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Influence of geographical factors and meteorological variables on nocturnal urban-park temperature differences—a case study of summer 1995 in Göteborg, Sweden

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ABSTRACT: This study deals with the magnitude of influence of various geographical factors and meteorological variables on the air temperature difference between a park and a built-up area (ΔT_{u-p}). The statistical analysis focuses on the time of nocturnal maximum ΔT_{u-p} in summer in Göteborg, Sweden, during May to October 1995. The geographical factors include sky view factor, height above sea level and distance from the park border. The meteorological variables considered include wind, cloud cover and type, global radiation, air temperature, subsurface temperature and humidity. Principal component analysis is used to identify temporal and spatial patterns of the temperature anomaly along a transect across the built-up area and green area. The first principal loading is found to explain 71% of the total variance. It represents a kind of mean pattern and depicts the dominant distribution of the anomaly along the transect, which is interpreted as being created by the differences in surface characteristics. Distance from the park border accounts for 86% of the spatial variation in air temperature. The magnitude of this pattern is mainly modulated by the average wind speed and the average cloud index, i.e. cloud cover and type, from sunset until the time of interest, i.e. 27 and 13% respectively of the variation in ΔT_{u-p} can be explained by these variables. Subsurface temperature and urban-park vapour pressure difference can explain minor parts of the variation in ΔT_{u-p}. The wind direction affected both the spatial pattern and the magnitude of ΔT_{u-p}. The influence on magnitude under different wind directions was probably caused by the difference in relative sizes between the warm built-up area and the colder park and suburban area.

KEY WORDS: Air temperature · Wind · Cloud · Global radiation · Air humidity · Sky view factor · Principal component analysis · Summer

1. INTRODUCTION

1.1. Background

In a statistical approach the present paper examines the importance of both geographical factors and meteorological variables for the development of air temperature differences between parks and their surrounding urban areas. The background to this analysis is earlier investigations of the influence of parks on the urban climate, carried out in Göteborg, Sweden, and Copenhagen, Denmark. Some results from this investigation (data from clear and calm nights following a clear day) are presented in Upmanis et al. (1998). This former paper shows that both the magnitude of the urban-park temperature difference (ΔT_{u-p}), and the extension of the cold park climate into the built-up area increased with increasing park size. The results also indicate that distance to the park border and sky obstruction influenced the magnitude and extension. However, no comprehensive statistical analyses were performed in Upmanis et al. (1998).

The air temperature at a specific location is of course determined by the energy balance, which in turn depends on a number of both geographical factors and

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meteorological variables. Geographical factors, such as surface properties and sky view factor (SVF), are primary reasons for the temperature difference, while meteorological variables, such as wind speed and cloud cover, are the forcing factors. The interaction of the 2 kinds of factors determines the temperature characteristic of a location, and thus, for example, the magnitude of the temperature difference between the built-up area and the park.

Several other studies show that urban parks establish their own cold climate *in situ* and that larger parks have greater influence on surrounding temperatures (Chandler 1965, Jauregui 1975, Oke 1989, Honjo & Takakura 1990/1991, Jauregui 1990/1991, Saito et al. 1990/1991, Ahmad 1992, Spronken-Smith 1994, Spronken-Smith & Oke 1998). However, studies dealing with how the meteorological variables influence ΔT_{u-p} have to our knowledge not yet been published. Many studies examine the processes that favour the development of a strong urban heat island (UHI) (e.g. Sundborg 1950, Oke 1973, Park 1986, Kidder & Essenwanger 1995). The common findings are that wind speed and cloud cover for the time of interest are the main influencing variables. Only a few studies consider any variables for the preceding hours (Kawamura 1964, Chow et al. 1994). Other variables which may be important are air humidity, temperature (e.g. Sundborg 1950, Kawamura 1964, Lindqvist 1970), daily sum of direct global radiation, mean diurnal wind speed (Chow et al. 1994), air pressure (Moreno-Garcia 1994), cloud cover during the preceding day (Kawamura 1964) and maximum temperature amplitude during the sampling interval (automobile traverse or day), as a measure of long-wave radiation conditions (Kuttler et al. 1996). Other studies only conclude that anticyclonic weather is most favourable for the development of the UHI (e.g. Yagüe et al. 1991).

Most of the studies on the UHI deal only with point comparisons, i.e. 1 city station and 1 rural station are compared (e.g. Chandler 1965, Yagüe et al. 1991, Moreno-Garcia 1994). However, Park (1986) made both point comparisons and comparisons of urban-rural temperature profiles using 2 cloud groups. Many studies focus on only a few (2 or 3) meteorological variables, such as wind speed and cloud cover, for the time of interest. Quite often these studies concentrate on clear and calm weather situations (e.g. Oke 1973, Park 1986, Kidder & Essenwanger 1995, Kuttler et al. 1996). Some studies have examined the magnitude of the influencing variables (e.g. Sundborg 1950, Park 1986, Moreno-Garcia 1994). However, often only the most significant variables are named, with no magnitude of their importance given (e.g. Duckworth & Sandberg 1954, Yagüe et al. 1991, Kidder & Essenwanger 1995, Unger 1996).

A few studies discuss the influence of geographical factors on the park climate. The distance from the park border seems to be important, as it is established that a park influences its surroundings by decreasing the temperature (e.g. Spronken-Smith 1994, Spronken-Smith & Oke 1998, Upmanis et al. 1998). However, it is unclear how this cooling effect is correlated to distance from park border. The influence of the height above sea level was proved by Kuttler et al. (1996), but on the other hand the study by Upmanis et al. (1998) did not show any significant influence of height above sea level on ΔT_{u-p}. Thermal admittance is another factor which is probably of importance for the air temperature. Oke et al. (1991) have shown that thermal admittance for a surface (μ_s) has a strong influence on the surface temperature, and that relative magnitude of μ_s and thermal admittance for air (μ_a), is important in determining the sharing of sensible heat between the soil (Q_G) and the air (Q_H) such that $\mu_s/\mu_a = Q_G/Q_H$ (Oke 1990). Several studies have confirmed the influence of SVF on long-wave radiation and surface temperature, both in urban and rural areas (e.g. Oke 1981, Nunez & Sander 1982, Eliasson 1992, 1996, Gustavsson 1995). Blennow (1997) also showed that there is a good relationship between SVF and air temperature at 0.25 m above the ground in a forest. A recent study (Karlsson 1999) shows a strong relationship between SVF and average air temperature at 2 m above the ground inside a rural forest. Yamashita et al. (1986) showed similar relationships inside urban areas in Japan. However, no other studies have found the relation between SVF and air temperature in urban areas to be statistically significant (e.g. Eliasson 1996), even though good relationships have been found between SVF and surface temperature (e.g. Oke 1981, Bärring et al. 1985).

