VARIABILITY OF AIR QUALITY AND BIOCLIMATIC CONDITIONS IN AN URBAN AREA: A CASE STUDY OF LUBLIN, POLAND

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Abstract: The paper analyses biometeorological conditions in Lublin based on the Universal Thermal Climate Index (UTCI), and air quality based on the Common Air Quality Index (CAQI). The used data were obtained from the database of IMGW-PIB and RDEM, and cover the period 2015–2021. The most frequently occurring biometeorological conditions were classified as no thermal stress. They were observed with a frequency of 34.3%. Conditions unfavourable for the human organism accounted for 65.7% in total, including those belonging to thermal stress classes related to cold stress (52.3%), and heat stress (13.4%). In the analysed years, 75.5% of cases were with very low and low air pollution. High and very high air pollution usually occurred during biometeorological conditions related to cold stress (from slight cold stress to strong cold stress). During extreme thermal phenomena, such as a cold wave (January 2007) and hot wave (August 2015), unfavourable biometeorological conditions were accompanied by low aerosanitary conditions (low air quality). In the analysed period, and particularly in recent years, an improvement in air quality has been observed, potentially associated with limited mobility of people during the COVID-19 pandemic.

Key words: air pollution; Common Air Quality Index; Universal Thermal Climate Index; urban bioclimate

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Introduction

Atmosphere pollution is becoming an increasingly important issue in many regions around the globe, affecting a growing number of people. Increased concentrations of pollutants in the air are harmful for the human organism and the natural environment, and worsen the quality of life. Next to the progressing climate change (IPCC 2022), air pollution is one of the most important environmental factors contributing to the worsening of human health (Krzyżanowski et al. 2002). Air pollution is estimated to be the cause of premature death of approximately 417 thousand people annually in Europe alone (EEA 2020).

Next to air pollution, human health can be negatively affected by weather, which shapes human thermal impressions, physiological processes, and in certain situations also wellbeing and state of health. Components of the environment, such as solar radiation, temperature, air humidity, wind speed, air pressure, atmospheric precipitation, pollutants, atmosphere ionisation, and noise, reach the organism in the form of atmospheric stimuli (Kozłowska-Szczęsna et al. 1997). The intensity and duration of exposure

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to the stimuli determine various responses of the organism. A harmful effect is characteristic of strong stimuli that cause intense stress of the organism (Kozłowska-Szczęsna et al. 2004, Błażejczyk, Kunert 2011).

Specific biometeorological and bioclimatic conditions typical of urbanised areas result from among others strong human pressure and considerable transformation of the environment. In comparison to non-urbanised areas, a number of elements of the atmospheric environment are modified in cities, among others the radiation and humidity relations, wind field, noise, and air quality (among others Landsberg 1981, Błażejczyk 2002, Fortuniak 2003, Szymanowski 2004, Sikora 2008, Bokwa 2010).

The growing number of residents of cities exposed to modified biometeorological stimuli generates demand for information regarding the variability of thermal impressions and air quality in urbanised areas, and knowledge on the periods of occurrence, duration and number of cases of biometeorological situations strongly affecting the human organism.

The effect of air quality on the human organism, combined with strenuous meteorological conditions, has been the subject of many studies, and is well documented (Grass 2008, WHO 2013, Williams et al. 2014, Mannshardt, Naess 2018, EPA 2019). Other authors have primarily focussed on the issue of air quality during biometeorological conditions causing thermal stress (Lokys et al. 2018, Fahad et al. 2021). This type of research has not been conducted for this part of Poland to date. The present paper aims to fill this gap.

The objective of the paper is the analysis of the effect of the atmospheric environment in a city on the human organism with particular consideration of conditions unfavourable from the point of view of bioclimatology and conditions of low air quality. Special cases of accumulation of unfavourable atmospheric conditions include heat waves and cold waves, when air pollution accompanies situations negatively affecting the human organism. Therefore, this paper presents the analysis of a period when air pollution was recorded during the strongest heat wave in the study period, namely that from August 2015 (Krzyżewska, Dyer 2018), and during the strongest cold wave from January 2017 (Krzyżewska et al. 2019), as well as biometeorological conditions during days with high concentrations of air pollutants. Conducting detailed air quality monitoring, covering both the aerosanitary and biothermal conditions in the city, will permit better planning of activities of the authorities and planners in terms of warning residents against threats related to the atmospheric environment, and will allow residents to adjust their activity to the outdoor environment. It should be remembered that thermal comfort and good air quality are among the most important factors shaping the health and comfort characterising the lives of residents of cities.

Study area

The city of Lublin was selected as the study area. It is one of the largest cities in Poland, and the largest one in its eastern part (Fig. 1). It covers an area of 147.5 km^2. Lublin is the capital of the Lublin Voivodeship and an important academic centre. Its population is approximately 331,200 (USL 2023). From the environmental point of view, the city features diverse land relief, with numerous gullies and dry erosional-denudational valleys. This contributes to high topo- and bioclimatic variability. Due to this, Lublin is an interesting area for this type of research.

In the division of Poland into bioclimatic regions according to Kozłowska-Szczęsna et al. (1997) and Błażejczyk (2004), Lublin is located in region V – that is to say the south-eastern region. It is characterised by a high number of onerous days related to high air temperature (Kozłowska-Szczęsna et al. 1997). The analysis of the frequency of occurrence of types, subtypes and classes of weather in the region points to its most strenuous biothermal conditions at the scale of the country, with a high share of very hot weather, and a high number of days with strong sultriness (Błażejczyk, Kunert 2011). Such unfavourable biothermal conditions, combined with high air pollution, cause an even greater stress for the human organism.

Current state of research on the bioclimate of Lublin

The effect of weather conditions on residents of Lublin has been the subject of research already since the 1960s. The first studies of the type concerned the frequency of occurrence of sultry days

(Kruczko 1962) and preliminary characteristics of the climate and bioclimate in economic terms (Zinkiewicz 1969). The first used simple index reflecting the effect of the atmospheric environment on the human organism was the air-cooling value determined based on measurements by means of a Hill's katathermometer (Hill et al. (1922, 1992, Kaszewski et al. 2006). Thermal-humidity conditions in the period 1997–2006 were described based on the Humidex index (Dobek et al. 2008), and in more complex terms by means of the Standardised Temperature Index (STI), with comparison of thermal impressions from the period 1991–2005 in Lublin and Lesko (Wereski et al. 2010). The spatial variability of biometeorological conditions in Lublin was analysed by Dobek et al. (2013).

In recent years, research on the bioclimate of Lublin has been increasingly frequently employing the modern UTCI index. It has been applied among others by Bartoszek et al. (2017) in description of thermal stress in relation to atmospheric circulation, and by Dobek and Krzyżewska (2015) in studying the bioclimate in the city centre. Wereski et al. (2020) used UTCI to analyse the biothermal conditions of the winter season in Poland, including station Lublin-Radawiec. For the summer season, such research was conducted by Krzyżewska et al. (2021). In a longer-term perspective, in the period 1976–2015, UTCI was applied in research on the frequency of thermal stress in Lublin and its suburbs by Dobek et al. (2020).

