Thermal Influence of a Large Green Space on a Hot Urban Environment

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Abstract

City-scale warming is becoming a serious problem in terms of human health. Urban green spaces are expected to act as a countermeasure for urban warming, and therefore better understanding of the micro-climate benefits of urban green is needed. This study quantified the thermal influence of a large green park in Tokyo, Japan on the surrounding urban area by collecting long-term measurements. Apparent variations in the temperature difference between the park and surrounding town were found at both the diurnal and seasonal scales. Advection by regional-scale wind and turbulent mixing transfers colder air from the park to urban areas in its vicinity. The extent of the park’s thermal influence on the town was greater on the downwind side of the park (450 m) than on the upwind side (65 m). The extent was also greater in an area where the terrain slopes down toward the town. Even on calm nights, the extent of the thermal influence extended by the park breeze to an average of 200 m from the park boundary. The park breeze was characterized by its divergent flow in a horizontal plane, which was found to develop well in calm conditions late at night (regional scale wind <1.5 m s⁻¹ and after 02:00 LST). The average magnitude of the cooling effect of the park breeze was estimated at 39 Wm⁻². This green space tempered the hot summer nights on a city block scale. These findings can help urban planners in designing a heat-adapted city.

Core Ideas

• The park is 1.5 to 3 K cooler than the surrounding town in summer daytime.
• The park cooler air was advected to the urban area until a maximum extent of 450 m.
• The extent of thermal influence gets larger on the slope down to the town.
• The park breeze occurred more frequently in calm conditions late at night.
• Amount of town cooling by the park corresponds to 2600 room air-conditioning units.

More than half of the world’s population currently lives in urban areas, and urban populations are increasing (United Nations, 2012). Urban areas are suffering from climate change due to two warming phenomena: global warming and warming at the local city scale. Urban air temperature at a local scale is increasing more rapidly than global warming in large Japanese cities (Fujibe, 2009). This urban warming, especially on hot summer nights, can cause human health problems (Ihara and Genchi, 2008). In 2014, more than 10,000 people in 20 large cities in Japan suffered from heat stroke, and approximately 30% of them became ill at night (National Institute for Environmental Studies, 2015). The Japanese government has developed a policy framework for reducing the urban heat island effect; this framework proposes that urban greening can provide a cooling effect as one countermeasure against urban warming (Japanese Inter-Ministry Coordination Committee to Mitigate Urban Heat Island, 2004). In response, many local governments in Japan have planned urban greening efforts.

Many previous studies have shown that urban green spaces are cooler than the surrounding town; this difference is known as the “park cool island” (Spronken-Smith and Oke, 1998). A synthesis review of the thermal influence of parks was provided by Bowler et al. (2010). The cooler air of the park expands into urban areas in its vicinity (Hamada and Ohta, 2010; Doick et al., 2014). In some cases, this expansion of cold air may be more important than the park cool island itself. For example, as noted, nocturnal warming is a serious problem in Japanese cities, and fewer people are present in the parks at night. The influence of the cooler air from the park extends several hundred meters from the park boundary and is considered to be related to park size, weather conditions, and terrain (Upmanis et al., 1998; Doick et al., 2014). The urban area of Tokyo includes the strongly sloped terrain of a former river valley with elevation differences of a dozen meters. Much of the sloped area has been left undeveloped as green space, and the thermal benefit of this area needs to be evaluated. Only a small number of previous studies have addressed the cool island phenomenon and the extent of cooler...
Air in sloped green areas (Upmanis et al., 1998). The thermal influence of sloped terrain on the surrounding town is one of the questions to be clarified in this study.

The expansion of cooler air from the park to its vicinity should occur as an outflow of cold air from the park; however, very few studies have focused on the wind field in and around urban parks. Eliasson and Upmanis (2000) measured the outflow from parks in Scandinavia during calm nights and described its basic features. Additional studies are needed in a variety of locations and climates to ascertain the common features of park outflow and to apply this knowledge to urban planning. This study clarifies the thermal structure and conditions for occurrence of the park breeze at night.

One of the difficulties in applying what is known about cool green space to urban planning is the lack of generality of the current state of knowledge. Although studies have been conducted at different parks in multiple countries, many previous studies have been based on a short measurement period, most lasting only several days or less (Bowler et al., 2010). Seasonal variations in the effect of green space have been reported in very few studies (Hamada and Ohta, 2010). In this study, we conducted intense observations of microclimate over four consecutive summer periods as well as simple temperature measurements for 1 yr. These observations revealed the temporal features of the cool green space effect.

