Cooling effect of an urban park by enhanced heat transport efficiency

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Abstract

The mitigation of the urban heat island effect is an important environmental issue for sustainable urban development. We quantified the relative contributions to surface cooling associated with land use changes from an urban center to an urban park using the temperature decomposition method, with one-year paired eddy covariance measurements in Sakai, Japan. The enhanced heat transport efficiency achieved through park creation decreased daytime surface temperatures by 3.9–4.9 K, which was the greatest contribution to daytime surface cooling throughout the season. The disappearance of anthropogenic heat flux due to park creation reduced nighttime surface temperatures by 0.1–0.6 K, which was the greatest contribution at night in summer months. Enhancing heat transport efficiency through urban greening is thus a good mitigation strategy for cooling urban surfaces.

Key words: Eddy covariance, Land cover change, Local climate, Perturbation analysis, Surface energy exchange

1. Introduction

Human-induced land cover change alters surface energy exchange, resulting in changes in local and regional climate. The urban heat island (UHI) phenomenon is the most commonly known problem that alters surface energy exchange (Oke *et al.*, 2017). UHI was first detected in terms of surface air temperatures measured within the urban canopy layer at fixed points (Landsberg, 1981) but was recently detected in terms of surface temperatures (skin temperatures often measured by remote sensing) and air temperatures above the urban boundary layer (Oke *et al.*, 2017). The differences in the UHI effects could be due to different processes at the microscale for surface temperature UHIs, at the local scale for surface air temperature UHIs, and at the local to mesoscale for boundary layer temperatures (Oke *et al.*, 2017).

The intensity of the UHI is determined by superimposed changes in multiple radiative and biophysical factors. Zhou *et al.* (2016) found, that in China, the magnitudes of the daytime UHI intensities for surface temperatures were greater in cities located in regions with higher precipitation, suggesting the importance of evaporative cooling in surrounding regions. Other factors also play important roles in the UHI effect, including changes in evaporation (Taha, 1997), heat transport efficiency (Zhao *et al.*, 2014), surface albedo (Kolokotroni and Giridharan, 2008), and anthropogenic heat (Ichinose *et al.*, 1999). The relative contributions of these factors are currently under debate and could depend on the cities (Cao *et al.*, 2016; Zhao *et al.*, 2014). To date, the direct measurements of surface energy exchange for elucidating the detailed mechanisms of the UHI effect are lacking.

Urban parks are often cooler than surrounding cities and are thus often known as park cool islands (Spronken-Smith and Oke, 1998). Air temperatures in urban parks were found to be up to 5 K lower than those in their surroundings (Chen *et al.*,

2012; Sugawara *et al.*, 2016; Spronken-Smith and Oke, 1998). Factors contributing to park cooling effects are low heat storage, tree shade (Hamada and Ohta, 2010), and evaporative cooling (Spronken-Smith *et al.*, 2000). The cool island phenomenon has been measured in urban parks, but the detailed mechanisms of cooling have still not been quantitatively evaluated.

The consequence of land use change on the local climate has been evaluated by analyzing the surface energy balance (Bright *et al.*, 2015). The temperature decomposition method is a kind of linear perturbation analysis that utilizes paired measurements of surface energy exchange from contrasting land cover types in the same region (Lee *et al.*, 2011). This method quantifies the contributions of each biophysical component to surface cooling and warming by land use change (Cao *et al.*, 2016; Chen and Dirmeyer, 2016; Zhao *et al.*, 2014). Zhao *et al.* (2014) combined this method with an earth system model and clarified that the UHI for surface temperatures in North America was mostly caused by reduced heat transport efficiency (3.0 ± 0.3 K warming) in the daytime under humid climates and by large heat storage (approximately 1–2 K warming) at night in all climate zones. The application of this method with direct flux measurements could be helpful in clarifying the role of urban green space and providing effective mitigation plans for UHIs.

