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Original Research

Intensity of Urban Heat Island and Air Quality in Gdańsk during 2010 Heat Wave

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Abstract

During summer unfavorable bioclimatic conditions in cities are primarily related to thermal discomfort caused by the urban heat island, which often is additionally intensified by an increased concentration of air pollution. Temporary deterioration of aero sanitary conditions occurs during summer heat waves and is accompanied by an increased tourist flow toward regions particularly attractive in that time of year, consequently increasing traffic pollution. The objective of the present work is to statistically assess the influence of the intensity of the urban heat island on aero sanitary conditions in the central part of Gdańsk in excessively hot conditions during July 2010. The study is based on hourly air temperature and pollution concentration values included in the Common Air Quality Index: nitrogen dioxide (NO_2), tropospheric ozone (O_3), carbon monoxide (CO), particulate matter PM_{10} and $PM_{2.5}$, and sulphur dioxide (SO_2). The results of automatic measurements were obtained from four stations operating within the network of the Agency of Regional Air Quality Monitoring in the Gdańsk metropolitan area (ARMAAG). The intensity of the urban heat island was determined by means of differences of the hourly values of air temperature between stations situated in central and peripheral parts of Gdańsk, including the station in the direct vicinity of Gdańsk Bay. It was found that the urban heat island had a statistically significant influence on thermal sensitivity measured with the use of effective temperature ET. The highest intensity of UHI occurred between the central district (Gdańsk Wrzeszcz) and a typical seaside district (Gdańsk Nowy Port). In approximately 70% of cases, the intensity was in the range 1-3ºC, and its maximum values, over 4ºC, occurred in the morning (7-9 a.m.) and evening (5-8 p.m.). Urban heat island intensity in July 2010 had a statistically significant impact on concentrations of all analyzed pollutants and contributed to the decreased air quality in the centre of Gdańsk. In general, the strongest influence of the urban heat island intensity was manifested with a 1-5 hour delay, depending on the time of day and type of pollution.

Keywords: UHI, air pollution, correlation, thermal sensitivity, July

Introduction

Urban heat island (UHI), defined as a temperature increase in cities as compared with their surrounding areas, is one of the most spectacular features of any urban area. UHI is a common phenomenon in metropolitan areas found in various latitudes [1-6], and its intensity is directly connected with the size and urban structure of a city – derivatives of population. The most commonly used measure of the UHI assessment is its intensity, which is most pronounced in cloudless and windless weather conditions [7-9]. The temperature field in a city also can be strongly mod-

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ified by local circulation shaped not only by the city itself, but also by other topographic characteristics, such as substratum type [10-12].

UHI as a peculiarity with a broad spectrum of influence is a subject of interest to scientists. However, another urban characteristic that significantly modifies the topoclimate of a city and at the same time decreases the quality of life is a high concentration of air pollution [13-16]. Therefore, there are numerous attempts to assess and estimate the concentrations, especially in industrial areas [17-20].

Studies investigating the direct relationship between UHI intensity and air pollution are relatively rare. A significant influence of UHI on the level of pollutant immission was shown by Sarrat et al. [21] using the modeling method in Paris. A study conducted by Poupkou et al. [22] in summer in Thessaloniki proves that low air quality is directly connected with more frequent occurrences of greater UHI intensity. Moreover, the same study substantiates a strong synergy between sensibility and poor air quality. A similar relationship occurring in Athens is presented by Theoharatos et al. [23] and Papanastasiou et al. [12]. Many Europeans have felt the negative effects of the synergic influence of high temperature and excessive concentration of pollution in September 2003 [24, 25]. The climate change scenarios indicate that in the near future the heat waves will become more intense, more frequent, and long-lasting [26]. Combined with the forecasted increase of pollutant immission levels (ozone in particular [27]), it will account for a significant decrease of the quality of life and health of urban populations, especially in large metropolitan areas [28]. Therefore, there is a need for practical applications of current knowledge of intensity, frequency, and spatial variability of thermal and aero sanitary conditions of air in metropolitan areas and its interactions, for example in drawing up plans for anthropo-climatic land amelioration [29].

The aim of this study was to assess the impact of urban heat island on air quality in the central part of Gdańsk during a hot July 2010.

Materials

Study Area

Gdańsk is a Baltic seaport on Gdańsk Bay, the capital of Pomeranian Voivodeship, and the centre of a tri-city metropolitan area. The Tri-City agglomeration consists of three connected cities: Gdańsk, Gdynia, and Sopot. Gdańsk is the country's sixth largest city in terms of area (almost 262 km^2) and population (around 457,000). It is the biggest seaport in Poland, with the Gdańsk Industrial Region a principal shipbuilding centre. The industrial sections of Gdańsk include electromechanical, electronics, woodworking, furniture and food industry (mainly fish processing). Gdańsk metropolitan area is a transport node of northern Poland.

Meteorological Station Network and Data

The essential materials were based on the hourly values of air temperature, relative humidity, and wind speed automatically registered in July 2010 at stations belonging to the Agency of Regional Air Quality Monitoring in the Gdańsk metropolitan area (ARMAAG), and pollution concentration: nitrogen dioxide (NO_2), tropospheric ozone (O_3), carbon monoxide (CO), particulate matter (PM_{10}, $PM_{2.5}$), and sulphur dioxide (SO_2). The monitoring network of ARMAAG was designed on the basis of the multiyear data on meteorological conditions, population density and database on immission from point and surface pollution sources with the use of Monet software, which was lent from the Politecnico di Milano and positively assessed by

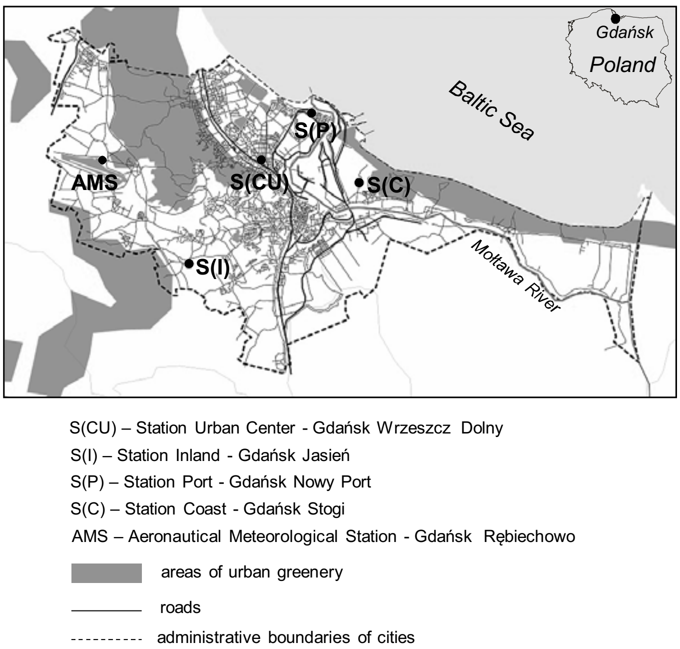

Fig. 1. Location of meteorological stations considered in the study.

