Dependence of the thermal urban climate on morphological variables

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Abstract

Urban meso- and micro-scale heat island conditions can be explained by energetic causes and properties of the urban surface and atmosphere. Urban morphological parameters, i.e. sealing factor, sky view factor or aspect ratio of street canyons, can also be used to explain their influences on the well-known phenomenon of urban climate, the urban heat island (UHI). Based on near-surface air temperature (T_a) data and statistical parameters that were calculated from measured T_a values, single and multiple regression analyses were carried out to determine the influence of the sealing factor and sky view factor on T_a characteristics. T_a values measured in the temporary climate network in Munich (South Germany), which was established from 1981-1985 within the scope of the research project "Urban Climate in Bavaria", represent the basis. The results of this re-analysis show that for the single regression the highest correlation can be reached with the sealing factor for the annual amount of total heat and mean annual T_a. In the multiple regressions the highest regression coefficients are found for the annual number of warm days, total heat and mean annual T_a.

Einfluss von morphologischen Variablen auf das thermische Stadtklima

Zusammenfassung

Die Bildung der urbanen Wärmeinsel (UHI) kann über energetische Ursachen und physikalische Eigenschaften der urbanen Oberflächen und Atmosphäre erklärt werden. Die Morphologie der urbanen Oberflächen und Strukturen, z.B. Versiegelungsgrad, Himmelsichtsfaktor (Sky View Faktor) oder das Höhen/Breitenverhältnis von Straßen, bilden eine adäquate Grundlage zur Beschreibung und Erklärung des bekanntesten Phänomens in der Stadtklimatologie, der urbanen Wärmeinsel (UHI). Auf der Grundlage von Messwerten für die bodennahe Lufttemperatur T_a sowie aus T_a abgeleiteten statistischen Kenngrößen wurden einfache und multiple Regressionsanalysen mit den Versiegelungsgrad und dem Sky View Faktor durchgeführt. Die verwendeten T_a Daten stammen aus dem temporären Klimamessnetz, das im Rahmen des Forschungsvorhabens STADTKLIMA BAYERN von 1981 bis 1985 in München eingerichtet worden war. Die Ergebnisse dieser Reanalyse zeigen, dass bei der einfachen Regression die höchsten Korrelationskoeffizienten zwischen Versiegelungsgrad einerseits sowie jährlicher Wärmesumme und mittlerem jährlichen T_a erzielt wurden. Bei der multiplen Regression ergab sich der höchste Korrelationskoeffizient für die jährliche Anzahl an warmen Tagen und mittlerem jährlichen T_a.

1. Introduction

Urban climate and its well-known phenomenon, the urban heat island (UHI), are of important interest due to different reasons. Therefore, considerable research has been conducted in recent years (www.urbanclimate.net or www.urban-climate.org). A main focus was given in the analysis on the quantification of the urban heat island and other related phenomena, especially the differences of the near-surface air temperature T_a between the city and its rural hinterland (OKE, 1973, 1987, JOHNSON et al., 1991, MATZARAKIS, 2001, HELBIG et al., 1999, KUTTLER, 2004a, b). Specific urban spaces, e.g. parks, have been the focus of interest regarding several parameters and factors, e.g. T_a

differences, moisture conditions or human-biometeorological indices (UPMANIS et al., 1998, MAYER and MATZARAKIS, 2006, MAYER et al., 2003, GULYAS et al., 2007, KUTTLER et al., 2007).

Many parameters play a significant role in the formation of the urban climate, UHI and urban heat archipelago (UHA), if the intra-urban thermal conditions are analysed. UHI and UHA are mainly caused by energetic features and fluxes (OKE, 1981, TSO et al., 1990; MATZARAKIS, 2001), which strongly depend on the increase of sealed surfaces (in horizontal and vertical directions) and the storage of heat in the urban materials. Two important factors can be used to quantify the urban morphology for UHI and UHA analyses (e.g. SHASHUA-BAR and HOFFMANN, 2003): the sky view factor SVF and the relative area of sealed surfaces in urban spaces indicated by the sealing factor F_v.