Eddy covariance measurements provide direct estimates of surface energy exchange in urban areas (Ando and Ueyama, 2017; Grimmond and Oke, 1999; Moriwaki and Kanda, 2004). Compared with those in natural and managed ecosystems, eddy covariance measurements are limited in urban areas, partly due to the difficulty of deploying instrumentation in urbanized areas (Oke *et al.*, 2017), resulting in uncertainties in the urban surface energy balance. Consequently, perturbation analysis, which is often conducted using eddy covariance measurements in ecosystem studies (Juang *et al.*, 2007; Stoy *et al.*, 2006), is not conducted in urban areas. The direct measurements of surface energy exchange could improve our understanding of the surface energy balance in urban areas.

In this study, we clarified the surface cooling mechanism of urban parks based on surface energy balance measurements in a dense urban built-up area (Ando and Ueyama, 2017) and

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a forested urban park (Ueyama and Ando, 2016) in Sakai, Japan. We quantified the relative contributions to the daytime and nighttime surface cooling associated with land use change from a dense urban built-up area to a large park (hereafter, park creation) using the temperature decomposition method. The estimated surface cooling is for surface temperature rather than air temperature, because translating surface to air temperature change could depend on the spatial scale of land cover change. Thus, the estimated cooling in this study is the upper limit of the expected air temperature change near the surface (Juang *et al.*, 2007).

2. Methods

2.1. Sites and observations

We measured surface energy fluxes and environmental variables at two urban locations in Sakai, Osaka, Japan (Ando and Ueyama, 2017; Ueyama and Ando, 2016). The Sakai City Office (SAC) site (34°34'25"N, 135°28'59"E) is located in a dense urban built-up area comprising both residential and commercial buildings. The mean building height is 10.7 m, but buildings higher than 20 m are an average of 36 m high (Ando and Ueyama, 2017). Plan area index for buildings is 0.33. Oizumi Ryokuchi (IZM) (34°33'48"N, 135°32'1"E) is a large urban park, 101.5 hectares in size, located 4 km east of SAC. The eddy covariance and meteorological observations at SAC were conducted on a tower on the roof of the Sakai City Office (111 m above ground level). The measurements at IZM were conducted on a tower (30 m above ground level) located at the eastern edge of the park. Supporting meteorological and environmental variables were also measured on the roof of a building at Osaka Prefecture University (34°32'N, 135°30'E) within the city. Details for the three sites, instrumental setup, analyses, and general characteristics of turbulent fluxes have been described by Ueyama and Ando (2016) and Ando and Ueyama (2017).

2.2. Data analysis

We estimated the surface cooling associated with park creation using the temperature decomposition method (Lee *et al.*, 2011; Zhao *et al.*, 2014). This method separates the contributions to surface temperature change into individual drivers: surface albedo (α), aerodynamic resistance to heat (r_a) ($s\ m^{-1}$), Bowen ratio (β), storage heat flux (Q_s) ($W\ m^{-2}$), and anthropogenic heat flux (Q_f) ($W\ m^{-2}$). The surface temperature changes ($\Delta T_{s,calc}$) associated with park creation can be decomposed as

$$\begin{aligned} \Delta T_{s,calc} \approx & \frac{-\lambda_0}{1+f} R_{sd} \Delta \alpha + \frac{-\lambda_0}{(1+f)^2} (Q^* - Q_s + Q_f) \Delta f_1 \\ & + \frac{-\lambda_0}{(1+f)^2} (Q^* - Q_s + Q_f) \Delta f_2 + \frac{-\lambda_0}{1+f} \Delta Q_s + \frac{-\lambda_0}{1+f} \Delta Q_f \\ & + \frac{-\lambda_0}{1+f} \Delta R_{sd} + \frac{-\lambda_0}{1+f} \Delta R_{ld}, \end{aligned} \quad (1)$$

where $\lambda_0 = 1/4\sigma T_s^3$ is the local climate sensitivity ($K\ W^{-1}\ m^2$), σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8}\ J\ m^{-2}\ s^{-1}\ K^{-4}$), f (> 0) is the energy redistribution factor, R_{sd} is the downward shortwave radiation ($W\ m^{-2}$), R_{ld} is the downward longwave radiation ($W\ m^{-2}$), Q^* is the net radiation ($W\ m^{-2}$), and Δ is the land cover change effect, which is represented by the values at IZM minus those at SAC. f , Δf_1 , and Δf_2 are expressed as

$$f = \frac{\rho_a c_p}{4r_a \sigma T_s^3} \left(1 + \frac{1}{\beta} \right), \quad (2)$$

