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Intra-urban relationship between surface geometry and urban heat island: review and new approach

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ABSTRACT: This paper provides a comprehensive review of the intra-urban sky view factor (SVF)–temperature relationship. A new approach to reveal the real connection between SVF and air temperature in an entire city is presented. The results found in the literature are rather contradictory, possibly due the fact that previous investigations were limited to the central or specific parts (e.g. inner city, urban canyons) of cities and used few sites and measurements. Comparisons were often based on element pairs measured at selected sites. In some cases areal means were also discussed, but always in connection with one of the variables examined. For comparison, the present study in Szeged, SE Hungary, utilizes a large number of areal means of SVF and air temperature. The values are related to almost a whole city and based on numerous measurements. The results show a strong relationship in the intra-urban variations of these variables, i.e. urban surface geometry is a significant determining factor of the air temperature distribution inside a city if the selected scale is appropriate. Therefore, investigation of a sufficient number of appropriate-sized areas covering the largest part of a city or the entire city is needed to draw well-established conclusions.

KEY WORDS: Sky view factor · Air temperature · Surface temperature · Urban environment · Scale · Linear regression · Szeged · Hungary

1. INTRODUCTION

Built-up areas appear as uneven artificial terrains with building materials partly different from those of natural surfaces. In addition, anthropogenic processes release excess heat and pollution to the ambient air. Together they result in higher urban temperature compared to the relatively natural surroundings — this is the so-called urban heat island (UHI), or urban heat archipelago if the spatial structure is multi-cellar. Generally, the strongest development occurs at night when the heat (stored in the daytime) is released. It is important to note the distinction in the scale of UHI investigations between the urban canopy layer (UCL) and the urban boundary layer (UBL) (Oke 1976). The distinction allows differentiation of processes operating at the microscale, below roof level (UCL), and those operating at the mesoscale, generally above roof level (UBL). The significance of the UHI is based on its socio-economic, health and meteorologic impacts in the urban environment (Table 1). In the present study, focus is on the UHI observed below roof level amongst the urban canyons.

The UHI intensity (ΔT) for a given urban location is defined as the difference between temperatures of a given urban site and of a carefully selected nearby non-urban (reference) site or of a mean of non-urban sites (e.g. Lowry 1977, Oke 1997). ΔT depends strongly on the land use and urban parameters (e.g. built-up ratio, green surface ratio, sky view factor, etc.) characterizing the immediate environment of the site of the measurement (e.g. Oke 1987, Golany 1996, Unger et al. 2004).

Nocturnal cooling processes are primarily forced by outgoing longwave radiation. In cities, narrow streets and high buildings create deep canyons. This 3D geometrical configuration plays an important role in regulating longwave radiative heat loss. Due to the fact that only a smaller part of the sky is seen from the surface (because of the partly horizontal, partly vertical un-

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Table 1. Socio-economic, health and meteorologic impacts of urban heat island (UHI) in cold and hot climate urban environments (Oke 2002, Urban heat islands: an overview of the research and its implications. Urban Heat Island Summit, Toronto, Canada, available at: www.city.toronto.on.ca/cleanairpartnership/uhis_summit.htm)

Impact	Cold climate	Hot climate
Socio-economic and health impacts		
Human comfort and mortality	Positive (winter) Negative (summer)	Negative (all seasons)
Energy use	Positive (winter) Negative (summer)	Negative (all seasons)
Air pollution chemistry	Negative	Negative
Air pollution dispersion	Both positive and negative	Both positive and negative
Water use	Negative	Negative
Biological activity	Positive	Probably neutral except disease
Ice and snow	Positive	Not applicable
Meteorological impacts		
UHI circulation, breezes, stability, turbulence, convergence, uplift, mixed layer depth, cloud, precipitation, relative humidity, dewfall, evaporation, fog, visibility, snow, 'contamination' of long-term temperature records		

evenness of the surface units themselves), the outgoing longwave radiation is more restricted here than in rural areas.

The intra-urban distribution of the temperature excess is largely dependent on local surface characteristics, such as geometry: building heights (H), street (canyon) width or spaces between buildings (W). The H/W ratio describes how densely buildings are spaced with respect to their heights. Together with the growing values of H/W, an increasingly large portion of the cold sky is replaced with the relatively warm flanks of buildings. A more appropriate measure of radiation geometry of a given site is its sky view factor (SVF), i.e. the fraction of the overlying hemisphere occupied by the sky (Oke 1981). The SVF is a dimensionless measure between 0 and 1, representing totally obstructed and free spaces, respectively (Oke 1988). The decreased SVF below roof level reduces radiative loss and also reduces turbulent heat transfer in the often calm canyon air. Therefore, theoretically it is considered to be a major component of the UHI phenomenon.

Thus, the first objective of this paper is to provide a comprehensive review on the intra-urban surface geometry (SVF, H/W)–temperature relationships found in the literature. The second objective is to contribute to this context: to describe related investigations in Szeged, south-eastern Hungary, especially presenting the recent development as well as the importance of obtained results compared to the previous studies.

2. REVIEW OF THE LITERATURE

The literature includes several papers dealing, at least partly, with the relationship between surface temperature (T_s) and SVF, and/or between the screen level (air) temperature (T_a) and SVF (H/W).

Based on screening angle measurements in 16 directions and 12 mo temperature observations at fixed stations in Reading, UK, Parry (1967) recognized that the 'open' and 'enclosed' sites in an urban environment have different daily minimum temperatures (Table 2). There is no report on the level of angle and T_a measurements. He presented circle-shaped figures on the exposure of the stations very similar to the recently used figures delineating sky obstruction (like photographs taken with a fish-eye lens) to determine SVF values.

