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ASSESSMENT OF AIR QUALITY IN LEGNICA (POLAND, LOWER SILESIAN VOIVODESHIP) BASED ON SELECTED GASEOUS POLLUTANTS AND SUBJECTIVE TEMPERATURE INDEX

Robert Krzysztof Sobolewski✉

Institute of Landscape Architecture, Faculty of Environmental Engineering and Geodesy, Wrocław University of Environmental and Life Sciences, ul. Grunwaldzka 55, 50-357 Wrocław

ABSTRACT

The aim of this study is to evaluate time distribution of gaseous pollutants' concentration levels, sulphur dioxide (SO_2, μg · m^{-3}), nitrogen dioxide (NO_2, μg · m^{-3}) and to characterise biothermal conditions, based on subjective temperature index (STI, °C) in Legnica, Lower Silesian Voivodeship. Assessment of the seasonal and daily SO_2 and NO_2 concentration and STI values in the studied period was based on descriptive statistics. The analysis of NO_2 and SO_2 concentration frequency was performed in reference to the scale applied in the interpretation of the STI. The assessment of the analysed period's biothermal conditions did not show an occurrence of thermal sensation "boiling hot". The most adverse aerosanitary conditions caused by high concentration of SO_2 in the air are accompanied by a sensation of "freezing". The highest fluctuation in the content of NO_2 and SO_2 in the air was characteristic for the winter with the occurrence of "freezing" and "very cold" sensation. The highest concentration of SO_2 amounting to 234 μg · m^{-3} was recorded in the winter of 2005 and highest NO_2 concentration was recorded in the spring of 2009, amounting to 184 μg · m^{-3}. The NO_2 and SO_2 concentration shows a reverse circadian course in comparison to the course of apparent temperature.

Key words: NO_2, SO_2, biothermal conditions, bioclimate

INTRODUCTION

The quality of atmospheric environment in urban areas is related with forms of land use, due to an intense heterogeneity of cities (Huang et al. 2013, Karnia et al. 2007). While, the sources of SO_2 emissions can be found mainly in individual household furnaces within housing estates, the sources of NO_2 can be tracked down to road communication areas. The levels of pollution are directly affected by meteorological elements such as wind speed, precipitation, temperature and relative humidity (Żyromski et al. 2014, Rozbicka and Michalak 2015). High concentrations of SO_2 and NO_2 occur mainly in winter (Kalbarczyk and Kalbarczyk 2008, Huang et al. 2013, Żyromski et al. 2014). Deteriorating aerosanitary conditions have an adverse influence on human health, especially on people suffering from ailments connected to cardiovascular and respiratory diseases. It may lead to an increased risk of morbidity and even mortality due to a failure of these systems (Kowalska et al. 2008, San Tam et al. 2015). In Zabrze, NO_2 was indicated as a main pollution increasing the risk of hospitalization. The multifactor analysis confirmed a significant correlation between the concentration of NO_2 and the circadian number of hospitalisations, taking account of atmospheric pressure, temperature and relative humidity (Kowalska et al. 2008). Research suggests a reciprocal impact of air pollution and meteorological elements on health, and thus the comfort of living in urban areas.

✉e-mail: robert.sobolewski.lubawka@gmail.com

Adverse aerosanitary conditions are often accompanied by equally adverse biotermal conditions (Ramsey et al. 2014, Kalbarczyk et al. 2016). A correlation between the mortality rates and biothermal conditions has been found by Błażejczyk and McGregor (2007). It has been proven that in London from 20% to 29% of deaths can be explained by adverse biothermal conditions occurring three days earlier. In Paris and Barcelona approx. 35%, in Budapest and in London 10–25% of the mortality rates during the summer period can be linked with a high thermal load on the organism. One of the measures that can be applied in the assessment of biothermal conditions is the subjective temperature index (STI), developed for biothermal-meteorological weather classification (Błażejczyk and Kunert 2011). The STI indicator describes the intensity of atmospheric environment's thermal stimuli experienced by a human before activating the organism's adaptive processes (Błażejczyk 2003, 2005). In Poland, for the assessment of biothermal conditions STI indicator was used by a.o.: Koźmiński and Michalska (2010), Mąkosza and Michalska (2010), Wereski et al. (2010), Pełech (2013).

The purpose of this paper was to characterize and assess time distribution of SO_2 and NO_2 gaseous pollutants' concentration and accompanying biothermal conditions in Legnica in particular seasons based on apparent temperature between 2005 and 2014.