$$\Delta f_1 = \frac{-\lambda_0 \rho_a c_p}{r_a} \left(1 + \frac{1}{\beta} \right) \frac{\Delta r_a}{r_a} \quad (3)$$

and

$$\Delta f_2 = \frac{-\lambda_0 \rho_a c_p}{r_a} \frac{\Delta \beta}{\beta^2}, \quad (4)$$

where ρ_a is the air density ($kg\ m^{-3}$) and c_p is the specific heat ($1004\ J\ K^{-1}\ kg^{-1}$). In Eq. 1, the terms on the right side are the surface temperature difference between the urban built-up area and the urban park associated with the difference in surface albedo (term 1), heat transport efficiency (term 2), evaporation (term 3), heat storage (term 4), anthropogenic heat emissions (term 5), downward shortwave radiation (term 6), and downward longwave radiation (term 7). In this study, we neglected terms 6 and 7, because the two sites were located less than 4 km apart; thus, the averaged downward radiations were assumed to be the same.

The qualified sensible and latent heat fluxes (Ando and Ueyama, 2017; Ueyama and Ando, 2016) were used for the period from January 28, 2015 to March 10, 2016. We eliminated the low turbulence data when the friction velocity was less than $1.0\ m\ s^{-1}$. Based on the flux footprint model (Kormann and Meixner, 2001), we only used data in which more than 80% were contributed by urban areas for SAC (Ando and Ueyama, 2017) and 50% were contributed by the urban park for IZM (Ueyama and Ando, 2016). For analysis in IZM, we chose the relaxed criterion to increase data coverage. Despite the relaxed criterion, the qualified data showed a clear biological signal, such as daytime CO_2 uptake (Ueyama and Ando, 2016), and thus, could be used as a flux at the urban park. The flux divergence of the sensible heat flux between the surface and the measurement height was estimated based on a storage flux by air temperature at the height of 111 m and found to be 17% on average at the SAC site. Nevertheless, we did not correct this effect, because a single point measurement could not represent the heterogeneous air temperatures and humidity within the flux footprint. We only used the non-gap-filled eddy covariance data for the temperature decomposition method; thus, Eq. 1 was only applied for the periods when the paired data were available at the two sites.

The aerodynamic resistance to heat (r_a) was estimated by the logarithm law, which is expressed as

$$r_a = \frac{1}{ku_*} \left[\ln \left(\frac{z-d}{z_m} \right) + \ln \left(\frac{z_m}{z_h} \right) - \psi_h \left(\frac{z-d}{L} \right) \right], \quad (5)$$

where k is the von Kármán constant ($= 0.4$), u_* is the friction velocity ($m\ s^{-1}$), z is the measurement height (m), d is the displacement height (m), z_m is the roughness length for momentum (m), z_h is the roughness length for heat (m), ψ_h is the integrated stability function for heat, and L is the Obukhov length (m). Because the measurement height in SAC (111 m) was much higher than that in IZM (30 m), the value of z in IZM was adjusted to 111 m when calculating r_a using Eq. 5. For SAC, d and z_m were estimated by the method proposed by Kanda *et al.* (2013), considering the vegetative fraction (0.11; Ando and Ueyama, 2017) (Kent *et al.*, 2017): $d = 19.5\ m$ and $z_m = 1.78\ m$. For estimating the plan area index for the vegetative surface, we used

a constant leaf-on value of 0.2 for the aerodynamic porosity due to the lack of information on evergreen/deciduous fraction at the site. This value could overestimate d and z_m , but the overestimates were minimal because of the low vegetative fraction (Kent *et al.*, 2017). The plan area index, including vegetation, was calculated as 0.42 for SAC. For IZM, d and z_m were estimated at 0.7 and 0.1 times the mean tree height (12.3 m), respectively.