According to Oke's (1981) widely known and referred results the observed maximum ΔT_a at screen level is related to the average SVF and H/W values calculated for the central areas of the towns and cities (Table 2). In this case, information on H and W was based on ground-level and aerial photos, as well as on the data set of building and street dimensions. ΔT_a is the observed (and possible) maximum value for a given city and occurs usually at night under favourable (calm and cloudless) weather conditions and when the anthropogenic heat is of negligible importance to the energy balance (Oke 1981). Urban geometry is the basic physical control on heat island intensity as the obtained equations suggest:

$$\Delta T_{a,max} = 15.27 - 13.88 \times SVF \quad (1)$$

$$\Delta T_{a,max} = 7.45 + 3.97 \times H/W \quad (2)$$

The relationships in Oke (1981) were based on data from several North American, European and Australian cities with a population range between 1100 and 8 500 000 determined by himself and by other investigators. The number of measurements and the extent of the examined urban areas, however, were not mentioned.

Johnson (1985) found a 'close' negative connection between the maximum cooling rate of air temperature (at 1.4 m) and SVF at 27 almost equidistant sites along an urban traverse route in Birmingham, UK, on summer nights (Table 2). T_a was measured repeatedly by mobile observations on 8 occasions. There is no information on the measuring level of SVF.

Bärring et al. (1985) determined a strong relationship between street T_s and SVF in Malmö, Sweden (Table 3). The study area stretched from rural areas to the city centre along a strip. T_s was evaluated from an infrared thermography taken in winter at 21:00 h under conditions of clear sky and slight wind. In order to determine SVF, fish-eye photos were taken at mid-width and in most cases at mid-block length in street canyons and in the crossings at 'eye-level'. The sites of the mobile T_a measuring program were among those used for T_s, and the observations were taken at 'standard level' (Table 2). Bärring et al. (1985) verified that T_a, at least its small-scale fluctuations, is 'not so strongly correlated' to SVF as T_s. Their important conclusion was that 'A decreasing effect of local canyon geometry and an increasing integrated effect of regional heat island generating factors will probably exist with increasing height above the street surface.'

Yamashita et al. (1986) investigated 5 cities in the Tama River Basin, Japan (Table 2). They found a 'fairly strong relationship' between SVF and T_a based on a mobile observation in each city. The SVF was calculated using fish-eye photos at 1.2 m height, like T_a. The number of sites is not mentioned, but from his figures it can be calculated that the number of element pairs may range between 9 and 21 by city. For each city, he used minimum SVF values and a ΔT_a based on measurements made in both February and May, once during the day and once at night, and he also established 'fairly good relations'. There are no details on the correlation coefficients and significance levels.

Park (1987) used his own observations as well as data from the literature (Table 2). In Japanese and Korean cities he determined mean SVF for the central business districts (CBD) of the cities, applying fish-eye photos at an unknown height above the surface. In order to obtain ΔT_a values, he made mobile measurements 'many times' in 20 Japanese cities and 'produces some observational data' in 5 Korean cities. According to the results 'the SVF is closely related to the formation of the heat island', as shown by the equations obtained for the cities in different regions:

Japanese cities: $$\Delta T_{a,max} = 10.15 - 12 \times SVF \quad (3)$$

Korean cities: $$\Delta T_{a,max} = 12.23 - 14 \times SVF \quad (4)$$

North American cities: $$\Delta T_{a,max} = 16.34 - 15 \times SVF \quad (5)$$

European cities: $$\Delta T_{a,max} = 13.20 - 10 \times SVF \quad (6)$$

In addition, in Mitsukaido City, Japan (population of 41 000), extra mobile T_a (1.5 m) and T_s measurements were taken over a 25 h period in April by Park (1987). He found a negative relationship between T_s measured at 05:00 h and SVF at 'selected' points in the urban area (Table 3). There is no information on the measuring level of SVF. His related figure differs from others in certain points, namely that it shows SVF *as a function* of T_s, which must be wrong since the urban surface geometry cannot depend on surface temperature. In this form the formula makes no sense:

$$SVF = 1.08 - 0.08 \times T_s \quad (!) \quad (7)$$

Eliasson (1990/91) calculated street T_s using an infrared image taken from the air, as well as by car, also determining corresponding SVF values in the canyons of Göteborg, Sweden, a city of more than 500 000 inhabitants (Table 3). She presented figures showing negative relations between the 2 variables. There are no details on the measuring level of SVF, on the strength of the relationships or on significance levels.

Eliasson (1992) analysed the connection between SVF and T_s in several areas also in Göteborg from infrared images taken from a helicopter and data from a measurement trip by car on a winter evening (Table 3). The relations were 'statistically significant' and the linear regression equation based on the airborne data is as follows:

$$T_s = 7.1 - 4.7 \times SVF \quad (8)$$

In the case of air temperature at 0.2 and 2 m, the results showed 'no statistical significance' (Table 2). There is no report on the measuring level of SVF.

In a further study by Eliasson (1996), the investigation in Göteborg concentrated on the horizontal temperature distribution within the inner city and in areas of different land use types in relation to the urban structure. Mobile traverses were made on T_s and T_a at 0.2 and 2 m in late evenings of the cold season under fine weather conditions. The SVF was calculated at the street surface of a given surface unit (canyon, crossing and open area). Applying regression analysis and hypothesis test, Eliasson concluded that T_s is affected by SVF, but T_a is not (Tables 2 & 3): 'There is no evidence for a statistically significant relationship between the air temperature and the sky view factor in central Göteborg.'