MATERIALS AND RESEARCH METHODS

The study draws on data of hourly concentration of gaseous pollutants: sulphur dioxide (SO_2, $\mu g \cdot m^{-3}$) and nitrogen dioxide (NO_2, $\mu g \cdot m^{-3}$), and hourly meteorological data from years 2005–2014. The data obtained from the State Environmental Monitoring station in Legnica (Lower Silesian Voivodeship) – a station of an urban background type – was marked with an international code PL0190A. Data was compiled for Universal Time (UTC). The assessment of bioclimatic conditions was made on the basis of the subjective temperature index (STI, °C) using Błażejczyk's nine-point scale (2005) (see: Table 1).

The values of STI were calculated by the Bioklima 2.6 program (https://www.igipz.pan.pl/Bioklima-zgik.html). Wind speed at the input has been reduced to a height of 2 m n.p.g. on the basis of Sutton's formula (Mąkosza and Michalska 2010, Kalbarczyk et al. 2015). While, the assessment of aerosanitary conditions was conducted with regard to the analysis SO_2 and NO_2 immissions. In the 2012 and 2013 winter seasons and in the spring of 2013 no data on hourly concentration of SO_2 was recorded. In addition, totally no data was shown for hourly concentration of NO_2 in the 2012 summer and autumn seasons and the winter and spring of 2013. The hourly concentration data of SO_2 and NO_2 pollutants and the STI was characterized in accordance with the descriptive statistics of position measurements: average, maximum and minimum in the winter (XII–II), spring (III–V), summer (VI–VIII) and autumn (IX–XI) of the studied decade. Furthermore, the frequency of hourly concentration of gaseous pollutants in the adopted intervals and human thermal comfort classes were assessed. The average hourly concentration of gaseous pollutants value and STI values were used to rate the circadian course of immissions of pollutants and biothermal conditions of the analysed seasons. In order to determine the level of gaseous pollutants accompanying the biothermal conditions, the frequency of their occurrence in the classes of human thermal comfort was evaluated.

Table 1. STI scale (Błażejczyk 2005)

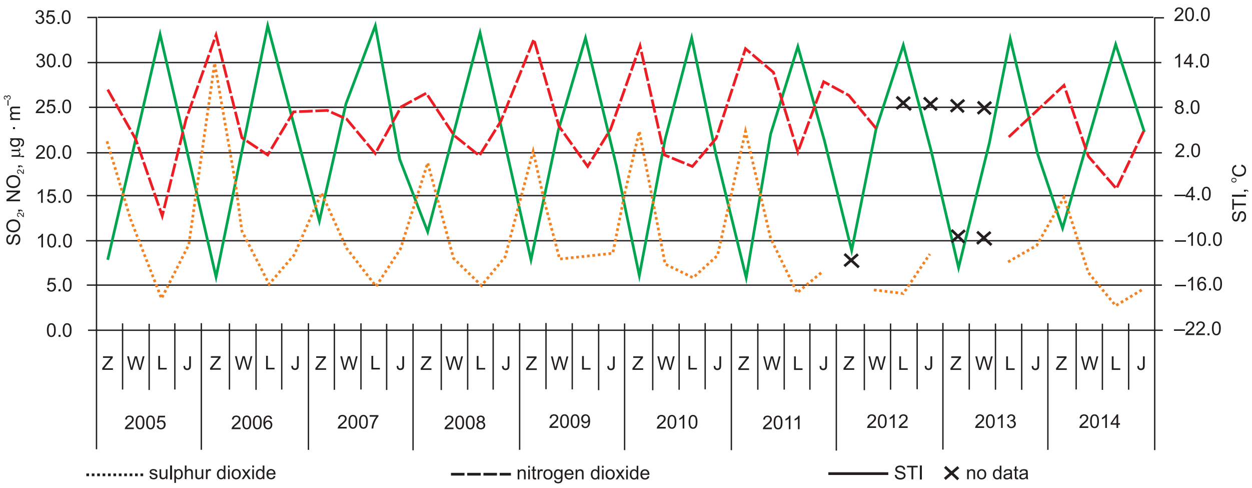
Temperature, °C	Thermal comfort class
< –38,0	freezing
–38,0÷–20,1	very cold
–20,0÷–0,5	cold
–0,4÷22,5	cool
22,6÷31,9	comfortable
32,0÷45,9	warm
46,0÷4,9	hot
55,0÷9,0	very hot
>70,0	boiling hot