the Institute of Environmental Protection [30]. The locations of measurement stations, the results from which are used in our paper, are shown in Fig. 1. Although all stations are classified as urban background stations, Gdańsk Wrzeszcz station is located in the central part of the metropolitan area, within the limits of intense urban sprawl, trading, and service companies, and traffic routes that spread through the Tri-City area, marked on the work as S(CU). The system of communication includes not only a dense network of bus and tram routes, but also a railway station which is a stop for almost every long-distance train and Fast City Rail. The station located the farthest from the city centre, around 6 km to the southwest, is Gdańsk Jasień – S(I). The open area is the station's closest vicinity, to the west of the station there is a housing development with multi-family and detached houses. Two stations (Gdańsk Nowy Port and Gdańsk Stogi) are situated on the northern and eastern outskirts of the urban agglomeration at Gdańsk Bay. The first of the stations, Gdańsk Nowy Port, S(P), is situated in a district of typically small town characteristics. It is separated from the rest of the area by the wide fairway of the Martwa Wisła river and a port channel from the north and east. From its south side it is separated from the metropolitan area by vast areas of allotments and the remains of Zaspa lake; the western border of the district is marked by a train overpass and railway tracks. The station Gdańsk Stogi, S(C), is situated in a district called Stogi on the Port Island (approximately 26 km²), surrounded by the Baltic Sea and two river branches of the Vistula River (Wisła Śmiała, Wisła Martwa). Its northern part is the Westerplatte peninsula. Coastal meadows (NW) and a wide sandy beach with sand dunes (N) make up the station's direct surroundings.

Methods

The most reliable index of UHI intensity is the difference in temperatures between the city and the rural. In the present paper the intensity of the UHI was determined by means of differences of hourly values of air temperature between T city and T suburbs, therefore: S(CU)-S(I), S(CU)-S(P), and S(CU)-S(C).

The effect of UHI intensity on the quantity and the variability and of immission of nitrogen dioxide, ozone, carbon monoxide, sulphur dioxide and particulate matter PM_{10} and $PM_{2.5}$ in the city centre S(CU) was determined using the correlation analysis and linear regression analy-

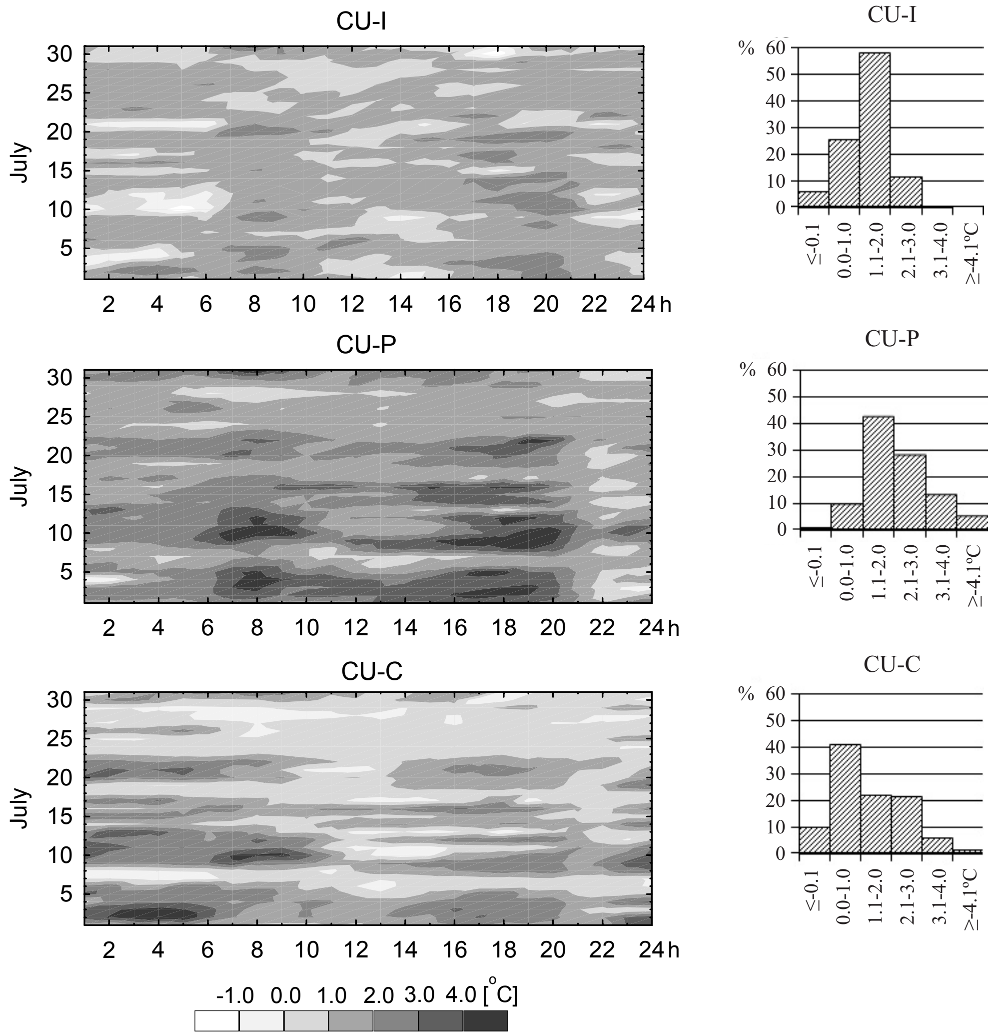

Fig. 2. Daily course of UHI and frequency of occurrence of UHI intensity in the agglomeration of Gdańsk in July 2010.

sis with statistical significance α = 0.05 and α = 0.01. Four periods were determined from a 24-hour day, each period lasting six hours: 1-6 am, 7-12 am, 1-6 pm, and 7 pm till midnight.