Related to SVF, a closer examination of the data on 3 occasions of mobile traverses—on T_a and T_s differences—between canyons and adjoining crossings and/or open areas was made and presented by diagrams. At T_s: 'A trend is distinguishable …, as higher

Table 2. Survey of sky view factor (SVF) or height/width (H/W) ratio (independent variable) versus air temperature (T_a) (dependent variable) investigations: study area (CBD: central business district) and its size, measurement methods, range of independent variable, number of element pairs, regression coefficients a and b ($Y = a + bX$, where Y is temperature or cooling rate and X is SVF or H/W) and significance level (–: no information) are shown. CC: Central city, CP: Central park, T: Transition

Urban area	Size	SVF (or H/W) (methods)	Range of SVF (or H/W)	T_a	No. of pairs	a	b	Significance	Source
Mainly the inner part of a city (Reading, UK)	~8–9 km^2	Surveying techniques by sites	0.83–0.97	Mean daily minimum	6	–	–	–	Parry (1967)
Central parts of different cities	–	City mean from average H/W	0.30–0.86	Observed $\Delta T_{a,max}$	31	15.27	–13.88	1%	Oke (1981)
		City mean of H/W	0.30–3.25			7.45	3.97	1%	
Along an urban transect (Birmingham, UK)	20 km long	Surveying techniques by sites	0.73–0.99	Max. cooling rates from mobile measurements in 8 d	27	–	–	1%	Johnson (1985)
~1 × 8 km strip from rural area to the centre (Malmö, Sweden)	~8 km^2	Fish-eye photos by sites	0.52–0.95	T_a from 1 mobile measurement	75	–	–	1%	Bärring et al. (1985)
				Mean T_a from 5 mobile measurements	75	–	–	1%	
5 Japanese cities (Tachikawa, Fuchu, Fussa, Higashimurayama, Akikawa)	~9–26 km^2	Fish-eye photos by sites	0.4–0.85	T_a from 1 mobile measurement by cities	9–21	4.11 0.93	–1.00 –3.00	1% 5%	Yamashita et al. (1986)
		Fish-eye photos, minimum value by cities	0.40–0.72	ΔT_a from 2 mobile measurements by city, 1 by day and 1 at night	5	–	–	–	
CBD in Japanese cities	–	Fish-eye photos, means of 36 sites	0.26–0.78	$\Delta T_{a,max}$ from 'many' mobile measurements	13	10.15	–12.00	1%	Park (1987)
CBD in Korean cities	–		0.36–0.84	$\Delta T_{a,max}$ from 'some' mobile measurements	6	12.23	–14.00	1%	
Central parts in North American cities	–	From Oke (1981)	0.28–0.86	From Oke (1981)	18	16.34	–15.00	1%	
Central parts in European cities			0.40–0.75		11	13.20	–10.00	1%	
Different parts of a city (Göteborg, Sweden)	–	Surveying techniques by sites	–	T_a from 1 mobile measurement at 2 levels	17	– –	– –	No No	Eliasson (1992)
Different parts of a city (Göteborg)	~4 km^2	Surveying techniques by sites complemented by fish-eye photos	0.33–1.00	T_a from 6 mobile measurement	10–30	–	–	No	Eliasson (1996)
			0.41–1.00	Mean T_a of 3 mobile measurements (canyon-crossing/open area)	18	–	–	–	
Along an urban transect (Göteborg)	8 km long		0.33–1.00	T_a from 1 mobile measurement	–	–	–	–	
Different parts of a city, along urban transects (Göteborg)	~2 km^2	Fish-eye photos by sites	0.39–0.91	T_a from fixed sensors in 21 mo and from 16 mobile measurements	42	–	–	No	Upmanis et al. (1998)
Different parts of a city (Göteborg)	~1.5 km^2		0.43–0.91	Mean cooling rates from fixed sensors on 22 nights	6	–	–	–	
Along an urban transect (Göteborg)	~3.3 km long	Fish-eye photos by sites	0.43–0.91	T_a anomaly from the mean of fixed sensors on 55 nights	14	–	–	–	Upmanis & Chen (1999)

Table 2 (continued)

Urban area	Size	SVF (or *H/W*) (methods)	Range of SVF (or *H/W*)	T_a	No. of pairs	*a*	*b*	Significance	Source
Along an urban transect including 5 land use types (Göteborg)	–	Fish-eye photos by sites	0.38–1.00	Mean T_a from 6 mobile measurements in winter	8 in CC	–	–	No	Upmanis (1999)
					8 in T	–	–	10%	
	–		0.41–1.00	Mean T_a from 9–10 mobile measurements in summer	7 in CC	–	–	No	
					8 in T	–	–	11%	
			0.60–0.80		6 in CP	–	–	3%	
	–		0.40–1.00	T_a from 1 mobile measurement at 2 levels (2 and 0.3 m) on 8 July 1994	8 in CC	16.10	2.40	21%	
					8 in CC	17.70	2.50	11%	
	–			T_a from 1 mobile measurement at 2 levels (2 and 0.3 m) on 14 Feb 1994	8 in CC	–3.80	–1.20	22%	
					8 in CC	–3.60	–1.80	11%	
17 housing estates (Singapore)	0.45–12.76 km^2 by estates	Median *H/W* by estates based on 3D database of buildings and streets	1.28–2.72	Max. ΔT_a from 2 mobile measurements by estates	17	0.02	0.95	1%	Goh & Chang (1999)
One district of a city (Belo Horizonte, Brazil)	~2 km^2	3D database of buildings and topography (Autocad, MapInfo)	0.43–0.61	T_a from 1 mobile measurement	7, 19:00 h	27.75	–2.56	10%	Santos et al. (2003)
					7, 06:00 h	–	–	20%	
					7, 15:00 h	–	–	No	
One city (Szeged, Hungary)	26.75 km^2	Mean SVF by cells from several mesurements by surveying techniques	0.67–1.00	Mean ΔT_a from 35 mobile measurements	107	5.90	–4.62	1%	Present study
				Mean ΔT_a from 17 mobile measurements (defoliated season)	107	5.99	–4.81	1%	
				Mean ΔT_a from 18 mobile measurements (green season)	107	5.81	–4.44	1%	
				ΔT_a from 1 mobile measurement on 18 Sep 2002	107	10.49	–9.23	1%	
				ΔT_a from 1 mobile measurement on 25 Mar 2003	107	13.28	–12.03	1%	