1.2. Present study

Although several studies have examined the influence of meteorological variables on the UHI, the literature review given above shows the need for more comprehensive view of the problem. Even more important is the question of whether these studies on the UHI (small warm area and large cold area) are directly applicable to intra-urban temperature variations as ΔT_{u-p} (large warm area and small cold area). The borders between parks and the surrounding built-up areas are often more distinct than the borders between urban and rural areas, which in most cities are a diffuse transition from pure urban areas through suburban areas. The abrupt land use change found between parks and built-up areas may have a great effect on the physical processes and resulting temperatures. One example is the maximum urban-park temperature difference found in Göteborg, which is 5.9°C over a distance of about 1.5 km (Upmanis et al. 1998). Compared to the urban-rural temperature difference, which has a maximum mean value (over a distance of 14 km) that ranges from 4.0°C in winter to 5.5°C in summer (Eliasson 1994), this is a high value. One theory is that local geographical factors play a large role in the development of intra-urban temperature differences.

There is certainly a need for more comprehensive studies which, with different methods and techniques, examine the relative impact of different factors and variables in order to understand the development of intra-urban temperature differences. The present study focuses on a statistical analysis of the magnitude of the influence of several different factors (SVF, distance from park border, height above sea level) and variables (wind, cloud cover and type, global radiation, air humidity, air and subsurface temperature) on ΔT_{u-p}. The statistical method used here is principal component analysis, which to our knowledge has not been applied before in similar studies. The method reveals dominant spatial patterns of ΔT_{u-p} by separating the temperature variation in space and time. The method offers an effective way of identifying spatial patterns and their associated evolution in time. Our intention in using of this method is to identify the most influential factors and variables, and to determine the magnitude of their influence. The study is built on nocturnal summer data from several locations in a profile through built-up and park areas, and data from a variety of weather types are used. Data collected 4 times per night is examined and 1 of these times is studied in greater detail. The influence of weather of the previous hours on ΔT_{u-p} is also examined.

Fig. 1. Aerial photo of the study area in Göteborg. The park (Slottsskogen) can be seen in the right part of the photo, and the bridge station (Älvsborgsbron) can be seen in the upper left corner

2. STUDY AREA

The study was carried out in the city of Göteborg (57° 42' N, 11° 58' E), situated on the Swedish west coast. The Göteborg area has about 700 000 inhabitants and can be described as a fissure valley landscape, dominated by a few broad, large valleys trending in both north-south and east-west directions. The inner city consists of an old, densely built-up part with streets having a SVF of 0.25 to 0.45, and a more recently built area with broader streets and squares with a SVF of 0.5 to 1.0. Swedish cities have quite a high density of green areas and Göteborg is no exception, providing a lot of natural green spaces.

The study area was a large park and its built-up surroundings. The park, Slottsskogen (Figs. 1 & 2), is the largest park in Göteborg with an area of about 156 ha. On the north side there are high buildings with SVFs of 0.4 to 0.7 at the midpoint of the streets. On the west and south sides there are suburban areas with a lot of green spaces. A large traffic route on the eastern side separates the park from a villa area (Änggården) which is bordered by a botanical garden and a forest. The park has an elevation difference of up to about 55 m and is a mixture of different land types. It includes forest and grass-covered areas with scattered trees and bushes, open waters, roads and asphalt footpaths, buildings and sand-covered areas.

3. DATA AND METHODS

Nocturnal data from May 15 until October 1, 1995, were used in the study. From a meteorological point of view this is a sufficiently long period of time. From a climatological point of view, however, one may argue that 1 season is not enough for this type of study. However, the Swedish climate is very variable and a variety of different situations were present during the study period. Thus, this suggests that the study will give valid answers to the questions raised. Criteria for using the data were that all stations should be operating at

Fig. 2. Map of the points of measurements in Slottsskogen (156 ha), including Änggården (4 ha) (Stns 12 to 14) (see Table 1 for description)

the same time, and no occasions with rain or fog were included. Despite technical problems, theft and vandalism a total of 55 nights' data could be used. The beginning of the summer (May and June) was somewhat colder than normal (–0.9°C), while the 3 last months were warmer than normal (+1.2°C), according to the Swedish Meteorological and Hydrological Institute (SMHI) (Väder och vatten 1995).

Measurements were made at permanent stations, including small data loggers (Intab tinytalks) and masts with logger equipment. In total, 14 locations were chosen to represent different distances from the park border, height above sea level and areas with different SVF (Table 1, Fig. 2).

3.1. Site and instrumentation

Nineteen tinytalks (Table 2), which include both logger and sensor, were used. Of these, 14 measured air temperature and 5 measured relative humidity. The tinytalks will hereafter be referred to as fixed sensors for temperature and humidity. The sensors were placed along a transect through the park and its surrounding built-up areas (Table 1, Fig. 2). The height of 2.5 m was chosen because of problems with vandalism and stolen instruments. Because of this problem, they were also chained and padlocked. The fixed sensors for humidity were placed at Stns 1, 7, 9, 12 and 14 (Table 1, Fig. 2). The instruments were protected by radiation shields covered with highly reflective film, tilted 45° to the horizontal and positioned facing north to avoid insolation.

The manufacturer's specifications indicate that the fixed sensors for temperature have an accuracy of ±0.2°C, and a resolution of 0.16°C in the measurement span. The time constant of the instrument is about 15 min. The fixed sensors for humidity measure in the interval 0 to 95%. They have an accuracy of ±0.3% at 25°C and the temperature drift is 0.2% °C^{-1}. The time constant is 2 min.

To determine if there were any inter-instrument differences between the fixed sensors, they were run next to each other for a number of days. The temperature sensors were run in a climate-chamber, constructed to keep a specific constant air temperature, for 3 d (N = 311). The instruments were tested for temperatures ranging from –5 to 19°C, and then corrected for the differences. The climate chamber intercomparison showed that the majority of the absolute errors lay within ±0.1°C, and that all fell into the span of ±0.2°C. The instruments were also run outdoors at the same location for several weeks to check for differences. The results of these measurements support the climate-chamber results, and show that the bias is independent of other variables. For the humidity sensors the differences are systematic. They were run for 12 d (N = 722) both indoors and outdoors and tested for relative humidity between about 15 and 95%. The data were corrected for the differences, and 80% of the variation lay within ±2%. For all data the difference fell into the span +7 to –10%.