The impact of SVF is particularly important with respect to nocturnal cooling rates, where long-wave radiation is trapped by warm surfaces as opposed to being released to the cold sky hemisphere. Such a decrease in long-wave radiation loss is directly related to SVF and considered to be a major component of the UHI phenomenon (BARRING et al., 1985, OKE et al., 1991, MOIN and TSUTSUMI, 2004).

Based on existing data sets for near-surface T_a, i.e. near the bottom of the urban canopy layer (UCL), the aim of the present study is to improve the existing knowledge of the impact of the selected urban morphological parameters SVF and F_v on the intra-urban thermal conditions. The statistical analyses were performed for the city of Munich (South Germany), where a temporary urban climate network consisting of 20 climate stations was established from 1981-1985 in the UCL within the scope of the big research project “Urban Climate in Bavaria” (STADTKLIMA BAYERN). Working hypothesis, objectives, applied investigation design and results of STADTKLIMA BAYERN are explained in detail in the literature (e.g. BAUMGARTNER et al., 1985; BRÜNDL et al., 1986; MAYER, 1986, 1987, 1988)

2. Methods

SVF is a dimensionless parameterisation of the quantity of visible sky at a certain location. Represented as a value between zero and one, SVF will approach unity in perfectly flat and open terrain, whereas locations with obstructions such as buildings and trees will cause SVF to be proportionally less (BARRING et al., 1985, OKE et al., 1991, SVENSON, 2004). F_v describes the percentage of the built up area. In STADTKLIMA BAYERN, it was determined for a horizontal circle with a radius of 100 m around each of the 18 temporary climate stations in Munich (Fig. 1, Table 1). All climate stations were of a similar type (Fig. 2). All sensors used were of the same type (thermo-hygrographs) to measure and record T_a and the relative humidity RH continuously during the complete investigation period. The sensors were calibrated at regular intervals at each station.

UHI and UHA, respectively, were not only detected by the spatial and temporal patterns of T_a but also through statistical values calculated from T_a (Tab. 1). The following statistical values were available (BRÜNDL et al., 1986):

- mean annual air temperature (MIT) of T_a,

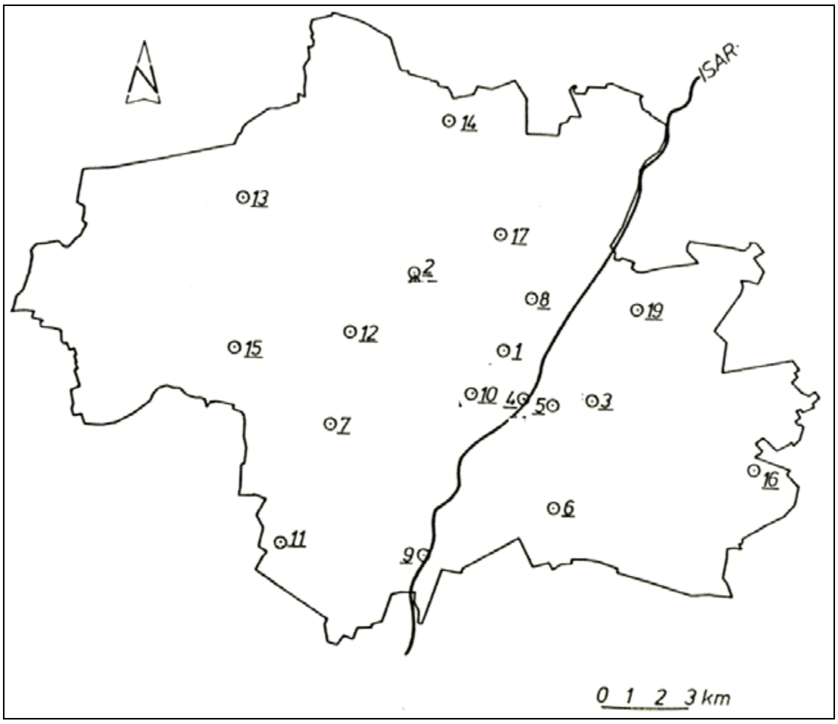


Fig. 1: Screen level urban climate network in Munich (South Germany) from 1981-1985 within the scope of the STADTKLIMA BAYERN project (according to BRÜNDL et al., 1986, modified)