SVF show larger negative values.' Differences in T_a were 'close to zero' at almost all SVF values (Tables 2 & 3). As her Fig. 10 shows, her investigation on temperature gradients between different districts (city centre, park and suburban area), measured by a traverse, revealed that variations in T_s followed very well variations in SVF. Variations in T_a between districts was greater than in the city centre but 'sites of similar density may show different air temperatures if the sites are located in different urban regions.'

The investigations in Göteborg were continued by Upmanis et al. (1998) (Table 2). They studied SVF and T_a pattern in 3 urban parks and their surrounding built-up areas using fixed sensors at 2.5 m and car traverses during calm and clear nights (2 to 3 h after sunset). There is no information on the measuring levels of SVF and T_a for the car traverses. Considering distance from the park border, they showed that 'the higher the sky obstruction the higher the temperature', but a simple regression analysis 'did

Table 3. Survey of sky view factor (SVF) (independent variable) versus surface temperature (T_s) (dependent variable) investigations: study area and its size, measurement methods, range of independent variables, number of element pairs, regression coefficients *a* and *b* ($Y = a + bX$, where Y is temperature and X is SVF) and significance level (–: no information) are shown. CC: Central city, T: Transition

Urban area	Size	SVF (methods)	Range of SVF	T_s	No. of pairs	*a*	*b*	Significance	Source
~1 × 8 km strip from rural area to the centre (Malmö, Sweden)	~8 km^2	Fish-eye photos by sites	0.52–0.99	T_s from 1 airborne infrared image	99	–	–	1%	Bärring et al. (1985)
One city (Mitsukaido City, Japan)	1 km^2	Fish-eye photos by sites	0.44–0.87	T_s from 1 mobile measurement	14	Inverse no sense	Inverse no sense	1%	Park (1987)
Part of a city (Göteborg, Sweden)	–	Surveying techniques by sites	0.30–0.92	T_s from 1 airborne infrared image	58	–	–	–	Eliasson (1990/91)
Part of a city (Göteborg)	–		0.25–0.98	T_s from 1 mobile measurement	–	–	–	–	
Different parts of a city (Göteborg)	~0.16 km^2	Surveying techniques by sites	0.25–1.00	T_s from several infrared images from 1 flight	55	7.10	–4.70	1%	Eliasson (1992)
Different parts of a city (Göteborg)	–		–	T_s from 1 mobile measurement	17	–	–	1%	
Different parts of a city (Göteborg)	~4 km^2	Surveying techniques by sites complemented by fish-eye photos	0.33–1.00	T_s from 6 mobile measurements	10–30	–	–	Yes	Eliasson (1996)
			0.41–1.00	Mean T_s from 3 mobile measurements (canyon – crossing/ open area)	18	–	–	–	
Along an urban transect (Göteborg)	8 km long		0.33–1.00	T_s from 1 mobile measurement	–	–	–	–	
Along an urban transect including 5 land use types (Göteborg)	–	Fish-eye photos by sites	0.38–1.00	Mean T_s from 6 mobile measurements in winter	8 CC	2.40	–4.00	2%	Upmanis (1999)
	–				8 T	–	–	No	
	–		0.41–1.00	Mean T_s from 10 mobile measurements in summer	7 CC	–	–	No	
	–		0.40–1.00	T_s from 1 mobile measurements in 'Central city'	8 (8 Jul 1994)	–	–	19%	
					8 (14 Feb 1994)	3.40	–6.30	4%	
Part of a city (Göteborg)	~4 km^2	Fish-eye photos by sites	0.26–0.99	T_s from 1 mobile measurement	24	–	–	No	Lindberg et al. (2003)
One city (Lisbon, Portugal)	82.5 km^2	3D database of buildings and trees on one site by cells (Computer Aided Design, RayMan)	–	T_s from 1 LANDSAT image	330	–	–	No	Vieira & Vasconcelos (2003)
Three (A, B, C) sample areas in a city (Lisbon)	~7.2 km^2				A	–	–	Yes	
					B	–	–	No	
					C	–	–	No	

not show a statistical significant relationship' between urban-park temperature difference and SVF. In addition, they analysed nocturnal cooling rates using fixed sensors and presented some details in reference to the largest park, concluding that 'some relation exists between SVF and cooling rate'.

Upmanis & Chen (1999) used SVF values and corresponding T_a observations by fixed sensors at 2.5 m along a transect through a park and its surrounding built-up areas in Göteborg in summer (Table 2). T_a data were selected according to the times of interest (at sunset, at 2 to 3 h after sunset, at 2 to 3 h before sunrise and at sunrise), excluding nights with rain and fog. There is no report on the measuring level of SVF. The applied principal component analysis did not reveal any relationship between SVF and T_a within the urban-park areas: 'no significant influence on the principal loadings, and thus on the air temperature, could be shown.'