To estimate aerodynamic resistance to heat, we calculated the value of kB^{-1} , which is defined as $\ln(z_m/z_h)$. For SAC, we used a model for kB^{-1} (Kanda *et al.*, 2007), which was developed using turbulent flux measurements at an idealized miniature city that consisted of an aligned array of 1.5 m concrete cubes over a 100 m $\times$ 50 m concrete surface. For IZM, the value of kB^{-1} was the weighted mean of each land cover from the literature for each land cover type: 2.25 for vegetation (Garratt, 1994; Ma *et al.*, 2008), 4.0 for bare soil (Ma *et al.*, 2008), and the model value (Kanda *et al.*, 2007) for concrete. The areal fractions in IZM were 0.74 for vegetation, 0.07 for bare soil, and 0.19 for concrete. Finally, 25% to 75% percentile of kB^{-1} ranged from 13.1 to 16.3 for SAC and 4.1–4.5 for IZM.

The representative bulk surface temperatures (T_s) were estimated based on bulk sensible heat transfer

$$T_s = \frac{Q_H r_a}{\rho_a c_p} + \theta_a, \quad (6)$$

where Q_H is the sensible heat flux (W m^{-2}) and θ_a is potential temperature at the reference height (K).

The net radiation was estimated from the sum of the shortwave and longwave radiation components. The downward shortwave radiation was measured at each site. The upward shortwave radiation was measured at SAC, but it was estimated for IZM based on the surface albedo. The surface albedo at IZM (0.16) was the weighted mean of each land cover. We used the measured albedo at IZM for paved roads ($\alpha = 0.07$; fraction is 0.12), grasses ($\alpha = 0.21$; fraction is 0.22), bare soil ($\alpha = 0.19$; fraction is 0.07), and a pond ($\alpha = 0.07$; fraction is 0.06) and literature-based albedo (Oke, 1978) for trees ($\alpha = 0.17$; fraction is 0.52) and buildings ($\alpha = 0.16$; fraction is 0.01). The downward longwave radiation was based on the measurements at the roof of the building at the Osaka Prefecture University in Sakai (Ando and Ueyama, 2017). The upward longwave radiation was estimated by the Stefan–Boltzmann law using the estimated bulk surface temperatures from Eq. 6. We used a literature-based emissivity: 0.95 of urban canopy for SAC (Oke *et al.*, 2017) and 0.97 of forests for IZM (Arya, 2001; Oke *et al.*, 2017).

The storage heat flux and anthropogenic heat flux were estimated based on previously established methods (Ando and Ueyama, 2017). The storage heat flux for SAC was estimated by the Objective Hysteresis Model (Grimmond *et al.*, 1991) whereas those for IZM was the energy balance equation assuming the energy imbalance is negligible. The anthropogenic heat flux was estimated by multiple regression based on inventories (Kayaba *et al.*, 2010) for SAC (details are shown in Ando and Ueyama, 2017) but was assumed to be negligible for IZM.

To apply the temperature decomposition method, we separately estimated the cooling effect during the daytime ($R_{sd} > 100 \text{ W m}^{-2}$) and nighttime ($R_{sd} < 10 \text{ W m}^{-2}$). All terms in Eqs. 1 to 4 were calculated at the half-hourly timescale. Due to the

complexity in nighttime turbulent fluxes, the value of β at night was difficult to determine. Because the nighttime turbulent heat fluxes were generally small, contributions from term 3 in Eq. 1 were considered of negligible importance. Consequently, we determined that term 3 was zero at night. We excluded the data of ΔT_{calc} when the absolute value of $(f+1)$ was less than 0.2.

To verify ΔT_{calc} from the temperature decomposition method, we compared the surface temperature differences between the two sites based on two different methods. First, we used the surface temperature difference estimated based on Eq. 6 (ΔT_{bulk}). The consistency between ΔT_{calc} and ΔT_{bulk} supports the linear assumption in the perturbation analysis; in other words, high-order terms could be considered negligible for explaining the temperature differences. Second, ΔT_{calc} was compared with the surface temperature differences between SAC and IZM based on Eq. 6 and the satellite-based radiometric surface temperatures. We used cloud-free images from band 10 of Landsat-8, with a spatial resolution of 100 m. The thermal images were obtained for a 2-km radius of the Sakai City Office and the area of Oizumi Ryokuchi. The brightness temperatures from the Landsat images were converted to surface temperatures based on Weng *et al.* (2004). The thermal images were available for only four days at 10:34, Japan Standard Time, in the study period: February 16, July 26, September 28, and October 14 in 2015.