Two permanent masts (Table 2) were placed in the park (Fig. 2, Stn 10) and at Älvsborgsbron (bridge sta-

Table 1. Description of stations in and around Slottsskogen chosen to represent different distances from the park border, varying heights above sea level and a variety of SVFs (sky view factors) in the park and the built-up area (see Fig. 2 for locations). Distance from northern park border is the north-south distance from Stn 6

Stn	Description	Distance from northern park border (m)	Height (m)	SVF
1	Square with a few trees	–1000	2	0.91
2	Broad street with alley	–645	4	0.74
3	Broad street with alley	–450	8	0.69
4	Narrow street	–170	14	0.47
5	Narrow street	–95	17	0.43
6	Street located between park and urban	0	21	0.77
7	Trees close to open area	135	28	0.74
8	Trees close to a large open area	500	24	0.62
9	Forest	610	60	0.64
10	Large open grass area with a few trees	700	20	0.89
11	Road lined with bush/trees & open	1050	18	0.73
12	Wide street with alley, low houses, gardens	1235	24	0.76
13	Wide street with alley, low houses, gardens	1300	24	0.76
14	Forest	1495	50	0.59

tion, Fig. 1), at the west border of the city. The bridge station measured at 100 m above the ground and can be regarded as showing the general wind for the Göteborg area. The anemometers have a threshold and an accuracy of 0.4 and 0.1 m s^{-1}, respectively. The wind vanes have a threshold, an accuracy and a resolution of 0.3 m s^{-1}, ±2.8° and 5.6°, respectively. The data were saved with a Campbell Scientific CR10.

In addition to the above-mentioned stations, data from 2 standard meteorological stations were used (see Table 2). At the Göteborg station, located in central Göteborg, the global radiation was measured with a Kipp-zonen pyranometer. It has a sensitivity of 4 to 6 µV (W $m^2)^{-1}$, a non-linearity of ±0.6% and response time of less than 5 s (l/e, 99%). Global radiation was measured about every second and 6 min averages were recorded, from which hourly average data were calculated. The other station is located at Säve airport, which lies about 9 km north-west of the city.

3.2. Temperature anomalies

In order to analyse the spatial pattern of the temperature difference between the park and the built-up area quantitatively, a temperature anomaly (T_a) was calculated as follows. $T_a(x,t)$ is the temperature anomaly at a station (x) for each time of measurement (t):

$$T_a(x,t) = T(x,t) - \frac{\sum_{x=1}^{M} T(x,t)}{M} \quad (1)$$

where $T(x,t)$ is the temperature at the station and M is the number of stations.

3.3. Factors and variables considered

As mentioned above it is the energy balance that determines the air temperature at any location, i.e. $Q^* = Q_H + Q_E + Q_G + \Delta Q_A$, where Q^* is net all-wave radiation, Q_H is sensible heat, Q_E is latent heat, Q_G is conduction to or from the ground and Q_A is advection. At night Q^* is largely a function of incoming and outgoing long-wave radiation (i.e. $L^* = L\downarrow - L\uparrow$). L^* is affected by the sky obstruction, and also by the properties of surface materials, temperature and the energy balance during the previous day. During the day energy balance is largely a function of the net long- and shortwave radiation flux (i.e. $L^* + K^*$, where $K^* = K\downarrow - K\uparrow$). Both day and night Q_A may have a large influence on Q^*. Thus, factors and variables tested in this study have been chosen according to their possible influence on any of the variables in the day and/or night energy balance.

One of the geographical factors considered was the SVF as a measure of sky obstruction, determined by fish-eye photographs (Holmer 1992); another was the distance from the park border, which influences the advection; and a third was the height above sea level. As surface properties are very important for the energy balance (e.g. Oke et al. 1991), it would have been ideal to use values of thermal admittance, μ_s. However, as μ_s varies with humidity, and therefore is very difficult to estimate for a location over a long period, it was impossible to include this factor. For the distance from the park border the distances were separated into 4 groups (south, north, east and west) according to wind direction. Stations inside the park and on the downwind side of the park were included in the analysis. The meteorological variables considered and their abbreviations are shown in Table 3. Wind speed and wind direction are included since they influence Q_A. Global radiation is proportional to K^*, and cloud cover and cloud type influence both K^* and L^*. The differences in humidity between park and built-up area may induce differences in Q_E between the 2 areas, thereby influencing Q^*.

Wind speed and wind direction from the bridge station were used to represent the general wind for the Göteborg area. Ground temperature is influenced by the temperature of the foregoing hours. Therefore the 24 h average of average air temperature for the transect was used as a rough estimate of the magnitude of the subsurface temperature in the area. The vapour pressure difference between park and urban areas was calculated as the difference between 2 representative stations (Stns 1 and 12, Fig. 2). The influence of cloud cover and cloud type is combined in the index c_i, which is derived from the following: The incoming longwave radiation at night ($I\downarrow$) provides the main forcing from the atmosphere. It can be estimated by an empirical function such as (Geiger 1961, Sellers 1965):

$$I\downarrow \;=\; I_0(1-k_s n^2) \qquad (2)$$

where $I\downarrow$ is the counterradiation, I_0 is the counterradiation from a cloudless sky, k is a coefficient dependent on cloud type and n is the cloud cover (varies between 0 and 1.0). It is the formula inside the parentheses that shows the influence of the clouds, and therefore c_i was developed to indicate the influence

$$c_i \;=\; \sum_{s=1}^{q}\left[1-k_s\left(\frac{N_s}{8}\right)^2\right] \qquad (3)$$

where N is cloud cover in octas, s is the 'layer' where the clouds occur and q is the number of cloud layers.