To date, the most detailed investigation was made by Upmanis (1999) in Göteborg; this work shows some surprising and confusing results which partly support and partly contradict the previous results. She measured SVF, T_s and T_a (0.3 and 2 m) by car at 37 sites grouped according to land use types as 'Central city', 'Central park', 'Park', 'Transition' and 'Outskirts'. There is no report on the measuring level of SVF. Data were collected at night under calm and clear weather conditions in winter ('defoliated period') and in summer ('green season'). The examinations concentrated on relations between intra-urban variations of SVF and T_s/T_a in different land use areas, in winter and summer and also on selected individual days. As Tables 2 & 3 show, significant relationships occur for certain seasons, days and land use types. Nevertheless, several times there are no statistical connections between the same type of parameters. Positive correlations between SVF and T_a, for example in the 'Transition' area in summer, are particularly surprising (Table 2). Upmanis (1999) explained that, among other reasons, this is due to 'the fact that the shadow patterns and greater insolation at open locations during daytime also influence temperatures during the night.' All equations presented by Upmanis (1999) are related to the 'Central city' area and are as follows:

Winter: $T_s = 2.4 - 4.0 \times \text{SVF}$ (9)

on 8 Jul 1994: $T_s = 22.8 + 4.0 \times \text{SVF}$ (!) (10)

on 8 Jul 1994, 2 m: $T_a = 16.1 + 2.4 \times \text{SVF}$ (!) (11)

on 8 Jul 1994, 0.3 m: $T_a = 17.7 + 2.5 \times \text{SVF}$ (!) (12)

on 14 Feb 1994: $T_s = 3.4 - 6.3 \times \text{SVF}$ (13)

on 14 Feb 1994, 2 m: $T_a = -3.8 - 1.2 \times \text{SVF}$ (14)

on 14 Feb 1994, 0.3 m: $T_a = -3.6 - 1.8 \times \text{SVF}$ (15)

Finally, she concluded: 'The results thus indicate that SVF does not have a large importance on city temperatures, especially not air temperature, and that it should not be assigned to much importance.' Because 'many studies use surface temperature as a measure of air temperature' she recommended that 'great caution should be taken' using this procedure.

Goh & Chang (1999) determined temperature patterns of new housing estates in Singapore by car traverses using 8 to 18 observation points in several estates under dry weather conditions over a 3 mo intermonsoon period (Table 2). There is no information on the measuring level of air temperature. ΔT_a was defined as the difference between the spatial maximum and minimum temperatures by estates. Because of the irregularly shaped buildings, they calculated a weighted H/W index. The median H/W value was used as a predictor in a linear regression:

$$\Delta T_{a,max} = 0.952 \ H/W_{median} - 0.021 \quad (16)$$

In order to compare their results to Oke's (1981) investigations, Goh & Chang (1999) employed a logarithmic fit, but 'the logarithmic model was not significant' at the 5 % level. As an explanation, they noted the difference in various meteorological processes operating for tropical and temperate climates.

Lindberg et al. (2003) studied the connection between SVF and T_s measured at 2 m by car on 4 occasions in April in a selected central area of Göteborg (Table 3). Presenting in the form of a figure the result of only 1 measurement, they established that 'the diagram shows a large scatter and the correlation is low'.

Santos et al. (2003) presented a study on the influence of SVF on T_a measured at 2 m by car in a district of Belo Horizonte, Brazil, over a 24 h period in summer (Table 2). Three transects were taken under clear and calm weather conditions: at sunset, sunrise and 15:00 h. Despite the low number of element pairs (only 7), they calculated 3 linear regressions to reveal the relationship between SVF and T_a. In the daytime, at 15:00 h 'the correlation was almost null'. As an example, the obtained equation at sunset (at 19:00 h) 'points out a tendency of higher temperatures in the most obstructed areas during the typical period of the UHI occurrence':

$$T_a = 27.75 - 2.56 \times \text{SVF} \quad (17)$$

Vieira & Vasconcelos (2003) applied a 500 × 500 m grid on Lisbon, Portugal, which consisted of 330 cells for the entire city (Table 3). In order to represent the 3D geometry of each cell, they determined only 1 SVF value by cell with the explanation 'having a prior knowledge of the city, one should try to find a street that typified the entire cell'. The T_s map, produced for the daytime, was at satellite overpass time of about 10:00 h. The pixel sizes for the parameters were not equal. The obtained regression applied to the entire city 'did not reveal a clear relation' between the parameters. After selecting 3 smaller sample areas (A, B and C), only one of the areas 'could express this relation with a high level of significance'.

In summary, it can be established that the obtained results are rather contradictory. Previous investigations were limited to the central, or specific parts, or only some urban canyons of cities (e.g. Park 1987, Eliasson 1996), and used few sites and measurements (e.g. Park 1987, Goh & Chang 1999). Therefore, any examinations of possible connections were also based on a small number of element pairs. Comparisons were often based on element pairs measured at selected sites (e.g. Johnson 1985, Upmanis et al. 1998). In some cases areal means were also discussed, but always in connection with one of the variables examined (e.g. Oke 1981, Goh & Chang 1999, Vieira & Vasconcelos 2003).

3. STUDY AREA, MEASUREMENTS AND EVALUATION METHODS

3.1. Land use classes

Szeged is located in SE Hungary (46° N, 20° E) at 79 m above sea level on a flat plain (Fig. 1). The River Tisza passes through the city; there are no other large water bodies nearby. The river is relatively narrow and its influence is negligible (e.g. Unger et al. 2001). The area is in Köppen's climatic region Cf (temperate warm climate with a fairly uniform annual distribution of precipitation). The annual mean temperature is 10.4°C and the amount of precipitation is 497 mm. The number of inhabitants is 160 000 within an administration district of 281 km^2.