RESULTS

The winter of 2005/2006 can be distinguished by the highest concentration of studied pollutants out of all seasons within the analysed period, with an average seasonal value of SO_2 and NO_2 respectively 30 μg · m^{-3} and 33 μg · m^{-3} (see: Fig. 1). The average concentration of NO_2 above 30 μg · m^{-3} was also noted in the winter seasons: 2008/2009, 2009/2010 and 2010/2011. The average value of NO_2 in all considered seasons was higher than the value of the SO_2 in the air, on average of 12.5 μg · m^{-3}. The lowest STI value for the 2005––2014 period, equalling –14.6°C, was recorded in winters at the turn of years 2005/2006, 2009/2010 and 2010/2011. In summer seasons, the average STI value fluctuated from approx. 16 to 19°C. The highest average apparent temperature, which totalled 18.9°C, was recorded in the summer of 2007. The smallest difference between the concentration of SO_2 and NO_2, only about 3.0 μg · m^{-3}, was recorded in the winter of late 2005/2006 with the apparent temperature of –14.6°C. The highest difference between the concentration of SO_2 and NO_2 was registered in autumn 2011, 21,1 μg · m^{-3}, with the apparent temperature of 3,5°C. The immision of SO_2 and NO_2 showed a reverse seasonal course in relation to the distribution of STI values in the examined period.

The highest maximal concentration of SO_2, 274 μg · m^{-3} in the studied period was recorded in the winter of 2005 (see: Fig. 2). In summer the highest concentration of SO_2, which totalled 167 μg · m^{-3}, was noted in 2005, while in spring of the same year it equalled 103 μg · m^{-3} and 226 μg · m^{-3} in autumn of 2012. The highest concentration of SO_2 for the winter of 2014 reached 94 μg · m^{-3} and was lower than the highest concentration in the examined period by 180 μg · m^{-3}. The highest concentration of NO_2 for the years 2005–2014 was recorded in spring 2012 and it totalled 184 μg · m^{-3}, whilst the lowest out of the maximum seasonal concentration occurred in autumn 2007, reaching only 54 μg · m^{-3}. The maximum apparent temperature of the studied period's summer seasons, exceeding 50°C, showed up in 8 out of 10 considered seasons. The highest maximum value of the STI was 58.4°C, in the spring of 2007. In the same year, the highest minimum apparent temperature STI (–15.7°C) against the rest of spring seasons was shown. The smallest difference between the maximum and the minimum value of the STI in the summer season occurred in 2007, and amounted to 52.6°C, while the largest was observed in 2012, reaching 63,7°C. The lowest STI value, –45°C, compared to the rest of the examined period's seasons was recorded in winter 2009.

The biggest differences in the concentration of SO_2, with regard to all seasons, occurred in winter (see: Fig. 3). The highest hourly values of SO_2, above 80 μg · m^{-3}, were reported in winter, accounting for 6% of all cases. The concentration values within the select-

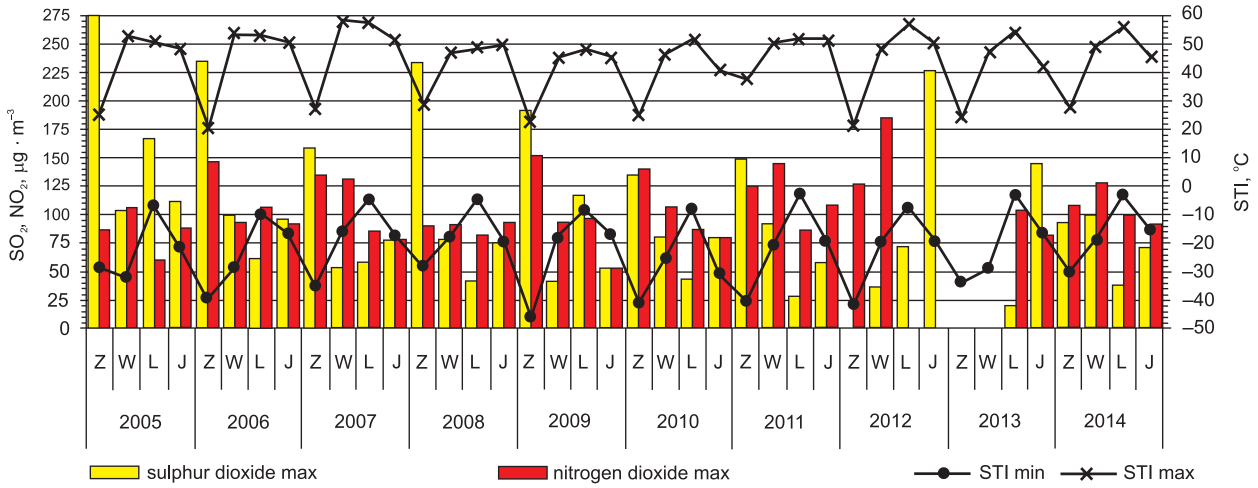


Z – winter, W – spring, L – summer, J – autumn

Fig. 1. Time distribution of average concentrations of sulfur dioxide, nitrogen dioxide and STI according to the seasons of the year, 2005–2014

ed range of 61–80 μg · m^{-3} in the winter season accounted for 2.0%. In summer, the concentration above 80 μg · m^{-3} made 0.04% and in autumn 0.07% of all cases. The concentration of NO_2, above 20 μg · m^{-3}, were more frequent than the concentration of SO_2 in all seasons of the studied period. In winter, over 20% of cases of NO_2 concentration exceeded 40 μg · m^{-3}. The concentration of NO_2 above 80 μg · m^{-3} in winter were total of 1.9%. The concentration above 80 μg · m^{-3} accounted for just 0.2% of all cases.

