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IMPACT OF BUILD-UP AREAS AND HOUSING ESTATE VEGETATION ON DIVERSITY OF THE LOCAL CLIMATE IN WARSAW

Abstract. The more important research results on the impact of building development and vegetation on the local climate, conducted in Warsaw in the years 1959–2009 by the Department of Climatology, are presented. Majority of the issues associated with determining the deformation of air temperature limits (urban heat islands), humidity and wind vector areas, because of buildings in housing estates, located in various parts of the city, were resolved in master's thesis. Areas with high building density are characterized by slow cooling and warming pace, especially during the summer months. Spatial changes in the urban heat islands in the east-west direction well describe the latitudinal profiles (W-E) of air temperature differences ($\Delta T \geq 0$) between the city and its urban fringe. The urban heat island ΔT does not appears till 5PM, initially in the Central City District. Spatial diversity of effective temperature and catathermal cooling allowed to mark off in housing estates („Stawki", „Służew nad Dolinką", „Sady Żoliborskie") places with perceptible conditions, e.g. heat, warmth, comfort, cold.

Key words. Intensity of heat island, diurnal changes, annual changes, air temperature, latitudinal profiles, town.

INTRODUCTION

The objective of the paper is to define the range of diversity of meteorological and biometeorological conditions depending on the character of building development and vegetation in housing estates and their location in Warsaw, with particular attention to diurnal and annual changes.

Research carried out by the Department of Climatology on the impact of different types of buildings and vegetation on the local climate in Warsaw was carried out in 1959–2009. Housing estates located in different city districts, approximately on the north-south profile (Fig. 1) were of particular interest.

1. „Białołęka Dworska" – large share of vegetation, majority of low buildings (up to 4 stories) and multi-storied buildings.
2. „Chomiczówka" – on the one hand, diversified built-up area, with majority of high and well spaced buildings and on the other, well spaced, low and medium buildings with small share of vegetation.
3. „Sady Żoliborskie" – the example of quarter development (Sady I) and street development (Sady IV) and high buildings (Sady II), vegetation takes up a large part of the surface in the housing estate and its surroundings.
4. „Stawki" – on the northern edge of the City Centre District, surrounded by green areas, with well spaced, high apartment buildings.
5. „Szwoleżerów" – built-up areas constitute 16% of the area, green areas – 57%. Alongside the housing estate, the buildings are not taller than trees and multi-storied buildings are in the south-western part of the housing development. From the west is Wisłostrada, a busy thoroughfare.

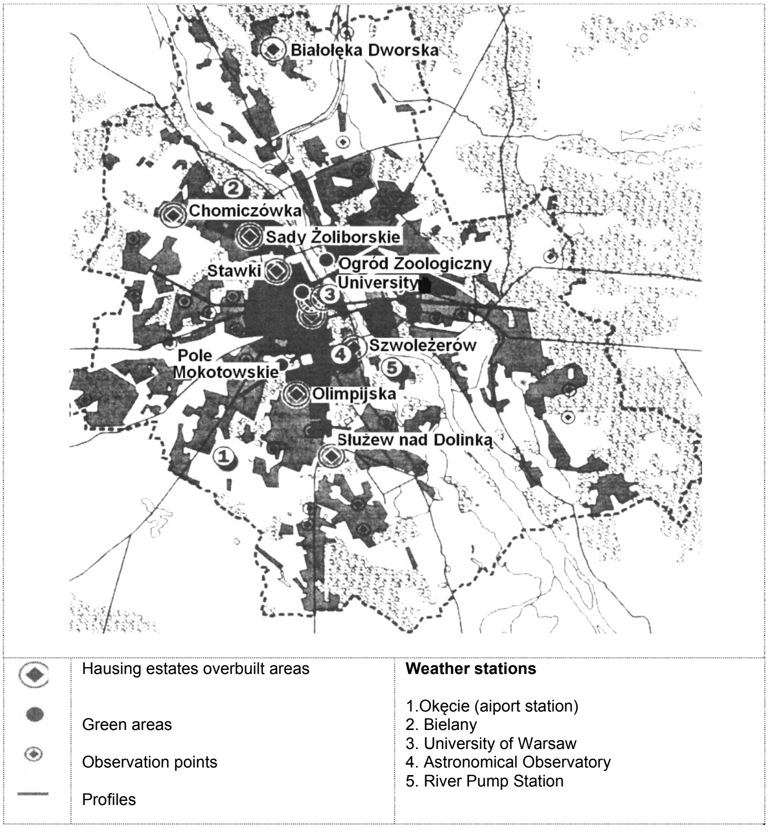

Fig. 1. Climatological field studies carried out in Warsaw by the Department of Climatology