The bioclimatic conditions were characterized by means of effective temperature (*ET*) reflecting the complex influence of air temperature, relative air humidity and wind speed on sensitivity during air bath in shadows. Effective temperature (*ET*) was calculated using A. Missenard's equation [31]:

$$ET = 37 - \frac{37 - T}{0.68 - 0.0014 \cdot f + \frac{1}{1.76 + 1.4 \cdot v^{0.75}}} - 0.29 \cdot T \cdot (1 - 0.01 \cdot f)$$

...where: *t* is air temperature (ºC); *f* is relative air humidity (%); and *v* is wind speed exceeding 0.2 $m \cdot s^{-1}$ at 2 m above ground level.

The results of *ET* calculation were grouped according to the seven-step "sinusoidal" scale developed by Baranowska et al. [32, 33]. The individual classes of sensibility in July correspond to the following *ET* values: very cold (below 3.1ºC), cold (3.2-7.1ºC), cool (7.2-11.2ºC), comfortable (11.3-14.9ºC), warm (15.0-18.9ºC), hot (19.0-21.8ºC), and very hot (above 21.8ºC). This classification was developed on the basis of effective temperature and takes into consideration the seasonal and regional variabilities in thermal sensibility during the whole year in the climatic conditions of Poland, and is used as a reference method by the Institute of Meteorology and Water Management (IMGW) in biometeorological forecasts.

The assessment of air quality was made using Common Air Quality Index (CAQI). The formula of this index was developed as part of the CITEAIR project, congruent with the current standards of the European Union on air quality. Observed values of the CAQI across cities are updated every day on an interactive web service [34]. In the present paper air quality was assessed hourly and on an hourly basis and with the use of urban background index values. The urban background index takes into account three main pollutants (NO_2, PM_{10}, and O_3) and three auxiliary pollutants ($PM_{2.5}$, SO_2, and CO).

Results

The heat wave in July 2010 that initially hit Germany moving to the eastern regions of Europe greatly increased mean monthly temperature in Poland. According to the measurements taken at Aeronautical Meteorological Station Gdańsk-Rębiechowo (AMS), belonging to measurement network of Institute of Meteorology and Water Management and situated in the westernmost part of the metropolitan area, the temperature in July 2010 was 20.2ºC, or 2.9ºC higher than the mean multiannual in the period 1986-2010. In the metropolitan area, Gdańsk Wrzeszcz district S(CU) was by far the warmest (21.8ºC), whereas Gdańsk Nowy Port district S(P) was the coldest area (19.7ºC). The temperature in July in districts Jasień S(I) and Stogi S(C) was 20.4°C.

As is shown in Fig. 2, the greatest and almost completely positive differences of hourly temperature values were recorded between stations CU and P. In approximately 70% of cases, temperature differences ranged from 1 to 3ºC, predominantly 1-2ºC and were pronounced during a natural day. However, as opposed to the results given in studies, the highest intensity of the UHI, over 4ºC, occurred in daytime, particularly in the morning (7-9 a.m.) and in the evening (5-8 p.m.). Equally high maximum differences of temperature also occurred between S(CU) and S(C), but with lesser intensity and predominantly in night-time. Most often that is approximately 40% of cases, the differences of mean hourly temperature values did not exceed 1ºC. Such intensity range and the type of temporal structure of UHI, characteristic for cities with populations of several-thousand, are widely recognized in other studies. Likewise, mean annual intensity of the UHI in Polish cities does not exceed 1ºC [6, 8, 35]. However, the mean maximum UHI intensity identified by Szymanowski [8] in Wrocław during the summer season in conditions of anticyclonic weather, reached as much as 4.1ºC. During the heat wave in 2006 in Szczecin, the maximum hourly difference in temperature between the centre of the city and its outskirts reached 6ºC [6].

The intensity of UHI determined in relation to the furthest district of Gdańsk, on the southwest border of the urban complex S(I), was the lowest, since in 80% of cases it did not exceed 2ºC (with the dominance of the range of 1-2ºC), and its daily structure was similar to that recorded in G1-G4.

The intensity and daily structure of the UHI in Gdańsk metropolitan area were arguably shaped by local circulation, which is connected with the city's location near Gdańsk Bay. The influence of sea breeze and modification of thermal conditions in large urban complexes such as Athens or New York were demonstrated by Gedzelman et al. [7] and Kassomenos, Katsoulis [11]. Greater differences of temperatures during the daytime between Gdańsk Wrzeszcz and Nowy Port can be associated with the stronger cooling effect of this region by an intensive sea breeze. It can be assumed that the smaller influence of day breeze in Gdańsk Stogi is a consequence of the district's location – further from Gdańsk Bay, and the presence of the natural protective barrier of the city forests and sand dunes, which causes the greatest differences of temperature to be most pronounced during the night.

The pronounced thermal advantage of the central part of the city in July 2010 in comparison with the districts on the outskirts of the city, S(I) and S(C), is made evident by greater frequency of thermal sensations very hot and slight of cold (Fig. 3). In S(CU) district the most onerous bioclimatic conditions shaped by sensations very hot and hot occurred in July mainly during the periods from 8 a.m. to midnight with over 30% frequency in the period from 11 a.m. to 6 p.m. In S(I) district the frequency of occurrence of both categories of thermal sensibility together usually did not exceed 20%, including a very hot class of 7%. In the seaside district of S(C) the period of thermal discomfort occurred in the similar time period as in S(I) district, yet it was markedly more often connected with a very hot thermal sensation. Moreover, this district was characterized by a high percentage share of comfort conditions, occurring with comparable frequency during the natural day, whereas in S(I) district thermal comfort sensations occurred mainly in the afternoon and evening hours. The frequency of periods of extreme categories of thermal sensibility cold in the districts of S(I) and S(C) were very similar despite different distances of the districts to Gdańsk Bay. The fact that S(C) is located in the near vicinity of the sea area is pronounced by higher frequency of cool category during the day and smaller at night. The lack of measurements of relative humidity and wind speed in S(P) district prevented the assessment of thermal sensibility in the part of the city that was coolest in July 2010.