3.4. Principal component analysis

Principal component analysis was applied to reveal the dominant spatial patterns of the temperature anomaly. The analysis decomposes the original anomaly matrix T_a, which is a function of location x and time t, as follows (e.g. Reyment & Töreskog 1996):

$$T_a(x,t) \;=\; \sum_{j=1}^{n}\alpha^j(t)p^j(x)+b(x,t) \qquad (4)$$

where $p^j(x)$ is the jth spatial pattern represented by the related principal loading, $\alpha^j(t)$ is the principal component and $b(x,t)$ is the residual and may be interpreted as noise. In this way the temperature anomaly is decomposed into 2 parts. One is a number of deterministic functions (principal loadings) and the associated stochastic coefficients (principal components) repre-

Table 2. List of instruments, locations, and sensors, with their measuring heights and measuring intervals

Station	Location (Figs. 1 & 2)	Run by	Parameters measured	Instrument	Height above ground (m)	Data
Masts	Slottsskogen	Author; Dept of Physical Geography, Göteborg University	Wind speed + direction	Vaisala Anemometer WAA 15 A	5	Every 10 min and hourly averages
	Älvsborgsbron		Wind speed + direction	Vaisala Wind Vane 15 A	100	
Fixed sensors (10 × 10 × 5 cm)	Profile through park and built-up area	Author	Temperature, air humidity	Intab tinytalks (Pt100-element, relative humidity)	2.5	Every 24 min
Standard meteorological station	Säve airport Göteborg	Swedish Military Weather Service SMHI	Cloud cover, type and height	Visual observation	–	Every 1 h
			Global radiation	Ventilated Kipp-zonen pyranometer CM11	–	Hourly averages

Table 3. List of meteorological variables and abbreviations. For definition of the cloud index, see text

Variable	Parameter/average	Abbreviation
Wind speed	1 h average	ws_1
	Average from sunset until time of interest	ws_2
	Daily (12 h) average	ws_3
Wind direction	1 h average	wd
Global radiation	Daily sum	G
Total cloud cover	For time of interest	cc_{t1}
	From sunset until time of interest	cc_{t2}
Cloud amount in first 'layer'	For time of interest	cc_{11}
	From sunset until time of interest	cc_{12}
Cloud amount in second 'layer'	For time of interest	cc_{21}
	From sunset until time of interest	cc_{22}
Cloud index	Time of interest	c_i
	Average from sunset until time of interest	c_{i2}
Air temperature in temperature profile	Time of interest	T
	24 h average	T_{24}
Air humidity difference between park and urban as vapour pressure	Time of interest	Δe_{u-p1}
	From sunset until time of interest	Δe_{u-p2}

senting the signal, and the other is considered to be noise.

The principal component decomposition has 2 properties convenient to statistical modellings such as regression: (1) The principal loadings are orthogonal to each other, and (2) the factor scores are not correlated to each other. The strength of the method lies in the fact that it provides an effective way to separate the variation in space and time, and thereby of identifying spatial patterns and their associated evolution in time. Furthermore, principal component analysis is an effective spatial filtering technique which can help filter out small-scale variability that is not the focus of this study.

3.5. Regression analysis

Two criteria have been used in the regression analysis: (1) The parameter should be included in the results from the regression analysis, and (2) the influence of the parameter should also be physically correct. Both simple and stepwise multiple regressions were used to check which geographical factors and meteorological variables were of interest for the principal loadings. If nothing else is mentioned, the multiple regressions were performed so factors included in the final equation were accepted at the 99 % level. Also, polynomial regression analyses have been used on some occasions to identify possible non-linearity.

3.6. Hours studied

The analysis was based on nocturnal data, with especial focus on the time of maximum ΔT_{u-p}. However, a total of 4 selected times of the night were also examined using of principal component analysis to study the temporal stability of principal component patterns. The chosen times are sunset and sunrise, the time of largest ΔT_{u-p} (t_x hours after sunset) and t_x hours before sunrise. As the results from Upmanis et al. (1998) show that maximum ΔT_{u-p} for Slottsskogen occurs 2 to 3 h after sunset, data from 2 to 3 h after sunset and before sunrise are used in the analysis.

4. RESULTS AND DISCUSSION

4.1. Principal component analysis

For the time of nocturnal maximum ΔT_{u-p} during the night, the principal component analysis showed that the first 2 principal loadings explained 83 % of the variation in T_a in time (Table 4). This high percentage led to a decision to concentrate on the first 2 principal loadings and ignore the rest.

Fig. 3 shows the 2 principal loadings as a function of the distance for maximum ΔT_{u-p}. Also plotted are the heights above sea level and the SVF. The spatial pattern, which can be regarded as the variation of T_a in space, of Principal loading 1, is very similar for all of the 4 selected times during the night. For Principal

Table 4. Percentage of variation in T_a explained by Principal loading 1 and Principal loading 2, respectively, for the 4 times of interest during the night

Number	Time of night	Principal loading 1 (%)	Principal loading 2 (%)
Time 1	Sunset	74	10
Time 2	Time of maximum ΔT_{u-p} (i.e. 2 to 3 h after sunset)	71	12
Time 3	2 to 3 h before sunrise	64	14
Time 4	Sunrise	59	17

loading 2 the pattern at sunset differs somewhat from the others, as it is lowest at the park border and highest at Stn 13. The fact that Principal loading 1 explains such a large part of T_a implies that the influence of local factors is of similar magnitude during the night.

For the variation of T_a in time, on the other hand, it is clear that in the morning (Times 3 and 4) the 2 first principal loadings differ somewhat from the principal loadings at the beginning of the night (Times 1 and 2) (Table 4). This implies that the magnitude of influence of different variables may differ during the night. However, this fact is not the focus of the current study and should be further examined in another study.

4.2. Influence of geographical factors

As mentioned above we now focus on the time of maximum ΔT_{u-p} during the night (Time 2, Table 4). The first principal loading accounted for 71% of the total variation and was most important for this analysis; the second principal loading explained only 12% of the total variation (Table 4).

Principal loading 1 (Fig. 3) shows a dominant spatial pattern which is positive in the built-up area and negative in the park. The transition zone is sharp and occurs mainly within about 200 m, and totally within 600 m, from the park boundary. This indicates a strong pattern of temperature contrast caused by differences in surface cover. Overall, Principal loading 1 seems to be a good indicator of the difference between built-up and green areas, and it is clear that the specific characteristics of the park and urban areas are very important. This is consistent with earlier results showing that the park develops its own cold climate *in situ* (i.e. Spronken-Smith 1994, Spronken-Smith & Oke 1998, Upmanis et al. 1998), and can be explained by the differences in surface characteristics between the built-up area and the park. To study the possible influence of distance from the park border, the data set was, as mentioned above, divided into 4 groups according to wind direction. However, the resulting pattern for the different wind directions are almost exactly the same. This implies that not only advection influences the temperature pattern in and around the park, but that diffusion also may be of importance. The resulting pattern according to distance to the upwind park border can be seen in Fig. 4. Multiple regressions showed that Principal loading 1 was correlated to the distance from the park border (R = 0.69, N = 33), but a parabolic function gives the best fit (R = 0.73, N = 33) (Fig. 4). However, there is a noticeable exception in the green area (Stn 9), not representative of the park area. If this station is excluded, the parabolic function gives a correlation of 0.93 (N = 30). Thus, for the first and second parabolic functions, distance from the park border can explain 53 and 70% respectively of the variation in T_a between stations. Principal loading 2, on the other hand, was not significantly correlated to the distance from the park border.