6. „Wyględów-Olimpijska" – with well spaced one-family buildings, with a large share of vegetation.
7. „Służew nad Dolinką" – on the southern edge of Warsaw, with high and well spaced flat buildings.
8. „Kabaty" – on the southern edge of Warsaw, with diversified low and high buildings with a diversified share of vegetation.
9. „Osiedle Przyjaźń – Jelonki" – a fire station tower is situated on the edge of the one-family house complex, with a large share of vegetation.
10. „City Centre District" – includes densely built mid-size buildings, with a small share of vegetation.

Good many of the results refer to densely built buildings in the City Centre District, with a small share of vegetation, with special focus on the Śródmiejska Stacja Meteorologiczna Warszawa – Uniwersytet (the City Centre District Meteorological Station – Warsaw-University).

The results of own research usually referred to data from the synoptic station of Instytut Meteorologii i Gospodarki Wodnej Warszawa-Okęcie (Institute of Meteorology and Water Management Warszawa-Okęcie), representing conditions from outside the city, from the south-west side. It is located in an area where the city has the smallest impact on climate, with dominant winds from the western sector. They were referred to the closest surroundings, i.e. stations set-up outside the housing developments.

THERMAL CHARACTERISTICS OF THE LOCAL CLIMATE OF A LOWLAND CITY

Measuring of meteorological elements during the year allowed to focus on the following issues:

Deformation of areas of meteorological variables in the scale of the entire city, with special attention paid to air temperature (urban heat islands).

The impact of the character of built-up areas and vegetation on climate diversity on the local scale.

Qualification of the role of urban vegetation in determining the thermal-humidity conditions.

Air temperature in dense building developments in the City Centre District is much higher than in the city edge areas. Above all, this stems from a larger active surface, a large building mass and limited long wave radiation by polluted atmosphere. The heat island in Warsaw is characterized by periodic oscillations: daily (Fig. 2) and annual (Fig. 3, Table 1). The greatest temperature differences between the city and its vicinity occur in the evening and at night and annually, from April to October. The smallest differences are observed at noon – in November and March. The heat island ΔT manifests itself the most in the summer (July), achieving, on the average, in the central regions of the city, a difference of more than 2°C.

