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Nocturnal Airflow from Urban Parks-Implications for City Ventilation

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With 5 Figures

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Summary

The spatial and temporal pattern of nocturnal airflow in and around two urban parks in Scandinavia were analysed. The results, based on 724 field measurements during 21 case studies, showed that both parks generated a local airflow during clear and calm weather conditions. The spatial pattern was characterised by calm in the middle of the park and a steady airflow towards the surrounding built-up areas at the park borders. The airflow from the park started one to two hours after sunset and continued during a period of four to eight hours. The wind speed was low ($< 0.5\,\mathrm{ms}^{-1}$) and the local air flow reached a short distance from the park border. In the flat park in København, Denmark, the air flow from the park was attributed solely to the development of a thermally induced park breeze. The park breeze development was also predominant in the park in Göteborg, Sweden, but the influence of topography could not be totally excluded. The origin of the airflow from the park and its importance for urban air quality were discussed.

1. Introduction

This paper emerged from an urban park-climate project based at Göteborg University in Sweden. Some earlier publications show that a large temperature difference (up to 6 K) exists between a large park and the surrounding built-up areas in the city of Göteborg (Gothenburg), (Lindqvist, 1992; Eliasson, 1996; Upmanis et al., 1998). Statistical analysis show that the maximum median value for this urban-park temperature difference (ΔT_{u-p}) during clear and calm nights is 3.5 K (Upmanis et al., 1998). The studies thus show that intra-urban temperature differences in Göteborg are of a magnitude similar to the urban-rural temperature differences. The urban heat island in Göteborg has a maximum mean value that ranges from 4.0 K in winter to 5.5 K in summer (Eliasson, 1994).

Several other studies show that urban parks establish their own temperature climate in situ (Chandler, 1965; Jauregui, 1975; Oke, 1989; Honjo and Takakura, 1990/1991; Jauregui, 1990/1991; Saito et al., 1990/1991; Ahmad, 1992; Spronken-Smith and Oke, 1998). However except for Spronken-Smith and Oke, 1998, who report temperature differences up to 7 K, the values usually vary between 1.5 to 4 K (Upmanis et al., 1998). Most studies, including the study in Göteborg, show that the cooler park climate extends beyond the park and thus influences the temperature in the surrounding city. The magnitude of the park influence is related to the park size, meaning that larger parks have a greater influence on surrounding temperatures (e.g., Jauregui, 1990/1991; Spronken-Smith and Oke, 1998; Upmanis et al., 1998). The largest park in Göteborg ($1.5\,\mathrm{km}^2$) influences its surroundings up to 1 km from the park border (Upmanis et al., 1998). The cause of this outward diffusion of cool air from the park has only briefly been discussed in the literature. One explanation for the influence of cool air in the surrounding city and the relatively low ΔT_{u-p} found in some temperate cities is the park breeze (Oke, 1989). The theory of park breeze is based on the fact that the ΔT_{u-p} induces a pressure gradient leading to a divergent outflow of cool air at a low level from the park (e.g., Whiten, 1956; Gold, 1956; Wainwright and Wilson, 1962; Oke, 1989; Avissar, 1992). The hypothesis, however, lacks field support (Oke, 1989).

This paper presents the results from 21 case studies carried out in two large urban parks in Sweden and Denmark. The work started in January 1996 with a pilot study in Göteborg, which showed an outward diffusion of cool air from the park during clear and calm nights (Häger and Svensson, 1996). Extensive measurements during the summer of 1996 confirmed the spatial pattern of the local airflow from the large park in Göteborg. The reason for the airflow was, however, not evident, as the height differences in the specific park might induce cold air flows. Therefore complementary measurements were carried out in the flat Danish Capital København (Copenhagen) during the summer of 1997. The measurements in København confirmed that a steady airflow towards the park borders existed during nights with clear skies and light winds.

Field data on this subject has, to our knowledge, not yet been presented in the literature. Not only is there a basic research interest in this outward diffusion of air from urban parks but it can also be very important for the air quality in the city. Thus, the purpose of this paper is to analyse and discuss the spatial and temporal pattern of the nocturnal local air flow observed in and around the two urban parks. The data interpretation is followed by a discussion about the origin of the flow and its implications for city ventilation.

2. Study Areas

The metropolitan Göteborg area, including the city centre and suburbs, has a population of approximately 700,000. Göteborg is located on the west coast of Sweden. Slottsskogen ($1.5\,\text{km}^2$) is the largest park in Göteborg. The park has a central forested hilly part with slopes with a general gradient of 40 m in 250 m. The central part is surrounded by extensive flat grass areas with bushes and trees. The built-up area north of the park has street canyons about 20–30 m high and 18–40 m wide. Multi-storey blocks 3 to 8 storeys in height interspersed with green spaces, dominate the suburbs west and south of the park and east of the park is an area with detached houses which in turn borders an urban forest.

The København area has about 1.8 million inhabitants and the city is located on the east coast of the island Sjælland. The city mainly comprises areas with high building density interspersed with large roads and clearly-defined green areas of different sizes. Fælledparken ($0.8\,\text{km}^2$) is flat with large open grass areas, bushes and deciduous trees. The roads bordering the park are quite wide (40 m), but the street canyons surrounding the park comprise stone buildings 4 storeys in height and 20 m wide streets.