Current state of research on air quality in Lublin

The first dustiness measurements were conducted in the centre of Lublin in 1953. The first documented descriptions of air pollution in

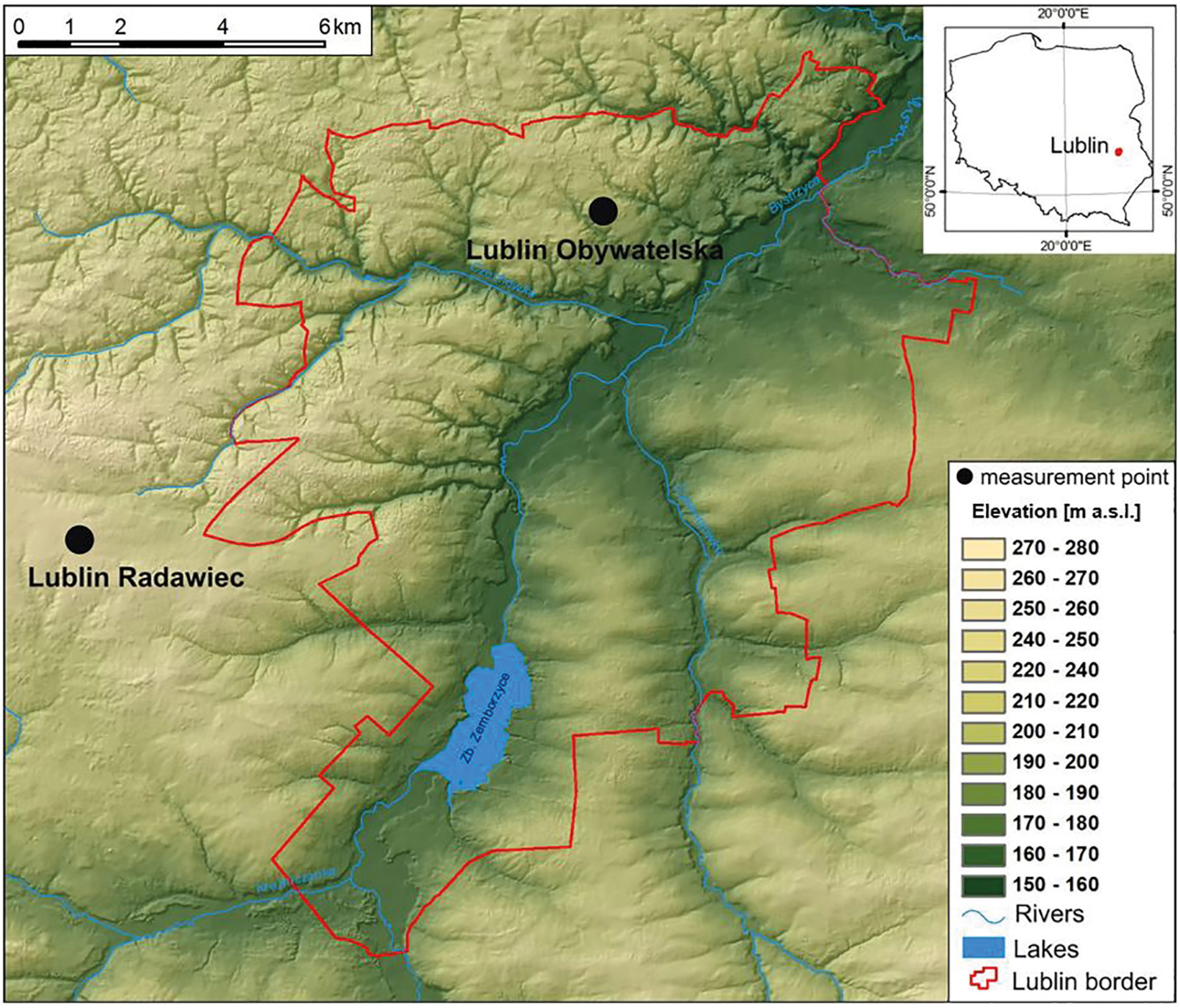

Fig. 1. Location of measurement points.

Lublin, primarily based on visual observations, date back to the 1960s. They concerned higher-than-average air dustiness caused by mineral particles blown by the wind from SE Europe. In subsequent years, research on dustiness was continued by means of various measurement devices. It indicated that higher dustiness in the cool period occurred in the city as a result of low emission in areas with dense building development (Kaszewski 2020). In summer, rural areas were prone to dustiness caused by aeolian blowing of wind containing organic matter from arable fields (Sierosławski 1959). These results were confirmed by research conducted in the following years (Bilik, Nowosad 1998, Nowosad 2000). In the cool season, higher-than-average concentrations of PM10 were recorded in comparison to the warm period (Duda, Pomorska 2007). Spatial research on concentrations of air pollutants in autumn and spring was conducted by Chmielowiec-Korzeniowska and Popiołek-Pyrz (2008). They evidenced that traffic is one of the primary sources of dust pollutants in Lublin. They also pointed to a considerable air-cleaning role of trees in the city space. The results of monitoring research on air quality conducted in the scope of the network of the National Environmental Monitoring showed that in Lublin, predominantly in the cool period, norms regarding the concentrations of PM2.5 and PM10 were not met (Żelazny et al. 2016, Lisicka et al. 2020). Research on concentrations of NO_2, conducted in the years 1991–1994 in an academic campus far from sources of emission from household furnaces, showed evident annual cyclicality (Kozak et al. 1994, 1995). The highest values were recorded in summer, which the authors explain by pointing out the fact of higher traffic intensity as a predominant causative factor. It was also emphasised that the highest concentrations of NO_x were recorded during circulation from the eastern sector. Other research on concentrations of NO_x in the period 2000–2001, conducted in the vicinity of a transport road and single-family housing, showed that the highest NO_x concentration occurred in the winter season. The authors associated it with numerous household heating systems near the measurement point (Stępniewska, Szafranek 2002). The authors focussed on the weekly course of NO_2 concentration, pointing to the lowest pollution values on days free from work, and higher ones on week days (Stępniewska, Szafranek 2003). In the centre of Lublin, the levels of emission of traffic pollutants were also analysed, namely NO, SO_2, CO and HC. It was determined that road traffic had an impact with a range of up to 100 m from the road axis, where exceedance of all monitored gases was recorded, except for SO_2 (Wyszkowski 1998). In the period 2007–2009 in Lublin, research was conducted regarding the concentration of CH_4, O_3, NO_2 and SO_2. It showed an increase in mean annual concentration of CH_4, O_3 and SO_2, and a decrease in NO_2 in the analysed period. In the case of NO_2, no exceedance of the acceptable mean monthly concentrations was recorded. No exceedance of norms of SO_2 concentration in a day was determined either. Annual values O_3 were also not exceeded, although 8-h values were exceeded repeatedly (Stępniewska et al. 2014).

Data and methods

For the purpose of the present research, meteorological data were obtained from the station of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) in Lublin-Radawiec (Fig. 1) for the years 2015–2021. The data are from the database published at danepubliczne.imgw.pl/ (accessed 4.07.2022), and cover the following: air temperature, relative humidity, wind speed, degree of cloudiness and daily minimum and maximum temperature. The analysed data come from 12 UTC, in bioclimatology considered as a term representative of the time of day with the highest human activity (Kozłowska-Szczęsna et al. 1997). Moreover, during the heat wave and cold wave, and on days with the highest pollution, hourly values of selected data and meteorological characteristics were used. In the case of data regarding air pollution, gaps in data occurred, accounting for a maximum of 2.7% in the case of PM2.5 and CO. A heat wave is defined as at least 3 consecutive days with daily maximum temperature >30°C (Krzyżewska 2019). A cold wave is defined as at least 3 consecutive days with daily minimum temperature <−10°C, with an allowed 1-day break if the mean minimum temperature does not fall below −10°C (Krzyżewska et al. 2019).