The study area was divided into 2 sectors and subdivided further into 500 × 500 m cells (Fig. 1). It consists of 107 cells covering the urban and suburban parts of Szeged (26.75 km^2). The outlying parts of the city, characterized by villages and rural features, are not included in the grid, with the exception of 4 cells to the west of the area. This latter part was taken in order to determine urban–rural temperature contrasts. Descriptions and features of the main land use types within the study area covered by the grid network are as follows (Fig. 1):

(b) Open spaces along the banks of the river, in parks and around the city's outskirts: recreational and agricultural areas with abundant vegetation and water surfaces, 0.94 to 1.00 SVF.

(c) Areas used for industry and warehousing: 1 to 2 storey extended buildings, little vegetation, 79 to 98 % built-up density, 0.91 to 0.98 SVF.

(d) Zones occupied by single houses: 1 to 2 storey houses, medium vegetation, 39 to 87 % built-up density, 0.79 to 0.98 SVF.

(e) Large housing estates with tall concrete blocks of flats set in wide green spaces: 5 to 11 storey apartment buildings, medium vegetation, 62 to 91 % built-up density, 0.79 to 0.97 SVF.

(f) Densely built-up centre with medium wide streets: 3 to 5 storey buildings, relatively little vegetation, 77 to 94 % built-up density (range of cell values), 0.67 to 0.93 SVF (range of average cell values).

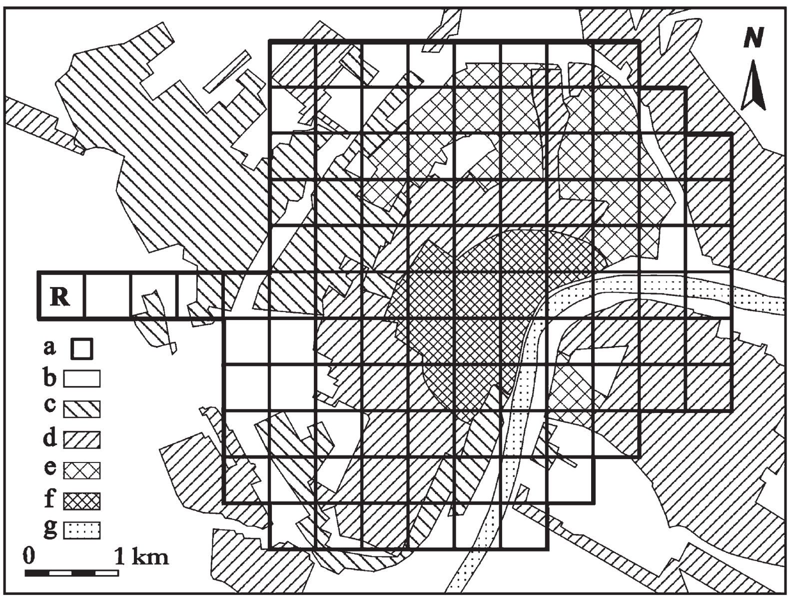

Fig. 1. Land use classes and the study area with a grid of 500 × 500 m in Szeged, south-eastern Hungary: (a) grid cells, (b) agricultural and open land, (c) industrial and warehouse area, (d) single houses, (e) apartment buildings, (f) historical city core and (g) river. R: rural cell

3.2. UHI intensity (ΔT)

Mobile measurements were taken by 2 cars in the 2 sectors at the same time on fixed return routes over a 1 yr period, altogether 35 times. Moving observation in ΔT_a detection with different vehicles (car, tram, helicopter, airplane, satellite) is a common process (see e.g. Tables 2 & 3). The approximately 10 d frequency of car traverses provided sufficient information under different, but dry, weather conditions.

Return routes of about 3 h through all cells by sectors were taken to make time-based corrections. Readings were obtained using radiation-shielded LogIT HiTemp resistance sensors connected to LogIT DataMeter 1000 data loggers. A major advantage of studying UHI is that the parameter of interest is not the absolute urban temperature, but the difference between urban and rural areas (Streutker 2003). The possible error in accuracy of the sensor is systematic and is thus removed in the differencing procedure. Data were collected every 10 s, so at a car speed of 20 to

30 km h^{-1} the distance between measuring points was 55 to 83 m. Sensors were mounted at 1.45 m above ground. The logged values at forced stops were deleted from the data set. Having averaged the 15 to 20 measurement values by cells, time adjustments to a reference time (4 h after sunset, namely the likely time of the strongest ΔT_a in the diurnal course, based on earlier measurements) were applied. ΔT_a values were determined by cell(s) averages referring to the temperature average of the rural (R) cell (Fig. 1).

3.3. Sky view factor

SVF is commonly determined using either analytical (geometrical), photographic or software methods, employing surveying techniques (e.g. theodolite), digital camera with a fish-eye lens, automatic canopy analyzer or available 3D urban morphology database (see Tables 2 & 3, as well as Matzarakis et al. 2000, Chapman et al. 2001, Grimmond et al. 2001, Souza et al. 2003). The photographic technique is particularly well suited to urban environments, where buildings are variable in size and shape and vegetation is present, so that simple relations based on building parameters using the analytical technique result in some errors (Grimmond et al. 2001). The SVF values of the present study can be regarded as estimations of the real SVF values, because the analytical method where 2 elevation angles to the top of buildings were measured normal to the axis of streets in both directions, using a 1.5 m high theodolite, was applied. According to Oke (1981, 1988), SVF can be calculated from these data (for more details, see Bottyán & Unger 2003).

SVF was determined along the measuring routes used for temperature sampling. A total of 532 points were surveyed and the obtained SVF data were averaged by cell. Angle measurements taken higher within a canyon (1.5 m), exclude more of the terrain (non-sky) and result in a small over-estimation of SVF after the calculation. This effect is more pronounced in canyons with low H/W ratios (Grimmond et al. 2001). Due to technical difficulties, there are no measurement points in crossings, so the calculated SVF values are probably a bit lower than the real ones. Furthermore, where there were parks, wooded areas or water surfaces in a particular direction, 0° was assigned as an angle value. The main reason for doing this was that it was difficult to determine SVF modified by the vegetation and the results were not unambiguous (Yamashita et al. 1986).