In the examined period between 2005 and 2014, 8 out of 9 classes of thermal sensations were indicated, from "freezing" to "very hot" (see: Fig. 4). The sensation of "freezing" represented only 0.2% of cases in winter, while "very cold" 12.1%. In the winter season the sensation of "cold" was noted as the most frequent, accounting for 78.5% of all sensations. During the summer season of the studied period there was no documented case of the sensation of "boiling hot". The sensation of "very hot" was re-



Z – winter, W – spring, L – summer, J – autumn

Fig. 2. Basic statistics describing the values of SO_2, NO_2 and STI for the seasons in following years, 2005–2014

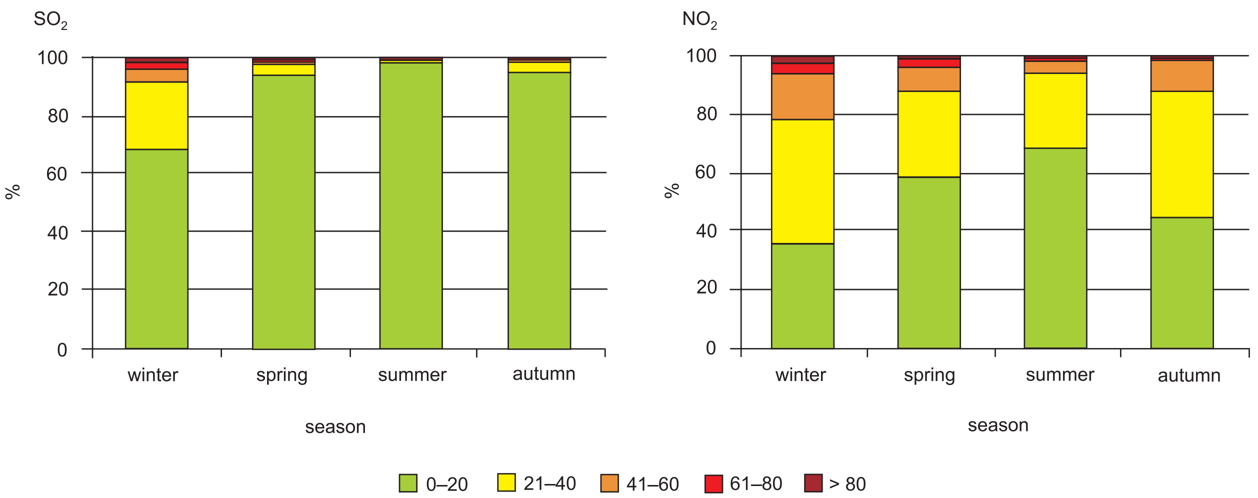


Fig. 3. The frequency of hourly concentrations of NO_2 and SO_2 (μg · m^{-3}) for year seasons, 2005–2014

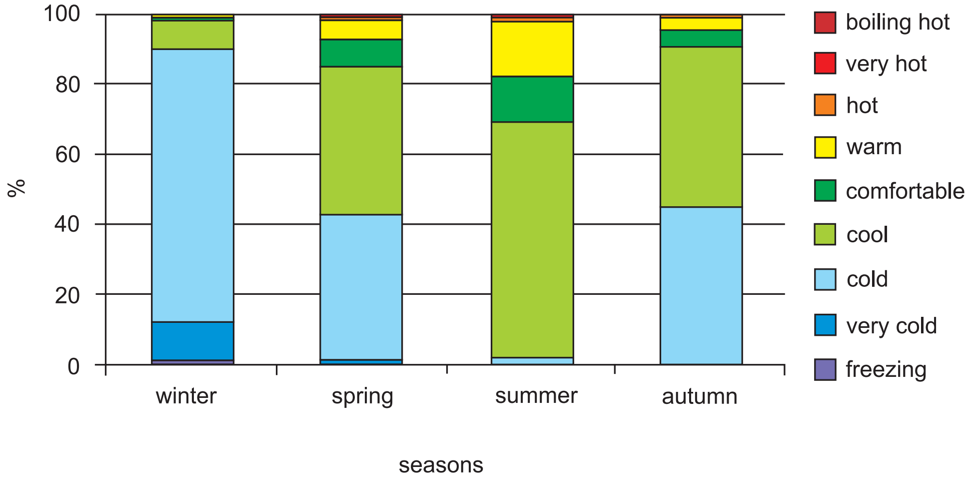


Fig. 4. The frequency of human thermal sensations according to subjective temperature index (STI), 2005–2014

