in the daytime (55.6%) is larger than that in the nighttime (46.6%). The normalized regression coefficients of PER and RH are larger in the daytime than in the nighttime. The signs of the normalized regression coefficients for seasonally classified datasets except for RH are the same, but the magnitudes differ. The percentage of the total variance explained by the multiple linear regression model is smaller in winter than in other seasons. This is contrasted with the result for Seoul that shows the smallest percentage of the total variance in spring (Kim and Baik, 2002). The smaller percentage of the total variance in winter than in other seasons for Ulaanbaatar means that factors other than the four meteorological parameters affect the daily maximum UHI intensity more in winter than in other seasons. One of the important factors is anthropogenic heat. The anthropogenic heat would be larger and thus have a greater influence on the daily maximum UHI intensity in winter than in other seasons. The larger anthropogenic heat in winter can be one of the reasons for the smaller percentage of the total variance in winter. In spring and summer, the most important parameter is CL and the second most important parameter is PER. In autumn and winter, PER is the most important parameter and CL is the second most important parameter. Different weather conditions and anthropogenic heat amounts according to season are to some extent responsible for the different relative importance.

4. Summary and conclusions

Ulaanbaatar is a high-altitude metropolitan city located in a valley. In this study, the characteristics of the Ulaanbaatar UHI were for the first time documented using surface meteorological data for the 31-year period 1980-2010. The average UHI intensity for the period was found to be 1.6°C. The UHI intensity shows seasonal variations, being strongest in winter (3.3°C) and weakest in summer (0.3°C). The average daily maximum UHI intensity was found to be 4.3°C. The strongest daily maximum UHI intensity occurs in winter with an average intensity of 6.4°C, and the weakest daily maximum UHI intensity occurs in summer with an average intensity of 2.5°C. The occurrence frequency of the daily maximum UHI intensity in the nighttime is 5.6 times that in the daytime. These UHI features for Ulaanbaatar are qualitatively similar to UHI characteristics in many other cities around the world. The Ulaanbaatar UHI in winter, however, appears to be strong compared to the UHI in other cities (e.g., Seoul). We attribute this to the peculiar geographical features of Ulaanbaatar, wintertime weather that is strongly influenced by Siberian high, and anthropogenic heat resulting from the burning of coal and wood.

The relative importance of meteorological parameters that affect the daily maximum UHI intensity was examined through a multiple linear regression analysis. The parameters considered are the previous-day maximum UHI intensity, wind speed, cloudiness, and relative humidity. For all data, the multiple linear regression model explains half of the variance (49.8%). The previous-day maximum UHI intensity was found to be the most important parameter, showing a positive correlation with the daily maximum UHI intensity. Cloudiness is the second most important parameter, showing a negative correlation with the daily maximum UHI intensity. It was shown that the relative importance of the four meteorological parameters changes when the data are classified into daytime/nighttime and season. Cloudiness is the most important parameter in spring and summer, but the previous-day maximum UHI intensity is the most important parameter in autumn and winter.

Synoptic/mesoscale weather conditions can greatly affect UHIs. Classification and characterization of the UHI in Ulaanbaatar according to synoptic/mesoscale weather conditions (e.g., synoptic wind direction, non-precipitation days vs. precipitation days) would be an interesting research subject. The result that the multiple linear regression model explains half of the variance for all data implies that other parameters contribute equally to the daily maximum UHI intensity in Ulaanbaatar. Finding other influential parameters and including them in a multiple linear regression model would be another interesting research subject.

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