Taking the tree vegetation into account, from the point of view of sky obstruction, 2 half-year periods can be clearly distinguished in the climatic region of the present study: the defoliated season (October to April) and the season with foliage (April to October). Upmanis (1999) also investigated the summer and winter cases separately in Göteborg. In Szeged, the trees standing along the streets of the measurement routes are deciduous and are more abundant in the small side streets in the outskirts than in the more compact inner city. In the areas of large housing estates, the trees are significantly smaller than the buildings. In general, the leaf condition of trees may cause seasonal changes in SVF at places where trees are more numerous. Since the method of the present study for estimating SVF is only based on parameters of buildings, this change does not occur in the SVF values herein, but it may occur in temperature variations in case of any statistically significant SVF – T_a relationship. Therefore, besides the case of annual mean T_a, the average and, as an example, one individual case by season are also investigated.

4. RESULTS

In this section, a relatively new process is applied to examine the surface geometry – T_a connection within an urban area. This means a utilization of a large number of cell averages of SVF and ΔT_a as element pairs in a statistical investigation using linear regression. This examination of the influence of SVF on intra-urban temperature distribution is more comprehensive than the previous ones because the obtained data set represents almost the entire urban area, the number of element pairs used for comparison is large (107) and the cell areas (0.25 km^2) are not too small, i.e. the selected scale of the investigated urban units is not micro- but rather topo-scale.

(1) The relationship between SVF and the 1 yr average of ΔT_a calculated from 35 night measurements at the time of its best expression (see Section 3.2 above) is examined. The effects of different weather situations (favourable and not favourable for heat island development) are amalgamated in these ΔT_a averages. (2) The relationships in the defoliated and the green seasons are studied separately. According to expectation, the connection between SVF and ΔT_a average will be stronger in the defoliated season, because estimation of SVF is based only on building geometry and it shows more connection with the real SVF situation in the colder than in the more vegetated warmer half-year. (3) Not every condition is favourable for a local climatic phenomenon, so in order to promote the recognition of the influence of urban geometry, 2 special cases were selected. In both cases, local surface features might have been the primary driving force in the development of intra-urban local climates, i.e. the prevailing weather conditions supported the formation of UHI. One case (25 March 2003) occurred in the

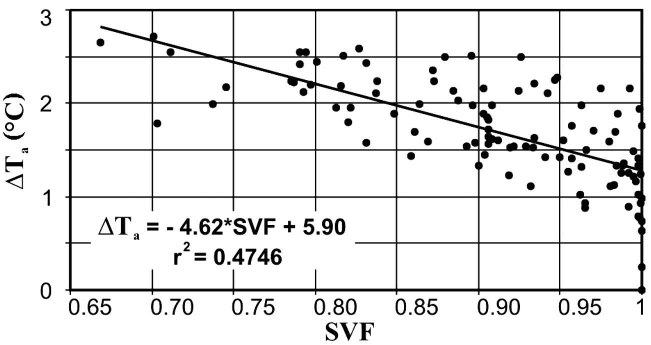

Fig. 2. Average urban heat island (UHI) intensity (ΔT_a) as a function of sky view factor (SVF) with the best fit regression line in the examined 1 yr period (April 2002 to March 2003) in Szeged (n = 107)

colder (defoliated) season, while the other (18 September 2002) occurred in the warmer (green) season. This means altogether 5 statistical investigations.

Naturally, the cell means of SVF are the same in all cases, because the surface elements practically did not change over the 1 yr study period. Their values ranged between 0.67 and 1.00 in the centre and outskirts, respectively.

Over the 1 yr period, mean ΔT_a ranged between 0 and 2.72°C inside the city. The highest ΔT_a values occurred in the central areas, almost in the geometrical centre of the investigated area. As Fig. 2 shows, there is a linear connection between SVF and ΔT_a in the urban area of Szeged. According to the obtained statistical measurements, the intra-urban variations in temperature excess can be explained by the variations in SVF of 47%. The correlation coefficient is –0.69, which means a strong negative relationship at the 1% significance level (n = 107). The calculated equation describing this relationship is as follows (Table 2):

$$\Delta T_{a,year} = 5.90 - 4.620 \times SVF \qquad (18)$$

The highest ΔT_a in the defoliated and green seasons reached 2.63 and 2.79°C, respectively. The comparison between the colder and warmer half-years revealed that the connection was stronger (at a significance level of 1%) in the colder season than in the warmer seasons, as expected (not shown), but the difference is not large. Correlation coefficients of –0.695 and –0.665 indicated negative relationships, meaning only a difference of 4% in the explanation of ΔT_a variation caused by the variation in SVF. This shows that the canopy of leaves in the summer has little influence on the ΔT_a values in comparison to the values in winter. One would expect less outgoing longwave radiation in areas with foliated trees because of the additional obstruction effect of the vegetation in a mixed urban environment with buildings and trees, resulting in higher temperatures. However, it is possible that the smaller SVF values result in smaller insolation because of altered shadow patterns during the daytime, which may influence the air temperature at night. At the present stage of this investigation it is assumed that the role of the foliated trees in determining the T_a along the measurement routes is minor compared to the obstruction effect of buildings, which is the same in both seasons. In the literature, Upmanis (1999) found only 1 similar investigation, but as previously mentioned her results were a bit surprising and confusing. The calculated equations describing these relationships in Szeged are (Table 2):

$$\Delta T_{a,defoliated} = 5.99 - 4.81 \times SVF \qquad (19)$$

$$\Delta T_{a,green} = 5.81 - 4.44 \times SVF \qquad (20)$$

Let us consider the individual case in the green season. On 18 September 2002, sunset was at 16:53 h UTC (universal time coordinated). Therefore, the considered reference time of the temperature measurement (see Section 3.2) was at 21:00 h UTC. In the wider time period of the measurement (between 19:00 and 23:00 h UTC), a light wind blew (0.73 to 2.03 m s^{-1}) at an average speed of 1.42 m s^{-1}. The sky was only slightly cloudy with an average value of 2 okta. ΔT_a reached a maximum value of 4.47°C on this night.