Previous studies have expressed the thermal influence of a park in terms of two physical values: (i) the temperature difference between the park and the town and (ii) the extent of the cooler area. However, these values do not adequately represent the park’s cooling ability for two reasons. First, these variables do not capture the volume of cooler air in the town. The thickness of the cooler air mass in the park could be a 12 m (Sugawara et al., 2014) or 30 m (Eliasson and Upmanis, 2000). However, the upper limit for the technically realizable measurement of vertical temperature profiles is 2 m (Jansson et al., 2007). Hamada and Ohta (2010) conducted profile measurements up to a height of 10 m; however, these were restricted to fixed points in the town.

The second limitation of the variables used in previous studies is that the amount of cooling caused by the park is not fully represented by the temperature distribution. The cooler air flowing outward from the park is heated by urban surfaces (e.g., roads) and gradually approaches the temperature of the town as it moves further from the park (Shashua-Bar and Hoffman, 2000; Jansson et al., 2007). At the same time, the urban surfaces that come into contact with the park outflow are cooled. This interaction between advection and the surface heat budget was reported by Spronken-Smith et al. (2000), although they focused on the ground surface inside the park. The amount of cooling of surfaces cannot be captured solely by the air temperature distribution. Therefore, the indexes of temperature difference and thermal extent distance are not sufficient for evaluating the cooling ability of a green park. However, the temperature distribution does provide us with the boundaries of the cooler area, and this is valuable knowledge because people within that area receive the benefit of cooler air. On the other hand, observations of cooling amounts measured in Watts (or Joules) are also valuable for estimating the value of green spaces in urban areas. This cooling amount can be evaluated using a heat budget analysis of the park’s forest canopy.

Methods and Materials

Site Location

The study site was Shirogane Park, the urban park of the National Museum of Nature Study located in downtown Tokyo, Japan (Fig. 1). The summer climate is subtropical and humid (average temperature and humidity in August are 30.8°C and 73%, respectively). The surrounding area is a business district dominated by compact midrise buildings in an urban climate zone (Stewart and Oke, 2012). Some arterial roads around the park experience heavy traffic (~28,000 cars d⁻¹). The park’s area is 0.2 km², and 90% is covered by deciduous forest with a mean canopy height of 14 m. The northern part of the park and the adjacent urban area are located on a north-facing slope. The town transect (Fig. 1, N1–N9) is gently sloped (0.8%); however, there is a cliff in the park (X = 650–700) with a height of 15 m. The earthwork on which the point N was located lay around the park boundary. The southern part of the park and its adjacent urban area are located on flat terrain.

Measurements

The primary set of measurements was conducted during four summer periods (July–September) from 2009 to 2012. Some measurements were collected year-round. The sensor setup is shown in Fig. 1, although it varied slightly from year to year. The collected measurements can be categorized into four parts: (i) air temperature distribution in the park and the surrounding town, (ii) urban temperature, (iii) heat flux measurements, and (iv) wind measurements at the park boundary.

The air temperature distribution in the park and the surrounding town was measured using a recording thermistor thermometer (RTR-52A, T&D) installed with a naturally ventilated radiation shield. The horizontal distribution of temperature was measured at 38 points distributed primarily along the north–south transect of the study area (Fig. 1, solid line). The sensor height was 2.5 m. All thermometers used were calibrated to within 0.1 K error before measurement. The sampling interval was 1 min, and data were block-averaged at 10-min intervals. In addition to the horizontal measurement, we collected temperature profile measurements at three points (the center tower, north, and south) in the park from 2010 onward. Thermostats of the same type as those used in the horizontal measurement were installed at eight heights, from 2 m above the ground to the top of the canopy (18 m).

Urban temperature was also measured at three locations in the nearby town (within 1.5 km of the park). These urban sites were established at 1.5 m above ground level (AGL) in school gardens. The instrument used was the same type of thermometer mentioned above with a Stevenson screen. The time interval for measurement of urban temperature was 10 min. To clarify the seasonal variation in the cool island effect, these urban sites were operated year-round from 2011 onward. The park air temperature was also measured year-round at 1.5 m AGL in the center of the park.