3. Materials and Methods

The analysis is based on data from three periods including the pilot study in Göteborg. During the first period, January to March 1996, the trees were defoliated (10 case studies). However during the second, August to September 1996 in Göteborg, and third measurement period, June to July 1997 in København, there were leaves on the trees (11 case studies). Field surveys were made on nights when the weather forecast reported clear skies and light winds for the night. Mobile measurements of temperature and wind at 2 m height, were carried out in transects through the parks and surrounding built-up areas. The instruments were mounted on a tripod which was transported around the transect. Information about the instruments and methods are given in Table 1. The choice of methods for measurements of wind direction requires a comment. During the pilot study in the beginning of 1996 it was shown that the observed outflow was weak, often below $0.5\,\text{ms}^{-1}$, and that conventional wind vanes were not appropriate for the observations. Thus a decision was made to use two more simple methods in order to detect the spatial pattern of the outflow, and motivate a second study with more sophisticated instruments. One method is based on release of smoke cartridge and the other is based on the use of a light thread as a wind vane. Earlier studies have shown that these methods are reliable for detecting spatial

Table 1. *Information About Instruments and Methods Used in the Study. G = Göteborg, K = København, st = Starting Threshold, dc = Distance Constant*

Type of measurement	Name (location)	Parameter (height)	Instrument/method	Accuracy	Sampling interval
Mobile	Park tripod (G,K)	Temperature (2 m)	Semiconductor Sensor with self ventilated radiation shield	± 0.1 °C	Every tenth second during five minutes
Mobile	Park tripod (G,K)	Wind speed (2 m)	Cup anemometer 1 (R. M. Young) case study G1-G15	$St = 0.5\,ms^{-1}$ dc = 2.3 m	Every tenth second during five minutes
Mobile	Park tripod (G,K)	Wind speed (2 m)	Cup anemometer 2 (Synchrotac 480) case study G16-K21	$st < 0.2\,ms^{-1}$ dc = 0.8 m	Every tenth second during five minutes
Mobile	Park tripod (G,K)	Wind direction (2 m)	Smoke (Miniax KS, Björnax AB) and compass	± 20°	Every tenth second during five minutes
Mobile	Park tripod (G,K)	Wind direction (2 m)	Light thread (wool) and compass	±20°	Every tenth second during five minutes
Permanent	Park station (G)	Wind speed and direction (5 m)	Cup anemometer (Vaisala WAA 15) and Wind vane (Vaisala WAV 15)	$\pm 0.1\,ms^{-1}$ ± 3°	Hourly average
Permanent	Bridge station 3 km W of city (G)	Wind speed and direction (100 m)	Vaisala WAA 15 and Vaisala WAV 15	$\pm 0.1\,ms^{-1}$ ± 3°	Hourly average
Permanent	Säve airport, 9 km NW of city (G)	Wind speed and direction (10 m) cloud cover	Vaisala WAA 15 and Vaisala WAV 15 Observation by eye	$\pm 0.1\,ms^{-1}$ ± 3° –	Average of the last 10 minutes of every hour
Permanent	Avedøre station 8 km SW of city (K)	Wind speed and direction (10 m)	Cup anemometer Malling sensor 882.312 and wind vane Malling sensor 884.312	2% ± 1.4°	Average of the last 10 minutes of every hour
Permanent	Kastrup airport, 10 km SE of city (K)	Wind speed and direction (10 m) cloud cover	Malling sensor 882.312 & Malling sensor 884.312 Observation bye eye	2% ± 1.4° –	Every third hour

Table 2. *Description of Measurement Points in and Around Slottsskogen and Fælledparken (see Figs. 1 and 2 for location)*

Park	Measurement point	Height above sea level (m)	Distance from closest unporous object (m)	Direction of unporous object (m)	Description of measurement points
Slottsskogen	1	26	5	E	Street with alley
	2	29	100	N	Open grass/asphalt area
	3	32	50	NE	Border open/tree covered
	4	28	200	N	Tree covered
	5	21	100	W	Open grass area
	6	16	100	N	Open grass/asphalt area
	7	20	50	NW	Tree covered
	8	20	50	W	Tree covered
	9	22	100	SE	Open
	10	24	150	SW	Tree covered
	11	22	100	W	Open grass area
	12	34	50	W	Border open/tree covered
Fælledparken	1	5	5	W	Street with alley
	2	5	50	N	Broad street with alley
	3	5	100	NE	Open asphalt area
	4	5	200	N	Open
	5	5	200	W	Open grass area
	6	5	150	SW	Open grass area

wind patterns in urban areas. Smoke has successfully been used to detect the heat island circulation by for example Okita (1965) and Eliasson and Holmer (1990). The thread method was tested by Holmer (1978), who found this method to be useful for observations of light winds and rapid changes in wind direction, i.e., to determine if the wind has a steady direction or if strong turbulence gives rapid changes in wind direction. The methods are based on systematically readings of the wind direction, in terms of 8 sectors of the compass, every tenth second. Tests have shown that both methods gives good indications of the main direction of the flow and that the accuracy of the methods lie within ± 20°. Data was finally presented in a wind rose in order to distinguish steady flows from rapid changes in wind direction. The measurement sites used for the mobile measurements were chosen with respect to the topography and vegetation. A description of the measurement points is given in Table 2. Each case study comprised 2–6 transects with 6–16 measurement points. The time for a transect was restricted to about one hour.