3. Results and discussion

The temperature differences that were determined using the temperature decomposition method were consistent with those determined by other methods. The magnitudes of the cooling by the temperature decomposition method (ΔT_{calc}) were consistent with those estimated by the bulk equation (ΔT_{bulk}) (Figs. 1, 2). The difference between ΔT_{calc} and ΔT_{bulk} was 0.5 K during the day and 0.2 K at night on an annual basis (Fig. 1). On a seasonal basis, the difference between ΔT_{calc} and ΔT_{bulk} was 0.1–2.2 K during the daytime and ~ 0.4 K at night (Fig. 2). The magnitude of daytime ΔT_{calc} was comparable to those from the satellite-derived radiometric surface temperatures (Landsat-8). The satellite-based surface temperature differences between SAC and IZM ($= -3.9 \pm 0.1$ K; four-day mean and standard error) were similar to the differences in the daytime ΔT_{calc} ($= -5.6 \pm 0.2$ K; Fig. 1a).

The enhanced heat transport efficiency (Fig. 3; Table 1) most strongly explained the daytime park surface cooling (Figs. 1a, 2a; Table 2) through park creation. The daytime and nighttime r_a in the dense urban area were, on average, 2.9 and 2.4 times larger than those in the urban park, respectively (Fig. 3b; Table 1). On an annual basis, the daytime surface cooling achieved through park creation was estimated to be 5.6 ± 0.2 K based on the temperature decomposition method (Fig. 1a; Table 2). Among the cooling components, the decreased r_a solely contributed 4.5 ± 0.1 K to the daytime park surface cooling.

The effective cooling owing to the decreased r_a following park creation was apparent throughout the seasons (Fig. 2a; Table 2). The surface cooling owing to the decreased r_a was 3.9–4.9 K throughout the year, which contributed 75–91% of the total surface cooling. Even in the summer when evapotranspiration was high (June to August; Table 1), the enhanced heat transport efficiency most strongly contributed to the daytime surface cooling (Fig. 2a).

Fig. 1. The surface temperature (T_s) change associated with the land use change from a dense urban built-up area to an urban park during the day (a) and night (b) on an annual basis. Based on the temperature decomposition method, the contributions in each component were calculated: albedo, heat transfer efficiency, Bowen ratio, storage heat flux (Q_s), and anthropogenic heat flux (Q_r). The values of $\Delta T_{s_{calc}}$ and $\Delta T_{s_{bulk}}$ represent the surface temperature differences estimated based on the temperature decomposition method and bulk transfer equation, respectively. The daytime was defined as the period when downward shortwave radiation was greater than 100 W m^{-2} , whereas the nighttime was defined as when downward shortwave radiation was less than 10 W m^{-2} .

Fig. 2. Seasonal variations in surface temperature (T_s) change associated with the land use change from a dense urban built-up area to an urban park during the day (a) and night (b). We defined spring as March–May (MAM), summer as June–August (JJA), autumn as September–November (SON), and winter as December–February (DJF). The values of $\Delta T_{s_{calc}}$ and $\Delta T_{s_{bulk}}$ represent the surface temperature differences estimated based on the temperature decomposition method and bulk transfer equation, respectively. Daytime was defined as the period when downward shortwave radiation was greater than 100 W m^{-2} , whereas nighttime was defined as when downward shortwave radiation was less than 10 W m^{-2} .

Although the latent heat flux in the park was 2.2 times larger than that in the urban area in the summer (Table 1), the daytime cooling by evapotranspiration ($1.6 \pm 0.1 \text{ K}$) was smaller than the cooling due to the decreased r_a ($4.4 \pm 0.2 \text{ K}$) in the summer (Fig. 1a). This result indicates that the enhanced heat transport achieved through greening mitigated the daytime UHI effect more effectively than enhanced transpiration capacity, even in the summer.