The characteristics of the bioclimatic conditions of Lublin were determined using the

Universal Thermal Climate Index (UTCI). It is based on a model of human temperature regulation called the Fiala model (Fiala et al. 2001, 2012), considering two parameters of regulation of heat exchange between the human organism and the surroundings. The passive element covers heat transport inside the organism and on the body surface. The other element, called active, reflects the physiological mechanisms of thermoregulation. Expressed in degrees centigrade, values of the UTCI index are obtained based on multiple calculations of the human heat balance. The UTCI index can be presented as the following function:

$$\mathrm{UTCI} = f\,(\mathrm{Ta}, \mathrm{vp}, \mathrm{va}, \mathrm{dTmrt})$$

where:
- Ta represents air temperature (°C),
- vp vapour pressure (hPa),
- va wind speed at a height of 10 m above ground (m · s^{-1}), and
- dTmrt difference between mean radiation temperature and air temperature (°C).

Table 1. Scale of assessment of thermal stress of the organism according to UTCI, and ways of counteracting unfavourable biothermal conditions from a given class (Błażejczyk et al. 2013).

UTCI [°C]	Stress category	Physiological responses
>46	extreme heat stress (EHS)	– Increase in rectal temperature (Tre) time gradient – Steep decrease in total net heat loss – Averaged sweat rate >650 g · h^{-1}, steep increase
38.1–46.0	very strong heat stress (VSHS)	– Core to skin temperature gradient <1 K (at 30 min) – Increase in Tre at 30 min
32.1–38.0	strong heat stress (SHS)	– Dynamic thermal sensation (DTS) at 120 min >+2 – Averaged sweat rate >200 g · h^{-1} – Increase in Tre at 120 min – Latent heat loss >40 W at 30 min – Instantaneous change in skin temperature >0 K · min^{-1}
26.1–32.0	moderate heat stress (MHS)	– Change of slopes in sweat rate, Tre and skin temperature: mean (Tskm), face (Tskfc) and hand (Tskhn) – Occurrence of sweating at 30 min – Steep increase in skin wettedness
9.1–26.0	no thermal stress (NTS)	– Averaged sweat rate >100 g · h^{-1} – DTS at 120 min <1 – DTS between −0.5 and +0.5 (averaged value) – Latent heat loss >40 W, averaged over time – Plateau in Tre time gradient
0.1–9.0	slight cold stress (SlCS)	– DTS at 120 min <−1 – Local minimum of Tskhn (use gloves)
−12.9 to 0.0	moderate cold stress (MCS)	– DTS at 120 min <−2 – Skin blood flow at 120 min lower than at 30 min (vasoconstriction) – Averaged Tskfc <15°C (pain) – Decrease in Tskhn – Tre time gradient <0 K · h^{-1} – 30 min face skin temperature <15°C (pain) – Tmsk time gradient <−1 K · h^{-1} (for reference)
−26.9 to −13.0	strong cold stress (SCS)	– Averaged Tskfc <7°C (numbness) – Tre time gradient <−0.1 K · h^{-1} – Tre decreases from 30 min to 120 min – Increase in core to skin temperature gradient
−39.9 to −27.0	very strong cold stress (VSCS)	– 120 min Tskfc <0°C (frostbite) – Steeper decrease in Tre – 30 min Tskfc <7°C (numbness) – Occurrence of shivering – Tre time gradient <−0.2 K · h^{-1} – Averaged Tskfc <0°C (frostbite). – 120 min Tskfc <−5°C (high risk of frostbite)
<−40.0	extreme cold stress (ECS)	– Tre time gradient <−0.3 K · h^{-1} – 30 min Tskfc <0°C (frostbite)

Tmrt, called mean radiation temperature, reflects values of temperature of the thin layer of air surrounding the human body. The value is determined by streams of short-wave and long-wave heat reaching the human organism. A detailed description of the index, its elements, and verification of the results obtained using the index are presented in papers by among others Błażejczyk et al. (2012, 2013), Bröde et al. (2012), Fiala et al. (2012), Havenith et al. (2012) and Kampmann et al. (2012). The calculation of the UTCI value was performed using BioKlima 2.6 software by K. Błażejczyk and M. Błażejczyk (www.igipz.pan.pl/BioKlima.html, accessed 18.07.2022). Table 1 presents classes of thermal stress of the human organism according to UTCI.

The UTCI index is a tool currently commonly applied in bioclimatology. In recent years, it has been used by among others Di Napoli et al. (2018) for selected European countries, Nemeth (2011) in Hungary, Pecelj et al. (2021) in Serbia, Nastos and Matzarakis (2012) in Greece, Urban and Kyselý (2014) in Czechia and Burkart et al. (2016) in Portugal. Outside Europe, UTCI has been applied among others in Brazil (Bröde et al. 2012), India (Dash et al. 2017), Japan (Ohashi et al. 2018) and China (Ge et al. 2016), as well as Iran (Baghideh et al. 2016, Roshan et al. 2018), South Africa (Roffe et al. 2023) and China (Lin et al. 2022).

In Poland, UTCI has been applied in the description of bioclimatic conditions in Warsaw (among others Lindner-Cendrowska 2011, 2013, Błażejczyk et al. 2014, Rozbicka and Rozbicki 2018), Gdańsk (Nidzgorska-Lencewicz 2015) and Kłodzko (Głogowski et al. 2022). In research on bioclimate in regional terms or at a scale of the entire country, UTCI has been used by among others Tomczyk and Owczarek (2020), Wereski et al. (2020), Krzyżewska et al. (2021), Kuchcik (2021), Kuchcik et al. (2021a, b), Tomczyk (2021), and Błażejczyk et al. (2022).

Data regarding air pollution were obtained from the monitoring station of the Regional Department of Environmental Monitoring Lublin (ul. Obywatelska 13, Fig. 1). They are hourly data providing information on the concentration of the following in the atmosphere: NO_2, O_3, CO, SO_2 and particulate matter PM2.5 and PM10 (GIOŚ 2022).

The determination of the level of concentration of selected atmospheric pollutants and facilitation of reporting on the level of atmosphere pollution employ various air quality indices, frequently proposed by the national services dealing with air quality monitoring, or various research teams (Karavas et al. 2020). Many different air quality indices have been developed over the years, differing in input data, target groups and application (Plaia, Ruggieri 2011, Mandal, Gorai 2014, van den Elshout et al. 2014, Kumar 2022). This paper employs the Common Air Quality Index (CAQI), which was developed as part of the scope of project INTERREG IIIC and IVC, co-financed from the resources of the European Union (van den Elshout et al. 2008).

The CAQI index presents information regarding air quality in the form of a number corresponding with one of five classes. Pollution levels are determined on a scale from 0 (very low) to >100 (very high) (Table 2). Depending on the character of the study area and available data,

Table 2. Scale of the estimation of air quality according to the CAQI calculation grid (van den Elshout et al. 2014).