The data analysis included a classification of each transect based on the occurrence of a local airflow and its direction in relation to park borders and regional wind. For this purpose data from meteorological stations, three in Göteborg and two in København, were used (Table 1). The maximum ΔT_{u-p} and the median wind speed were also calculated for each transect. Each transect was then classified into three classes ($Y = $ yes, $I = $ indications and $N = $ no) according to the occurrence of a local flow directed towards the park border and opposite to the regional wind. The different transects for each case study were then compared in order to interpret the spatial and temporal development of the wind pattern during each night. Based on this interpretation the case study nights were classified into three classes: P-nights, with a developed local airflow from the park, X-nights, without any local air flow, and PI-nights with indications of an outflow.

3. Results

3.1 Spatial and Temporal Characteristics of the Outflow

The characteristics of the 21 case studies, which altogether include 724 measurements in 88 transects, are presented in Table 3. Seven of the

Table 3. *Characteristics of the 21 Case Studies and 88 Transects*

City & Case study	Time of sunset CET	No. of T and No. of m T (m)	Start time for T (CET) T1, T2, T3, T4, T5, T6	Median w.s. for T (ms^{-1}) T1, T2, T3, T4, T5, T6	Max ΔT_{u-p} for T (K) T1, T2, T3, T4, T5, T6	Local park flow opposite to regional wind? T1, T2, T3, T4, T5, T6	Class
G 1	1624	4 (24)	1413, 1454, 1723, 1807	0.5, 0.6, 0.9, 0.9	−0.1, −0.4, 1.9, 1.0	N, N, N, N	X
G 2	1625	4 (24)	1440, 1537, 1755, 1845	0.6, 0.6, < 0.5, < 0.5	1.3, 0.5, 3.3, 3.2	N, N, N, N	X
G 3	1630	6 (40)	1500, 1557, 1654, 1825, 1915, 2002	0.8, < 0.5, 0.7, 0.6, 0.6, 0.8	1.3, 1.2, ?, 1.7, 1.7, ?	N, N, N, N, N, N	X
G 4	1650	5 (36)	1452, 1538, 1625, 1718, 1750	0.6, < 0.5, < 0.5, < 0.5, < 0.5	0.2, 0.4, ?, 1.5, 0.8	N, N, Y, I, Y	P
G 5	1741	6 (42)	1608, 1655, 1735, 1840, 1915, 1950	0.7, 0.5, < 0.5, < 0.5, < 0.5, < 0.5	−0.4, 1.5, ?, 1.7, 1.1, ?	I, I, Y, Y, Y, Y	P
G 6	1743	3 (36)	1608, 1641, 1724	1.8, 1.2, 0.8	0.2, 0.9, ?	N, N, Y	P
G 7	1745	6 (44)	1556, 1640, 1705, 1825, 1907, 1940	1.2, 1.4, 0.5, 0.6, < 0.5, < 0.5	−0.2, 0.5, ?, 0.8, 0.8, ?	N, N, N, N, N, N	X
G 8	1800	3 (36)	1945, 2048, 2128	< 0.5, < 0.5, < 0.5	?, 1.0, 1.0	Y, N, N	P
G 9	1805	6 (48)	1736, 1629, 1704, 1840, 1910, 1953	< 0.5, 0.8, < 0.5, < 0.5, < 0.5, < 0.5	−1.5, 0.8, ?, 0.7, 1.1, ?	N, N, N, N, N, I	PI
G 10	1821	6 (44)	1603, 1640, 1715, 1841, 1922, 1956	0.6, < 0.5, < 0.5, < 0.5, < 0.5, < 0.5	−2.3, 0.6, ?, 1.3, 0.8, ?	N, N, N, N, I, I	PI
G 11	2014	3 (30)	1810, 1950, 2120	0.8, 0.6, 0.5	−0.2, 0.2, −0.3	N, N, N	X
G 12	2002	2 (32)	1808, 2107	0.7, 0.5	−0.5, −0.3	N, N	X
G 13	2000	2 (32)	1756, 2100	1.0, 0.7	0, 0	N, N	X
G 14	1944	2 (20)	1820, 2039	< 0.5, < 0.5	1.8, 1.4	N, N	X
G 15	1939	5 (50)	1811, 2044, 2338, 0238, 0526	< 0.5, < 0.5, < 0.5, < 0.5, < 0.5	3.3, 2.7, 2.4, 1.2, 1.8	N, Y, Y, Y, N	P
G 16	1848	5 (50)	1733, 2033, 2300, 0158, 0614	0.8, 0.3, 0.3, < 0.2, 0.2	1.4, 1.8, 1.1, 1.2, 0.5	N, Y, Y, I, N	P
G 17	1818	4 (40)	1632, 1951, 2325, 0254	1.1, 0.6, 0.9, 0.5	0.6, 1.7, 0.3, 1.1	N, N, N, N	X
K 18	2047	4 (24)	1945, 2154, 2359, 0345	0.7, < 0.2, < 0.2, 0.4	0, 2.1, 2.0, 0.4	N, Y, Y, N	P
K 19	2048	4 (24)	1931, 2158, 0000, 0211	0.7, 0.3, 0.6, 0.9	0.7, 0.4, 0.4, 0.1	N, N, N, N	X
K 20	2037	5 (30)	1925, 2200, 0003, 0210, 0400	0.2, < 0.2, 0.4, 0.8, 0.7	1.1, 1.2, 1.0, 0.4, 0.9	N, I, N, N, N	PI
K 21	2036	3 (18)	1930, 2200, 0100	1.2, 1.3, 1.7	0.7, 1.5, 0.9	N, N, N	X

G = Göteborg, K = København, T = transects, m = measurements, CET = central european time, w.s. = wind speed in the park, ΔT_{u-p} = urban-park temperature difference, Y = transect with local park flow opposite regional wind, I = transect with indications of local park flow opposite to regional wind, N = transect with no local park flow, P = night with local park flow, X = nights without local park flow, PI = nights with indications of a local flow.