Heat flux measurements were collected above the forest canopy. Instruments for turbulence and radiation measurement were installed at the top of a tower (20 m from the ground and 6 m from the forest crown, located at the center of the park). A sonic anemometer (SAT-540, Kaijo) and a H₂O/CO₂ analyzer (LI-7500, Licor) measured the turbulence in the air at a
sampling frequency of 10 Hz. The vertical turbulent heat flux was calculated from the turbulence data using the eddy covariance method (Aubinet et al., 2012) for every 30-min period, and corrections for air density (Webb et al., 1980) and axis rotation for the terrain following flow (Wilczak et al., 2001) were applied. The radiometer (CNR-1, Kipp & Zonen) measured upward and downward radiation flux in the shortwave and longwave ranges every 1 min. The wind measured at this height was taken to represent the regional wind, representing the mean wind flow for a large district including the park and surrounding town. The phenology of the park vegetation, including leaf-out and leaf fall, was monitored year-round using a pyranometer installed at the forest floor and one at the top of the tower. The turbulence sensors were close to the forest canopy, so the measured flux does not represent the whole canopy. However, we choose this sensor height to be inside the internal boundary layer of the park.

Wind measurements were taken at the park boundary. Air outflow from the park to the surrounding town was captured by a sonic anemometer (windsonic, GILL) at 1-s intervals. Measurements were collected at two points at the northern and southern park boundaries beginning in 2009, and an additional two measurement points (east and west park boundaries) were established in 2010. The same type of thermometer used for the plane measurements was installed at every point. The height of these sensors was 1.5 m AGL. Data were block-averaged at 10-min intervals. Here, the wind measured at the park boundary is termed the “surface wind,” distinguishing it from the regional wind measured at the top of the tower.

Heat Budget Analysis of the Forest Canopy Layer

The heat budget of the forest canopy in the park was analyzed. We describe here the essentials of the methodology; details are presented in Sugawara et al. (2014). The inspection volume covers the forest canopy, including the soil surface at the forest floor. The heat budget of the volume is written as:

\[ Q_H + Q_E + R_{net} + Q_g + Q_{adv} + Q_a + Q_w = 0 \]  

All terms are positive when heat flows from the inside to the outside of the inspection volume. \( Q_H \) and \( Q_E \) are the sensible and latent heat fluxes, and \( R_{net} \) is the net radiative flux. These fluxes are acquired by the sensors at the top of the tower. \( Q_g \), \( Q_a \), and \( Q_w \) represent the heat storage by the canopy air mass, vegetation (trunks, stems, and leaves), and soil surface, respectively (these values are evaluated from the temporal variation in temperature), and \( Q_{adv} \) is the advective heat flux at the park boundary, evaluated as:

\[ Q_{adv} = c_a r a h_L (T_{park} - T_{town}) U/S \]  

where \( c_a \) is the heat capacity of air, \( h \) is the depth of cold air flow at the park boundary, \( L \) is the circumference of the park, and \( S \) is the area of the park. The value for \( h \) was acquired from the temperature profile in the park. \( T_{park} \) and \( T_{town} \) are the air temperatures of the park and surrounding town, respectively. We used the average of 24 points measured in the park as \( T_{park} \); \( T_{town} \) was measured in a residential district 1.3 km from the park, which was outside of the thermal influence of the outflow from the park. \( U \)
is the wind speed component perpendicular to the park boundary and was estimated as the average of the measurements at the park boundary (north and south). Analysis was conducted for each 30-min interval with the data collected at night in 2009. The total cooling amount for the town is calculated as the sum of the heat flux at the top of the canopy and the lateral boundary of the inspection volume, $Q_{\text{H}} + Q_{\text{lad}}$. Note that $Q_{\text{H}}$ is not included because the latent heat flux does not cool the town directly.

### Results and Discussion

#### Intensity of Green Cool Island

The difference in air temperature between the park and the surrounding town (cool island intensity, CII) was investigated. Figure 2 presents hourly composites of the mean temperature in the park (horizontal average of 13 measurement points along the transect line) and the town (three urban sites in school gardens), respectively. The data are separated into different panels representing sunny days (>20 MJ m\(^{-2}\) d\(^{-1}\) solar radiation and <6/10 cloud cover) and cloudy days (<20 MJ m\(^{-2}\) d\(^{-1}\) solar radiation, more than 8/10 cloud cover, and no precipitation). The temperature difference on sunny days exhibited clear diurnal variation, with an early afternoon peak of 3 K and a minimum of 1.5 K in the evening. However, this variation was not observed on cloudy days, when the temperature difference was close to zero. This discrepancy between sunny and cloudy days indicates that the temperature difference is a result of the differing surface heat budgets between the park and town (Spronken-Smith and Oke, 1998). The anthropogenic excess heat from cars, air conditioning units, and other sources that increases the urban temperature was probably less influential than the effect of land cover difference in this case. Wind conditions were similar for both cases (mean regional wind speeds of 1.96 and 2.02 m s\(^{-1}\) for sunny and cloudy days, respectively), and therefore regional wind could not be the cause of the difference in the CII, although the CII is negatively correlated to wind speed (Sugawara et al., 2006).