Index	Grid	City background					
		Core pollutants			Pollutants		
		NO_2	PM10	O_3	PM2.5	CO	SO_2
		[$\mu g \cdot m^{-3}$]					
very low class (VLC)	0	0	0	0	0	0	0
	25	50	25	60	15	5000	50
low class (LC)	25	50	25	60	15	5000	50
	50	100	50	120	30	7500	100
medium class (MC)	50	100	50	120	30	7500	100
	75	200	90	180	55	10,000	350
high class (HC)	75	200	90	180	55	10,000	350
	100	400	180	240	110	20,000	500
very high class (VHC)	>100	>400	>180	>240	>110	>20,000	>500

the index can be determined two-fold: as the so-called city background, reflecting air quality over the city, or traffic index, representing an area with increased traffic intensity, e.g. vicinity of busy streets. The city background considers three core pollutants (NO_2, PM10 and O_3), and three auxiliary ones (PM2.5, CO and SO_2). The traffic index is based on two core pollutants (NO_2 and PM10) and two auxiliary ones (PM2.5 and CO). The paper employed city background CAQI.

CAQI is used among others for the determination of the level of air pollution in selected European cities (Airly 2022). The index has also been applied in research on air quality, e.g. in Czechia (Hajek, Olej 2015), Germany (Lokys et al. 2018) and Greece (Kyriakidis et al. 2012, 2013). In some European cities, air quality in reference to CAQI has also been analysed by Karavas et al. (2020), Nidzgorska-Lencewicz (2015), Nidzgorska-Lencewicz and Czarnecka (2015) and Poupkou et al. (2011).

Results

Characteristics of biometeorological conditions in the period 2015–2021

In the period 2015–2021, at 12 UTC, the most frequently occurring biometeorological conditions belonged to the class no thermal stress. They were recorded with a frequency of 34.3% (Fig. 2).

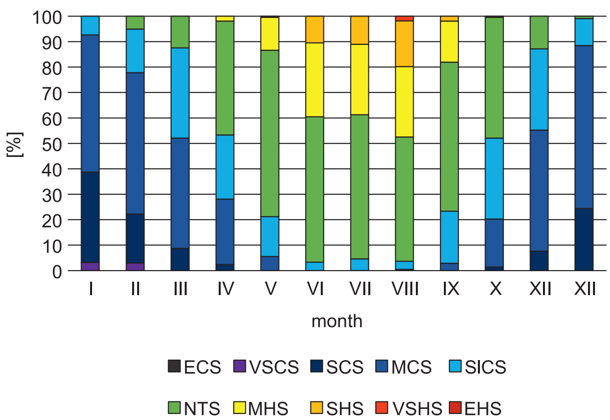

Fig. 2. Frequency of occurrence of thermal stress classes (UTCI) at 12 UTC.
EHS – extreme heat stress; ESC – extreme cold stress; MHS – moderate heat stress; MSC – moderate cold stress; NTS – no thermal stress; SCS – strong cold stress; SHS – strong heat stress; SICS – slight cold stress; VSCS – very strong cold stress; VSHS – very strong heat stress.

These conditions, favourable for the functioning of the organism, primarily occurred from April to October, with the highest frequency in June.

Thermal stress classes from the group of cold stress were recorded much more often than heat stress (very strong cold stress–slight cold stress). During 17.2% of cases in a year, slight cold stress was observed. Even more frequent occurrence (26.4%) was determined for the moderate cold stress thermal stress class. Such conditions particularly characterised the months from November to March, usually occurring in December. Also in that period, with a frequency of 8.3%, the class strong cold stress was recorded, although considerably more seldom, with a frequency of 0.5% in a year. It only occurred in January and February with a mean frequency of approximately 3.0% of cases in a month. Pursuant to recommendations regarding such conditions, the time spent outdoors should be limited to a necessary minimum (Table 1).

The occurrence of heat stress in Lublin covered the months from April to October. The class moderate heat stress (9.7% of days in a year) was usually recorded in June as well as in July and August (27.0–29.0% days in a month). Strong heat stress showed a frequency of 3.5% days in a year. Such conditions usually occurred in August (18% days in a month). During strong heat stress, it is necessary to hydrate, stay in shaded areas as much as possible and limit outdoor physical activity. Very strong heat stress at 12 UTC occurred only four times in the analysed years, and only in August. No conditions causing extreme heat stress were recorded in the analysed multiannual period.

Air quality in Lublin in the period 2015–2021

The legal document regulating acceptable levels of substances in the air in Poland is the Regulation of Minister of the Environment as of 24 August 2012 on levels of certain substances in the air (Journal of Laws 2021.845). Although the values specified in this regulation have been formulated for the purpose, among others, of promotion of the cause of not only human health protection but also plant protection, they differ from those recommended by the World Health Organisation (Table 3).

Table 3. Acceptable levels of selected substances in the air (Journal of Laws 2021.845, WHO 2006, 2021).

Pollutant	Unit	Averaging time	AQG level (WMO 2005 recommendation)	AQG level (WMO 2021 recommendation)	Dz.U.2021.845
PM2.5	$\mu g \cdot m^{-3}$	Annual	10	5	20[c]
		24-h	25	15[a]	–
PM10		Annual	20	15	40[c]
		24-h	50	45[a]	50[c]
O_3		Peak season		60[b]	
		8-h	100	100[a]	120[d]
NO_2		Annual	40	10	40[c]
		24-h	–	25[a]	–
SO_2		Annual		–	20
		24-h	20	40[a]	125
CO	$mg \cdot m^{-3}$	24-h	–	4[a]	–

a – 99th percentile (i.e. 3–4 days of exceedance in a year)
b – mean daily value of maximum 8-h O_3 concentration in 6 subsequent months with a higher level of O_3 concentration
c – level acceptable in terms of health protection
d – maximum 8-h mean value among rolling averages calculated from 1-h means in a day; each resulting 8-h mean is ascribed to the day in which it ends; the first calculation period for each day is the period from 17:00 of the previous day to 10:00 of the following day; the last calculation period for each day is the period from 16:00 to 24:00 of that day, all time yardsticks being based on Central European Time (CET).

In the analysed period in Lublin, mean annual SO_2 concentration in the air was 4.5 $\mu g \cdot m^{-3}$, varying from 3.6 $\mu g \cdot m^{-3}$ in 2015 to 5.2 $\mu g \cdot m^{-3}$ in 2017 (Table 4). The annual course showed an increase in monthly mean values of the substance in the months of the cold half-year to 7.2 $\mu g \cdot m^{-3}$ in January. In July, mean SO_2 concentration was 3.0 $\mu g \cdot m^{-3}$. The same dependency concerns the distribution of the 25th and 75th percentiles. In summer months, the interquartile range was approximately twice smaller than in winter months (Fig. 3). SO_2 is among the most important and hazardous pollutants in the environment, both for people and for other living organisms (Kociołek-Balawejder, Stanisławska 2012). The main source of emission of the substance in Lublin is the municipal-household sector, and particularly household incinerators that activate in the heating season (Rogulska 2021).

Table 4. Mean annual concentration values ($\mu g \cdot m^{-3}$) of selected air pollutants in Lublin (2015–2021).

Pollutants	2015	2016	2017	2018	2019	2020	2021	2015–2021
SO_2	3.6	3.8	5.2	4.8	4.8	4.3	5.0	4.5
NO_2	23.3	21.7	21.7	21.5	19.5	17.2	17.0	20.3
CO	300	400	400	400	300	300	300	400
O_3	45.1	37.4	48.0	48.8	50.6	43.1	37.6	44.4
PM2.5	28.1	26.6	22.0	24.5	20.3	18.7	23.9	23.4
PM10	36.4	30.8	32.5	33.6	26.5	22.3	28.9	30.1

The mean annual NO_2 value was 20.3 $\mu g \cdot m^{-3}$, and varied from 17.0 $\mu g \cdot m^{-3}$ in 2020 to 23.3 $\mu g \cdot m^{-3}$ in 2015 (Table 4). In the annual course, the highest concentration values of the substance in the air were recorded from January to March (22.7–23.3 $\mu g \cdot m^{-3}$), and in October (22.7 $\mu g \cdot m^{-3}$). In June and July their value was approximately 15.0–16.0 $\mu g \cdot m^{-3}$. From April to July, the interquartile range was the smallest (Fig. 3). Since NO_2 emission is primarily related to road transport, a high concentration of the substance is recorded in urbanised areas with high intensity of car traffic. This affects the annual, weekly and particularly daily cycle of NO_2 concentration (Kociołek-Balawejder, Stanisławska 2012). The daily course evidently shows two maximums corresponding with traffic peaks; smaller, 07–8 UTC and larger, 18–20 UTC.