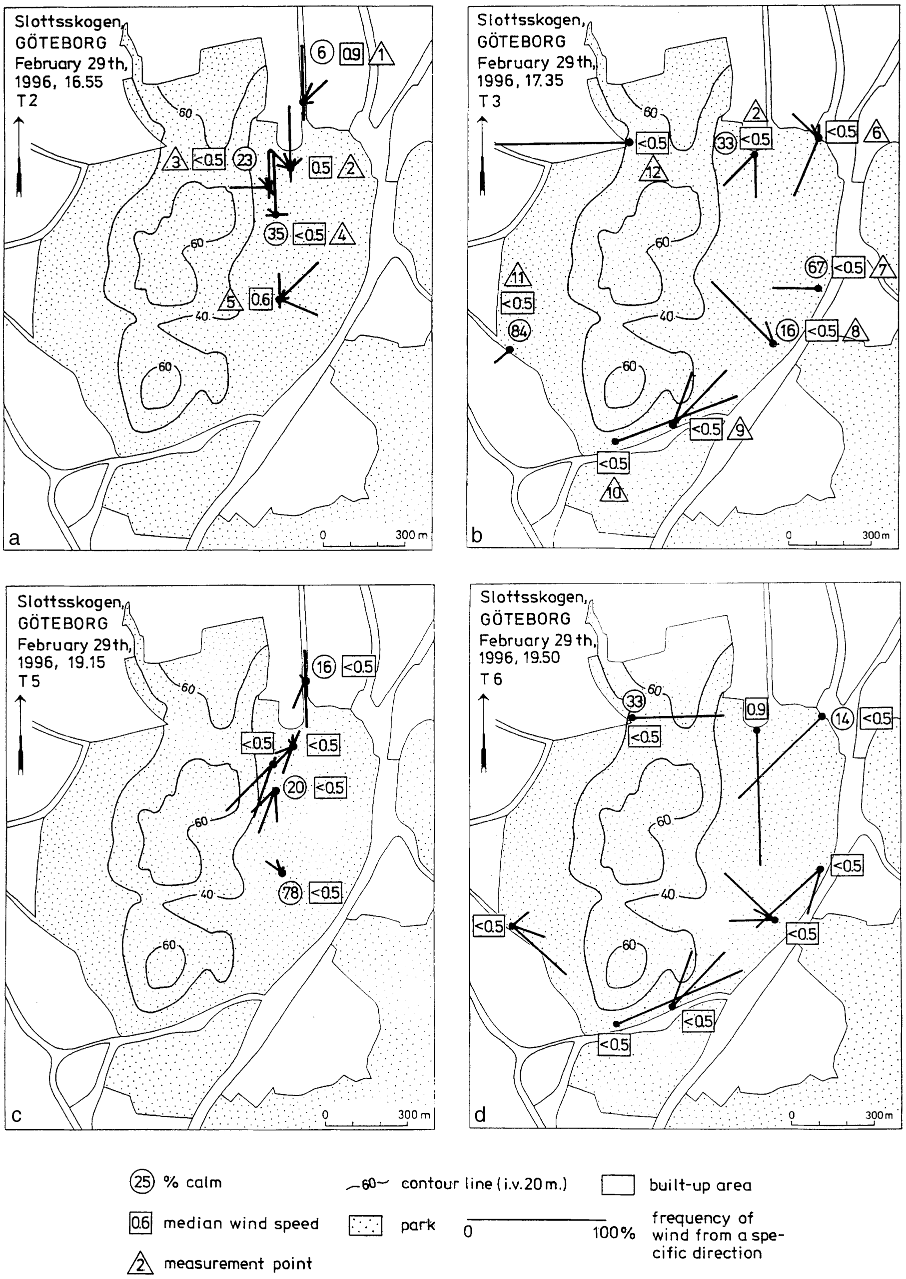

Fig. 1. Case study G5 (Table 3) in Slottsskogen, Göteborg during February 29th, 1996. Regional winds were from northwest (Fig. 3). The measurements included six transect of which four is shown in the figure. Each map is marked with starting time of the transect and the transect number TX. For description see also Table 4. The local airflow is shown by windroses consisting of bars. The length of the bars represent the frequency (%) of the flow in 8 sectors of the compass. The flow is directed towards the measurement point marked with a dot. A number in a circle show the occurrence and frequency of calm at the specific point. Information about the median wind speed is also given in the figure. Figure a and b shows the number of each measurement point, see also Table 2

case study nights were classified as P-nights, three as PI-nights and the remaining 11 nights were classified as X-nights.

Two examples from Göteborg and København clearly illustrates that a transect with a well developed local airflow was characteristed by calm in the middle of the park and a steady airflow towards the built-up areas at the park borders (Figs. 1 and 3, Tables 4, 5 and Table 3: G5 & K18). All the P-nights show this spatial pattern during at least one transect. PI-nights were also characterized by an airflow directed towards the built-up areas, however, a weak wind was measured in the centre of the park. The measurements showed that the steady airflow from the park faded rapidly when entering the built-up areas. In Göteborg the flow disappeared within a distance of 250 m and in København within 100 m from the park borders. The temporal development of the airflow is also illustrated by the two examples in Figs. 1 and 2. On both these occasions the sky was clear and a north-westerly wind prevailed during the night at the meteorological stations at the city borders.