The comparison of data in Figs. 2 and 3 shows that the time of occurrence of the greatest thermal discomfort, connected with sensations of hot and very hot, in the central part of the city did not correspond to the time of occurrence of the greatest differences in temperature in relation to the peripheral stations. The correlation analysis indicates that

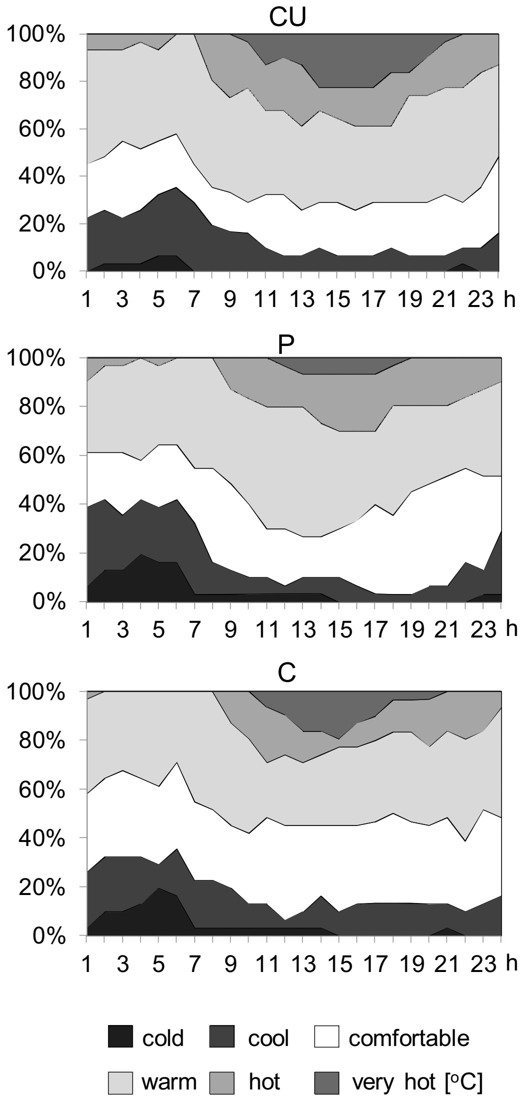

Fig. 3. The frequency of occurrence of ET index during 24h in the agglomeration of Gdańsk in July 2010.

there were statistically significant correlation relationships between ET values in Gdańsk Wrzeszcz S(CU) and UHI intensity in all three versions (CU-I, CU-P, and CU-C). As observed by means of visual analysis, the value of effective temperature in the central part of the city was most closely connected with the greatest differences in temperature that is determined for S(P) district – this was substantiated by the greatest coefficient of determination, which amounted to approximately 17%. The relationship of ET with differences in temperature in respect to S(I) and S(C) were approximately two times weaker.

In the conditions of air temperature markedly higher than standard temperature, pollution concentrations in July 2010 did not diverge from concentrations registered in 2005-09. Furthermore, the concentrations were even smaller than in July 2006 or 2008 (NO_2), which could be the effect of the size of emission as well as many other factors and meteorological elements [30].

A standard structure of daily variability of the analyzed pollutants is a result of increased traffic intensity and meteorological conditions intensifying photochemical reactions and influencing dispersion conditions in the atmosphere [13, 14, 36-39]. In July 2010 diurnal variability of immissions of the analyzed pollutants did not vary from the average [40, 41]. Despite the holiday season in its full swing, two periods of increased traffic intensity – in the morning and late evening – can be distinguished in the layout of the hourly concentrations of most of the pollutants (Fig. 4). Increased tourist flow possibly counterbalanced the decreased intensity of communication, resulting from summer holidays in schools and universities. The number of students in Tri-City was approximately 90,000 in 2008-10. Gdańsk is a city of explicitly seasonal character of tourist flow, out of which approximately 39% falls during two summer months: July and August [42]. In 2010 most tourists came to Pomorskie Voivodeship in July and the greatest number of people staying overnight was reported in Gdańsk [43].

Morning rush hours contributed to sudden increases in concentrations of carbon dioxide with maximum at 7 a.m., and nitrogen dioxide concentrations that were high from 6 to 7 a.m. The second, late evening period of a gradual increase in immission of both of the pollutants was markedly longer, and night maximum at midnight was higher than that in the morning hours, which unmistakeably was connected with the summer season and greater activity of residents and tourists. The characteristic distribution of ozone concentration increased to approximately 80 $\mu g \cdot m^{-3}$ between 1-6 p.m., which predominantly reflects the processes behind its origin under the influence of solar radiation. The course of the diurnal variability of concentrations of the remaining pollutants was not as clear. Insofar as there were periods of slight increase in the hours around afternoon and in the late evening in the concentrations of PM_{10} and sulphur dioxide in the diurnal course, the fluctuations of mean hourly concentration values of particulate matter $PM_{2.5}$ were minor during the predominant part of a natural day. The values of standard deviation indicate that the night time of a natural day was characterized by higher variability in hourly immission in July 2010, and the markedly higher variability between day and night was pronounced by immission of NO_2. The most contrastive concentrations of particulate matter of both fractions occurred that month at 2 a.m., yet variability of the hourly immission of $PM_{2.5}$ on particular days was higher and generally less varied on the hourly basis in comparison with immission of PM_{10}. Concentrations of SO_2 showed totally different layout of variability. Slight variability in concentrations during the month was registered in the hours 00-07 a.m., and very high in the hours around noon and in the late evening, particularly at 11 a.m. and at 9 p.m.

The assessment of aero sanitary conditions of air made on the basis of the CAQI index shows that air quality during an excessively hot July 2010 generally did not cause a health threat (Fig. 5). Out of the three classes of satisfactory air quality, the greatest share in the predominant part of a natural day was on the part of low class, whereas the conditions determined as medium occurred in 10% of the time, mainly from 8 a.m. to 10 p.m., that is, the time of day with high thermal contrasts in relation to the Nowy Port district (CU-P). The class 4, high, marking bad air quality that is of pollution level which poses a health threat to the sensitive group, occurred only incidentally at 1a.m. and was a result of an extremely high $PM_{2.5}$ concentration. According to the formula of CAQI index the assessment of the aero sanitary conditions of air took into consideration the levels of all the pollutants, yet the final classification of air quality in July 2010 to the weakest medium class (out of those occurring in that month) was based on concentrations of the three pollutants, mainly $PM_{2.5}$ (in 26 cases) and equally often – concentrations of ozone and PM_{10}, respectively 14 and 13 cases. The results given by Poupkou et al. [22] for Greece indicate that concentrations of PM_{10} and ozone are decisive factors during a year for the three classes of CAQI index: medium, high, and very high; however, in the summer both in daytime as well as during night the level of ozone immission is of main importance.