Urban air temperature is quite spatially heterogeneous, and collecting representative air temperature measurements is difficult (Sugawara et al., 2004). The estimation of the CII is greatly influenced by this heterogeneity, similar to the evaluation of urban–rural thermal differences (Grimmond et al., 1993). The spatial variation in urban temperature represented by the error bar in Fig. 2 ranges from 0.2 to 0.8 K. The lower end of this range is close to the spatial variation in nocturnal air temperature (0.3 K) in downtown Tokyo measured using a thermometer mounted on a car (Takano et al., 2003). This spatial variation is as much as 10 to 26% of the CII and is therefore not negligible. This heterogeneity of urban temperatures complicates the comparison of CII values among different parks and different studies; however, the magnitude of spatial variation is not reported here for urban temperature (or for the park temperature). To tackle this problem of thermal heterogeneity, we compared our results with those of a previous study of another park in which the analysis procedure was similar to ours. Sugawara et al. (2006) measured air temperatures in Gyoen Park (0.58 m\(^2\), located in Shinjuku, Tokyo) and its surrounding urban area for 1 yr and estimated the urban temperature from three measurement sites in urban school gardens. They reported CII of 1 ± 0.5 K in daytime and 0 to 2 ± 0.3 K at nighttime during the summer, where ± indicates the degree of spatial variation (SD). Although the CII of a park should be positively correlated to its size (Bowler et al., 2010), a larger daytime CII was found in Shirogane Park in spite of its smaller area. This is likely the effect of tree shading. Shirogane Park is mostly covered by tall trees, whereas Gyoen Park is partly occupied by an open lawn.

The seasonal variation in CII was explored using the year-round temperature measurements in the park and town. The CII in winter could be a factor to be considered in urban planning because a wintertime park cooling effect would not be beneficial for human health in temperate cities. Figure 3 presents a 1-yr time series of temperature, temperature difference, and the transmittance of solar radiation in the forest canopy layer. The transmittance is the ratio of solar radiation below the forest canopy vegetation to that above the canopy, and it varies with leaf-out and leaf fall. The town temperature was calculated as the average of three urban sites; however, the park temperature was based on a point measurement, as noted in the previous section.

The daytime CII exhibited significant seasonal variation, whereas the nocturnal CII did not. The daytime CII peaked in summer and became more moderate in autumn. A negative CII, where the town is cooler than the park, could be observed in early spring. However, this negative CII was less than 0.5 K, and it may not be significant due to the thermal heterogeneity in the town and park. Similar patterns of seasonal variation have also been observed at other parks in Japan (Sugawara et al., 2006; Hamada and Ohta, 2010). The change in tree shading, captured by the transmittance measurements, would be one reason for the seasonal variation in daytime CII. Tree shading disappeared in winter, and the ground surface was then heated directly by solar radiation (Hamada and Ohta, 2010). Another possible reason is the variation in solar elevation angle. The shading of the ground surface by buildings increases in the town as the solar elevation angle decreases toward winter, and this shading decreases the urban temperature. The solar elevation angle at noon on winter solstice is 35° in Tokyo, at which time urban streets whose aspect ratio (building height/street width) is more than 0.7 are fully shaded by buildings. The aspect ratio of the urban sites used in this study ranges from 0.5 to 3.0.
Figure 4 presents the distribution of normalized temperatures along the transect line shown in Fig. 1. The temperature anomaly relative to the park average at each point (points G1 to S) is normalized by the difference between the town (average of points N1 to N9 and S1 to S3) and park (G1 to S) and then averaged for different periods. Therefore, the normalized temperature is 1 if it equals the average town temperature, and 0 is the average park temperature. This normalization eliminates differences in the absolute magnitude of the CII at each period and enables us to discuss the pattern of temperature distribution. Plots are separated by the direction of the regional wind into north and south winds. Calm wind conditions (regional wind < 2 m s\(^{-1}\)) were excluded from this analysis. Data from two summer periods in 2011 and 2012 were used and included 94 and 582 data points with north and south wind, respectively. Data in both daytime and nighttime are used in this figure, and the ratios of daytime and nighttime data points were 56 and 38 for north wind and 398 and 184 for south wind.