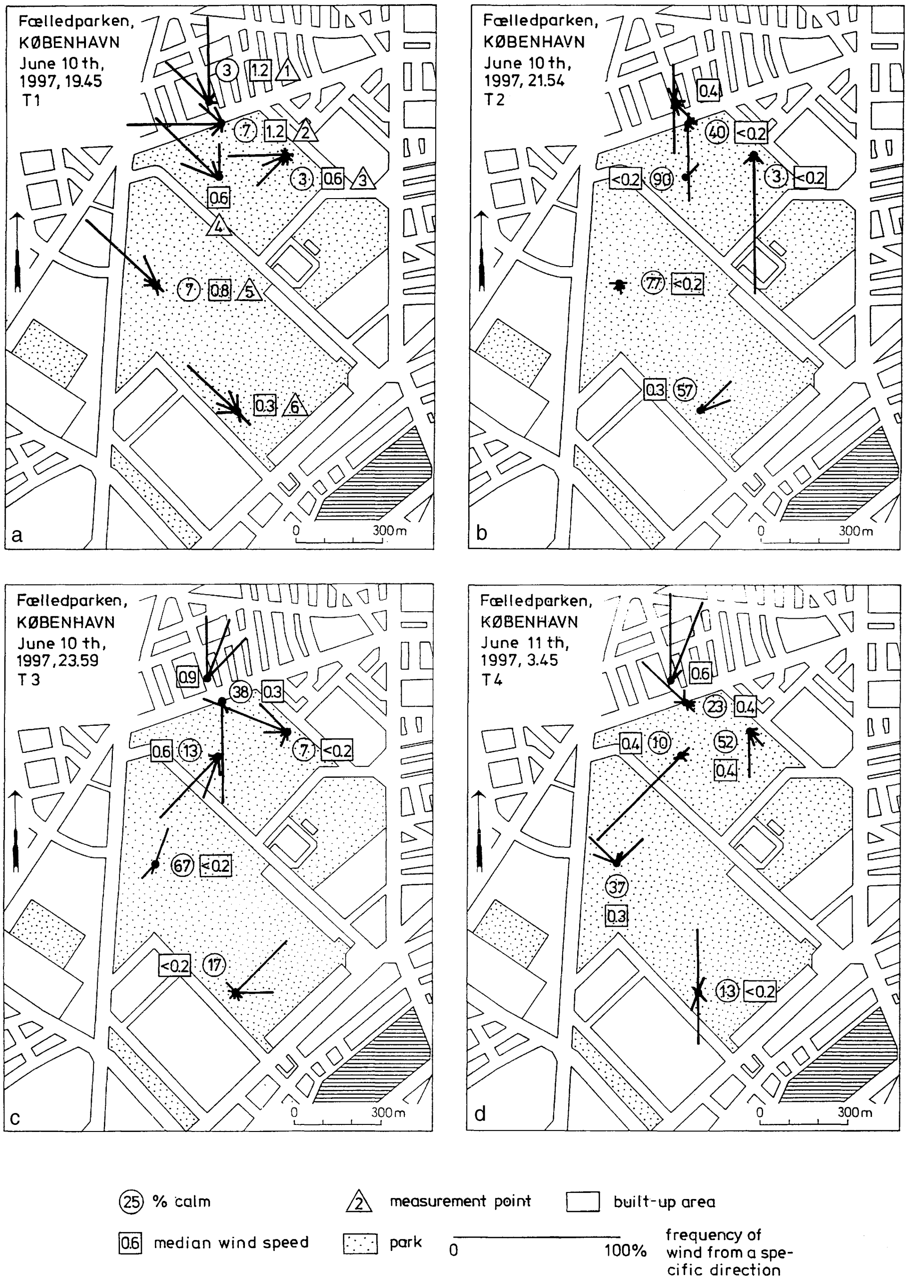

Fig. 2. Case study K18 (Table 3) in Fælledparken, København, during June 10^{th} to 11^{th}, 1997. The measurements included four transect. Regional winds were from northwest. Each map is marked with starting time of the transect and the transect number TX. For description see also Table 5. The local airflow is shown by windroses consisting of bars. The length of the bars represent the frequency (%) of the flow in 8 sectors of the compass. The flow is directed towards the measurement point marked with a dot. A number in a circle show the occurrence and frequency of calm at the specific point. Information about the median wind speed is also given in the figure. Figure a shows the number of each measurement point, see also Table 2

Measurements before sunset showed a local flow strongly influenced by the regional wind on both these occasions, and the characteristic outflow was developed after sunset (Figs. 1 and 2, Tables 4 and 5). In general the local airflow started to develop during a period from sunset to about two hours after sunset (Table 3). The start and breakdown of the flow has been possible to determine either through direct field observations, as in the example in Fig. 2, or through a wind shift at the permanent park station in Göteborg (Fig. 3). Field observations of the duration were made at three case studies (Table 3: G15, G16, K18) and a wind shift at the permanent park station was recorded at four case studies (Table 3: G4, G5, G8, G15). These results showed a period of four to eight hours duration.

