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Influence of meteorological conditions on urban air pollution

Bożkowa W. W., Liudczik A. M., Umrejko S. D. **Wpływ warunków meteorologicznych na zanieczyszczenie powietrza w miastach.** Zanieczyszczenie powietrza zależy głównie od intensywności źródeł emisji. Jednak na stężenie zanieczyszczeń powietrza, przyczyniając się do ich kumulacji w powierzchniowej warstwie atmosfery lub rozproszenia, wpływają również warunki meteorologiczne. Na podstawie danych obserwacji z Centrum Hydrometeorologicznego w miastach obwodowych Białorusi określono główne cechy sezonowych i dobowych wahań stężeń ozonu i antropogenicznych zanieczyszczeń, takich jak NO, NO_2, CO, benzen, toluen i ksylen. Stężenia zanieczyszczeń antropogenicznych rosną od lata do zimy, a stężenie ozonu powierzchniowego spada. Decydujący wpływ na to zachowanie ma sezonowa zmiana pionowej stabilności atmosfery. Maksymalne dzienne stężenia zanieczyszczeń antropogenicznych są rejestrowane rano i wieczorem, a szczyt wieczorny przesuwa się na późniejszy czas wiosną i latem. Zmiana ta wynika z sezonowych zmian dobowego przebiegu prędkości wiatru. Przyczyną pojawiania się porannych i wieczornych maksimów zanieczyszczeń antropogenicznych jest zmniejszenie intensywności emisji w porze nocnej i aktywacja procesów rozprzestrzeniania się zanieczyszczeń w ciągu dnia. Dobowe maksimum zanieczyszczenia antropogenicznego odpowiada lokalnemu minimum stężenia ozonu przy powierzchni.

Божкова В. В., Людчик А. М., Умрейко С. Д. **Влияние метеорологических условий на уровень загрязнения воздуха в городах.** Антропогенное загрязнение воздуха в мегаполисах в последние годы достигло опасного уровня. В первую очередь степень загрязненности воздуха зависит от интенсивности источников выбросов, и улучшить экологическую обстановку можно за счет уменьшения выбросов в атмосферу загрязняющих веществ. Метеорологические условия также влияют на концентрацию загрязнений городского воздуха, способствуя их накоплению в приземном слое атмосферы или рассеянию.

С использованием данных наблюдений Гидрометеорологического центра за качеством воздуха в областных городах Беларуси определены основные особенности сезонного и суточного хода концентраций антропогенных загрязнений (NO, NO_2, CO, бензола, толуола, ксилола) и озона. Концентрации антропогенных загрязнений растут от лета к зиме, а концентрация приземного озона падает. Определяющее влияние на такое поведение оказывает сезонное изменение вертикальной устойчивости атмосферы. Максимумы суточных концентраций антропогенных загрязнений регистрируются в утреннее и вечернее время, причем вечерний пик весной и летом смещается на более позднее время. Это смещение обусловлено сезонными изменениями суточного хода скорости ветра. Причиной появления утреннего и вечернего максимумов антропогенных загрязнений является снижение интенсивности источников выбросов ночью и активация процессов рассеяния загрязнений в дневное время. Суточным максимумам антропогенного загрязнения отвечают локальные минимумы концентрации приземного озона.

Бажкова В. В., Людчык А. М., Умрэйка С. Дз. **Уплыў метэаралагічных варункаў на ўзровень забруджвання паветра ў гарадах.** Антрапагеннае забруджванне паветра ў мегаполісах ў апошнія гады дасягнула небяспечнага ўзроўню. У першую чаргу ступень забруджанасці паветра залежыць ад інтэнсіўнасці крыніцаў выкідаў, і, адпаведна, каб палепшыць экалагічную абстаноўку трэба, паступова змяншаць выкіды ў атмасферу забруджвальных рэчываў. Метэаралагічныя варункі таксама ўплываюць на канцэнтрацыю забруджванняў гарадскога паветра, спрыяючы іх назапашванню ў прыземным слоі атмасферы або рассейванню.