corded only in five cases in the summer, accounting for 0.02% of the 2005–2014 period. The sensation of "hot" equalled only 1.8% of the sensations in summer. Reaching 12.7% of all cases – being the most frequent – was the sensation of "comfortable" in the summer season. In spring, the "hot" feeling totalled just 0.3%, while in autumn there was no mention of this particular sensation. Autumn and spring in the studied period were marked by similar biothermal conditions, however in spring the sensations "warm" and "comfortable" occurred only twice.

The highest recorded in winter concentration of SO_2 was approx. 25 $\mu g \cdot m^{-3}$ between 17:00 and 18:00 (UTC) (see: Fig. 5). In summer, the circadian course of SO_2 immission maintained at a constant and low level approx. 3.5–7 $\mu g \cdot m^{-3}$. In the spring season, the highest average hourly concentration of SO_2, amounting to 11 $\mu g \cdot m^{-3}$, was reported between 16:00 and 17:00 (UTC), while in autumn 10 $mg \cdot m^{-3}$ from 18:00 to 19:00. The highest concentration of NO_2 was recorded in winter from 17:00 to 18:00 (UTC) and totalled 39 $\mu g \cdot m^{-3}$. In summer, the highest concentration was almost 30 $\mu g \cdot m^{-3}$ at 20:00 (UTC). The NO_2 immission indicated a clear circadian course during all seasons, with two maximums, one in the morning and one in the evening hours, whereby in the evening it was higher. In spring, the highest concentration of NO_2, accounting for 34 $\mu g \cdot m^{-3}$, was registered between 19:00 and 20:00 (UTC), while in autumn 36 $\mu g \cdot m^{-3}$ from 18:00 to 19:00 (UTC). In the autumn and spring seasons of the studied period the maximum increase in NO_2 was preceded by the maximum increase in concentration of SO_2 by 1–2 hours. The highest average hourly values of the apparent temperature (STI), about 30–31 °C, were appeared in summer from 8:00 to 12:00 (UTC), indicating the "comfortable" sensation. Whereas the lowest STI values, corresponding to the sensation of "very cold", in winter were below –14 °C, in the hours from 1:00 to 6:00 (UTC). In the spring season, the highest average STI value equalled almost 30 °C. This indicator shows an inverse circadian course, comparing to the course of NO_2 and SO_2 in all seasons, making itself especially clear in the hours before and after the noon. In winter, the highest average STI value, equal to –2.1 °C at 10:00 (UTC), was accompanied by the average hourly concentration of SO_2 and NO_2 of respectively 21.1 and 26.9 $\mu g \cdot m^{-3}$. While in summer, the highest average STI value, equal to 31,4 °C at 10:00 (UTC), coincided with the average concentration of SO_2 and NO_2 of respectively 6.49 and 11.7 $\mu g \cdot m^{-3}$. In summer, spring and autumn from 3:00 to 5:00 (UTC) the growth of STI value came with a significant increase in NO_2.

The winter season featured the largest differentiation levels of pollution with all accompanying human thermal sensations (see: Fig. 6). In the winter season, the "warm" sensation was recorded only in two cases. The cause of such even frequency distribution of pollutant concentration was due to both a small number of "warm" sensation cases in the studied period and