In the urban area near the northern boundary of the park (X = 850–950 m), the temperature was clearly lower than in the area farther into the town. Horizontal advection from the park to its surroundings should cool the urban areas in the northern vicinity of the park when there is a south wind. Under a north wind, although it is reverse to the direction of the regional wind, the vicinity north of the park was still cooled up to 65 m (N3) from the park boundary, most likely due to horizontal mixing by eddy motion. Except for point N4, the temperature north of the park was lower under a south wind than a north wind, a difference that was statistically significant (Z-test with the normal probability distribution; \(P < 0.01\)). This cooling was more significant when the regional wind was stronger (data not shown). In the urban area south of the park, similar to the northern side, the temperature was lower when the wind came from the park, with the exception of point S2. Therefore, the urban area downwind of the park was cooled more than the upwind side.

The temperature difference due to wind direction was significant at the farthest point (N9), indicating the whole northern transect is cooler when the wind comes from the park compared with the cases of opposite wind direction. The extent of the park’s thermal influence to the north is >450 m (across N9) if the extent of the influence is defined as the area where the normalized temperature changes due to the wind direction. South of the park, the estimated extent is 58 m (point S2, where the sign of the difference due to wind direction changes). The greater extent to the north of the park compared with that to the south is the result of the north-facing slope on the northern side of the park, in contrast with the flat terrain on the southern side. The extent of the thermal influence to the north was also greater than that in Gyoen Park, whose terrain is flat (200 m) (Narita et al., 2004). The association between a longer extent of influence and sloped terrain is supported by slope flow (Stull, 1988), where cold, dense air is accelerated by negative buoyancy. The idea of the effect of terrain slope on urban cooling and its potential to increase the cooling ability of a green area might be useful for urban planning.

### Cold Air Outflow from the Park at Night

The periods of calm regional wind that were excluded in the previous section are addressed in this section. Figure 5 shows a time series of temperature and wind at four locations at the park boundary on 7 and 8 Sept. 2011. The average temperature of
the three urban sites is also shown in each panel. The regional wind above the building canopy (74.5 m AGL), which was measured 7 km from the park by the Japan Meteorological Agency, is included at the bottom of the figure. This data source was used to measure regional wind because our instruments at the top of the tower in the park malfunctioned at this time. In the evening when the regional wind became calm, the direction of surface wind shifted to outflow from the park. This change occurred at all measurement points but at different times, occurring first at point E (16:00 LST) and last at point W (21:00 LST). The change in wind direction at point N is unclear because the direction of the regional wind was the same as the outflow direction (south), although the variation in the wind direction decreased after 18:00 LST at point N. The speed and direction of the surface wind were steady after the shift to the outflow pattern. The surface wind speed was <0.5 m s\(^{-1}\) but was within the detectable range of the sonic anemometer. The air temperature dropped more rapidly at the park boundary than in the urban areas when the direction of the surface wind changed. The wind direction change and temperature drop indicate the outflow of cold air that had accumulated in the park. A time–location section (Fig. 6) illustrates this transition, where the temperature difference from the park mean is shown. In the evening, cold air accumulated in the valley (\(X = 650–800\)). The temperature in the nearby town dropped at 23:00 LST, several hours after the shift to outflow. The maximum extent of cold outflow was 260 m from the park boundary north of the park (N7) if the maximum extent is determined as the distance where the normalized temperature = 1. The extent in the urban area south of the park was located outside of the measurement area. A precise distribution of temperature and wind in this case was described in Shimizu (2012), where the extent of the thermal influence of the park was 300 and 150 m from the park boundary on the northern and southern sides, respectively.