Паводле назіранняў гідраметэаралагічнага цэнтра за якасцю паветра ў абласных гарадах Беларусі вызначаныя асноўныя асаблівасці сезоннага й сутачнага ходу канцэнтрацый антрапагенных забруджванняў (NO, NO_2, CO, бензолу, талуолу, ксілолу) ды азону. З лета да пачатку зімы канцэнтрацыі антрапагенных забруджванняў узрастаюць, а канцэнтрацыя прыземнага азону, наадварот, змяншаецца Вызначальны ўплыў на такія паводзіны мае сезонная змена вертыкальнай стабільнасці атмасферы. Максімумы сутачных канцэнтрацыяў антрапагеннага забруджвання рэгіструюцца раніцай і ўвечары, пры гэтым вечаровы пік увесну ды ўлетку прыпадае на больш позні час. Гэткі здвіг абумоўлены сезоннымі зменамі сутачнага ходу хуткасці ветру. Прычынаю з'яўлення ранішняга й вечаровага максімумаў антрапагеннага забруджвання ёсць зніжэнне інтэнсіўнасці крыніцаў выкідаў уначы ды актывацыя працэсаў рассейвання забруджвання ўдзень. Сутачным максімумам антрапагеннага забруджвання адпавядаюць лакальныя мі-німумы канцэнтрацыі прыземнага азону.

Key words: anthropogenic air pollution, surface ozone, seasonal variations, daily variations, meteorological parameters

Słowa kluczowe: antropogeniczne zanieczyszczenie powietrza, ozon powierzchniowy, zmiany sezonowe, zmiany dobowe, parametry meteorologiczne

Ключевые слова: антропогенное загрязнение воздуха, приземный озон, сезонные изменения, суточные изменения, метеорологические параметры

Ключавыя словы: антрапагеннае забруджванне паветра, прыземны азон, сезонныя змены, сутачныя змены, метэаралагічныя параметры

Abstract

Air pollution depends mainly on the intensity of emission sources. Yet, meteorological conditions also effect the concentration of air pollution, contributing to their accumulation in the surface layer of the atmosphere or dispersion.

Using data of observations conducted by the Hydrometeorological Centre in the regional cities of Belarus, main features of seasonal and daily variations in the concentrations of ozone and anthropogenic pollutants such as NO, NO_2, CO, benzene, toluene, and xylene are determined. Here, the concentrations of anthropogenic pollutants rise from summer to winter, and the concentration of surface ozone falls. The seasonal change in a vertical stability of the atmosphere has a decisive effect on this behavior. Maximum daily concentrations of anthropogenic pollution are registered in the morning and evening, with an evening peak shifting to a later time in spring and summer. This shift is due to seasonal changes in the diurnal course of a wind speed. The reason for appearance of morning and evening maxima of anthropogenic pollution is a decrease in the intensity of emission at night and activation of processes of pollution dispersion during the day. A daily maximum of anthropogenic pollution corresponds to a local minimum of the surface ozone concentration.

Introduction

In the era of scientific and technological progress, anthropogenic impact on the atmosphere tends to become more intense and large-scale thus making the consequences of air pollution a serious problem for humankind. In this regard, the importance of objective control for the state of the atmosphere cannot be overestimated.

The leading position in a list of the largest anthropogenic sources of atmospheric pollution is taken up by transport (*IPCC*, 2006). The incineration of materials in industry is also a source of $NO_x = NO + NO_2$ and CO emissions, while the burning of materials by domestic consumers is a source of CO emissions (*IPCC*, 2006).

Assessing the role of individual sources in atmospheric pollution may be often a difficult task, if based on results of air quality monitoring, and this is because of changing weather conditions. Brönnimann, Neu (1997), Almbauer et al. (2000), Finardi, Pellegrini (2004), MAKRA et al. (2010), SCHÄFER et al. (2014), CHEN, TANG, ZHAO (2015), GEIß et al. (2017), discuss the effect of meteorological conditions in the dispersion of pollutants which contributes to a decrease in their concentrations in the surface air. Usually, three groups of meteorological parameters are identified as playing a primary role in air cleaning. Those are the wind speed and direction, the vertical stability of the atmosphere, or close to this (in terms of physical meaning) the height of a mixing layer, and the air temperature near the Earth's surface.

As far as the last parameter is concerned, it should be noted that the surface air temperature is not directly related to the efficiency of dispersion of pollutants. First, its increase does not necessarily mean a gain in a thermal convection (a decrease in the vertical stability or an increase in the height of the mixing layer), since one of the dispersion determinants is not the temperature itself but its stratification in a boundary layer of the troposphere (a vertical temperature gradient) (MAKRA et al., 2010; SCHÄFER et al., 2014). Second, the air temperature significantly affects the rate of chemical reactions involving anthropogenic pollution and ozone thereby stimulating its generation in the lower troposphere (STOCKWELL et al., 2012; ZHANG, WANG, 2016).