The relationship between SVF and Principal loadings 1 and 2 was examined both for the whole profile and for the park and built-up area separately. However, no significant influence on the principal loadings, and thus on temperature, could be shown. Analyses were also made to examine if cloud cover influenced the relation between T_a and SVF, but no such relation could be found. As mentioned earlier, several studies

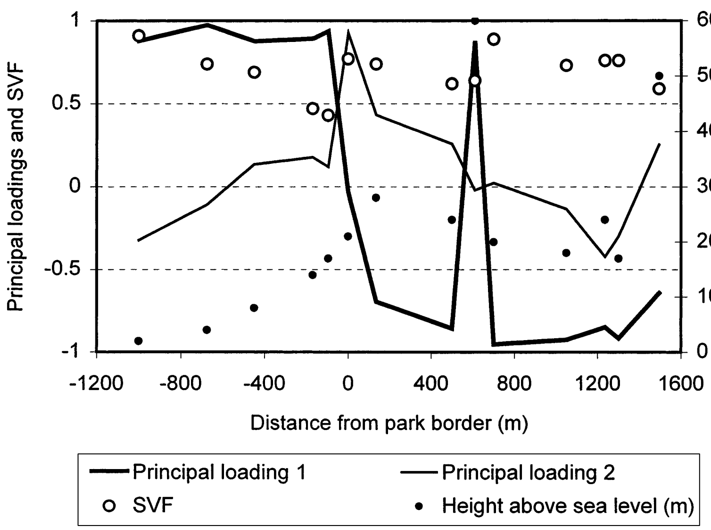

Fig. 3. Principal components of the first 2 principal loadings for time of maximum ΔT_{u-p} (i.e. 2 to 3 h after sunset) plotted against distance from the park border. Positive distances are within the park. Also plotted are the SVF and the height above sea level at each station

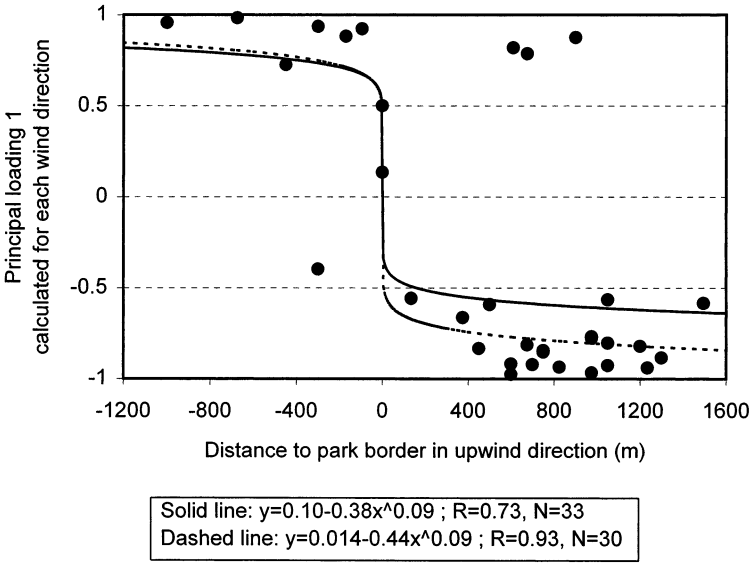

Fig. 4. Principal loading 1 for each wind direction, plotted against distance from the upwind park border. Lines show the functions given in the figure. In the second function Stn 9 is omitted (Table 1). Stations located 'parallel' to the park according to wind direction or in an upwind direction from the park border were omitted from the analysis. The south park border is very diffuse because of forest and suburban areas, and therefore stations inside the park were omitted when southerly wind directions prevailed

have shown that a relationship exists between SVF and surface temperature in built-up areas (e.g. Oke 1981, Bärring et al. 1985, Eliasson 1992). Oke (1973) also showed that between cities the UHI (air) is correlated to the city's average SVF, and the results of Upmanis et al. (1998) indicate that a relationship does exist between SVF and cooling rate. However, the present analysis does not show any relationship between SVF and air temperature within the urban-park areas, which is consistent with results presented by, for example, Bärring et al. (1985) and Eliasson (1996).

The first principal loading did not show any significant correlation to height above sea level, while the second principal loading at a quick glance seems to have some relationship with height (Fig. 3). However, multiple regressions showed that Principal loading 2 not even at the 60% level was significantly correlated to height above sea level, and neither simple nor polynomial regression analysis revealed any relationship. As mentioned above, the first principal loading represents a typical profile which is characterised by a positive anomaly in the built-up area and a generally negative anomaly in the green area. However, as mentioned above, there is a marked exception in the green area (Stn 9), which shows a high level positive anomaly similar to that in the built-up area. Even though no correlation could be shown between Principal loading 1 and height above sea level, this positive anomaly is probably due to the height of this site relative to its surroundings. Indeed, this site is the highest among all the sites (Table 1), which implies that the air at 2.5 m above the ground might have been affected more by advection from the built-up area than by the local energy balance. The second highest site at the right end of the profile also shows a tendency for increased temperature, which can be interpreted as support for the previous argument. The results showing that height above sea level does not influence air temperature support the results of Upmanis et al. (1998). Kuttler et al. (1996), on the other hand, showed that there is a correlation between height and temperature. This may be explained by the greater range of heights and larger area in that study. However, as mentioned above, height may have an indirect influence on some stations, in that the wind advects warm air from the built-up area, and thereby influences the temperature at higher levels.

4.3. Influence of meteorological variables

Since the difference in temperature is caused by geographical factors and forced by meteorological variables, the spatial pattern should mainly reflect the influence of local factors. The variation of the pattern in time, however, should be more closely connected to large-scale variables. To see if this was the case, both simple and stepwise multiple regression analyses were used to relate the principal component of each principal loading to the meteorological variables. In the analyses, all of the meteorological variables *(v)* were tested as v^1, v^2, v^3 and v^4 against Principal loadings 1 and 2. For abbreviations see Table 3. The wind direction does not have a continuous scale, and therefore this variable was analysed alone, as presented in the next section.