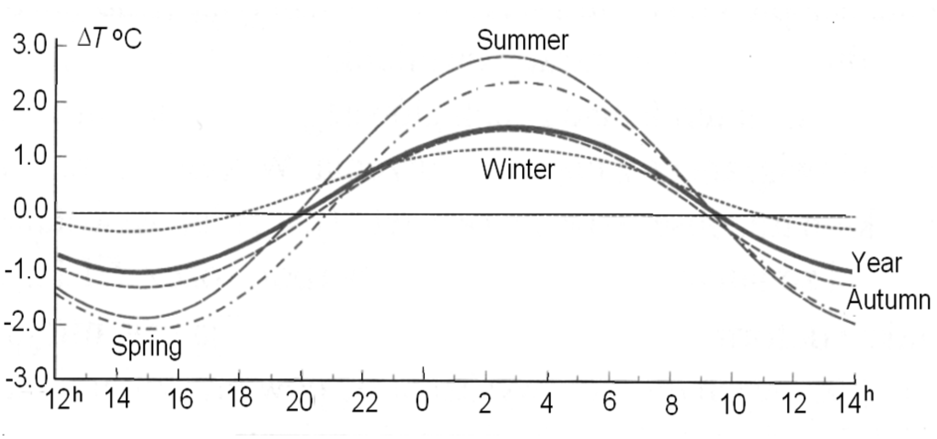

Fig. 2. Daily intensity changes of the „heat island" in Warsaw

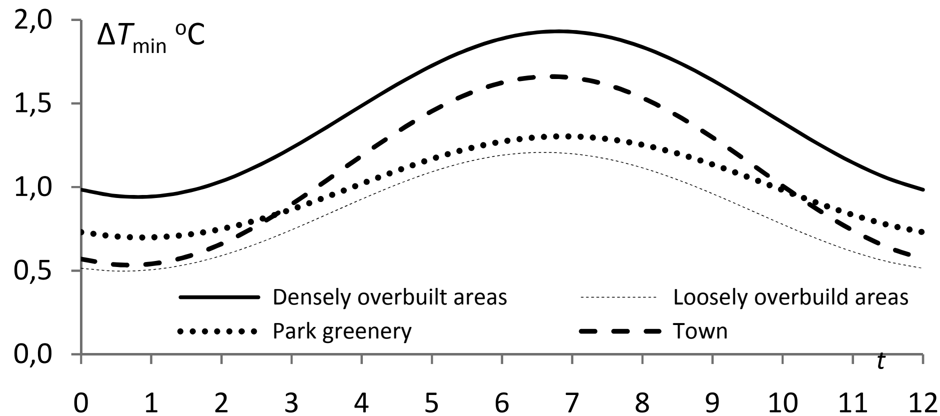

Fig. 3. Annual changes of air temperature differences between the city and its outskirts in Warsaw, in the years 1951-1965 (daily minimum ΔT_{min})

Table 1. Equations of sinusoids of annual changes in air temperature differences between the city and its outskirts in Warsaw, in the years 1951–1965, (daily minimum ΔT_{min})

	$\Delta T = a_o + b\sin(2\pi t/\Theta + c)$	R
Densely overbuild areas	ΔT_{min}= 1.436+0.495sin(2πt/12 -1..992)	0.82
Loosely overbuild areas	ΔT_{min}= 0.852+0.355sin(2πt/12 -1.880)	0.78
Park greenery	ΔT_{min}= 1.001+0.302sin(2πt/12 -2.031)	0.80
Town	ΔT_{min}= 1.097+0.564sin(2πt/1 2-1.933)	0.64

Values on the increase of air temperature (ΔT) deliver information about the pace of warming and cooling of the city in relation to the unbuilt areas (Table 2 and 3). Areas with high building density are characterized by a slowed down pace of cooling and warming, especially in the summer months.

It is also significant to become acquainted with the daily changes in the differences of ΔT between individual city districts and the outskirts which will allow to determine dates when the heat islands will appear, their maximum intensity and the time of their weakening and disappearance.

Table 2. Characteristics of an urban heat island during seasons in Warsaw

Seasons	Beginning (h)	Maximum (h)	End (h)	ΔT_{max}	ΔT (°C)
Winter	16-18	21-24	6-7	>0	9-11
Spring	17-18	about 24	7-8	<0	9
Summer	18-20	22-24	6-8	<0	8
Autumn	16-18	21-01	6-9	<0	8

Table 3. Pace of air warming and cooling in the centre of Warsaw and in the outskirts in seasons (°C/h.)

Seasons	Warming pace		Cooling pace	
	City Centre	Outskirts	City Centre	Outskirts
Winter	0.2-0.1	1.5-2.5	0.1-0.7	1-3
Spring	0.3-2	1-3	0.1-0.7	1-3
Summer	about 1	1-3	< 1	1-6
Autumn	1-2	1-3	1-2	2-3

THE PACE OF WARMING AND COOLING OF HOUSING ESTATES WITH HIGHT FLAT BUILDINGS (SŁUŻEW NAD DOLINKĄ, STAWKI) AND LOW VILLA DEVELOPMENTS WITH LARGE PARTICIPATION OF VEGETATION (OLIMPIJSKA)

The deformation meteorological variable areas may be examined not only in the scale of a city and its chosen districts but also in housing estates. This is significant, for example, in the planning of urban green areas (Stopa-Boryczka. Kopacz-Lembowicz, Boryczka, 1994). An attempt to solve this problem has been shown by the example of three Warsaw housing estates, with high flat buildings and well spaced („Stawki", „Służew nad Dolinką") and low villas with large vegetation participation (in the area of Olympjska and Racławicka streets). In order to describe the thermal characteristics of housing estates data were correlated (every 0,5 h) from measuring points situated in the housing estates and on their outskirts. These relations were described by simple regression equations, determining the period ranges (time): morning 7–11^{h}, noon 12–16^{h} and evening 17–21^{h} (Daylight Saving Time).