However, the comparison of data in Figs. 4 and 5 shows that daily structure of the three air quality classes was most of all determined by ozone concentrations. High

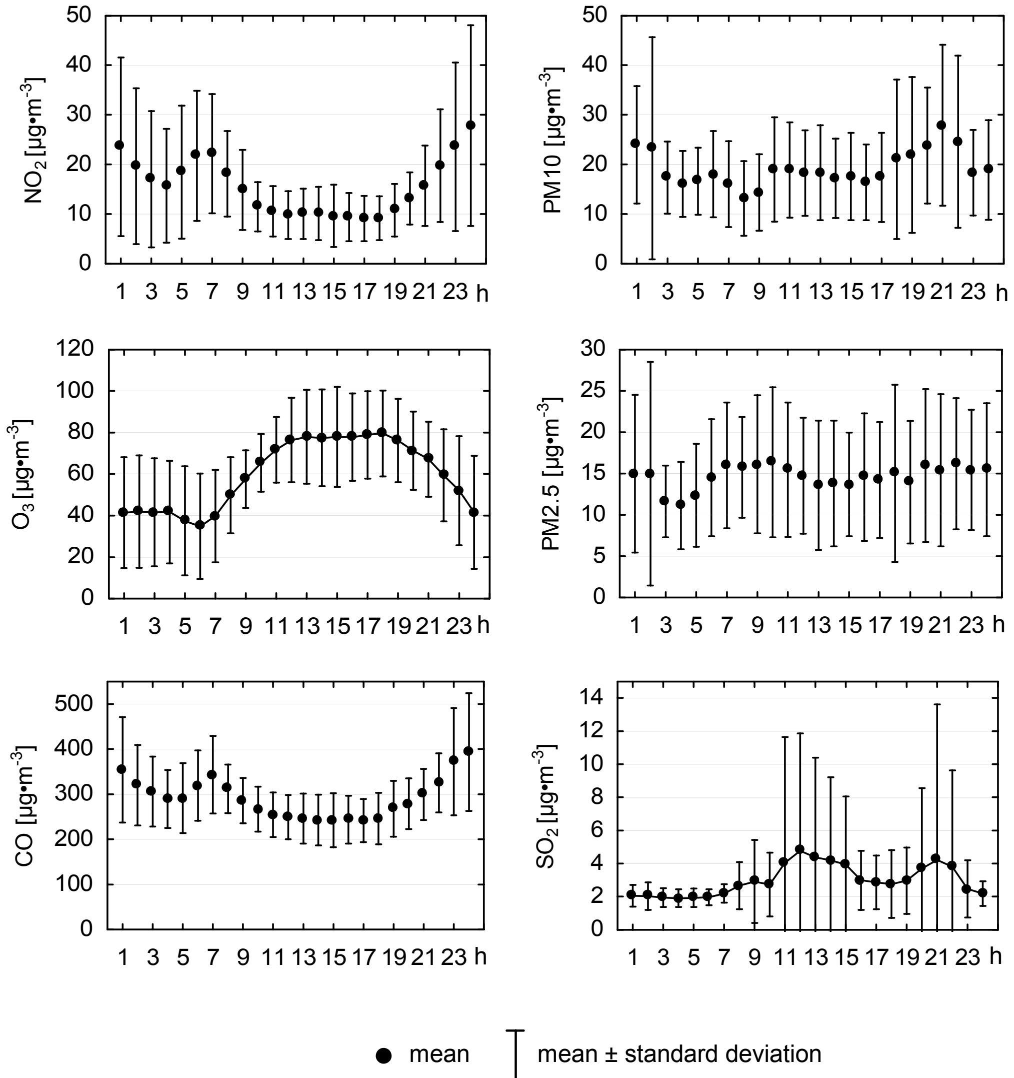

Fig. 4. Daily structure of concentrations of NO_2, PM_{10}, O_3, $PM_{2.5}$, CO, and SO_2 in Gdańsk Wrzeszcz (CU) in July 2010.

frequency of the best air quality during night time (from 04 a.m. even 60%) was a result of approximately two times lower immissions of O_3, and its increase in daytime resulted in the decrease of aero sanitary conditions of air, which reflects the predominant share of class 2 and appearance of class 3.

The distribution of the hourly concentrations of O_3, PM_{10}, and $PM_{2.5}$, affecting air quality in July 2010 in the central district of Gdańsk S(CU) shows some relationships of those with the analyzed characteristics of the thermal regime (Fig. 6). The relationship between immission and ET is more evident, which is obvious since as the complex indicator it includes an important, dynamic element of dispersion of pollutants that is wind speed. Less visible is the relationship between immission and differences in temperature between the city centre and Nowy Port district (CU-P).

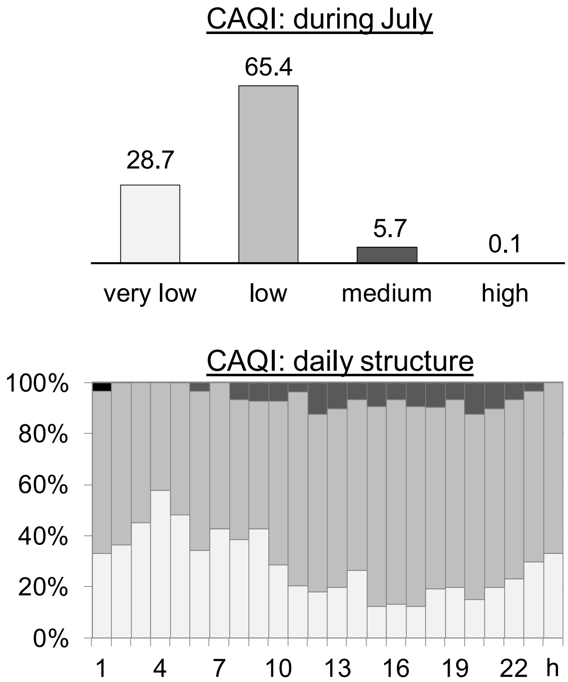

Fig. 5. The frequency of occurrence of CAQI index classes in Gdańsk Wrzeszcz (CU) in July 2010.