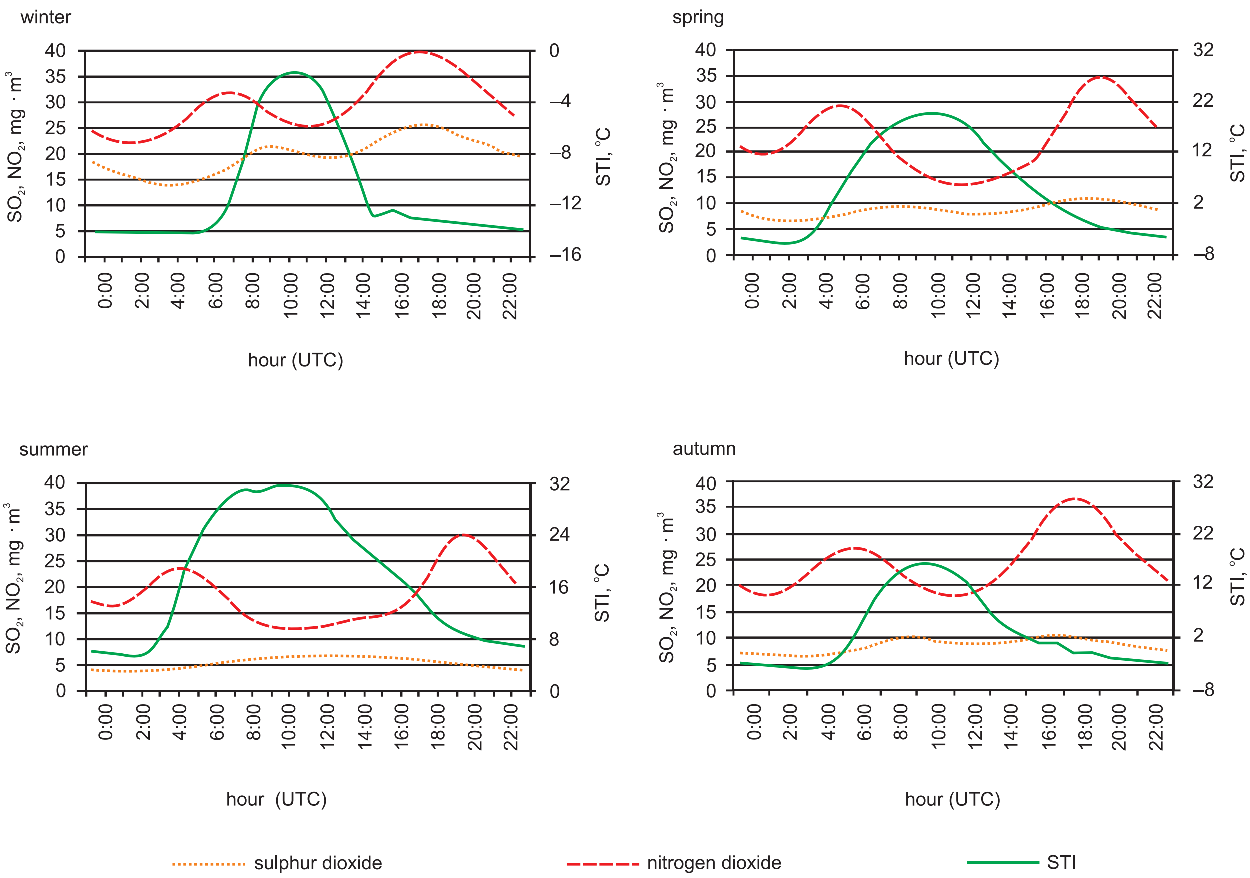


Fig. 5. Circadian distribution: NO_2, SO_2 and STI for the 2005–2014 period in all seasons

the lack of data on the pollution from the 2012–2013 period. The highest hourly concentration of SO_2 above 80 μg · m^{-3} in the examined period was indicated along with the "freezing" and "very cold" sensation, which were respectively accounted for 20.8% and 7.0% of all analysed cases. These sensations were characterised by the greatest differentiation of SO_2 levels in the atmosphere. The summer season manifested the lowest variability of SO_2 immission levels in the studied period – all the analysed sensations, in over 97% of cases, were accompanied by concentration in the range of 0–20 μg · m^{-3}. Only in spring with the sensation of "very cold" the concentration of SO_2 in all adopted ranges were recorded. Compared with autumn, in spring high levels of pollution were associated with cold stress more frequently. The highest hourly concentration of NO_2, above 80 μg · m^{-3}, occurred by the sensations of "freezing" and "very cold" in winter, which in turn was the total 11.6% and 9.6% of cases. In winter, the concentration of NO_2 over 80 μg · m^{-3} that would come along the "comfortable" sensation was not recorded. The sensation "very hot" was correlated in summer with the lowest hourly levels of NO_2 concentration, in contrast to the sensation of "cold" which was accompanied by the highest level of concentration of the analysed season.