CO is a by-product in incineration processes, mainly in the transport sector. Its concentration in Lublin in the period 2015–2021 averaged 0.4 $mg \cdot m^{-3}$ annually (Table 4). In the annual course, the lowest values were recorded in June and July (0.2 $mg \cdot m^{-3}$), and the highest in January and February (0.5 $mg \cdot m^{-3}$). From May to July, the interquartile range was twice smaller than in the winter months (January and February) (Fig. 3).

Tropospheric ozone (O_3) is a substance hazardous for living organisms, and it has a toxic effect. Its concentration in the atmosphere shows an evident annual cycle, and is related to higher emission of UV radiation from the sun in the summer months. In Lublin, the mean annual O_3 concentration was 44.4 µg · m^{-3}, ranging from 37.4 µg · m^{-3} in 2016 to 48.8 µg · m^{-3} in 2018 (Table 4). In the annual course, the highest values were recorded from April to August with a maximum in June reaching 63.7 µg · m^{-3}. In winter months, the O_3 concentration in Lublin was two to three times lower. It is reflected in the distribution of the lower and upper quartile, adopting higher values in months from April to August (Fig. 3).

Particulate matter, PM2.5 and PM10, belong to pollutants with a heterogenic character, and its particle size is of importance both in terms of

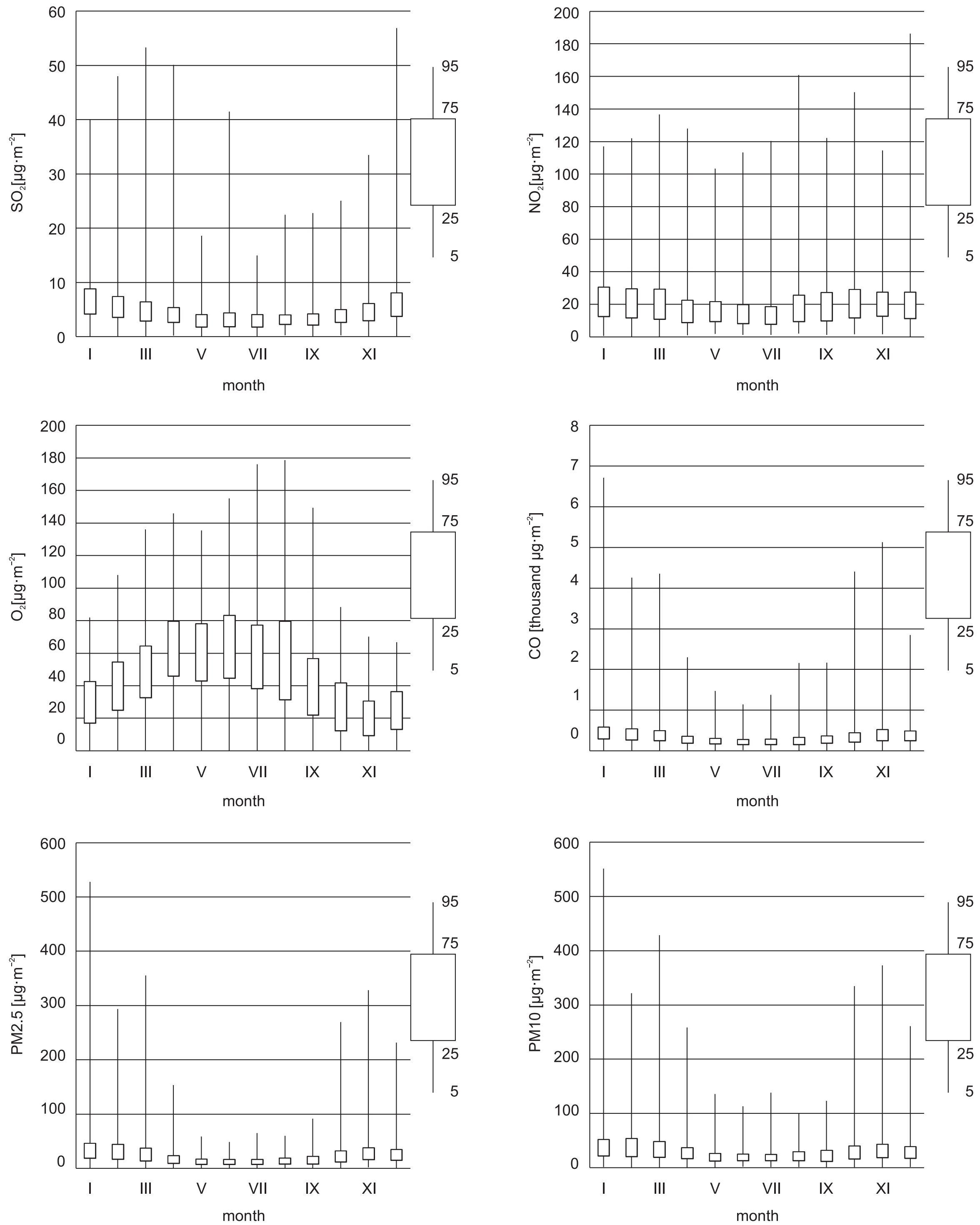

Fig. 3. Monthly values of the 5th, 25th, 75th and 95th percentiles of selected air pollutants in Lublin (2015–2021).

functioning of the natural environment and human health. Both PM2.5 and PM10 can enter the human respiratory system, and when the particulate diameter is smaller than 0.1 µm, these particles can also permeate into the circulatory system (Kociołek-Balawejder, Stanisławska 2012). The mean annual PM2.5 concentration in Lublin was 23.4 µg · m^{-1}, varying from 18.7 µg · m^{-3} in 2020 to 28.1 µg · m^{-3} in 2015. In the case of PM10, the mean annual concentration was 30.1 µg · m^{-3}, ranging from 22.3 µg · m^{-3} in 2020 to 36.4 µg · m^{-3} (Table 4). The annual norms recommended by the World Health Organisation were exceeded in both cases (Table 3). These air quality parameters are also characterised by high seasonal variability, with a maximum occurring in winter months (Fig. 3). The mean daily course shows an evident maximum by night and minimum by day. According to the report prepared by the Voivodeship Inspectorate of Environmental Protection in Lublin, the main source of emission of particulate matter in Lublin is the municipal-household sector (Rogulska 2021).

In the case of most of the analysed pollutants, a decrease in their concentration in 2020 and 2021 draws attention (Table 4). It can be associated with limited mobility of residents of Lublin and restrictions introduced during the COVID-19 pandemic. Similar trends were observed in other cities in the USA (Berman, Ebisu 2020), China (Bao, Zhang 2020) and Europe (Sicard et al. 2020, Muhamad et al. 2020). In the largest cities of Poland, PM2.5, PM10 and NO_2 concentrations decreased (Filonchyk et al. 2021). In comparison to the 10-year mean value, PM2.5 and NO_2 concentrations in Warsaw decreased by 15.0% and 30.0%, respectively (Grzybowski et al. 2021). Some study results, however, point to different trends of atmospheric pollutants' concentrations during the pandemic (Rogulski, Badyda 2021). Detailed analysis of the effect of the pandemic on pollution reduction requires further research.