The ineffective heat transfer in the urban area was caused by the so-called scale effect. In general, large elements develop a greater surface boundary layer near the elements (e.g., a microscale laminar layer on each building facet) than small elements, where heat transfer is controlled by molecular

Fig. 3. Seasonal variation (a) and annual mean (b) of the aerodynamic resistance to heat (r_a) in the dense urban built-up area (SAC) and the urban park (IZM) during the day and night. We defined spring as March–May (MAM), summer as June–August (JJA), autumn as September–November (SON), and winter December–February (DJF). Daytime was defined as the period when downward shortwave radiation was greater than 100 W m^{-2} , whereas nighttime was defined as when downward shortwave radiation was less than 10 W m^{-2} .

diffusion (Kanda *et al.*, 2007; Sakai *et al.*, 2012). Thus, larger elements have smaller heat transfer efficiency. Urban elements, such as buildings, are larger in scale as they are often several meters, whereas leaves are less than a few centimeters. Consequently, urban surface temperatures are higher than those for vegetative surface during the daytime.

Changing urban structures to vegetative surfaces increases z_h and promotes heat diffusion from the surface to the atmosphere. The importance of z_h has not been well evaluated on a city scale but has recently been predicted to play a major role in the UHI effect based on the earth system model (Zhao *et al.*, 2014). Previous observations have only discussed the effect of evapotranspiration or tree shade in terms of daytime park cooling (Hamada and Ohta, 2010; Spronken-Smith and Oke, 1998; Sugawara *et al.*, 2016). Our results based on direct flux measurements strongly suggest that increasing z_h is the most effective option for mitigating the daytime UHI effect (Sakai *et al.*, 2012).

The disappearance of anthropogenic heat flux most strongly contributed to nighttime cooling, with contributions of $0.3 \pm 0.1 \text{ K}$ on an annual basis (Fig. 1b; Table 2). The nighttime anthropogenic heat flux was estimated to be, on average, $15 \pm 0.1 \text{ W m}^{-2}$ in the urban area (Table 1). This difference indicates that anthropogenic heat directly increased the urban surface temperatures, and indirectly increased the surface temperatures by reducing the temperature differences between the air and surface with increasing nighttime air temperatures.

The decreased heat storage following park creation was the second most important component for explaining nighttime cooling on an annual basis (Fig. 1b). The magnitude of the nighttime negative Q_s was, on average, 7 W m^{-2} larger in the urban area than in the park (Table 1). Stored heat in urban structures during the daytime could contribute to reradiation at night. On an annual basis, the total nighttime cooling achieved through park creation was $0.4 \pm 0.1 \text{ K}$, of which decreasing heat storage contributed $0.2 \pm 0.1 \text{ K}$. Large storage heat fluxes have been measured in urban areas (e.g., Ando and Ueyama, 2017; Grimmond and Oke, 1999; Moriwaki and Kanda, 2004), representing a major mechanism of the surface UHI effect at night (Zhao *et al.*, 2014). Therefore, decreased heat storage by

Table 1. Seasonal and annual means of albedo (α), aerodynamic resistance to heat (r_a), Bowen ratio (β), storage heat flux (Q_s), anthropogenic heat flux (Q_F), and latent heat flux (LE) for the urban site (SAC) and the urban park site (IZM). The error value with plus/minus sign denotes the standard error, and n denotes the sample number. We defined spring as March–May, summer as June–August, autumn as September–November, and winter as December–February. Daytime was defined as the period when downward shortwave radiation was greater than 100 W m^{-2} , whereas nighttime was defined as when downward shortwave radiation was less than 10 W m^{-2} .