3.2 Statistics

An analysis of the amount of cloud cover and wind speed at the rural stations Säve airport (Göteborg) and Kastrup airport (København) show a mean cloud cover of 1.1 octas for P-

Table 4. *Description of the Spatial and Temporal Pattern of Case Study G5 (Table 3, Fig. 1)*

Description of the spatial and temporal pattern of the airflow in Slottsskogen, Göteborg, February 29th, 1996.
Map (a) The north-south transect, T2, one hour before sunset reflects the north-westerly wind recorded at the regional stations. The temperature difference between point 1 and 5 was 1.5 K. Highest wind speed were 0.9 $\mathrm{ms^{-1}}$ at point 1.
Map (b) At sunset a transect, T3, around the perimeter of the park showed an outflow from the park at the north, east and south borders. Wind speeds below 0.5 $\mathrm{ms^{-1}}$.
Map (c) One hour after sunset a north-south transect, T5, showed a southerly flow in the park opposite to the north-westerly regional wind at all points except for point 5 were the wind had ceased (78% calm). The temperature difference between point 1 and 5 was 1.1 K. Wind speeds below 0.5 $\mathrm{ms^{-1}}$.
Map (d) One and a half hour after sunset the transect, T6, around the perimeter of the park showed an outflow from the park at all sides. Wind speeds below 0.5 $\mathrm{ms^{-1}}$.

Table 5. *Description of the Spatial and Temporal Pattern of Case Study K18 (Table 3, Fig. 2)*

Description of the spatial and temporal pattern of the airflow in Fælledparken, København, June 10th and 11th, 1997.
Map (a) One hour before sunset at transect T1, the north-westerly regional wind was evident at all measurement points in the park. Wind speed varied between 0.3 and 1.2 $\mathrm{ms^{-1}}$ and the temperature difference between point 1 and 4 was zero.
Map (b) One hour after sunset, at transect T2, a distinct and steady airflow towards the park borders was recorded at the north and south borders while it was calm in the middle of the park. The highest wind speed was 0.4 $\mathrm{ms^{-1}}$ at point 1 and the temperature difference between point 1 and 4 had increased to 2.1 K.
Map (c) An outward directed airflow was also observed at the park borders during the third transect, T3, three hours after sunset but the wind speed had increased to 0.9 $\mathrm{ms^{-1}}$ at point 1. The temperature difference between point 1 and 4 was 2.0 K.
Map (d) The break down of the local airflow was evident during transect T4 around sunrise. The regional north-westerly wind influenced most of the measurement points. The highest wind speed was 0.6 $\mathrm{ms^{-1}}$ at point 1 and the temperature difference between point 1 and 4 had decreased to 0.4 K.

nights and 2.5 octas for the X-nights. The mean wind speed at the rural stations was 2.3 and 2.7 $\mathrm{ms^{-1}}$ for the P- and X-nights, respectively. It is thus clear that the local airflow from the park developed during very clear and calm weather. However, the difference in rural cloud cover and wind speed between the two groups is not statistically significant at the 95% level. This may be explained by the fact that the rural wind and cloud cover were recorded about 10 km from the urban parks. Unfortunately no cloud observation data were available for the two urban areas, but the wind speed at the Park station (5 m) in Göteborg was analysed. The results show a mean wind speed of 0.7 $\mathrm{ms^{-1}}$ for the P-nights and 1.0 $\mathrm{ms^{-1}}$ for the X-nights, but the difference between the two groups is not significant at the 95% level.

The urban-park temperature difference at 2 m, ΔT_{u-p}, was calculated for each transect. In Göteborg the difference is based on data from m.p. 5 in the park and m.p. 1 in the built up area north of the park (Fig. 1a). In København m.p. 4 represent the park temperature and m.p. 1 the built-up area temperature (Fig. 2a). Figure 4 shows the mean values and confidence intervals (95% level) of the ΔT_{u-p} for each of these transects-groups. The analysis is based on data from all of the 88 transects. The Y-transects have a mean value of 1.7 K and the N-transects have a mean value of 0.8 K. The confidence intervals are clearly separated and ΔT_{u-p} for the two groups are thus statistically different on the 95% level. The I-transects overlap both the N and Y transects. The median wind speed at 2 m was also calculated for each transect. The results

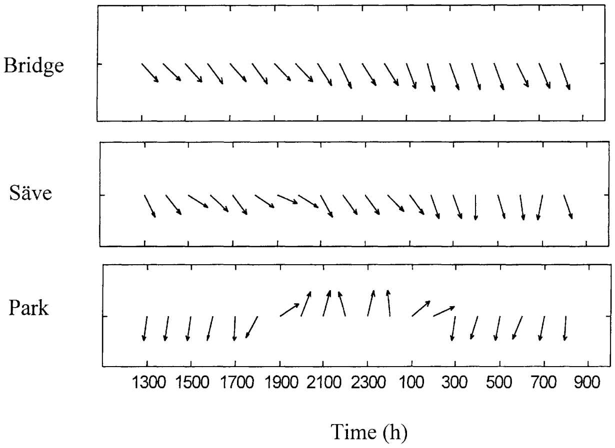

Fig. 3. Wind direction at three permanent stations in Göteborg during February 29th to March 1st 1996. Winds were from NNW at the Bridge and Säve stations located outside the city. A shift in wind direction from north (into the park) to south (out from the park) and back to north again was recorded at the Park station. This indicates a period of six to eight hours duration of the local airflow from the park (Fig. 1). See Table 1 for information about the stations