The air in housing estates with high flat buildings heats up slower by about 0.2°C/°C than the surroundings. The morning process of warming up the air in housing estates with low villas, with large participation of vegetation is different – the regression coefficients have values close to zero.

The impact of various types of build-up areas is even stronger in the evening cooling out process. Air in the high building complex of the „Służew nad Dolinką" and „Stawki" housing estates cools down slower by 4–0.3°C/°C than the surroundings. In the low building area at Olimpijska street cooling down is even quicker – by 0.13°C/°C.

Relative changes of the heat island in a housing estate, in relation to the temperature of the nearest surroundings, are described by simple regression equations and graphs in figure 4.

The cooling process in the „Stawki" and „Służew nad Dolinką" housing estates takes place with a mean intensity of 0.4°C/h and in the „Olimpijska" housing estate the cooling is even quicker – by 0.1°C/h.

Table 4. The simple regression equation of air temperature differences in Warsaw between housing estates and Okęcie, in relation to Okęcie (r – the correlation coefficient)

Housing estate „Stawki"		
Morning	$\Delta T = 2.314 - 0.163\ T$	-0.75
Noon	$\Delta T = 0.277 - 0.045\ T$	-0.15
Evening	$\Delta T = 6.353 - 0.301\ T$	-0.95
Housing estate „Służew"		
Morning	$\Delta T = 2.769\text{-}\ 0.167\ T$	-0.70
Noon	$\Delta T = 3.509 - 0.160\ T$	-0.45
Evening	$\Delta T = 7.878\text{-}\ 0.353\ T$	-0.99
Housing estate „Olimpijska"		
Morning	$\Delta T = 0.619 - 0.038\ T$	-0.62
Noon	$\Delta T = 1.716 - 0.085\ T$	-0.52
Evening	$\Delta T = 2.747 - 0.130\ T$	-0.81

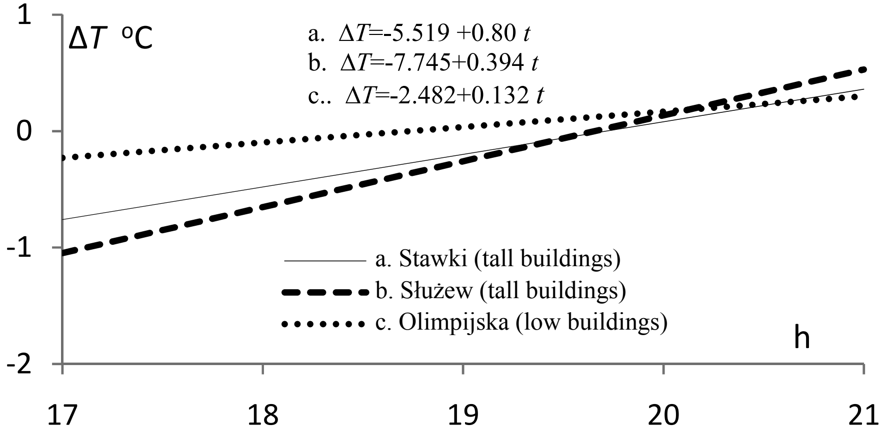

Fig. 4. The dependence of the difference (ΔT) between the average temperature in points inside the estates and an external reference point as a function of time

The time of appearance of the „housing estate heat island" may be read from the graphs, i.e. the moment when plus air temperature differences come into view. In the „Służew nad Dolinką" and „Stawki" housing estates the „heat islands" emerge later than in well spaced one family house complex with vegetation but is characterized by a smaller difference ΔT.

Change tendencies in differences of air temperature in the „Stawki" and „Służew nad Dolinką" housing estates, in reference to their surroundings, are negative in the morning hours and positive in the evening. In the morning, the housing estates remain cooler in comparison with their surroundings by 0.2°C/h. and in the evening are warmer by 0.3–0.4°C/h. The regression coefficients depend on the location of measuring points. The lowest negative values –0.6°C/h take place in the morning hours in both estates, in points located on the northern side of the buildings and the greatest – positive 0.6 °C/h in evening hours in the „Służew nad Dolinką" housing estate, at a point located on the eastern side of a building.