Table 5 shows the result of the multiple regression analysis on Principal loading 1, showing the significant meteorological variables in the first regression analysis. The result shows that ws_2 and c_{i2} explain 38 and 18%, respectively, of the variation in Principal loading 1. Since Principal loading 1 represents 71% of the variation in T_a, this means that 27 and 13%, respectively, of the variation in T_a can be explained by ws_2 and c_{i2} (Table 5, Figs. 5 & 6). The last significant variable, $T_{24}{}^4$, had only a minor influence on the temperature anomaly (i.e. 6.4%, see Table 5). Principal loading 2 was significantly correlated only to $\Delta e_{u-p2}{}^2$. However, the multiple correlation coefficient was only 0.34, and, since Principal loading 2 explains only a minor part (12%) of the variation in T_a, the influence of this variable is only 1.4%. Thus, there are 4 variables that have an influence on T_a. An increase in wind speed (27%) and cloud index (13%), i.e. cloud cover and type, results in a decrease in ΔT_{u-p}, while an increase in subsurface temperature (6.4%) and urban-park vapour pressure difference (1.4%) results in larger ΔT_{u-p}. This is supported by how the variables influence the physical processes, i.e. the energy balance.

The results thus show that wind speed and cloud cover and type are the most important factors influencing the magnitude of ΔT_{u-p}. This is consistent with the previous findings regarding the UHI, even though earlier studies take into account only cloud cover and do not include cloud type (e.g. Duckworth & Sandberg 1954, Park 1986, Moreno-Garcia 1994; see Table 6). A few earlier studies mention humidity (Sundborg 1950, Kawamura 1964, Lindqvist 1970), and show that it has only minor influence on the UHI, which supports the present results regarding ΔT_{u-p}. A few studies have found that air temperature at the time of interest has some influence on the UHI (Sundborg 1950, Kawamura 1964, Chandler 1965, Lindqvist 1970); however, the subsurface temperature has not been mentioned in earlier studies. Spronken-Smith (1994) suggests that in parks with extensive tree canopies, as is the case for the park in the present study, evaporative cooling may be important in creating a large urban-park temperature differential soon after sunset. Our results somewhat support this suggestion, but also indicate that the influence is small.

Our results also suggest that the global radiation (G; see Table 3) does not have any influence on ΔT_{u-p}. Yet simple regression analysis shows that 23% of the variation in Principal loading 1 (i.e. 16% of the variation in T_a) can be explained by G. However, G was, not surprisingly, found to be cross correlated with the cloud index, i.e. c_{i2}, and partly with cc_{t2}. Thus the influence of cloud and cloud type camouflage the influence of G. Chow et al. (1994) argued that total direct solar radiation played an important role in determining the magnitude of the UHI, and it may therefore also have an influence on ΔT_{u-p}. Our results partly support the results of Chow et al. (1994), even though they imply that the influence is not very large and cloud cover and type for the previous hours are more important. In contrast to Chow et al. (1994) we also found that total cloud cover has a greater influence than cloud amount in the lowest layer on the temperature difference. This is in line with the findings of the majority of other studies (Table 6).

Table 5. Meteorological variables influencing Principal loading 1, total correlation coefficient (R), magnitude of influence on Principal loading 1 (Pl 1), and magnitude of influence on the temporal pattern of T_a

Meteorological variable	R (N = 136)	Pl 1 (%)	T_a (%)
ws_2	0.62	38	27
c_{i2}	0.75	18	13
$T_{24}{}^4$	0.80	8.5	6.4

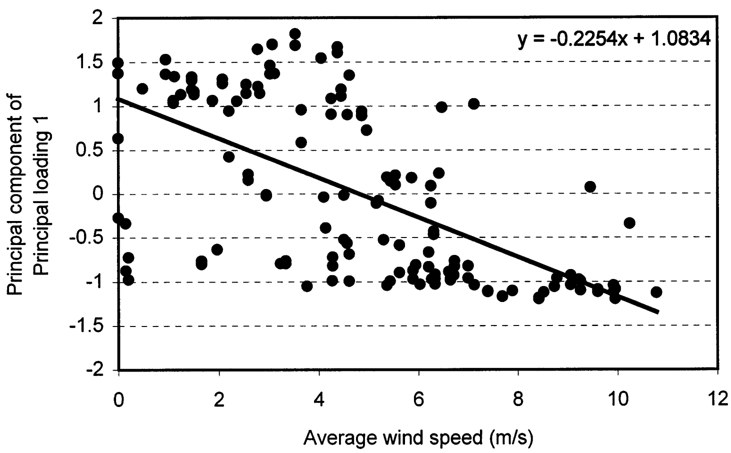

Fig. 5. Principal component of Principal loading 1 plotted against the average wind speed after sunset until the time of measurement. Solid line shows the linear equation given in the figure (total R = 0.62, N = 136)

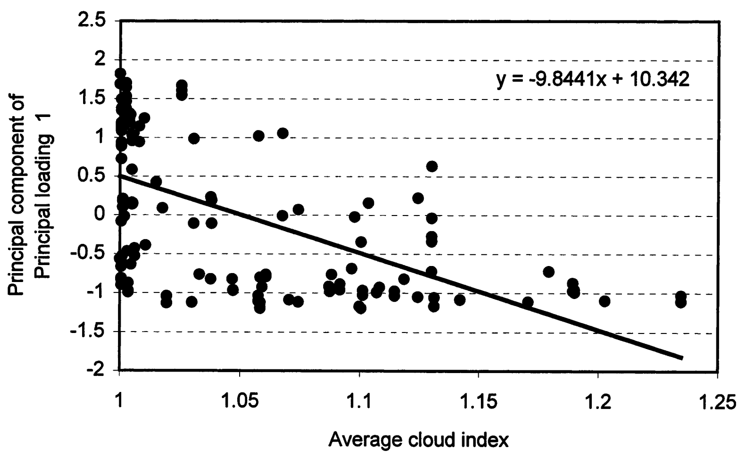

Fig. 6. Principal component of Principal loading 1 plotted against the average cloud index after sunset until the time of measurement. Solid line shows the linear equation given in the figure (total R = 0.75, N = 136)

In contrast to many other studies, our results also imply that the averages for the preceding hours, and not for the time of interest, are of greatest importance (Table 6). Chow et al. (1994) and Kawamura (1964) found that the mean diurnal wind speed and daily cloud cover were of great importance to the temperature difference. This, in part, supports our findings, even though average daily wind speed and the influence of daily cloud cover, represented by G, only have a minor influence on T_a.