The wind direction in Fig. 5 exhibits divergent flow on the horizontal plane in the park, with outflow from the park to the surrounding town at all locations along the park boundary. This distribution of air flow cannot be driven by the descent
of regional wind to the surface layer. Such a divergent flow system would be the result of a gravity current driven by the pressure gradient (Shimpson, 1997) between the colder park and the warmer town. Cooling produces a high-pressure system in the park and drives air flow to the town at any point along the park boundary. We confirmed this outflow at four points on the park boundary, which perhaps is not enough to confirm the presence of divergence across the whole park. Subsidence compensates for the divergence of the flow (Oke et al., 1989). However, the compensation flow from the upper air, evaluated from the mean speed of the surface wind (0.3 m s\(^{-1}\)) and mass budget, should be 0.018 m s\(^{-1}\), which is below the detection limit of the sonic anemometer. This divergent flow should be a phenomenon similar to the park breezes reported in several studies (Oke et al., 1989; Eliasson and Upmanis, 2000; Narita et al., 2004). Eliasson and Upmanis (2000) measured a park breeze in the nocturnal stable-stratified atmosphere. Their measurements were taken along the park transect line; however, we confirmed divergent flow at all quadrants of the park boundary.

**Occurrence of the Park Breeze**

The conditions in which the park breeze (nocturnal divergent flow) occurred were investigated using data spanning three summers beginning in 2010. Figure 7 shows the frequency of divergent flow in three periods at night. The occurrence of divergent flow was determined based on the surface wind direction at four points on the park boundary. The number of time periods (10 min) when air outflow from the park occurred at all four points is shown in the graph. For example, "6 times per hour in 19:00–22:00" means all 10-min periods in a 1-h period (19:00–20:00 or 20:00–21:00 or 21:00–22:00 LST).

The values denoted in the bar in Fig. 7 are the average regional wind speed above the forest canopy. The cases of higher frequency of outflow within 1 h occurred when the regional wind was weaker. In the period from 01:00 to 04:00 LST, the differences in wind speed between the periods with the highest outflow frequency (six times per hour) and those with other frequencies are statistically significant (Z-test; \(P < 0.06\)). Therefore, weak regional wind (<1.5 m s\(^{-1}\) above the canopy would be one of the weather conditions of divergent flow occurrence. The frequency of weak regional wind (<1.5 m s\(^{-1}\), 10 min mean) was greater later in the night (38, 59, and 69% in the periods of 19:00 to 22:00, 22:00 to 01:00, and 01:00 to 04:00 LST, respectively). The total number of outflow occurrences is also highest in the last period of the night, and it was more common for outflow to occur at a relatively higher frequency (4–6 times in 1 h) in this period (Fig. 7). The frequent occurrence of outflow in calm conditions supports the idea of a gravity current as the physical mechanism causing the park breeze because the gravity current occurs likely in the calm conditions (Stull, 1988).

Time period prone to the park breeze is compared with other studies. Park breeze occurred most frequently in the midnight period (22:00–01:00 LST) in Gyoen Park (Nagatani et al., 2007), which is not consistent with our case, where park breeze occurred most frequently later in the night. This difference can be explained by the sloping terrain present in the park studied here. The cold air accumulated in the park flows out from the park as a gravity current, which is driven by the pressure difference between the park and town. However, the sloping terrain prevents this accumulation, causing the park breeze to occur later than in parks with a flat terrain (e.g., Gyoen Park).

Eliasson and Upmanis (2000) showed that the park breeze in Goteborg began 2 h after sunset, which is much earlier than in our case. The reason for the difference in timing is likely the temporal variation in the CII. The maximum CII at night occurred in the evening in Goteborg (Upmanis et al., 1998); by contrast, a CII was found late night in our case (Fig. 2). The park breeze is driven by the thermally formed pressure difference, and its start time is likely related to the CII. This hypothesis is consistent with the fact that park breeze occurs likely in weak wind conditions because a larger CII is seen in weaker wind (Sugawara et al., 2006). Mori and Niino (2002) theoretically showed the transition of the flow regime in a stable stratified atmosphere. The horizontal convection induced by the bottom heating transitions from the diffusion regime to the gravity current regime as time passes if the stratification is weak. They showed that timing of the transition was negatively correlated to the horizontal gradient of temperature. Their results indicated that the timing of the transition, which corresponds to the beginning of the park breeze, depends on the horizontal gradient of temperature (CII).