As for the wind speed and the vertical stability of the atmosphere, they have proven to be the absolute "leaders" in a cleaning of urban air (ALMBAUER et al., 2000; CHEN, TANG, ZHAO, 2015; FINARDI, PELLEGRINI, 2004; GEIß et al., 2017; HAN et al., 2015; MAKRA et al., 2010; SCHÄFER et al., 2014; VERMA, DESAI, 2008). However, one should mark that the relative efficacy of the influence of these meteorological parameters depends on some specific conditions: the geographical position of a city, the urban landscape, and the features of its planning and architecture. For example, in Milan (FINARDI, PELLEGRINI, 2004) the vertical stability of the atmosphere is believed to be the main factor, since strong winds in the city surrounded by mountains in the Po Valley are extremely rare. On the contrary, the wind speed and its direction are determined as the main factor contributing to the dispersion of pollutants in Beijing (China) and Surat (India) (VERMA, DESAI, 2008; CHEN, TANG, ZHAO, 2015; HAN et al., 2015).

Wind effect on the level of anthropogenic air pollution varies significantly in a large city and rural areas. At a site located far enough from a source of anthropogenic emissions, air quality depends largely on a transfer of pollutants along with an air drift from their source (LOGAN, 1989; ADAME et al., 2012; BIAN et. al, 2018). However, in a city with intensive traffic and large industrial enterprises, that is, at the location of a source of pollution, the wind serves as a powerful "blowing-away" tool thus decreasing concentrations (CHEN, TANG, ZHAO, 2015). As for the thermal convection, it, most likely, acts similarly everywhere: the less stability of the atmosphere, the faster the cleaning of the polluted surface layer of air. However, if there are no increased concentrations of pollutants in a place of observation, it is obvious that a vertical mixing has no effect at all.

Unlike nitrogen oxides, carbon monoxide and volatile organic compounds, which are mainly of anthropogenic origin and are surface ozone precursors, the bulk of ozone is formed in the stratosphere as a natural constituent of the atmosphere. Located in the upper layers of the atmosphere, ozone protects the planet's biosphere from harmful solar ultraviolet radiation, yet, ozone in the surface air can endanger living organisms. The ozone concentration in the lower troposphere is influenced by the wind transporting ozone in a horizontal direction, the thermal convection that promotes a vertical exchange, the deposition rate on the underlying surface, and chemical reactions with other atmospheric constituents that lead to generation or destruction of ozone.

An increase in the concentration of surface ozone is facilitated by its photochemical generation in the presence of precursors under certain conditions (JENKIN, CLEMITSHAW, 2000; SILLMAN, 2000, 2003; CLAPP, JENKIN, 2001). Most often, anthropogenic air pollution leads to a decrease in ozone concentration. This is confirmed by publications usually indicating a lower concentration of ozone in the polluted air of cities if compared to rural areas (SOLBERG et al., 2004; ZVYAGINTSEV et al., 2016;). Therefore, the concentration of surface ozone in large cities normally increases under strong winds. This is also stemmed from a wind-induced turbulent mixing with higher tropospheric layers usually containing higher ozone concentrations (ZVYAGINTSEV et al., 2016).

The paper analyzes the behavior of anthropogenic air pollution and surface ozone in the cities of Belarus in comparison with the situation in an ecologically clean area – the Berezinsky Biosphere Reserve. The annual and daily courses of pollutant concentrations are treated. A particular attention is paid to the daily course of pollutant concentrations in different seasons and their reasons. Among these reasons, an important role is given to meteorological conditions.

Material and methods

Currently, automated air quality control centres of the National Hydrometeorological Center operate in all regional cities of Belarus (Brest, Viciebsk, Gomel, Grodno, Mogilev and Minsk) as well as in a number of other cities and at the Berezinsky Biosphere Reserve. Twenty-four-hour observations are conducted to monitor aerosol particles, sulfur dioxide SO_2, carbon monoxide CO, nitrogen oxide NO and dioxide NO_2, ozone O_3, and concentrations of volatile organic compounds (VOCs) such as benzene, toluene and xylene. In some cities, there are several sites located in different districts, varying in the level of air pollution. As for the Minsk city, it has five sites: Minsk 1, Minsk 4, Minsk 11, Minsk 13 and Minsk 16. They are located in places differing in a density of pollution sources, and this enables to quantify the effect of the level of anthropogenic pollution on the observed concentrations of surface ozone under the same meteorological conditions.