4.4. Influence of wind direction

As mentioned above, wind direction was analysed separately. To investigate this variable, wind directions were grouped to identify the difference between the influence of warm air from the built-up area north of the park and the influence of cold air produced inside the park. The situations were classified according to synoptic type, i.e. those with similar wind speed, cloud cover, air temperature, air humidity, cloud type, cloud height and average global radiation for the preceding day were grouped together. These situations were then classified according to wind direction into a south component group and a north component group. Wind from both the bridge station and the park station was examined in order to eliminate the possibility of different wind speeds associated with wind direction. From the data 5 pairs were chosen in which all variables were similar, apart from the wind directions, which were opposite to each other. For each pair the temperature anomaly patterns were compared.

All the pairs show the same shape of T_a as a function of distance from the park border, and it was clear that wind direction had an influence on T_a. Fig. 7 shows an example of 2 anticyclonic situations where all variables were of similar magnitude and only the wind directions were different. In the built-up area the pattern can be easily interpreted. When the wind came from the north (i.e. the built-up area), the temperature inside the built-up area increased towards the park border, and at the border the temperature decreased very quickly. The influence of the cold park climate could be seen only in the close vicinity of the park border. When the wind direction was from the south (i.e. from the park), the temperature increased more gently into the built-up area, since cold air was advected from the park into the surroundings. This is consistent with earlier results which show that wind direction influences the advection of cold air into the surrounding built-up areas by shifting the low temperature area to the leeward side of the park (e.g. Oke 1989, Honjo & Takakura 1990/1991, Saito et al. 1990/1991). Inside the park the pattern was more complex, and it is clear that variations in local factors inside the park significantly influence temperature. When the wind came from south, T_a inside the park was higher compared to when there were northerly winds. Stn 9 was an exception. This results in a profile with lower amplitude, i.e. lower ΔT_{u-p}, for southerly than for northerly winds (Fig. 7).

The results clearly indicate that wind direction influenced the advection of air at the border zone between a green area and its built-up surroundings. Moreover, it also had an influence on the magnitude of ΔT_{u-p}. The park and suburban areas both exhibit temperatures

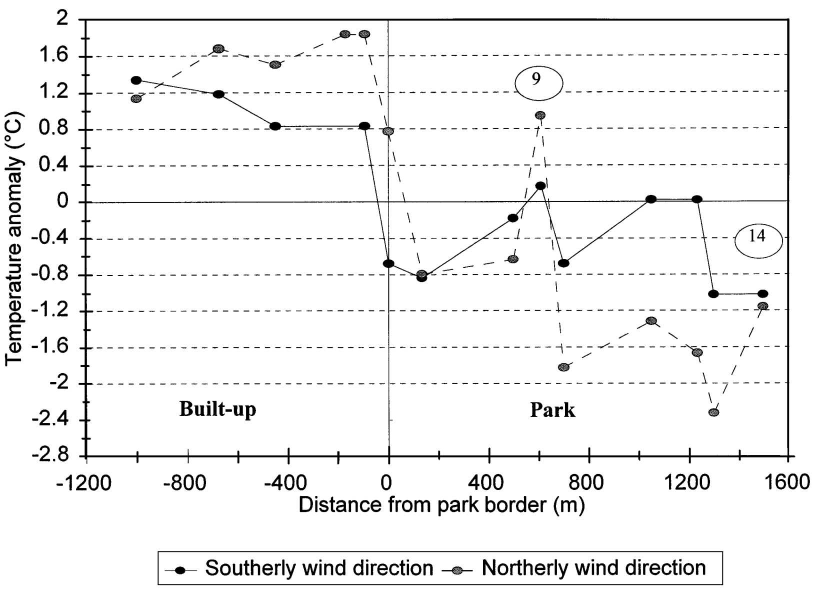

Fig. 7. Temperature anomaly at each station plotted against the distance from the park border for 2 anticyclonic situations with all variables similar except for the wind directions. Stns 9 and 14 are marked in the figure

Table 6. Meteorological variables influencing the nocturnal UHI. No studies dealing with ΔT_{u-p} were found. In 'Type of study; how compared; measurements' only the method used to study the influence of meteorological variables is mentioned. Abbreviations given in parentheses are those used by the authors. Cc = cloud cover; W = wind speed; T = temperature; ap = air pressure; vp = vapour pressure; cr = cooling rates; trav. = traverses; PC = point comparison

Source	Country City	Type of study; how compared; measurements	Weather conditions	Main influencing variables	Secondary influencing variables	Other influencing variables	Magnitude of influence/formula (°C) (authors' abbreviations used)	Temperature differences (°C)
Chandler (1965)	UK London	2 stations; PC; 1959–60, daily differences in max. and min. T	Varying weather	W (U_m) Cc (N)	Temperature amplitude (R_c)	Temperature (T_c)	Summer: $D = 1.72 - 0.12N - 0.17U_m + 0.01T_c + 0.15R_c$ Winter: $D = 1.69 - 0.13N - 0.10U_m + 0.04T_c + 0.08R_c$	20%: >5°C
Duckworth & Sandberg (1954)	USA 3 Californian cities	Automobile trav.; comparison of trav.; 35 surveys with several trav.	Varying weather	W	Cc	–	–	–
Kawamura (1964)	Japan Kumagaya	Automobile trav.; comparison of trav. and PC; Surveys during Sep 1956–Mar 1957	Varying weather	W (v)	Daily Cc (N)	Cc at time of obs. (n); T (T); vp (p)	$D_{natt} = 4.21 - 0.08N - 0.12n - 0.52v - 0.04T + 0.01p$	–
Kidder & Essenwanger (1995)	USA	Stations (4+3); PC; 2 mo yr^{-1} 1961–90 + Feb 1988–92	Varying weather	Wind	Cc	–	–	–
Kuttler et al. (1996)	Germany Stolberg	8 stations automobile trav.; one at a time; 14 trav., 1990–91	$Cc < 4/8$ $W < 2$ m s^{-1}	W	Max. T amplitude during trav.	Time of night	Critical $W^{a} \approx 2.5$ m s^{-1}	–
Lindqvist (1970)	Sweden Lund	Automobile trav.; average city-rural; day and night (100 each)	Varying weather	W (v), Cc (N)	–	T (T), vp (p)	$D_{night} = 3.01 - 0.31N - 0.29v - 0.06T + 0.16p$	–
Moreno-Garcia (1994)	Spain Barcelona	Automobile trav.; PC; 54 trav., Oct 1985–Jul 1987	ap:1014 – 35 hPa; N: 0–7 octas; V:4–25 km h^{-1}	Cc (N), W (V), ap (Pr)	–	–	$T_{u-r} = -0.583N - 0.077V + 6.443$; $T_{u-r} = -0.612N - 0.044Pr + 39.772$	Max. $T_{u-r} > 8$
Oke (1973)	Canada 10 cities	Automobile trav.; average city-rural; 11 cases, summer + winter	Clear skies (N = 0)	Regional W (u)	–	Population (P)	$\Delta T_{u-r} = 1.91\log P - 2.07u^{1/2} - 1.73$	–
Park (1986)	Korea Seoul+ surrounding cities	Automobile trav.; PC + profiles in 2 Cc groups; 11 trav. Jun–Aug 1982,	–	W (u)	Cc	Population	Critical $W^{b} \approx 3.9 - 11.1$ m s^{-1} Seoul: $\Delta T_{u-r} = -0.31u + 3.43$	Clear: ~7.1–3.7 Cloud/rain: ~0.8–1.2
Sundborg (1950)	Sweden Uppsala	Automobile trav.; PC; 200 times during 1 yr	Varying weather	W (U)	Cc (N)	T (Θ), absolute humidity (e)	$D_{night} = 2.8° - 0.10N - 0.38U - 0.02\Theta + 0.03e$	–