Fig. 2: Station "Sonnenstraße" as example for the stations in the temporary urban climate network from 1981-1985 in the UCL in Munich (South Germany) within the scope of the STADTKLIMA BAYERN project

Table 1: Numbers and name of the stations as well as their, specifications, sealing factors F_v and sky view factors SVF, stations in the temporary urban climate network in the UCL in Munich (South Germany) within the scope of the STADTKLIMA BAYERN project (BRÜNDL et al., 1986; MAYER, 1987)

station no.	station name	F_v	SVF
1	Universität	0.95	0.247
3	Einsteinstraße	0.75	0.382
4	Praterinsel	0.20	0.150
5	Kirchenstraße	0.80	0.410
6	Ständlerstraße	0.30	0.627
7	Füstenrieder Straße	0.60	0.614
8	Antonienstraße	0.75	0.336
9	Hinterbrühl	0.05	0.438
10	Sonnenstraße	0.90	0.326
11	Walliser Straße	0.20	0.385
12	Romanplatz	0.80	0.610
13	Franz-Nißl-Straße	0.45	0.649
14	Paulckestraße	0.60	0.507
15	Pasing Bahnhof	0.75	0.329
16	Wasserburger Landstraße	0.55	0.766
17	Bad-Kreuznacher-Straße	0.30	0.677
19	Knappertbuschstraße	0.70	0.410

- absolute 30 minute maximum (MAX) and minimum (MIN) of T_a per year,
- mean annual number of tropical days (TT), i.e. days with a daily maximum air temperature $T_{a,max} \geq 30$ °C,
- mean annual number of summer days (ST), i.e. days with a daily maximum air temperature $T_{a,max} \geq 25$ °C,
- mean annual number of warm days (wT), i.e. days with a daily mean air temperature $T_{a,mit} > 20$ °C,
- mean annual number of heating days (HT), i.e. days with a daily mean air temperature $T_{a,mit} < 12$ °C,
- mean annual number of frost days (FT), i.e. days with a daily minimum air temperature $T_{a,min} < 0$ °C,
- mean annual number of ice days (ET), i.e. days with a daily maximum air temperature $T_{a,max} < 0$ °C,
- mean annual number of cold days (kT), i.e. days with a daily mean air temperature $T_{a,mit} < -10$ °C,

- mean annual total of heat (WS), i.e. $\sum_{i=1}^{i=N} T_{a,mit,i}$ with N: number of days per year, and the limitation for daily mean T_a values: $T_{a,mit,i} > 0\,°C$,
- mean annual total of cold (KS), i.e. $\sum_{i=1}^{i=N} T_{a,mit,i}$ with N: number of days per year, and the limitation for daily mean T_a values: $T_{a,mit,i} < 0\,°C$.

In the statistical regression analyses, both mean annual T_a values and mean annual thermal characteristics calculated from T_a are the depending variables (Y), while F_v and SVF, respectively, represent the independent variable (X). The regression analyses were carried out in form of a linear regression

$$Y = a_0 + a_1 * F_v \quad (1)$$

$$Y = b_0 + b_1 * SVF \quad (2)$$

and in form of a multiple regression:

$$Y = c_0 + c_1 * F_v + c_2 * SVF \quad (3)$$

3. Results

The statistical calculations can be interpreted as a re-analysis of urban climate data measured and recorded approximately 20 years ago.

The results for mean thermal characteristics (Table 2) reveal an intra-urban variability, which depends on station-specific morphological parameters. They are exemplarily indicated by simple fish-eye graphics (Fig. 3).

For the urban climate stations in the inner city of Munich, which are characterised by high permanent buildings (with high density of residents) and low percentage of green areas (station 1), and urban spaces with a strong mixture of diverse buildings and a very low portion of green areas (station 10), the results show relatively high values of total heat and number of warm days, while the values for cold days as well as heating, frost and ice days are relatively low, i.e. a specific pattern of the UHA or urban hot spots was formed.