Air quality in Lublin based on the CAQI index

Air quality research with the use of CAQI in Lublin showed the occurrence of conditions from very low class to very high class over the year, whereas the highest class (very high class) was recorded in the months from October to April

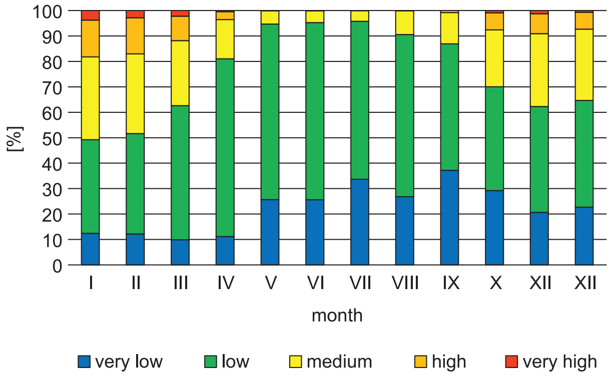

Fig. 4. Frequency of occurrence of air quality classes according to CAQI during the day.

(Fig. 4). In Lublin, conditions described as low class occurred most frequently. They constituted more than 50.0% of days in a year. In the annual course, they usually occurred from March to August (from 52.7% of days in March to 69.6% of days in June). Days with that air quality class were recorded the most seldom in January (36.8% of days in a month). The class very low class, characteristic of days with the highest air quality, usually occurred in the months from May to October with a maximum in July (33.7% of days in a month) and September (37.1% of days in a month). It was caused by considerably less use of household incinerators due to high temperatures and lower intensity of traffic in the holiday period, resulting in a decrease in concentration of particulate matter and nitrogen oxides (Rozbicka, Michalak 2015, Volná et al. 2021). In the warm period, the role of O_3 as a component of the CAQI index increases (Fig. 5) (Poupkou et al. 2011), and this is particularly evident during heat waves (Kovats et al. 2004, Pellegrini et al. 2007, Vautard et al. 2007, Theoharatos et al. 2010, Pyrgou et al. 2018, Khomsi et al. 2022). In the period from February to September, the worsening of air quality also somewhat affected the content of NO_2 in the atmosphere (Rozbicka, Michalak 2015).

The air quality class medium usually occurred from October to March, when the number of cases exceeded 20.0% of days in a month. In the warm period of the year, the share of days with such a level of pollutants considerably decreased (Fig. 4).

Unfavourable aerosanitary conditions occurred in Lublin from September to April. Pollution levels determined based on CAQI as high class and very high class were primarily related to the heating season (from December to

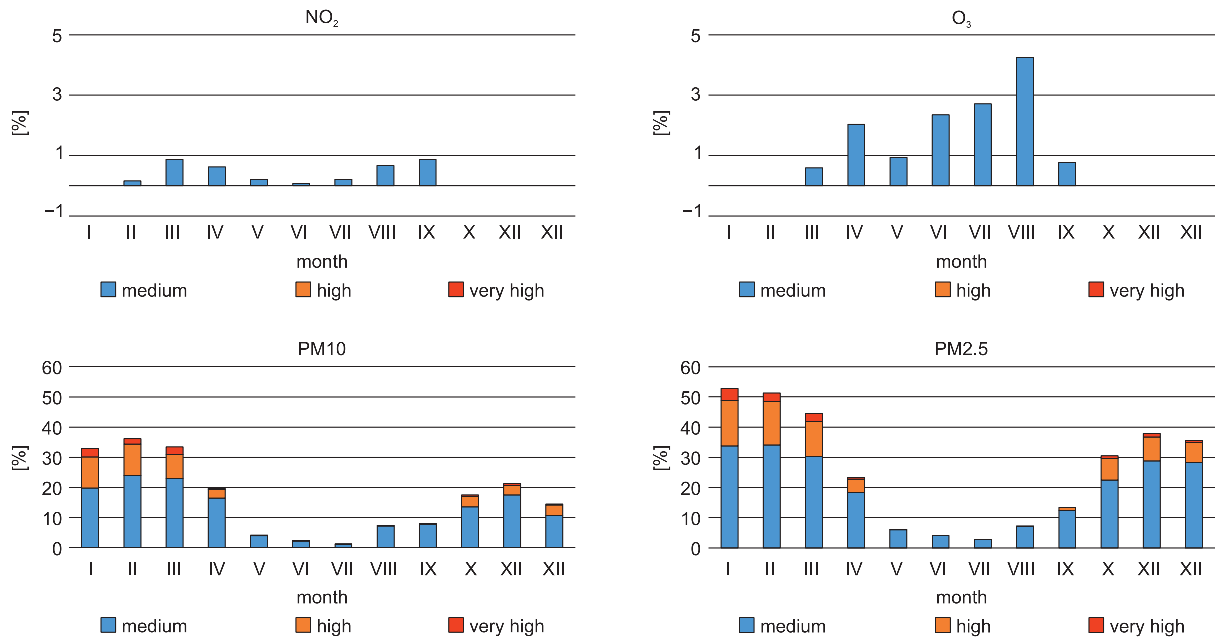

Fig. 5. Frequency of occurrence of air quality classes (CAQI) during the day, determined by NO2, O3, PM10 and PM2.5.

March). The emission of pollutants from so-called low emission sources increased in the city in that period (Żelazny et al. 2016). The worsening of air quality occurred mainly due to PM2.5 and PM10 (Fig. 5). Their emission was primarily related to individual heating of buildings and activity of collective heating systems. Moreover, low air quality in the period could have been strengthened by unfavourable weather conditions such as exceptionally low air temperatures and thermal inversions (Niedźwiedź et al. 2021). At lower air temperatures, the intensity of road traffic also increased, contributing an additional source of pollutants (Wine et al. 2022). In the cool period of the year, in cities of the temperate zone represented by Lublin, plant vegetation considerably decreases, directly translating into a substantially smaller filtering role of urban greenery (Badach et al. 2020). PM2.5 in the described period accounted for more than 50.0% of days with air quality corresponding with classes from medium class to very high class in January and February. A somewhat lower share (more than 30.0%) in a decrease in air quality in the city was reached by PM10 (Fig. 5).

Bioclimatic conditions in the context of air quality

During biometeorological conditions related to cold stress (UTCI classes from very strong cold stress to strong cold stress, where the UTCI is smaller than −13.0°C), the most frequently occurring CAQI class was low class, observed in approximately 45.0% of cases. The classes very low and medium occurred considerably more seldom (in 21.0% and 23.4% of cases, respectively). Low air quality (high class and very high class) occurred in more than 10% of cases in total (8.2% and 2.5%, respectively).

Biometeorological conditions causing heat stress (UTCI classes from strong heat stress to extreme heat stress, where the UTCI value exceeds 32.1°C) were usually accompanied by low class air quality (67.4% of cases). The second most frequent class was medium. It occurred in 26.3% of cases. Lower frequency (5.9%) was recorded for the best CAQI class, namely very low class. High class occurred sporadically, and no very high class was observed during conditions related to heat stress.