In the defoliated season on 25 March 2003, sunset was also at 16:53 h UTC, so the reference time of tem-

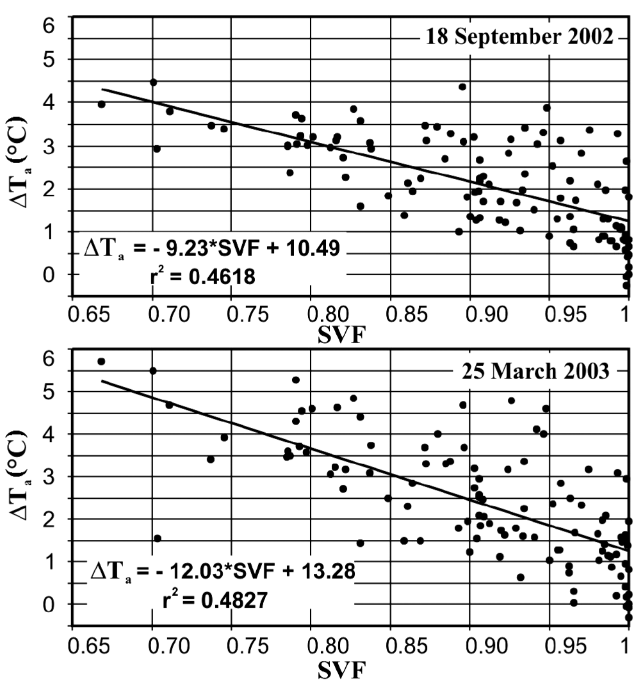

Fig. 3. Urban heat island (UHI) intensity (ΔT_a) as a function of sky view factor (SVF) with the best fit regression lines on 18 September 2002 and 25 March 2003 in Szeged (n = 107)

perature measurement was also at 21:00 h UTC. Between 19:00 and 23:00 h UTC, there was a light wind (1.08 to 2.20 m s^{-1}) at an average speed of 1.59 m s^{-1}. The sky was almost clear with an average value of 0.2 okta. The ΔT_a values reached a maximum of 5.70°C on this night, which was the second highest among the measured values during the 35 occasions.

As shown in Fig. 3, there are linear relationships similar to the average cases between the 2 variables. However, the steepness of the lines are higher than in average cases because the wider ranges of ΔT_a occurred on the investigated individual nights (4.47 and 5.70 vs 2.72, 2.63 and 2.79°C). The intra-urban variations in SVF explain 46 and 48% of the variations in ΔT_a in the green and defoliated seasons, respectively. Correlation coefficients are –0.68 and –0.69 in September and March, respectively, indicating strong negative connections at the 1% significance level (n = 107). The calculated equations describing these relationships are (Table 2):

$$\Delta T_{a,Sept} = 10.49 - 9.23 \times SVF \quad (21)$$

$$\Delta T_{a,March} = 13.28 - 12.03 \times SVF \quad (22)$$

According to the results herein, there is no significant difference in the influence of the SVF on the ΔT_a variations of differently vegetated seasons in the study area. The small (only 2 and 4% in explanation) seasonal differences in favour of the defoliated case versus the green case indicate a minor effect of tree conditions on the procedure for the estimation of SVF in the study area. It is interesting to note that—similar to the 'favourable' cases—weaker relationship is not be experienced over the 1 yr period. This may mean that the features of urban surface geometry influence (even under 'less favourable' weather conditions) the intra-urban temperature distribution to a great extent.

5. CONCLUSIONS

This study provides a review of the intra-urban SVF–temperature (T_a and T_s) relationship. In addition, a new approach was presented to reveal the real connection between SVF and T_a in an entire city.

The results found in the literature are rather contradictory. The investigations were restricted to specific parts of cities and used few sites and measurements. Therefore, any examinations of possible connections were also based on a small number of element pairs. Comparisons were often based on element pairs measured at selected sites. In some cases, areal means were also discussed, but always in connection with one of the examined variables.

For comparison, the present study utilized a large number of areal means of SVF and ΔT_a. Values were related to a large investigated area (almost a whole city) and based on numerous measurements. According to the results, there is a strong relationship between the intra-urban variations of these variables, i.e. urban surface geometry (described by SVF) is a significant determining factor of the T_a distribution inside a city.

Thus, after summarizing the results of international and recent investigations in Szeged, it can be concluded that while searching for the connections between urban geometry and temperature in a more adequate way, further studies should be based on an areal approach, i.e. on comparison of areal means. Measured values at sites might show large variations because of the influence of micro-variations on the immediate environs. Moreover, particularly in the case of T_a, measured values can be affected by advective effects from the wider environment (source area). Therefore, the first step of the investigation should be the selection of a proper scale. The application of areal means referred to an appropriate-sized urban area (e.g. a larger block) should gather and summarize the effects of micro-scale processes and should reveal the summarized results (values) representative for the given area. In addition, investigation of a sufficient number of appropriate-sized areas covering the largest part of a city or the entire city is needed to draw well-established conclusions on the relationship between SVF and temperature.

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