Table 1. The correlation matrix of concentrations of NO_2, O_3, CO, PM_{10}, $PM_{2.5}$, and SO_2 in Gdańsk Wrzeszcz and UHI intensity.

Type of pollution	UHI		
	CU-I	CU-P	CU-C
NO_2	-0.11**	0.08*	0.46**
O_3	0.16**	n.s.	-0.28**
CO	-0.13**	-0.09*	0.20**
PM_{10}	n.s.	0.10**	0.23**
$PM_{2.5}$	n.s.	0.29**	0.33**
SO_2	n.s.	0.18**	0.10*

* statistically significant at α = 0.05
** statistically significant at α = 0.01
n.s. – not statistically significant

The analysis of Fig. 2 shows that the temperatures in the central part of Gdańsk (CU) were not always higher than those registered on the outskirts. In approximately 10% of hours in July 2010, the recorded temperatures were higher for S(C). Jasień S(I) district enjoyed warmth twice less often than the S(CU) and S(P) districts only occasionally. Therefore, in further analysis only the cases of increased temperature in the central part of Gdańsk (CU) were taken into consideration.

The results of the correlation analysis of concentrations of nitrogen dioxide, tropospheric ozone, carbon monoxide, particulate matter PM_{10} and $PM_{2.5}$, and sulphur dioxide registered in the S(CU) and the differences of air temperature between the central and peripheral stations indicate a significant influence of UHI in July 2010 on the aero sanitary conditions of air. The correlation coefficients for the most part proved to be statistically significant, usually at α = 0.01 (Table 1). The significance of the relationship between air quality and UHI intensity has been stated in research by, among others, Agarwal and Tandom [44], Lai and Cheng [45], and Poupkou et al., [22].

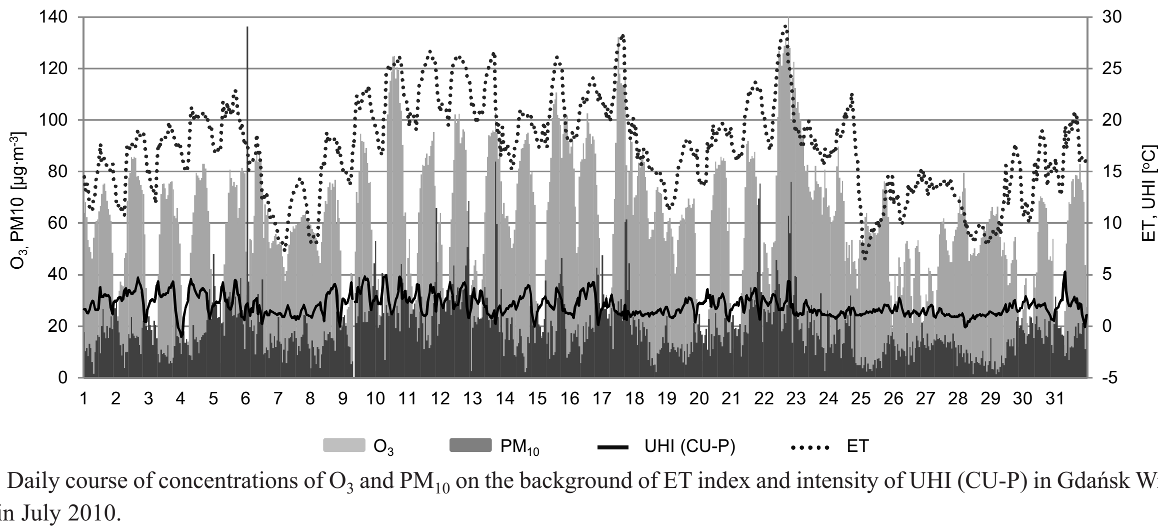

Fig. 6. Daily course of concentrations of O_3 and PM_{10} on the background of ET index and intensity of UHI (CU-P) in Gdańsk Wrzeszcz (CU) in July 2010.

Table 2. The coefficients of correlation of concentrations of NO_2, O_3, CO, PM_{10}, $PM_{2.5}$, and SO_2 in Gdańsk Wrzeszcz and UHI intensity determined between the city centre and the outskirts of Gdańsk.

Type of pollution	Period	Temperature differences AT		
		CU-I	CU-P	CU-C
NO_2	a	-0.302**	0.576**	0.649**
	b	0.416**	0.554**2	0.557**2
	c	-0.240**	-0.250**	-0.300**5(1)
	d	-0.365**	0.497**4	0.436**
O_3	a	0.395**	-0.604**	-0.604**
	b	-0.384**2	-0.517**2	-0.450**2
	c	0.282**	0.499**4	0.599**5
	d	0.297**	0.352**1	0.157*
CO	a	-0.372**	0.465**1	0.464**
	b	0.326**	0.467**2	0.445**2
	c	n.s.	-0.426**	-0.466**
	d	-0.464**	0.477**4	0.347**5
PM_{10}	a	n.s.	0.383**2	0.309**5
	b	0.224**3	0.458**3	0.457**3
	c	n.s.	0.230**2	0.302**
	d	-0.175*	0.449**1	0.375**1
$PM_{2.5}$	a	n.s	0.436**2	0.392**4
	b	0.252	0.488**2	0.561**5
	c	n.s	0.248**1	0.320**
	d	-0.240**	0.407**3	0.463**4
SO_2	a	0.221**	0.306**5	0.211**
	b	0.294**3	0.344**3	0.283**3
	c	-0.180*	0.297**4	0.269**
	d	n.s.	0.193*3	0.160*1

a) 1-6 am, b) 7-12 am, c) 1-6 pm, d) 7 pm till midnight,
* statistically significant at $\alpha = 0.05$
**statistically significant at $\alpha = 0.01$
n.s. – not statistically significant
1, 2, 3, 4, 5 (after stars) – the UHI intensity from one to five hours before