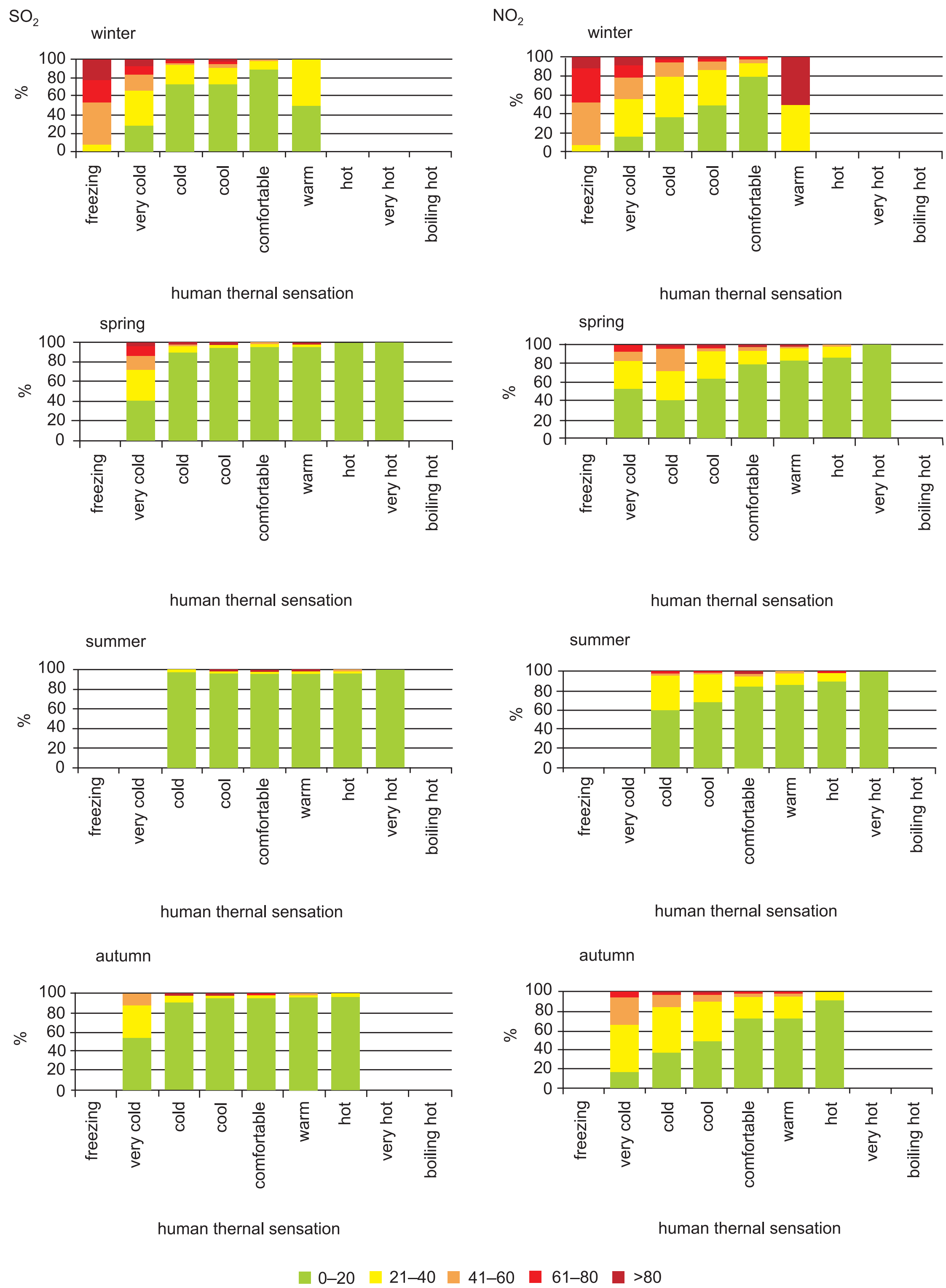


Fig. 6. The frequency of hourly NO_2 and SO_2 ($\mu g \cdot m^{-3}$) concentration in each human thermal sensation classes according to subjective temperature index (STI), 2005–2014