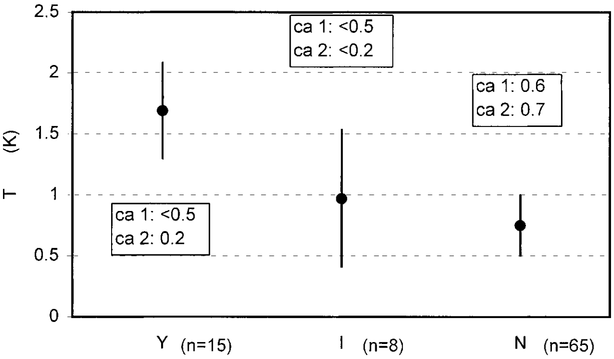

Fig. 4. Mean values and confidence intervals of the maximum ΔT_{u-p}, for Y-, I- and N-transects. Boxes show values on the median wind speed during Y-, I- and N-transects for cup anemometers (ca) 1 and 2 respectively. Y = evident local airflow in the park, I = indications, N = no local airflow

were divided into two groups (Fig. 4). The first group shows the result based on data from the first 63 transects when cup anemometer 1 was used (Table 1). The second group shows the results from the last 25 transects when cup anemometer 2 was used (Table 1). The analysis shows similar results for both groups. The median wind speed during N-transects was 0.6–0.7 ms^{-1}. During the Y-transects the speed was clearly below 0.5 ms^{-1} and the measurement with the sensitive anemometer (cup anemometer 2) showed a median wind speed of 0.2 ms^{-1}.

4. Discussion

The spatial pattern of the local airflow from the park resembled the description of the theorized park breeze, and the interpretation was that the observed local airflow in the two parks were strongly influenced by the development of a park breeze. However, in Slottsskogen the height differences in the park might induce cold air flows, and in both Göteborg and København the urban heat island circulation and land breeze might influence the observed pattern. Below follows a discussion about the possible origin of the nocturnal airflow developed in the parks.

4.1 Influence of the Park Breeze

The theory of park breeze is based on temperature differences as a driving force for the divergent outflow of cool air at low level (Oke, 1989). The first requirements for park breeze was thus stable weather conditions and a positive ΔT_{u-p}. The interpretation of the local flow (2 m) was based on its direction compared with the regional wind at higher levels. The flow was classified as a park breeze if an airflow with more than 90° difference from the regional wind direction occurred on the windward side of the park, and/or if it was possible to record an airflow directed towards the built-up areas at all borders of the park. All of the 14 Y-transects show positive ΔT_{u-p} and meet the requirements for park breeze. The P-nights include at least one Y-transect and these nights were interpretated as influenced by park breeze development (Table 3). As a strong temperature difference developed and a distinct outflow was recorded during the second and third transect in case study K18 (Fig. 2), this is an example of a night with a park breeze development. The park in København certainly has good conditions for development of large temperature gradients and park breeze as it is flat and surrounded by canyon areas. Indications of a park breeze development were obvious also during the first two transects in case study 20. However, an increased wind speed in the region during the late evening disturbed the pattern as obvious from the transect data, i.e., increased wind speed and decreased ΔT_{u-p} during T3–T5 (Table 3: K20). The conditions for a park breeze development are also good in

Göteborg and six nights were interpreted as park breeze nights (Table 3: G4, G5, G6, G8, G15, G16). The two case studies G15 and G16 each consist of five transects starting about 1 hour before sunset and ending a few hours after sunrise the next day. The spatial and temporal pattern of the park breeze development during these two nights were very similar to the København example in Fig. 2. Case studies G4 and G6 resemble G5 (Fig. 1) as a park breeze flow was established just after sunset. Changes in weather conditions during the night disturbed and weakened the pattern in case study G8 as well as during both PI-nights G9 and G10.

4.2 Influence of Topography

It is a well-known fact that a variation in topography induces cold air flows, but literature shows that the definition of "drainage flow" is broad (see for example; Schnelle, 1963; Geiger, 1965; Mahrt and Larsen, 1982; Lindqvist et al., 1983; Kondo and Sato, 1988). The park in København is flat, but in the park Slottskogen, Göteborg, occurrence of cold air flows could not be excluded. Almost all slopes in the park are, however, covered with trees and bushes, which according to some authors (e.g., Schnelle, 1963; Lindqvist et al., 1983) counteract the production of cold air. The possible influence of cold air drainage on each measurement point was analysed by map studies and discussed during field visits. As shown in Table 2, all measurement points, except two located in street canyons, were located 50 m or more from any disturbing object. The direction to the nearest unporous object is also given in Table 2. The location of the measurement points are thus supposed to reflect areas that were not influenced by cold air drainage or buildings. Even though cold air flows could not be totally excluded in Slottsskogen, the influence must be regarded small in comparison to the park breeze effect.