Due to its location within an urban park, the statistical values for the station 4 point out to a cold spot. With increasing distance to the city centre, the stations with single or more buildings (e.g. stations 13 or 16) are characterised by lower statistical values than for the hot spots in the city centre. Compared to the conditions within parks in the outskirts, the stations (13 or 16) can also be seen as hot spots.

The results of the linear regression analyses for F_v and SVF are contained in Table 3. The grey colour indicates a correlation coefficient r higher than 0.5. The results in Table 3 can be summarised as follows:

- The strongest correlation exists between F_v and the mean annual number of warm days followed by (i) the correlation between F_v and the mean annual total heat and (ii) the correlation between F_v and mean annual air temperature T_a.

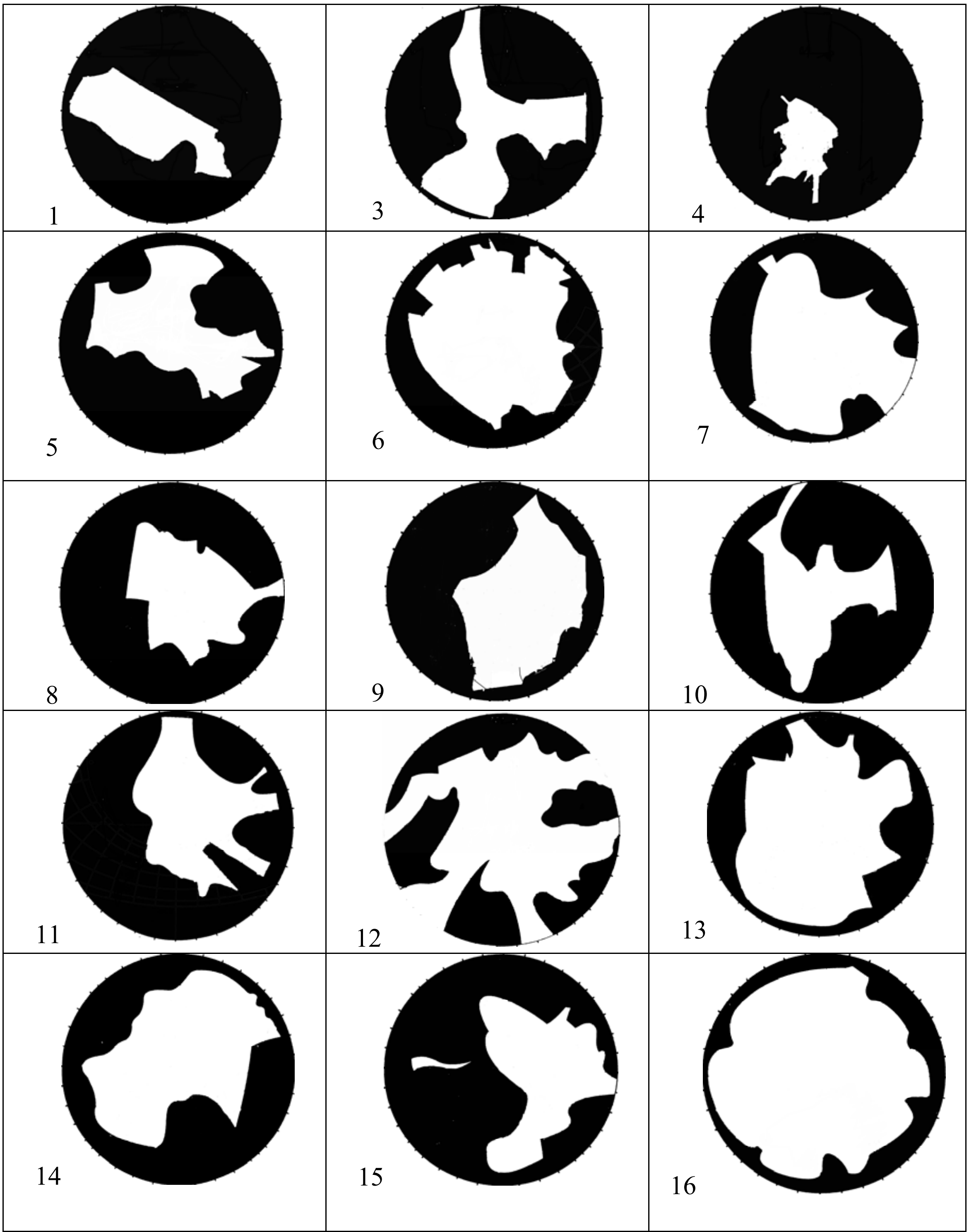
Table 2: Mean values of air temperature T_a (MIT), total of heat (WS) and cold (KS), absolute maximum (MAX) of T_a and absolute minimum (MIN) of T_a, mean annual numbers (n/a) of tropical days (TT), summer days (ST), warm days (wT), heating days (HT), frost days (FT), ice days (ET) and cold days (kT) at the stations in the temporary urban climate network in the UCL in Munich (South Germany) within the scope of the STADTKLIMA BAYERN project, averaging period: 1982-1984 (BRÜNDL et al., 1986; MAYER, 1987; MATZARAKIS, 2001)