In the divergent wind, warmer compensation inflow from the surrounding town would heat the park air. The heating would not be consistent with the fact that maximum CII is seen in the divergent wind. However, the park air temperature decreases throughout the night (Fig. 2). The heating would not be significant compared with the cooling by the radiation loss.
The distribution of average temperatures during periods of park breeze is shown in Fig. 8 and is compared with periods with no park breeze. Data collected at 05:00 LST are shown because the park breeze develops late at night (Fig. 7), although similar distributions were found for other times at night. The same normalization used in Fig. 4 was applied here. The rainy periods are not included in the non-park breeze periods. In the urban area north of the park, the temperature is lower and the temperature gradient is gentler during the park breeze periods compared with the non-park breeze periods, indicating that the cold air from the park reaches farther into the town. The range of the thermal influence of the park should be 200 m from the park if it is defined as the point where the normalized temperature reaches 1. In the urban area south of the park, the temperature was also lower when the park breeze was present. The difference between the northern and southern areas can be attributed to the difference in terrain, similar to the results of advection (Fig. 4). 

Eliasson and Upmanis (2000) discussed the positive influence of terrain on the park breeze. It is also possible that the 25-m-wide arterial road with traffic south of the park (near point S1) could interfere with the flow of the gravity current in that direction. Another case-study in the same area (Shimizu, 2012) found that the colder air flow coming from the direction of the park extended 150 m south of the park, a distance that crosses that road.

Eliasson and Upmanis (2000) showed observationally that the range of thermal influence of a park increases as the park size increases. Honjo and Takakura (1990) also derived similar results from a numerical simulation. However, the analytical procedure in their study differs greatly from ours, especially in the definition of the extent of influence, and therefore rigorous comparison with their results is not easy. Here, we compared the results of this study with two studies in which the procedure was similar to this one. Those previous studies found maximum thermal influence extents of 80 to 90 m for Gyoen Park (0.58 km²) (Narita et al., 2004) and 300 m for the Japanese Imperial Palace (2.3 km²) (Narita et al., 2011). In our study (Shirogane Park, 0.20 km²), the maximum extent was 200 m at the northern side of the park. This comparison does not support the idea that the extent of thermal influence is positively correlated to the park size. The larger extent of thermal influence for Shirogane Park could be caused by the sloped terrain facilitating the outflow of air from the park.

Evaluation of Cooling Amount

The cooling flux, $Q_H + Q_{adv}$, which indicates how much the park cools the surrounding town, is evaluated from the heat budget analysis. Figure 9 shows the relationship between the cooling flux and the net radiation loss at the top of the forest canopy at night. A negative value for the flux indicates that heat is coming into the park (i.e., the park is cooling the surrounding town). A filled mark indicates the reliable runs in which the residual of the heat budget is less than 20% of $Q_{adv}$. The mean ratio of $Q_H$ to $Q_{adv}$ is 7:10 in the reliable runs. The mean $Q_E$ was 6 W m⁻², indicating a small amount of cooling caused by the evapotranspiration of the vegetation at night. The cooling flux is larger in the reliable runs than in the others, perhaps suggesting an underestimation of $Q_{adv}$. The measurement of horizontal advection is technically difficult (Aubinet and Feigenwinter, 2010). Approximately half of the reliable runs are park breeze cases (Fig. 9, yellow square), which are associated with relatively larger amounts of cooling than the non-park breeze cases (Fig. 9, filled circle). The divergent flow system of the park breeze, which is driven by a gravity current, should be relatively stable, in which case the evaluation of $Q_{adv}$ may go well.

The cooling flux is positively correlated with the net radiation loss. The mean ratio of the cooling flux to the net radiation loss is 0.83 in the reliable runs, which indicates that the park cooled the surrounding town, with 83% of the cooled air generated by radiation loss. The cooling flux in the reliable runs ranges from...
20 to 70 W m\(^{-2}\) and averages 39 W m\(^{-2}\). The amount of cooling provided by the whole park (0.2 km\(^2\)) is 7.8 MW. To achieve the same amount of cold air by using the room air conditioner (Japanese typical house-use, 3 kW [unit\(^{-1}\]), we need 2600 units.

Conclusions

The main finding of this study is that the thermal influence of the green space extended beyond the park border into the surrounding urban area. The physical extent of the thermal influence, which is one of the major concerns of urban green planners, was a city block scale and reached a maximum 450 m at the downwind side of the park. The extent was larger where the terrain of the park sloped down to the town. The extent was also larger at the downwind side of the park, although the thermal influence appeared at the upwind side and during the calm wind period.

In this and in previous studies, daytime cooling in winter, which is not beneficial for human health in temperate cities, was less than in summer. This knowledge could assist urban planning, although its generality should be studied in other locations.

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References