In the analysed years, the CAQI classes very low class and low class constituted a total of 75.5%. The class medium was recorded in 18.2% of cases, including almost half (8.4% of all cases) corresponding with moderate cold stress. The UTCI classes strong cold stress, no thermal stress and slight cold stress reached a share from 2.5% to 3.4%. The class high constituted 5.3% of all cases, whereas more than half (2.9%) of them occurred during moderate cold stress, 1.0% during slight

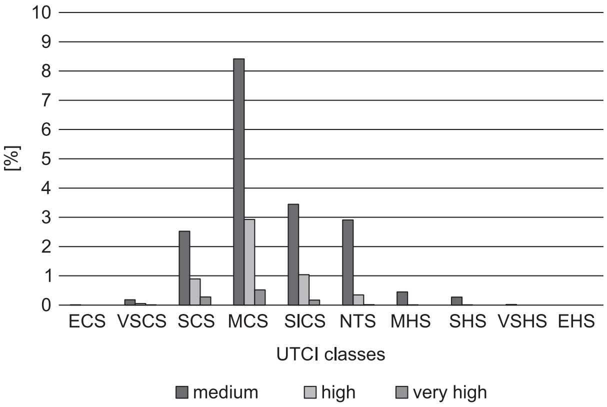

Fig. 6. Frequency of occurrence of classes of medium (MC), high (HC) and very high (VHC) CAQI air quality during particular types of UTCI thermal stress.
EHS – extreme heat stress; ESC – extreme cold stress; MHS – moderate heat stress; MSC – moderate cold stress; NTS – no thermal stress; SCS – strong cold stress; SHS – strong heat stress; SlCS – slight cold stress; VSCS – very strong cold stress; VSHS – very strong heat stress.

cold stress and 0.9% during strong cold stress. The class very high accounted for only 1.0% of all cases in a year, and usually occurred during moderate cold stress, strong cold stress and slight cold stress (Fig. 6). Low air quality usually occurred during classes related to cold stress.

Bioclimatic conditions and air quality during a cold wave

In Lublin, during the period 2015–2021, eight cold waves had occurred and they lasted on average for a duration of 5–6 days. The negative effect of the atmospheric environment on the human organism during low temperatures was investigated based on the analysis of a selected cold wave that occurred during 6–11 January 2017 in the Lublin region (Krzyżewska et al. 2019) (Fig. 7). During those days, the lowest air temperature of −21.8°C was recorded on 6 January at 04 UTC. Over the majority of the period, biometeorological conditions described as strong cold stress occurred. In only four measurement terms on those days, cold stress corresponded to the UTCI class moderate cold stress. The strongest cold stress was observed on the first three days of the wave, i.e. during 6–8 January. Weather conditions were then shaped by masses of dry and frosty Arctic air advecting over Poland from N and NE. From 8 January, the atmospheric conditions occurring over Poland favoured radiation inversion (Krzyżewska et al. 2019). In such synoptic situations, pollutants emitted from different sources remain in the near-ground layer of the troposphere, leading to the development of so-called smog (Niedźwiedź et al. 2021). A worsening of air quality is confirmed based on the results obtained from the CAQI index (Fig. 7). Air pollution in Lublin considerably increased from noon on 7 January from the CAQI index level medium class to high class. An increase in the concentration of pollutants from noon was related to human activity intensifying at that time of day, and to e.g. the need for more intensive heating of buildings. Norms of PM2.5 pursuant to the recommendations of WHO from 2005 (daily mean >25 μg · m^{-3}) were exceeded on almost all days of the wave except the first one. On the last day of the wave, the level of pollution was equal to the allowed norm multiplied by 17 (426 μg · m^{-3} at midnight). In the case of PM10, the recommended norms (daily mean >50 μg · m^{-3}) were exceeded only on 3 days, and on the last day of the wave by nine times.

At low temperature values, combustion engines, particularly from the moment of start-up to warm-up, emit more pollutants than at higher temperature values (Wine et al. 2022). The highest concentrations of pollutants were on average maintained from 17 UTC to 04 UTC. In the first phase, it should be associated with intensified commuting traffic, and in the second phase with heating of single-family houses after the return of their occupants from work or school. Particularly in the evening and by night (07–08, 9–10, 10–11.01), concentrations of pollutants exceeded a level of 100 CAQI. Such a rhythm related to the

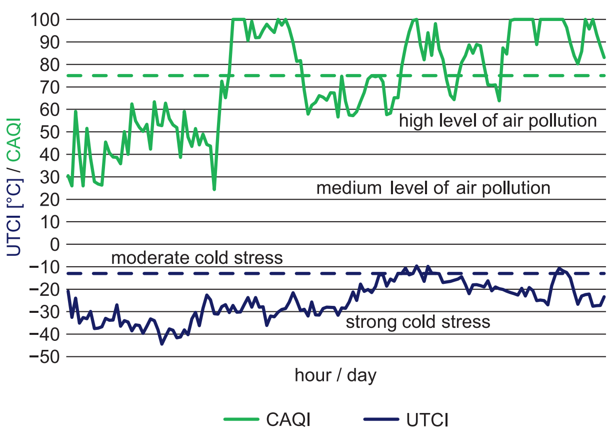

Fig. 7. Course of the CAQI and UTCI indices during the cold wave in Lublin during 6–11 January 2017.

activity of residents was maintained until the end of the discussed cold wave (Fig. 7).

Bioclimatic conditions and air quality during a heat wave

In years 2015–2021, there were nine heat waves, which usually lasted 3–4 days (with the exception of the 2015 August heat wave, which lasted 11 days). Biometeorological conditions and air quality in weather situations causing heat stress were analysed based on that longest selected heat wave that occurred in Lublin during 4–15 August 2015 (Krzyżewska, Dyer 2018). It was one of the two longest and most intense heat waves recorded since the 1950s (Krzyżewska 2019), called mega-heatwaves. The highest air temperature during the period reached 34.6°C. It was recorded on 7 August at 14 UTC. The mean air temperature during the wave was 25.1°C. High temperature values resulted from the effect of the advection of tropical air from S and SW. The high pressure ridge that had developed over Southern Europe permitted a northward advection of hot and dry air from over the West Sahara (Krzyżewska, Dyer 2018).

The biometeorological conditions described by UTCI values reflected thermal stress from three classes. Over the majority of duration of the wave, conditions described as moderate heat stress occurred (Fig. 8). They were mainly typical of the cooler part of the day, from afternoon to morning hours. On average from 09 UTC to 17 UTC, higher heat stress was recorded, classified as strong heat stress. These are biometeorological conditions in which it is necessary to hydrate,

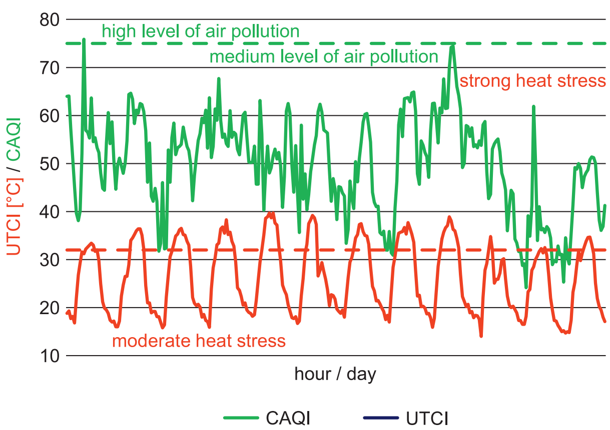

Fig. 8. Course of the CAQI and UTCI indices during the heat wave in Lublin during 4–15 August 2015.

and it is recommended to limit physical activity and stay in the shade (Table 1). During 4 days of the wave (6, 7, 8 and 11 August) around noon (on average from 10 UTC to 13 UTC), thermal stress from the class very strong heat stress was observed. These are biometeorological conditions hazardous for human health or even life. Pursuant to UTCI recommendations, it is necessary to periodically use air conditioned or shaded rooms. Hydrating is recommended at a rate of 0.5 L · h^{-1}, as well as avoiding intensive physical activity (Table 1).