		α				r_a (s m ⁻¹)				β			
Period		SAC		IZM		SAC		IZM		SAC		IZM	
Spring	Day	0.19 ± 0.00	<i>n</i> =1851	0.16* ¹		96 ± 1.09	<i>n</i> =888	31 ± 0.40	<i>n</i> =775	3.50 ± 0.19	<i>n</i> =379	1.68 ± 0.06	<i>n</i> =626
	Night					149 ± 3.34	<i>n</i> =805	60 ± 2.32	<i>n</i> =322	0.05 ± 0.05	<i>n</i> =145	-1.17 ± 0.06	<i>n</i> =169
Summer	Day	0.18 ± 0.00	<i>n</i> =1866	0.16* ¹		96 ± 0.94	<i>n</i> =923	36 ± 0.47	<i>n</i> =827	2.11 ± 0.10	<i>n</i> =500	0.48 ± 0.01	<i>n</i> =769
	Night					152 ± 2.63	<i>n</i> =788	74 ± 1.88	<i>n</i> =286	0.16 ± 0.03	<i>n</i> =181	-0.44 ± 0.03	<i>n</i> =152
Autumn	Day	0.20 ± 0.00	<i>n</i> =1403	0.16* ¹		91 ± 1.14	<i>n</i> =731	35 ± 0.65	<i>n</i> =361	2.97 ± 0.19	<i>n</i> =323	0.84 ± 0.04	<i>n</i> =336
	Night					137 ± 2.70	<i>n</i> =900	57 ± 2.65	<i>n</i> =158	-0.12 ± 0.05	<i>n</i> =140	-1.07 ± 0.07	<i>n</i> =113
Winter	Day	0.22 ± 0.00	<i>n</i> =1654	0.16* ¹		89 ± 1.03	<i>n</i> =687	29 ± 0.42	<i>n</i> =766	4.38 ± 0.21	<i>n</i> =276	2.60 ± 0.08	<i>n</i> =672
	Night					132 ± 2.43	<i>n</i> =1057	47 ± 1.08	<i>n</i> =902	-0.29 ± 0.06	<i>n</i> =151	-1.34 ± 0.04	<i>n</i> =493
Annual	Day	0.20 ± 0.00	<i>n</i> =6774	0.16* ¹		93 ± 0.53	<i>n</i> =3229	33 ± 0.24	<i>n</i> =2729	3.08 ± 0.08	<i>n</i> =1478	1.43 ± 0.03	<i>n</i> =2403
	Night					142 ± 1.39	<i>n</i> =3550	55 ± 0.88	<i>n</i> =1668	-0.04 ± 0.02	<i>n</i> =617	-1.13 ± 0.03	<i>n</i> =927

		Q_s (W m ⁻²)				Q_F (W m ⁻²)				LE (W m ⁻²)			
Period		SAC		IZM		SAC		IZM		SAC		IZM	
Spring	Day	106 ± 2.4	<i>n</i> =1851	120 ± 4.9	<i>n</i> =552	24 ± 0.10	<i>n</i> =1851	0* ²		44 ± 2.7	<i>n</i> =523	108 ± 2.8	<i>n</i> =635
	Night	-50 ± 0.3	<i>n</i> =2341	-45 ± 1.5	<i>n</i> =231	14 ± 0.16	<i>n</i> =2341	0* ²		12 ± 0.9	<i>n</i> =391	18 ± 1.1	<i>n</i> =249
Summer	Day	108 ± 2.3	<i>n</i> =1866	84 ± 3.7	<i>n</i> =770	27 ± 0.14	<i>n</i> =1866	0* ²		87 ± 3.5	<i>n</i> =538	193 ± 3.3	<i>n</i> =770
	Night	-45 ± 0.2	<i>n</i> =1927	-43 ± 1.5	<i>n</i> =215	12 ± 0.14	<i>n</i> =1927	0* ²		23 ± 2.1	<i>n</i> =364	21 ± 1.4	<i>n</i> =215
Autumn	Day	78 ± 2.4	<i>n</i> =1403	86 ± 4.7	<i>n</i> =338	23 ± 0.13	<i>n</i> =1403	0* ²		59 ± 3.4	<i>n</i> =369	128 ± 3.8	<i>n</i> =338
	Night	-49 ± 0.3	<i>n</i> =2356	-47 ± 2.0	<i>n</i> =140	13 ± 0.14	<i>n</i> =2356	0* ²		10 ± 0.8	<i>n</i> =460	31 ± 2.5	<i>n</i> =140
Winter	Day	61 ± 1.8	<i>n</i> =1659	76 ± 3.2	<i>n</i> =489	32 ± 0.04	<i>n</i> =1659	0* ²		27 ± 1.7	<i>n</i> =383	46 ± 1.1	<i>n</i> =699
	Night	-50 ± 0.2	<i>n</i> =3412	-40 ± 0.8	<i>n</i> =691	20 ± 0.19	<i>n</i> =3412	0* ²		8 ± 0.5	<i>n</i> =562	18 ± 0.7	<i>n</i> =836
Annual	Day	90 ± 1.2	<i>n</i> =6779	92 ± 2.1	<i>n</i> =2149	27 ± 0.07	<i>n</i> =6779	0* ²		56 ± 1.6	<i>n</i> =1813	120 ± 1.8	<i>n</i> =2442
	Night	-49 ± 0.1	<i>n</i> =10036	-42 ± 0.6	<i>n</i> =1277	15 ± 0.09	<i>n</i> =10036	0* ²		12 ± 0.6	<i>n</i> =1777	20 ± 0.6	<i>n</i> =1440

*¹ The value of albedo was assumed as 0.16 for the IZM site.