However, the data presented in Table 1 shows that the strongest relationships of immission were not related to the most intensive UHI (AT CU-P) – since the highest correlation coefficient was calculated for sulphur dioxide. The variability of concentrations of the remaining pollutants in the centre of Gdańsk explains the temperature differences with respect to S(C). Therefore, in further stage of the research, all three versions of UHI intensity were concurrently analyzed. Taking into consideration the variation of immission of the analyzed pollutants during the day, particularly ozone, nitrogen dioxide and carbon monoxide, in the next stage of the correlation analysis a natural day was divided into four six-hour periods. Due to the fact that the effects of UHI intensity are not immediate and can be pronounced with some delay (which can be seen at Fig. 6 with respect to $PM_{2.5}$) the concentrations of the analyzed pollutants were correlated not only with the UHI intensity occurring at the same hour, but also with the UHI intensity recorded 1, 2, 3, 4, and 5 hours before. For example, ozone concentration recorded at 4 p.m. was correlated with the UHI intensity recorded at the same hour as well as with the intensity recorded at 3 p.m., 2 p.m., 1 p.m, noon, and 11 a.m. The highest correlation coefficients are presented in Table 2. In almost all of the cases the coefficients proved to be statistically significant, yet there were some considerable fluctuations – from 0.157 to 0.649. The differences of temperatures between the central part of Gdańsk and its outermost district – Jasień (CU-I), had the least influence on variation of immission in the city centre. In contrast to the analysis conducted for a natural day (Table 1), generally the highest correlation coefficients were calculated for the UHI of the highest intensity that is CU-P. However, there were cases in which equal or even greater relationship was acknowledged for the differences of temperature determined with respect to S(C). A stronger correlation with CU-C in the predominant part of the day was

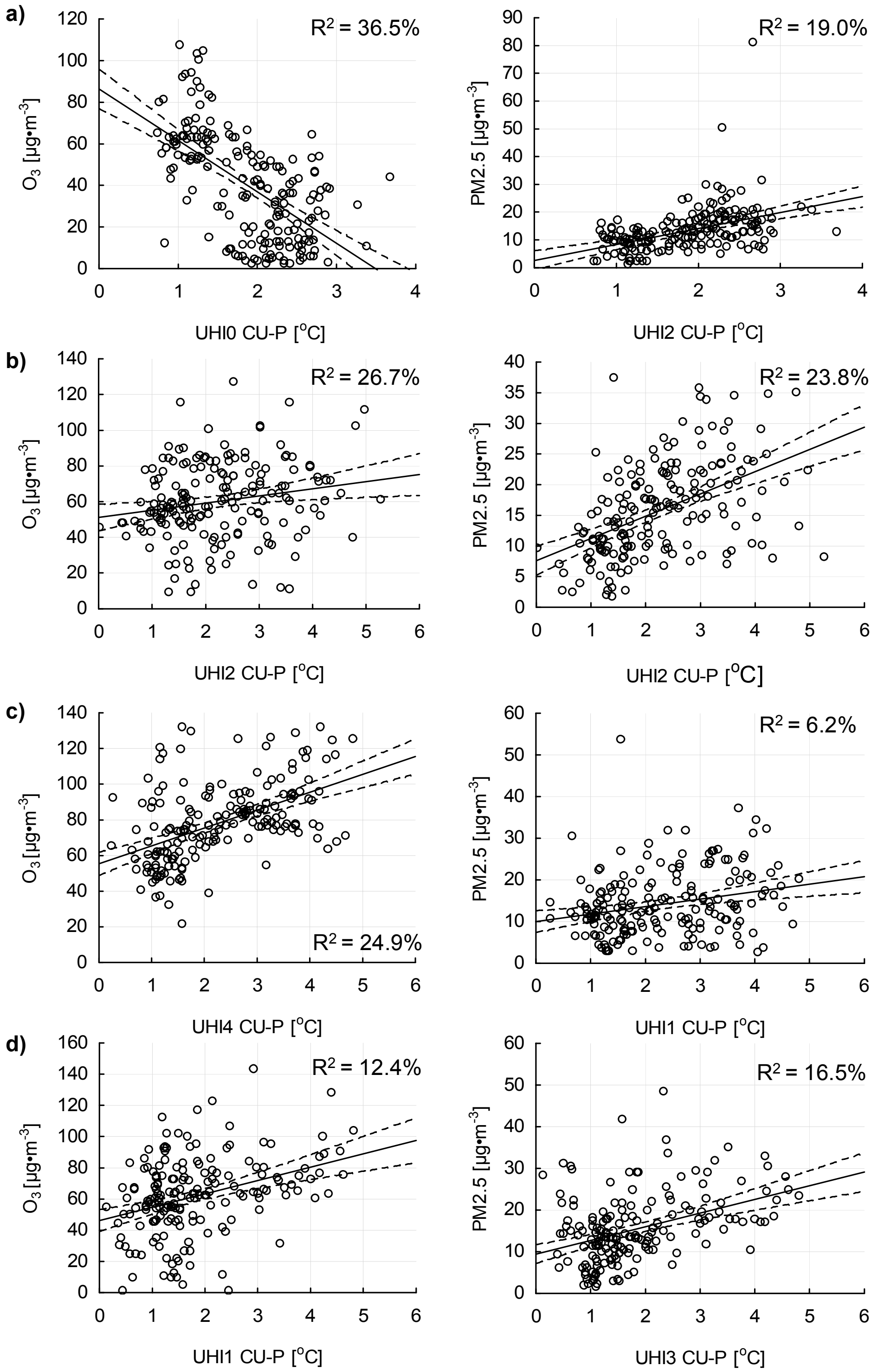

Fig. 7. The relationship between the hourly concentration of pollution (O_3 and $PM_{2.5}$) in Gdańsk Wrzeszcz and the intensity of UHI S(CU)-S(P) in July 2010.
a) 1-6 am, b) 7-12 am, c) 1-6 pm, d) 7 pm till midnight,
UHI1…4 CU-P – the UHI intensity from one to four hours before,
R^2 – coefficient of determination [%] statistically significant at α = 0.01.

observed in respect to NO_2 and $PM_{2.5}$ and during the night (1-6 p.m.) in respect to O_3, CO, and PM_{10}. The intensity of UHI as determined with respect to S(I) as a rule had the greatest influence on the concentration levels of the pollutants recorded at the same hours, with delay only in respect to O_3, PM_{10}, and SO_2 during 7-12 a.m. The role of UHI determined on the grounds of temperature differences with respect to both districts located at Gdańsk Bay (CU-P and CU-C) was most pronounced with time delay of 1 to 5 hours. Additionally, the slope coefficients show the differences in which the three analyzed versions of UHI affect air pollution in the central part of the city. Differences of temperature between S(CU)-S(I) – depending on the time of the natural day and the type of pollutants, contributed to an increase as much as to decrease of pollutant concentrations in the centre of the city. For most of the natural day, the increase of UHI intensity S(CU)-S(I) resulted in an increase of ozone concentrations and decrease of NO_2 concentrations. Only between 7-12 a.m. were the results different – NO_2 concentrations increased whereas ozone concentrations decreased. Coefficient of correlation of comparable value but of different directional coefficients was tested for the present version of UHI in respect to CO and $PM_{2.5}$. The effect of greater temperature differences between the centre of the city and districts located in direct vicinity of Gdańsk Bay, was an increase in immission. There was a clear increase of concentrations of sulphur dioxide and particulate matter PM_{10} and $PM_{2.5}$ during the natural day.