By cutting regression lines by the line $\Delta T = 0$ are received the border values of temperature T_o or the moment of appearance (t_p) and disappearance (t_z) of the housing estate heat island. In the smaller, more compact „Stawki" housing estate, it emerges in the late evening and with lower air temperature than in the peripheral, well spaced „Służew nad Dolinką" housing estate. In the morning, however, in the „Stawki" housing estate, the heat island remains longer and disappears at higher temperatures.

Determining empirical relations characteristic for different types of building complexes allows forecasting changes. Their use in designing urban housing estates may assure beneficial bioclimatic conditions for the residents.

MOVEMENT OF THE HEAT ISLAND IN WARSAW BY THE IMPACT OF WIND ON THE LATITUDINAL (W-E) AND MERIDIONAL (N-S) PROFILES

The phenomenon of heat island movement in Warsaw has been best presented in master's thesis on local climate variability on the profiles: west-east (Przybyłkowska, 1994) and north-south (Romańska, 1994).

Movement of the heat island depending on the wind direction was illustrated in D. Przybyłowska's study. It stated that with south-east wind heat islands occurred in the City Centre and in the western points of the profile. Under the impact of south-west wind, the heat island beyond the City Centre was observed in the eastern profile points where there was an influx of air most changed by the city.

Spatial changes of the urban heat island in Warsaw, in the west-east direction, during the hours 16 -21, well describe the latitudinal profiles of air temperature changes ΔT between the city and its outskirts (Okęcie) presented in figure 5. These are equations and graphs of a fourth degree multinomial regression of air temperature differences ΔT between 9 measuring points, situated in

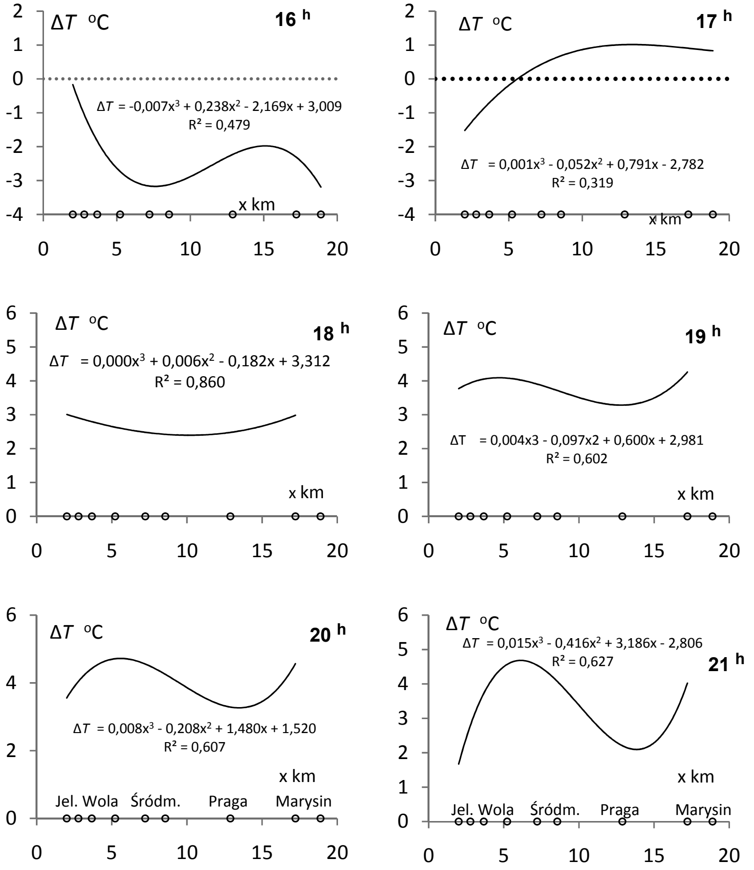

Fig. 5. Latitudinal profiles W-E (Jelonki, Wola, City Centre, Praga, Marysin) changes of air temperature differences between the city and its vicinity in Warsaw

the districts (Jelonki, Wola, City Centre, Praga, Marysin) and surroundings depending on the relative distance x (km)in the W-E direction. They were determined, assuming the coordinate axis of measuring points, and are listed in table 5.

Table 5. The relative distances of meridians x (km) from measuring points in Warsaw on the latitudinal profile

Profile (W-E)	Jelonki		Wola		City Centre		Praga	Marysin	
Nr	1	2	4	3	5	6	7	8	9
X km	2.00	2.78	3.67	5.22	7.22	8.56	12.89	17.22	18.89

The urban heat island ($\Delta T \geq 0$) appears not earlier than at 17:00 – at first in the City Centre. During the 18-21, it already emerges on the entire W-E profile, beginning in Jelonki.