Table 6. (continued)

Source	Country City	Type of study; how compared; measurements	Weather conditions	Main influencing variables	Secondary influencing variables	Other influencing variables	Magnitude of influence/formula (°C) (authors' abbreviations used)	Temperature differences (°C)
Chow et al. (1994)	China Shanghai	2 stations; PC; 1984 (154 days)	Varying weather	Total direct solar radiation (*S*), mean diurnal *W* (V_m), *W* (*V*), low *Cc* (*N*)	–	–	$\Delta T = 1.201 + 0.048S - 0.146V_m - 0.080V - 0.022N$	Example: 6.5
Unger (1996)	Hungary Szeged	2 stations; PC; 1978–80 (1034 days)	Varying weather	Anticyclonic, *Cc*, *W*	–	–	–	Max ΔT_{u-r} = 8.9
Yagüe et al. (1991)	Spain Madrid	2 stations; PC	Anticyclonic + cyclonic	Anticyclonic	–	–	–	Avg: 1.95 (SD 2.03)

[a]Above which inversions are no longer possible
[b]Above which the UHI is destroyed

lower than the built-up area, and they cover an area larger than the northern built-up area. With a southerly wind this results in cold air from a large area with low temperatures being advected into the built-up area in the north, thereby lowering the temperature inside the whole built-up area. This in turn lowers ΔT_{u-p}. When wind comes from the north, warm air from the built-up area is advected into the park. However, as the built-up area is much smaller than the areas with lower temperatures, the amount of warm air is too small to influence the temperature inside the park. The warm air also enhances evaporation from the more humid park and from dams (Fig. 2), which in turn lowers the temperature inside the park area. High temperatures in the built-up area and low temperatures inside the park result in a large ΔT_{u-p}.

From Fig. 7 it is clear that T_a at Stns 9 and 14 was higher when the wind came from the north than from the south. This supports the previous reasoning about the influence of the wind and neighbouring boundary layers at Stns 9 and 14. When there are northerly winds, the air comes from the warm, built-up, boundary layer and warm air influences the 2 elevated stations. With southerly winds the advected air comes from the cooler suburban areas and therefore results in a lower T_a at Stns 9 and 14 compared to when winds come from the north.

5. SUMMARY AND CONCLUSIONS

This paper presents a systematic statistical analysis, examining the magnitude of the influence of geographical factors and meteorological variables on the air temperature difference between a park and its built-up surroundings at nighttime in summer. We have successfully used principal component analysis to separate the variation in space and time, and have thereby been able to identify dominant spatial patterns and their associated evolution in time. For the time of maximum ΔT_{u-p} (i.e. 2 to 3 h after sunset) the first 2 principal loadings explained 83% of the variation in the air temperature anomaly (71 and 12%, respectively). The results can be summarised as follows:

- Among the geographical factors, only distance from the park border had any influence on T_a. About 86% of the variation in T_a between stations could be explained by the location of the station with respect to the park border.
- For the meteorological variables, it is clear that the wind speed and the cloud index, i.e. cloud cover and type, both averages from sunset until the time of measurement (i.e. about 3 h), had the largest influence on the temporal variation in T_a. These variables

explain 27 and 13% of the variation in T_a. The subsurface temperature and difference in air humidity between built-up and park areas explain a minor part, i.e. 6.4 and 1.4%, respectively, of the temporal variation in T_a.

- Wind direction was analysed separately, and no calculation of the magnitude of this variable was possible. However, it is clear that it influenced both the advection of air at the park border and the magnitude of ΔT_{u-p}. The influence on the magnitude of ΔT_{u-p} probably depends on the relative size of the small warm urban area compared to the large colder park and suburban area. Stations at higher levels were influenced by advection of warm air from the surrounding built-up areas.
- The principal component analysis of T_a at other times during the night suggests that the influence of geographical factors does not change with time. However, the influence of meteorological variables seems to be of different magnitude depending on the time of night. Thus, it is of importance that the time of measurement is taken into consideration in future studies.

The estimation of the influence of meteorological variables may be improved with measurements of more variables, such as wind, cloud and global radiation, inside the study area. In that way it would be possible to further define the magnitudes of the influence of the variables. Among the geographical factors, the SVF could not be shown to have any influence on the air temperature. This is somewhat surprising, since the method separated the data into a spatial and a temporal pattern. Many studies have found a close relationship between SVF and surface temperature (e.g. Oke 1981, Eliasson 1992, 1996), but it seems that the SVF has very little influence on the air temperature in an urban environment. A question about the suitability of the SVF is raised. Other ways to calculate the influence of surrounding sky obstructions may be required. Since there is still a large part of the variation in T_a among the stations that has not been explained, another question remains as to what the other factors of importance for the variation are. Thermal admittance may be such a factor, but further studies and better ways to determine thermal admittance in the field are needed before this problem is fully solved. The relative short period of data prohibits a straightforward generalisation of the results. Nevertheless, with its application of a principal component analysis to field data, the study is not only a contribution to the understanding of the physical processes behind the development of ΔT_{u-p}, but also a further step toward a combination of traditional and statistical climatology. This is important if a process-oriented approach (modelling) will be taken.

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