station	MIT	WS	KS	MAX	MIN	TT	ST	wT	HT	FT	ET	kT
	°C	°C	°C	°C	°C	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1	9.3	3572.9	-150.5	38.2	-13.4	8	38	36	219	81	29	1
3	8.3	3312.1	-192.6	36.8	-15.8	4	32	26	235	113	32	2
4	8.4	3260.0	-172.6	34.6	-14.2	2	20	17	217	97	30	1
5	8.9	3447.3	-161.5	37.5	-14.3	7	40	33	225	99	34	1
6	8.0	3152.0	-215.9	36.6	-14.8	5	32	21	237	91	29	1
7	8.7	3375.1	-192.6	37.8	-13.4	7	40	29	229	107	30	1
8	8.8	3420.4	-188.7	36.5	-15.8	4	29	28	227	95	34	2
9	7.4	2958.7	-224.2	36.2	-15.2	4	25	13	250	131	31	1
10	9.6	3643.2	-137.0	35.9	-13.4	7	42	37	218	80	24	0
11	7.9	3117.4	-219.7	37.9	-15.0	5	32	21	240	122	33	2
12	8.7	3422.6	-192.5	37.1	-15.1	5	36	27	227	109	32	2
13	7.7	3081.7	-251.9	36.2	-17.8	3	33	20	246	127	37	4
14	8.2	3224.4	-213.4	37.8	-15.0	7	38	24	236	114	32	2
15	8.6	3349.0	-187.1	37.1	-14.8	5	33	28	230	103	30	1
16	8.1	3193.2	-227.4	36.2	-19.5	6	36	20	238	122	31	2
17	8.6	3373.4	-203.6	37.2	-16.3	7	37	29	229	105	35	2
19	8.5	3339.7	-218.4	38.3	-17.8	7	40	28	230	107	34	3

- A trend exists that the statistical values of T_a have a higher correlation with F_v than with SVF. SVF mainly influences the radiation balance and the turbulent transport within the UCL. These effects seem to be lower than for other meteorological parameters in the formation of UHI and UHA, respectively.
- There are no correlations with $r > 0.5$, neither with F_v nor with SVF, for the statistical values of absolute T_a-maxima and the mean annual numbers of tropical, ice and cold days.

The results for the multiple regression analyses are compiled in Table 4. They show:

- As expected, the correlation coefficients for the multiple regressions are higher than the correlation coefficients for linear regressions.



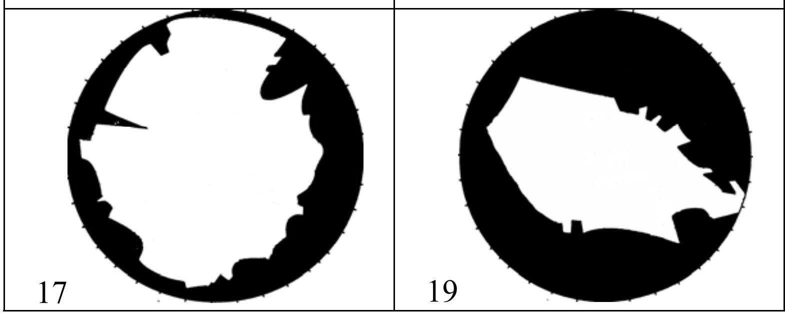


Fig. 3: Fish-eye graphics for the stations in the temporary urban climate network from 1981-1985 in the UCL in Munich (BAUMGARTNER et al., 1984)