DISCUSSION

Legnica belongs to the central biothermal region with an average temperature of 21.3°C in summer and 1.9°C in winter, at 12:00 (UTC). Whereby the summer season lasts for two months, from June to July, while the winter season from January to March (Błażejczyk and Matzarakis 2007). In Legnica during the studied decade, the sensation of "hot" had not occurred. Also, this sensation was recorded neither by Mąkosz and Michalska (2010) nor by Wereski et al. (2010), applying the STI indicator to west-central and south-east (Lublin and Lesko) Poland. This statement may indicate to a very occasional occurrence of the "hot" sensation in Polish climatic conditions. Bryś and Ojrzyńska (2016) on the basis of UTCI indicator point out a more frequent occurrence of loads associated with cold stress, compared to hot stress in the suburban areas of Wrocław. This is confirmed by author's own research in Legnica, located in the same bioclimatic area, as Wrocław. Papanastasiou et al. (2015) on the basis of the discomfort index (DI) and common air quality index (CAQI) showed the deteriorating air quality during the heat waves in Thessaloniki, Athens and Volos in the period from 2001 to 2010. Kalbarczyk et al. (2016) using the radiation-effective temperature (TRE) demonstrated that the occurrence of O_3 concentration levels above 80 μg · m^{-3} is more frequent in July and August, with the experience of "warm" and "hot" sensations than with other heat sensations. In April and May a high level of concentration of O_3 has been reported mainly with the sensation of "comfortable". The correlation between NO_2 and O_3 was strongest in winter months, while in summer season the strongest influence of the studied meteorological elements on the concentration of O_3 was registered. The strongest correlations between TRE and ozone were recorded in the period from April to September. Author's own research conducted between 2005 and 2014 indicates higher levels of NO_2 and SO_2 pollution in winter than in summer. In the years 2005–2009 in four cities of Lower Silesia, including Legnica, the analysis of aerosanitary conditions for the months November–April showed the strongest link between NO_2 immission and the wind speed in the coldest months (Żyromski et al. 2014). The conducted assessment in relation to the concentration of NO_2 and SO_2 in Legnica indicates the occurrence of the most adverse air quality under conditions of cold stress in winter with the "very cold" sensation. High hourly concentration of SO_2 and NO_2 were accompanied by the sensations of "freezing" and "very cold", although the "freezing" sensation appeared less frequently than the sensation of "very cold". This is confirmed by a research carried out in Gdynia, where the CAQI indicator was the most negative (high and very high) during the cold part of the year, with up to 3.5% in the city's centre and 1.2% on the outskirts (Nidzgorska-Lencewicz 2015). Schwarzak et al. (2014) in their study of Polish border region and Saxony indicate a significant reduction in deposition of sulphur and nitrogen oxides in the years 2000–2010. The improvement of air quality is also possible in Legnica, where the maximum concentration of SO_2 in the air in the winter of 2014 amounted to 94 μg · m^{-3}, when ten years earlier it reached 274 μg · m^{-3}. Due to lack of data for the 2012–2013 period, a confirmation of this observation is possible only by the monitoring of subsequent years.

CONCLUSIONS

1. In all seasons, a reverse circadian course of NO_2 and SO_2 concentration against the STI indicator was recorded.
2. In the years 2005–2014 in Legnica there was not a single case of "hot" sensation, what indicates a low frequency of thermal sensations with a strong stimulus of heat stress.
3. The highest average hourly concentration of SO_2 are preceded by the highest concentration of NO_2 by 1–2 hours.
4. In the examined period the "very cold" and "freezing" sensations were accompanied by the highest concentration of NO_2 and SO_2, what indicates adverse aerosanitary conditions in winter with the occurrence of severe cold stress.
5. In the summer season, all the human thermal sensations were accompanied by low concentration of SO_2 and NO_2, thereby improving the air quality compared to the winter season.

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OCENA JAKOŚCI POWIETRZA LEGNICY (POLSKA, DOLNY ŚLĄSK) NA PODSTAWIE WYBRANYCH ZANIECZYSZCZEŃ GAZOWYCH I WSKAŹNIKA TEMPERATURY ODCZUWALNEJ

ABSTRAKT

Celem pracy była ocena rozkładu czasowego poziomu stężeń zanieczyszczeń gazowych dwutlenku siarki (SO_2, $\mu g \cdot m^{-3}$) i dwutlenku azotu (NO_2, $\mu g \cdot m^{-3}$) oraz charakterystyka warunków biotermicznych Legnicy, położonej w województwie dolnośląskim, na podstawie temperatury odczuwalnej (STI, °C). Ocenę sezonowego i dobowego przebiegu imisji SO_2, NO_2 oraz wartości STI, w badanym wieloleciu, dokonano w oparciu o statystyki opisowe miar. Analizę częstości poziomów stężeń w przyjętych przedziałach SO_2 i NO_2 wykonano w odniesieniu do skali stosowanej przy interpretacji wskaźnika STI. Ocena warunków biotermicznych badanego okresu (2005–2014) nie wykazała wystąpienia odczucia ciepła „upalnie". Najbardziej niekorzystne warunki aerosanitarne spowodowane wysokimi stężeniami SO_2 w powietrzu towarzyszą odczuciu „mroźno". Największą zmiennością zawartości SO_2 i NO_2 w powietrzu charakteryzowała się zima podczas występowania odczuć „mroźno" i „bardzo zimno". Najwyższe stężenie SO_2, wynoszące 234 $\mu g \cdot m^{-3}$, odnotowano zimą 2005 r., natomiast najwyższe stężenie NO_2 – wiosną 2009 roku i wynosiło 184 $\mu g \cdot m^{-3}$. Imisja SO_2 i NO_2 wykazuje odwrotny dobowy przebieg w porównaniu do przebiegu temperatury odczuwalnej.

Słowa kluczowe: SO_2, NO_2, warunki biotermiczne, bioklimat