4.3 Influence of the Urban Heat Island Circulation and Land Breeze

The urban heat island circulation (UHIC) and the land breeze are two local wind flows which develop during clear and calm nights. Their influence on the urban wind pattern has been recognized and their effect on the present observations must therefore be analysed. As the reported speed for both breezes vary between 0.3 and 3 ms^{-1} their influence could not be excluded based only on wind speed data (Gold, 1956; Schreffler, 1978; Goldreich and Surridge, 1988; Eliasson and Holmer, 1990; Kuttler and Romberg, 1992; Gustavsson et al., 1995; Haeger-Eugensson and Holmer, 1999). A spatial analysis of the influence of the lower levels of the UHIC (the country breeze) and the land breeze could, however, only be based on theoretical considerations due to lack of field data. No data was available from København and observations of the country- and land breeze in Göteborg has not been made below 10 m height (Eliasson and Holmer, 1990; Holmer and Haeger-Eugensson, 1999). The characteristic spatial pattern of the local airflow from the park contradicts a pure influence of both the country and land breeze in both cities. In Göteborg, for example the park is located south of the city centre giving a theoretical south to north directed country breeze which only could explain the outflow at the north border in the park. The land breeze in Göteborg has a east-west direction and thus could only explain the outflow at the west borders of the park. A similar conclusion is made when analysing the theoretical influence of the two breezes on the case studies in København. Nothing in the present field data, therefore, indicate that the country breeze or the land breeze could explain the observed spatial airflow from the park.

5. Conclusions

This study clearly shows that the two parks generated a local airflow during clear and calm weather. The local airflow was weak but steady ($< 0.5\,\mathrm{ms}^{-1}$), reached to a distance of less than 250 m from the park border and was best developed between two and six hours after sunset. In the flat park in København the local airflow is in all probability an effect of a park breeze development, which in turn is induced by the urban-park temperature difference. In the hilly park in Göteborg cold air drainage may have a minor influence, but during the P-nights the park breeze development played a large role. The findings in this study thus showed that the park breeze phenomena exists and nothing contradicts the existence of park breezes in other cities in the world. As the Scandinavian climate is very variable it is even more likely that parks located in more stable climates, with higher frequency of clear and calm weather, might produce park breezes more often. There is certainly a strong need for closer examination of the physical limitations of the flow as for example its frequency, duration, entrainment in the urban area and park size limits. This includes further field measurements of both horizontal and vertical air movements, as well as development of models.

5.1 Park Breeze and City Ventilation

What is the significance of the park breeze for the city ventilation? The frequency of nights with weather conditions favouring park breeze is important. One third of the case studies presented above was classified as nights with park breeze, with a mean cloud cover of 1.1 octas and a mean wind speed of 2.3 ms^{-1}. According to a statistical analysis of the period 1961–1975, such weather conditions occurs at ten per cent of the nights during a year in Göteborg (Holmer, 1980). An occurrence of ten per cent is not insignificant for the air quality in the city, especially as the weather conditions favouring the breeze usually also promotes inversions and poor conditions for the city ventilation. At a first glance the effect of the park breeze thus seems to be positive, as the outflow increases the ventilation below the inversion by transporting "clean" air out from the park into the built-up surroundings. The local airflow in the park is, however, only one part of the complex urban micro advection, and it is very likely that the different local air flows act together or/and counteract each other in the urban canopy. A conceptual model based on the conditions in Göteborg during clear and calm nights, is shown in Fig. 5. The figure shows a schematic north-south cross section of the urban-park circulation (PC) and the UHIC. The lower parts of each circulation system (solid lines) are based on field data from Göteborg, while the upper circulation parts of the systems (dashed lines) are based on theories given in the literature (e.g., Vukovich, 1971; Oke, 1989). Earlier measurements in Göteborg give indications of a park breeze depth of about 30 m (Häger and Svensson, 1996), while the country breeze has been observed from a height of 10 m to 60 m above the ground (Eliasson and Holmer, 1990). However, neither the lower boundaries of UHIC nor the higher boundaries of the park breeze are statistically proved. Under the assumption that the two local flows exist during the same period of the night and at the same level in the urban canopy layer, the combined effect is probably not only positive for the urban air quality. The positive effect of promoting "clean" air from the parks has already been mentioned. However, if the park breeze is opposite to the country breeze or the regional wind, the result could be an obstruction of both flows, preventing the transport of both "clean" air out from the park and "polluted" air into the park.

To our knowledge there is no single study available which answers the question about the combined effects of the different local airflows observed in the urban environment. Still the scenarios of the effects of the complex urban micro advection on the air quality are very important for environmental discussions. If we want to realize the vision of the sustainable city during the new millennium, there is a strong need

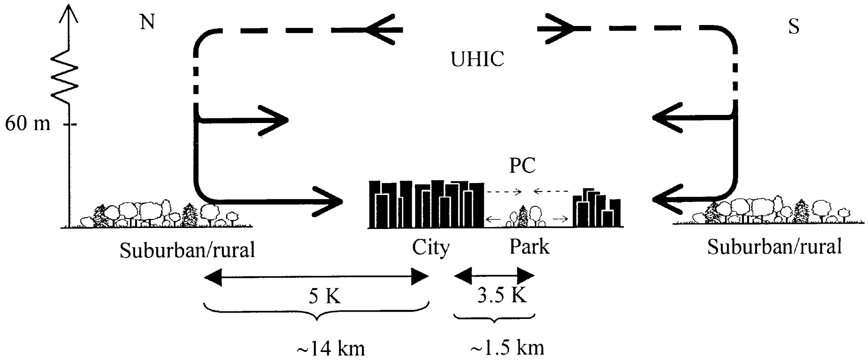

Fig. 5. Conceptual model of the urban heat island circulation (UHIC) and park circulation (PC) based on theories given in the literature and the field data from Göteborg, Sweden

for more climate research on the interaction of different local airflows in the city, as well as to achieve cooperation among disciplines important in the management of the urban air.

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