In Lublin, during the discussed heat wave, the CAQI pollution class medium was dominant (Fig. 8). A worsening of air quality usually occurred with an increase in stress of the human organism due to unfavourable biometeorological conditions. In the case of heat waves, a decrease in air quality can be primarily related to an increase in the content of O_3 (tropospheric ozone) in the atmosphere. An increase in O_3 concentration was usually recorded at 11–17 UTC. According to air quality norms recommended by the WHO in 2005, the maximum 8-h ozone concentration should not be higher than 100 µg · m^{-3} (Table 3). During the analysed heat wave, the norms were exceeded on all its days, and the highest hourly ozone concentration reached 179.0 µg · m^{-3} on 12 August 2015 at 14 UTC. It was also often accompanied by higher-than-average levels of particulate matter PM2.5 and PM10. According to the WHO, the average recommended daily norm of PM2.5 is 25.0 µg · m^{-3} (Table 3). That value was exceeded on 6 days of the heat wave. The highest PM2.5 concentration was recorded on 7 August at 04 UTC. In the case of PM10, the norm is 50.0 µg · m^{-3}. It was also exceeded on 6 days (in one case it did not overlap with the dates of exceedance of PM2.5). The highest concentration of the pollutant reached 93.0 mg · m^{-3}, and occurred on 4 August at 09 UTC.

Discussion and conclusions

In the period 2015–2021 in Lublin at 12 UTC, biothermal conditions were mostly unfavourable from the point of view of human health – totalling 65.7%, including those in thermal stress classes related to cold stress reaching 52.3%, and those related to heat stress 13.4%. Thermoneutral conditions were recorded only on one-third of days in a year. In those terms, the bioclimatic conditions of Lublin do not considerably differ from those in other cities in east and central Poland, e.g. Gdańsk (Nidzgorska-Lencewicz 2015), Warsaw (Lindner-Cendrowska 2011, Rozbicka, Rozbicki 2018) and Białystok (Kuchcik 2021).

In the analysed period (2015–2021) in Lublin, the CAQI index pointed to low and very low classes of air pollution the most frequently (more than 70.0% of cases combined). The classes high and very high of CAQI combined occurred in more than 6.0% of cases. In the annual course, high class and very high class of the CAQI index were mostly observed in the cold half-year, with a maximum in January and February. This confirms that low air quality in European cities usually occurs in the cold period of the year, and is associated with the emission of pollutants during heating buildings and from traffic sources (Duda, Pomorska 2007, Grass 2008, Mannshardt, Naess 2018, Wine et al. 2022). During biometeorological conditions related to cold stress (UTCI <−13.0°C), the most frequently recorded CAQI class was low (almost 50%). The classes very high and medium occurred twice more seldom (in 21.0% and 23.4% of cases, respectively). Simultaneously, biometeorological conditions related to cold stress (UTCI <−13.0°C) and low air quality (four and five classes, respectively) occurred in more than 10% of cases in total. The classes high and very high hardly occurred during biometeorological conditions causing heat stress (UTCI >32.1°C). In such situations, the air qualities low class (67.4% of cases) and medium class (26.3% of cases) were usually observed. The occurrences of high class (four) were extremely rare (only three cases in analysed period).

The best CAQI class, namely very low, was recorded more seldom (5.9%). Similar results regarding the relations of CAQI and UTCI were obtained by Nidzgorska-Lencewicz (2015), although, owing to a different methodology having been adopted in their study, no direct comparison should be made.

A decrease in pollution in 2020 and 2021 was largely determined by restrictions on human activity. The issue is a subject of numerous studies conducted in different parts of the world. It is estimated that in certain areas affected by the COVID-19 pandemic (Spain, France, Italy, USA and China), air pollution with NO_2 decreased by 30% (Muhammad et al. 2020). More detailed data from the United States show a decrease in NO_2 by 25.5%, and reduction of PM2.5 in urbanised areas (Berman, Ebisu 2020). Different results, however, obtained among others in Poland, point to the necessity for further research (Filonchyk et al. 2021, Grzybowski et al. 2021, Rogulski, Badyda 2021).

In cities of the temperate zone, represented by Lublin, during biometeorological conditions causing cold stress, residents are exposed to the additional stress of low air quality, particularly in the case of long-lasting low temperatures during cold waves (Niedźwiedź et al. 2021). During such days in January 2017, mostly low air quality was recorded, mainly related to pollution with PM10 and PM2.5.

As a result of the progressing climate change in Central Europe, the number of heat waves will continue to increase (Luterbacher et al. 2004, Meehl, Tebaldi 2004, Schär et al. 2004, Russo et al. 2015, IPCC 2022). They can be particularly severe in urbanised areas. The attention of residents of a region affected by a heat wave often focusses on the elements of weather rather than air quality. During the heat wave in August 2015, unfavourable biothermal conditions were additionally worsened by not only high ozone concentrations, characteristic of high temperatures, but also PM2.5 and PM10. Such air quality results in a decrease in the comfort of life during heat waves, and negatively affects the human organism. In cities of the temperate zone, often in the warm period of the year, information on air quality is published more seldom, and draws considerably less attention from residents. The role of e.g. local authorities and services issuing warnings, e.g. on heat waves, should also encompass the provision of information and education regarding health hazards and reduction of the comfort of life due to low air quality. Air pollution in the summer period is another important argument in favour of activities aimed at the improvement of the comfort of life in cities, and mitigation of the effects of climate change.

As for low classes of air pollution, their causes are not limited merely to meteorological conditions, since there are multiple factors influencing air quality, such as human activity – mostly emission sources (from the utilisation of technology, or possibly even having their origin in an avant-garde technology whose effects on the surroundings' air quality might not have been adequately investigated prior to the commencement of commercial runs), local and state politics and regulations, increasing society awareness, etc. To ensure that the public is afforded the opportunity to take the needed safeguards against exposure to a spectrum of adverse meteorological conditions, an important requirement is for there to be a timely system in place for informing and warning the population against not only high and low temperatures but also low air quality. Meteorological warnings should include biometeorological information reflecting the combined effect of several weather elements on the human organism. It is also necessary to supplement the information with data concerning air quality. The CAQI index used in the present study as an illustration appears to meet that condition by ascribing air quality at a given moment to a relevant pollution class in a simple and direct way, or informing on aerosanitary conditions. In the times of progressing climate change, in Central Europe manifested in among others milder winters, people may be less prepared for cold waves and the accompanying low air quality. The application of the UTCI and CAQI indices can facilitate the reaching of a greater number of residents and simplify reception of the provided information.

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Author's contribution

MD: Conceptualisation and design, Methodology, Data collection, Data analysis and interpretation, Manuscript writing and revision, Visualization; SW: Methodology, Data collection, Data analysis and interpretation, Manuscript writing, Visualization; AK: Methodology, Data analysis and interpretation, Manuscript writing and revision.

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