The most interesting fragment of R. Romańska's study is the definition of the impact of wind direction on the heat island (Table 6). Movement of the heat island, depending on the direction of air influx, was shown. The greatest temperature differences (ΔT) occurred in the area of the northern and north western air influx. In the central areas of Warsaw, an increase of air temperature was very visibly marked. With SW wind, throughout the entire research area, a decrease of air temperature was marked in relation to the Warszawa-Okęcie peripheral station.

Table 6. Dependence of air temperature differences (ΔT ^{o}C) between the city and outskirts (Okęcie) on the wind direction

	Measuring points	C	N	NE	E	SE	S	SW	W	NW
1	Chomiczówka	10.4	0.3	0.5	5.8	1	.	-1.6	1.9	2.6
2	Chomiczówka	11.6	3.6	-3.4	3.7	1.6	.	-4	4.1	2.7
3	Chomiczówka	.	1	2.8	7.8	0.7	.	-5.5	-2.4	2.1
4	Pl. Piłsudskiego	.	2	2.7	8.3	2.7	.	-2.6	0.3	1.2
5	Pl. Piłsudskiego	14.8	2.8	2.3	6.6	0.2	.	-3.9	-0.2	1.8
6	ul. Świętokrzyska	.	6.1	0.3	6.1	0.7	.	-5	2.9	4.9
7	Służew nad Dolinką	9	-0.5	2.1	2.4	2	.	-6.1	2.9	2.2
8	Służew nad Dolinką	12.3	0	-1	4.8	0	.	-3.2	1.7	-0.2
9	Służew nad Dolinką	10.4	-2.1	1	5	1.8	.	-3.9	-0.9	2.9

During air movement from SE, the „area" with increased temperature throughout the city included the City Centre and area of NW Warsaw, a windy area. With a north-western wind, the heat island was moved in the south-eastern direction of Warsaw, where was the greatest intensity and pace of change.

About disappearance of the urban heat island (ΔT) with an increase: air temperature of the surroundings (T), cloudiness (N) and the speed of wind (v) inform negative coefficients of the multiple regression in hyperplane regression equations (Table 7).

Table 7. Hyperplane regression equation of air temperature differences (ΔT) between the city and its outskirts in relation to the temperature of surroundings T, cloudiness N and wind speed v

X-III	$\Delta T = -0.0186\ T - 0.0687\ N - 0.1479\ v + 1.448$	R =0.58
IV-IX	$\Delta T = -0.0105\ T - 0.0105\ N - 0.1082\ v + 1.329$	R = 0.58
I-XII	$\Delta T = -0.0105\ T - 0.0105\ N - 0.1082\ \mathrm{v} + 1.329$	R = 0.56

The air temperature differences between the city and his surroundings disappear with strong winds and increase with small velocity. An increase of wind velocity by 1 m/s causes a decrease of temperature T differences by 0,11-0,15^{o}C. The growth of cloudiness also reduces the intensity of the heat island.

THE IMPACT OF LIGHTING (INSOLATION EXPOSURE AND SHADOW) ON THE DIVERSITY OF THERMAL CONDITIONS IN HOUSING ESTATES

This issue was best presented in the master's thesis written by W. Leoniuk (1986), A. Andrzejewska-Mamczarek (1988) and G. Dudzicka (1991). Their objective was to determine the deformation of areas of meteorological variables by the impact of built-up areas (high, well spaced, flat buildings) in the „Stawki" housing estate in Warsaw.

Temperature differences, air moisture, wind velocity, equivalent and effective temperature and catathermometric cooling between the housing estate and the surroundings were determined.

The observational network comprised 17 points on the housing estate and 1 outside it, in the time: 7–11, 12–16, 17–21 (every half-hour) July 1982. The points were located on the grass, at different distance from buildings with different exposure and one on a playground located on a sand substratum.