*² Anthropogenic heat flux was assumed to be negligible for the IZM site.

Table 2. Seasonal and annual means of the surface temperature (K) change associated with the land use change from a dense urban built-up area to an urban park during the day and night. Based on the temperature decomposition method, the contributions in each component were calculated: albedo (α), aerodynamic resistance to heat (r_a), Bowen ratio (β), storage heat flux (Q_s), and anthropogenic heat flux (Q_F). The values of $\Delta T_{s_{calc}}$ and $\Delta T_{s_{bulk}}$ represent the surface temperature differences estimated based on the temperature decomposition method and bulk transfer equation, respectively. Daytime was defined as the period when downward shortwave radiation was greater than 100 W m^{-2} , whereas nighttime was defined as when downward shortwave radiation was less than 10 W m^{-2} . The error with the plus/minus sign denotes standard error, and n denotes the sample number.

Period		$\Delta \alpha$	Δr_a	$\Delta \beta$	ΔQ_s	ΔQ_F	$\Delta T_{s_{calc}}$	$\Delta T_{s_{bulk}}$	n
Spring	Day	0.24 ± 0.05	-4.89 ± 0.23	-0.24 ± 0.18	0.44 ± 0.29	-0.92 ± 0.03	-5.36 ± 0.40	-4.29 ± 0.30	90
	Night		0.12 ± 0.11		-0.09 ± 0.13	-0.14 ± 0.16	-0.11 ± 0.14	-0.22 ± 0.14	29
Summer	Day	0.24 ± 0.03	-4.39 ± 0.18	-1.56 ± 0.08	0.83 ± 0.20	-1.00 ± 0.03	-5.88 ± 0.26	-6.09 ± 0.28	155
	Night		-0.20 ± 0.10		-0.33 ± 0.14	-0.60 ± 0.12	-1.13 ± 0.19	-1.03 ± 0.19	39
Autumn	Day	0.25 ± 0.06	-3.94 ± 0.25	-0.85 ± 0.18	0.62 ± 0.34	-0.87 ± 0.04	-4.80 ± 0.37	-4.69 ± 0.30	61
	Night		-0.13 ± 0.25		-0.28 ± 0.33	-0.34 ± 0.38	-0.75 ± 0.52	-0.90 ± 0.52	7
Winter	Day	0.28 ± 0.06	-4.73 ± 0.26	0.24 ± 0.19	-0.25 ± 0.32	-1.32 ± 0.04	-5.78 ± 0.50	-3.56 ± 0.35	50
	Night		0.18 ± 0.22		-0.10 ± 0.13	-0.16 ± 0.15	-0.09 ± 0.06	0.25 ± 0.06	86
Annual	Day	0.25 ± 0.02	-4.49 ± 0.11	-0.85 ± 0.08	0.54 ± 0.14	-1.00 ± 0.02	-5.55 ± 0.18	-5.04 ± 0.17	356
	Night		0.06 ± 0.12		-0.16 ± 0.08	-0.27 ± 0.09	-0.37 ± 0.08	-0.20 ± 0.08	161

urban greening should be able to mitigate the second strongest cause of the nighttime surface UHI.

4. Conclusion

Continuous flux measurements with the temperature decomposition method successfully explained the biophysical controls on the surface cooling in the urban park, and thus, could provide useful strategies for urban planning. Based on our analyses, effective arrangements of vegetation in urban areas can mitigate the surface UHI effect through enhanced heat transport efficiency. Enhanced heat transport efficiency achieved through

urban greening could improve human thermal comfort and mitigate the health impacts of heatwaves during hot summers. Although this study revealed the potential cooling mechanism in terms of surface temperatures, the relationships between surface and air temperatures are known to be complex (Oke *et al.*, 2017); thus, further studies on the effects on air temperature are important challenges that need to be addressed.

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