Table 3: Regression coefficients a_0, a_1, b_0 and b_1 from the equations (1) and (2) as well as correlation coefficients r, basis: statistical thermal values for 17 stations in the temporary urban climate network in the UCL in Munich (South Germany) within the scope of the STADTKLIMA BAYERN project, averaging period: 1982-1984, F_v: sealing factor, SVF: sky view factor, T_a: air temperature (according to BRÜNDL et al., 1986; MAYER, 1987; MATZARAKIS, 2001)

	independent variable F_v			**independent variable SVF**		
	a_0	**a_1**	**r**	**b_0**	**b_1**	**r**
mean annual air temperature T_a (°C)	7.5	1.6	0.780	9.0	-1.2	-0.371
mean annual total of heat (°C)	3008.0	529.6	0.818	3467.5	-344.0	-0.332
mean annual total of cold (°C)	-233.2	63.7	0.581	-146.7	-108.9	-0.622
absolute T_a-maxima (°C)	36.2	1.2	0.352	36.6	0.7	0.122
absolute T_a-minima (°C)	-16.0	1.0	0.167	-12.9	-5.3	-0.539
mean annual number / tropical days	3.7	3.1	0.488	4.7	1.7	0.171
mean annual number / summer days	26.6	13.6	0.640	29.1	11.3	0.331
mean annual number / warm days	14.4	20.0	0.835	29.4	-8.1	-0.211
mean annual number / heating days	242.1	-19.0	-0.555	218.3	28.3	0.518
mean annual number / frost days	122.3	-28.7	-0.528	87.5	40.0	0.460
mean annual number / ice days	33.0	-2.4	-0.220	29.0	5.6	0.322
mean annual number / cold days	1.9	-0.4	-0.109	0.6	2.2	0.401

Table 4: Regression coefficients c_0, c_1 and c_2 from the multiple regression equation (3) and the multiple correlation coefficient r; basis: statistical thermal values for 17 stations in the temporary urban climate network in the UCL in Munich (South Germany) within the scope of the STADTKLIMA BAYERN project, aver-aging period: 1982-1984, F_v: sealing factor, SVF: sky view factor, T_a: air temperature (according to BRÜNDL et al., 1986; MAYER, 1987; MATZARAKIS, 2001)

	c_0	**c_1**	**c_2**	**r**
mean annual air temperature T_a (°C)	7.9	1.5	-0.7	0.811
mean annual total of heat (°C)	3107.7	507.0	-187.8	0.837
mean annual total of cold (°C)	-184.0	52.5	-92.7	0.780
absolute T_a-maxima (°C)	35.6	1.4	1.1	0.402
absolute T_a-minima (°C)	-13.2	0.4	-5.2	0.543
mean annual number of tropical days	2.3	3.4	2.8	0.558
mean annual number of summer days	18.0	15.6	16.1	0.790
mean annual number of warm days	15.4	19.7	-2.0	0.837
mean annual number of heating days	229.8	-16.1	23.3	0.696
mean annual number of frost days	105.2	-24.8	32.4	0.642
mean annual number of ice days	30.3	-1.8	5.1	0.360
mean annual number of cold days	0.7	-0.1	2.2	0.403

- The correlation coefficient for the multiple regression related to the mean annual number of tropical days exceeds the 0.5 threshold.
- As for the linear regressions, the correlation coefficients of the multiple regressions for the absolute T_a-maxima as well as the mean annual number of ice and cold days do not exceed the 0.5 threshold.
- The mean annual number of warm days and the mean annual total of heat show the strongest multiple correlations with F_v and SVF, followed by the mean annual air temperature T_a and the mean annual number of summer.