The average air temperature in July was the highest in the afternoon (24,7°C at 15.30) and the lowest in the morning (16,8°C at 7.00). The maximum water vapour pressure (15,6 hPa) occurred in the morning hours (7.30–10.00) and the minimum (14,6 hPa) in the afternoon (16.00). The extreme values of relative air moisture were observed at 7.00 (80%) and 16.00 (48%). During this month, the wind velocity was the smallest (0,9 m/s) in the evening (20.30), and the greatest (2,1 m/s) in the afternoon hours (14.30).

The daily changes of equivalent and effective temperatures and catathermometric cooling were also similar. Both the equivalent temperature (T_e) and the effective temperature (T_E) were the lowest in the morning ($T_{e\,=}$ 39,9°C, T_E =12,3 – at 7.00) and the highest in the afternoon (T_e = 41,3°C at 14.00 and T_E =19,2 – at 15.30). Catathermometric cooling decreased from 11,6 mcal/cm^2·s at 7.00 to 7,3 mcal/cm^2·s – at 20.30.

During the day, the average air temperature in the housing estate was lower (even by 1,1 °C at 13.30) and in the evening and early morning hours, it was higher than in the surroundings. This was the result of the slower pace of heating up and cooling down of built-up areas. However, during the day, relative air humidity was much greater in the housing estate than in its surroundings, especially in the evening (7% at 17.00). At that time, the differences of water vapour pressure between the housing estate and the surroundings came to 1,5 hPa (at 18.30) which could be the result of greater wind velocity and lawn watering. The wind velocity inside the housing estates was also higher than in its surroundings (maximally by 0,6 m/s – at 10.30, 14.30, 17.30). The direction of wind was considerably distorted in relation to the dominant (Fig. 6).

During most of the day, the equivalent temperature (T_e) in the housing estate was higher than outside the housing estate. The greatest differences (ΔT_e = 2,4 °C) was observed in the evening hours (21.00). For most of the day, the effective temperature, was higher outside the housing estate

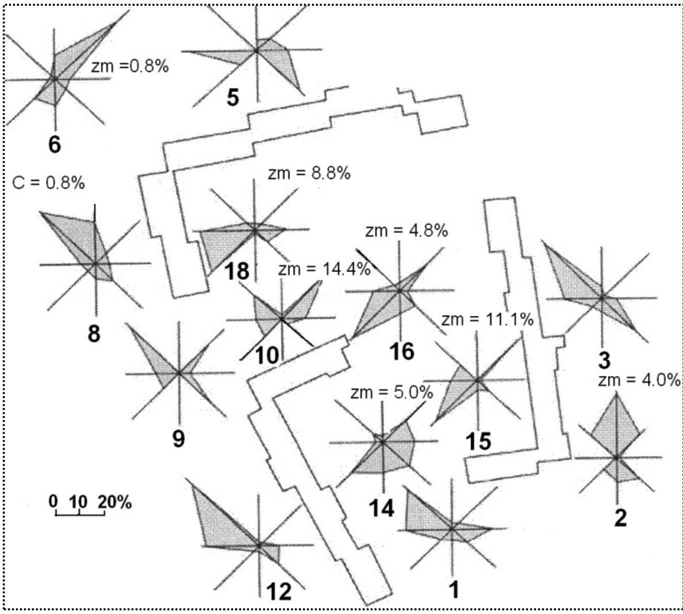

Fig. 6. Frequency of occurrence of various wind directions in the „Stawki" housing estate (July 1982)

(maximally about $\Delta T_E = 1{,}4$). The greater wind velocity in the housing estate contributed to better conditions of thermal perception than in the surroundings. Catathermometric cooling also indicates the occurrence of better *biometeorological conditions* in the housing estate. The values of this factor were greater the built-up area (maximally about 2,1 mcal/cm$^2 \cdot$s at 10.30). It should, however, be pointed out that in the „Stawki" housing estate and its surroundings there were, first of all, conditions of overheating (*warmt*h and *heat*), and *comfort* was experienced only in early morning and late evening hours.

It may be concluded from measurements in individual points that the fields of meteorological variables in a housing estate are deformed by the influence of solar and wind exposure as well as they depend on the distance between buildings. The morning period, when the solar exposure plays a dominating role, distinguished itself by the greatest thermal diversity. The smaller temperature differences occur at noon due to the intensive convection from the southern side of the buildings (Table 8).