A stronger relationship of particulate matter was observed in the case of $PM_{2.5}$ fraction. Scatter diagrams for the relationship between $PM_{2.5}$ concentrations and differences in temperature as for G1-G3 for four times the natural day is shown in Fig. 7. The directions of changes of O_3 and NO_2 immission due to increased UHI intensity were not the same at different times of day. For most of the natural day (1-12 a.m. and 7 p.m. till midnight), the increase of UHI intensity determined in respect to both S(P) and S(C) resulted in an increased concentrations of main traffic pollutants NO_2 and CO, the concentrations decreased only during the period of less traffic flow, 1-6 p.m. An increase of thermal contrasts between the central part of Gdańsk and districts located at Gdańsk Bay during the hours from midnight to noon caused a decrease of ozone concentration, whereas in the period from noon to midnight ozone concentration increased – Fig. 7. The greatest correlation coefficients of immission and UHI intensity were evaluated for ozone and nitrogen dioxide in the period 1-6 a.m. – the correlated variables were taken at the same hours. However, only in the case of the UHI determined between the S(CU)-S(C) – the strongest relationship of concentrations of both of the pollutants was identified for the same part of the natural day when the intensity reached its highest values. Such a correspondence was not identified for AT CU-P version. Ozone concentration in the next part of the natural day (7 a.m. – 12) was best expounded by the UHI intensity of two hours before, that is 5-10 a.m., and in the afternoon (1-6 p.m.) even by intensity of 4-5 hours before. This was pronounced in both versions of UHI in relation to the districts at Gdańsk Bay. The coefficients of correlation describing the role of UHI intensity in variability of CO concentration in particular times of a natural day are characterized by relatively small differences.

Conclusions

The intensity and temporal structure of thermal variety in Gdańsk in July 2010 demonstrated quite explicit differences depending on the location of the station classified as suburban, and it was difficult to confront them with the results presented in the literature on the subject and referring to the classic UHI classification assessed on the basis of a typical rural station. Significant or greater thermal contrasts between the urban station in the centre of the city and the two not-so-remote stations at Gdańsk Bay arguably resulted from the influence of sea breeze. The ranges characteristic for the UHI intensity determined in relation to the two seaside districts were different by one degree but their daily structure was unlike. The higher UHI intensity determined in relation to Gdańsk Nowy Port S(P) district was recorded during the daytime, whereas in relation to Gdańsk Stogi S(C) district – at night.

The possibilities of interpreting the precise relationship between concentrations of the pollutants and the intensity of UHI as well as the directions of the analyzed relationships are quite limited due to the complexity of reasons behind and conditions affecting air quality. The size of emission greatly influences air quality; other processes include chemical reactions of ozone formation and decay with nitric oxide and organic peroxides, but also dynamic meteorological elements that affect dispersion of pollution. A complicated local circulation poses an additional problem in seaside agglomeration areas. The local circulation results from the effect of urban, sea and land breeze, all of which are characterized by pronounced daily variability. Additionally, in different times of a natural day the effects of breeze circulation can overlap or even cancel each other out. A significant interaction between sea breeze and heat circulation connected with UHI was observed by Freitas et al. [46] in São Paulo. The urban heat island forms a strong convergence zone in the centre of the city and accelerates the sea-breeze front toward the centre of the city. In the conditions of the greatest differences of temperature between Gdańsk Wrzeszcz (CU) and Gdańsk Nowy Port (P) district during daytime, the compatible directions of an urban and sea breeze most likely contributed to the inflow of polluted air from the outskirts of the city. However, at night when the directions of urban and land breeze were opposite, the dominance of either breeze but also other factors accelerating or limiting vertical and horizontal exchange of polluted air could influence an increase or decrease of immission. Papanastasiou and Melas [12] and Papanastasiou et al., [47] point to the significant increase of pollutant concentration as a result of sea breeze. The development of circulation connected with sea breeze both in cold as well as in warm seasons of the year resulted in a pronounced increase of particulate matter PM_{10} and ozone concentrations. According to the authors, the role of breeze circulation in the shaping of pollution levels in a medium-sized coastal city is more important than pollutant transport from the neighboring industrial areas. In peak of PM_{10} the increase of immission amounted to approximately 30%. During the summer heat wave in 2007 in Greece, high concentrations of particulate matter PM_{10} expressed with the use of CAQI index occurred most often in the days with intensive breeze circulation, whereas during the absence of sea breeze a high concentration of PM_{10} was twice less common. According to Lai and Cheng [15], there is a link between the decreased air quality in the city centre in the conditions of intensive circulation connected with urban breeze and the number of hospital admissions due to respiratory problems.

The intensity of urban heat island in July 2010 had a statistically significant impact on concentrations of all analyzed pollutants and contributed to the decreased air quality in the centre of Gdańsk. The few cases in which UHI had a positive effect on ozone immission occurred in the period 1 a.m.-12 and on CO and NO_2 immission in the period 1-6 p.m. Generally, the strongest influence of UHI intensity on air quality occurred with a 1-5 hour delay, depending on the time of a natural day and the type of pollutant. Direct and at the same time the strongest relationship between immission and UHI intensity was identified only for ozone and nitrogen dioxide during the period 1-6 a.m.

It must be kept in mind that the results presented in this study are merely an attempt to statistically evaluate the influence of the urban heat island on aero sanitary conditions in the most polluted part of the city that is the city centre, during an abnormally warm July in just one month of the summer season. The present study is to signal the problem as it occurs also in higher geographical latitude with on average less frequent, yet increasing, precipitation [48, 49]. It is necessary to conduct longer observations in order to verify the results and the influence of UHI intensity on aero sanitary conditions of air needs to be evaluated in light of various factors, including those shaping dispersion and concentration of pollutants.

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