Based on T_a values from all stations in the temporary urban climate network in the UCL in Munich, Fig. 4 reveals an increase of mean annual T_a with increasing F_v and decreasing SVF. The correlation coefficients r for the linear regressions point out that the correlation between T_a and F_v is clearly stronger than for T_a and SVF.

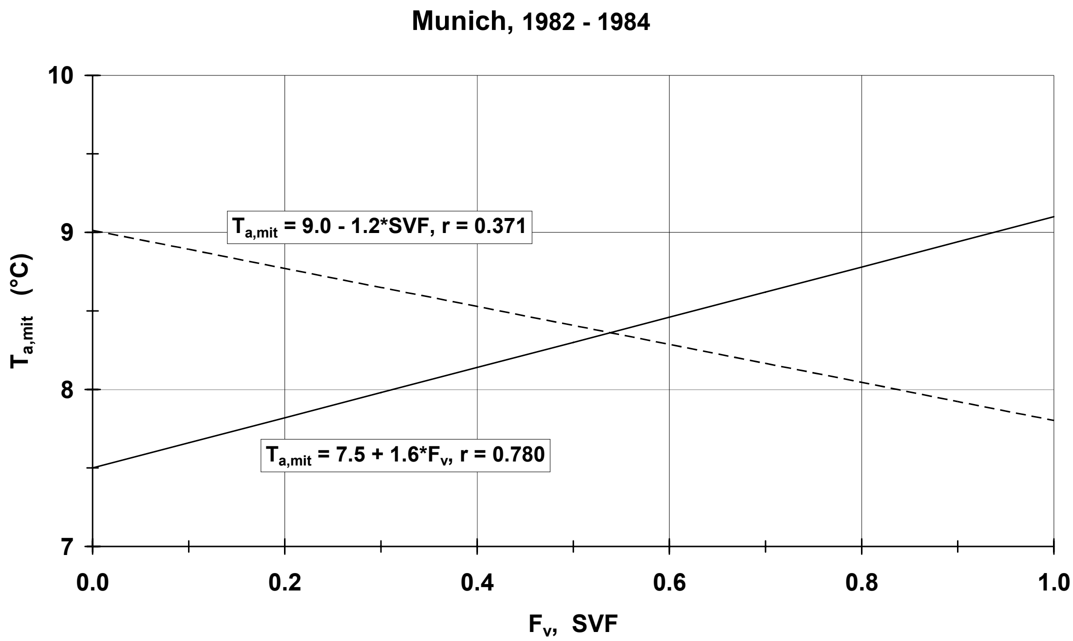


Fig. 4: Relationships between the mean annual air temperature T_a as well as F_v and SVF based on data recorded from 1982-1984 at stations in the temporary urban climate network in the UCL in Munich (South Germany) within the scope of the STADTKLIMA BAYERN project

4. Conclusions

Urban morphological parameters are dominating factors for the formation of the urban heat island UHI and the urban heat archipelago UHA, respectively. Typically, UHI is of a wide interest in numerous studies on urban climate. However, for several applications, e.g. human-biometeorological analyses, UHI or UHA are not the main cause for human heat stress in summer. Related to cities, which are not influenced by thermally induced regional and local circulation systems, the radiation heat is more important in this context.

Known urban morphology parameters are sealing factor, sky view factor, aspect ratio of street canyons, building density, material properties, and portion of green spaces. Each of these parameters has an influence on UHI and UHA, which was analysed in numerous investigations by use of different methodical designs (e.g. OKE, 1973, 1981, 1987).

For the formation of the thermal urban climate, the configuration of morphology also plays an important role. In addition, it has to be taken into account whether the SVF is determined by a building or green open space in order to quantify the upper and lower hemisphere in urban structures. Another important characteristic is the orientation of buildings as well as the location of green open spaces and other vegetation in their position in the sky view hemisphere.

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This article is dedicated to Prof. Dr. Dr. h.c. Albert Baumgartner, who passed away on 6 March 2008. He was the head of the Chair for Bioclimatology and Applied Meteorology at the Ludwig-Maximilians-University of Munich (South Germany) from 1972-1985. The big research project "Urban Climate in Bavaria" (STADTKLIMA BAYERN) was carried out under his scientific responsibility from 1980-1986.

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