Spatial diversity of effective temperature allowed to mark off places in housing estates with more or less favourable perception conditions. In the „Stawki" housing estate, the best perception conditions during mid summer occurred throughout the day on the external side of buildings with northern exposure and between the buildings. The areas most unfavourable to human organism were mainly located in the south-eastern part of the housing estate.

During the day, they changed from eastern exposure (in the morning), southern (during solar transit) and western (in the evening). To compare, the perception conditions of warmth in other housing estates („Służew nad Dolinką" and „Sady Żoliborskie" were presented (Table 9 and 10).

Table 8. Extreme meteorological variable differences in the „Stawki" housing estate – July 1982

Meteorological element	In the Morning		In the afternoon		In the evening	
	Difference in housing estate	Hour	Difference in housing estate	Hour	Difference in housing estate	Hour
Air temperature (°C)	min 0,9 max 2,6	7.00 10.30	1,2 2,1	12.00 13.30	0,9 1,7	19.30 17.00
Water vapour pressure j (hPa)	min 0,7 max 1,8	7.00 10.30	0,9 1,9	14.00 15.00	0,8 2,2	19.30 21.00
Relative humidity (%)	min 5 max 10	7.00 9, 10.30	4 10	14.30 12.30	2 10	19.30 21.30
Wind velocity (m/s)	min 0,8 max 1,3	10.00 8.30	0,7 1,6	16.00 13.00	0,7 2,6	19.30 19.00

Table 9. Frequency of conditions for feeling warmth in the housing estates: Stawki (July 1982), Służew nad Dolinką (June-July 1983), Sady Żoliborskie (July 1986)

State of feeling	Stawki			Służew nad Dolinką		Sady Żoliborskie			
	Inside	Outside	Outskirts	Inside	Outside	Outskirts	I	II	IV
Heat	17	9	10	3	6	27	41	26	43
Warmth	59	58	60	61	58	47	48	53	43
Comfort	22	17	22	14	21	24	10	18	12
Pleasant cool	2	12	7	20	12	2	1	2	2
Coolness	–	4	1	2	3	–	–	0.2	–
Cold	–	–	–	–	0.1	–	–	–	–

The results of research on Warsaw's climate show how the city deforms the limits of meteorological variables. Air temperature differences between the city and the surroundings (the so-called urban heat island) and the temperature differences inside the city are the measures of impact of artificial surfaces (with a small albedo) and buildings on temperature limits. Of significant cognitive meaning is determining the pace of warming up (during the day) and cooling off (during the night) of built-up areas and dates for appearance and disappearance of the urban heat island depending on the conditions of the atmosphere. Also important are threshold values of air temperature, cloudiness and wind velocity in which deformation of air temperature limits by the city is the greatest.

Table 10. Air temperature (*T*, °C), wind velocity (*v*, m/s) and catathermometric cooling (*H*, mcal/cm²·s) in the housing estates: Stawki, Służew nad Dolinką and Sady Żoliborskie (buildings: quarters (I), high (II), street (IV) on bright and cloudy days

	Variables	Bright day			Cloudy Day		
		Stawki	Służew nad Dolinką	Sady Żoliborskie	Służew nad Dolinką	Stawki	Sady Żoliborskie
Morning	T	22-29 7.0	19-26 7.0	21-28 7.0	12-16 4.0	11-16 5.0	12-18 6.0
	v	1-2	0.5-1.5	~1.0	2.0-3.5	2.0-3.5	1.0-2.0
	H	8-5 3.0	6-7.5 1.5	7-4 3.0	18.5-15 3.4	22.4-15.7 6.7	9-12 3.0
Afternoon	T	28-29 1.0	25-27 2.0	26-28 2.0	18-21 3.0	21-18 3.0	18-20 2.0
	v	1.0-1.5	1.0-2.0	0.5-1.5	2.0-4.0	3.0-5.0	1.5-2.0
	H	3-5 1.5	5-7.8 3.0	3-5 2.0	11-16.5 5.3	14-19 5.0	10-13 3.0
Evening	T	27-23 3.5	25-22 3.4	26-22.5 3.5	17-15 2.0	17-16 1.0	19-17 2.0
	v	1.5-2.0	0.7-1.5	1.0-2.0	0.5-2.5	2.0-3.0	1.0-2.0
	H.	7-9 2.0	7-5.5 1.5	6-9 3.0	7-14 7.0	13.17 3.6	9-13 4.0

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