To measure the concentrations of pollutants (ozone, nitrogen oxides and carbon oxide), gas analyzers of the ML series [Monitor (Europe) Ltd, Great Britain] and gas analyzers of the AP-370 series (HORIBA, Japan) are used at the air monitoring stations. Concentrations of volatile organic compounds are taken by gas chromatographs Syntech Spectras (Netherlands).

In Belarus, an air quality control system is at its development stage, so it is not always possible to obtain qualitative and continuous series of observations from individual sites. For this reason, in the analysis one employs data of 2014 for Minsk (observation sites 1, 4, 11, 13) and Viciebsk, data of 2014–2015 for the Berezinsky Reserve, and data of 2016–2017 for Brest, Gomel, Grodno and Mogilev (fig. 1).

Based on the available experimental data, average annual concentrations of pollutants were determined for each observation site. They are presented in table 1. In Minsk, site 1 is located in the area with a minimum of industrial enterprises, the remaining observation sites are close to major industrial centers. This specific feature is well illustrated by data given in the table.

Naturally enough, the lowest concentrations of anthropogenic pollution are revealed at the Berezinsky Biosphere Reserve, since this is a safeguarded wildlife reserve, where anthropogenic sources of air pollution are practically missing.

The urbanized regional centers demonstrate a higher level of air pollution, though, concentrations of pollutants, exceeding the hourly maximum permissible level (MPL), are found quite rare. Yet, most of the average annual values do not exceed the corresponding annual MPLs (as specified by the *Order of the Ministry of Health of the Republic of Belarus*, 2016). Only the observation sites Minsk 4 and Minsk 11 show the excess in MPL of nitrogen dioxide.

Proceeding from the data given in the table, there are no observation sites where all monitored substances show increased concentrations. One can only mark the highest average annual concentrations of individual pollutants at some sites in comparison with other sites. For example, the sites of Gomel and Minsk 4 give a high level of carbon monoxide. In Minsk, nitrogen dioxide concentrations exceed the annual MPL

Fig.1. The location of control sites whose data are used for analysis
Rys.1. Lokalizacja punktów kontrolnych, z których dane zostały wykorzystane do analiz
Рис. 1. Расположение контрольных пунктов, данные с которых использованы для анализа

Table 1. Average annual concentrations of pollutants
Tabela 1. Średnie roczne stężenia zanieczyszczeń
Таблица 1. Среднегодовые концентрации загрязняющих веществ

Concentration, ppb	CO	NO_2	NO	O_3	Benzene	Toluene	Xylene
MPL (annual average)	430.00	20.80	80.00	45.00 (daily average)	3.100	2.600	4.600
The Berezinsky Reserve	57.90	3.74	2.73	28.61	0.045	0.022	0.003
Brest	252.24	14.60	5.75	28.89	0.121	0.245	0.041
Viciebsk	294.93	6.36	6.53	37.07	0.481	0.925	0.384
Gomel	394.40	12.06	17.28	22.23	0.125	0.313	0.206
Grodno	238.77	9.60	5.04	28.31	0.214	0.350	0.083
Mogilev	237.15	10.18	12.21	21.53	0.101	0.251	0.092
Minsk 1	132.90	12.97	7.67	24.09	0.086	0.382	0.274
Minsk 4	325.30	23.86	21.41	20.95	0.244	0.683	0.360
Minsk 11	262.34	27.62	18.69	24.16	0.451	1.064	0.197
Minsk 13	223.33	20.20	13.05	21.04	0.184	1.233	0.762

at the observation sites 4 and 11. The level of nitrogen oxide is high nearby these sites as well as in Gomel. Increased concentrations of benzene, toluene and xylene are characteristic of Viciebsk, Minsk 11 and Minsk 13.

A high average annual ozone concentration is typical for Viciebsk, a low one – for Minsk, Mogilev and Gomel. At the cleanest site – the Reserve – the level of ozone takes an intermediate value. Thus, the average annual ozone concentrations do not display anticorrelation with the other pollutants. However, if analyzing non-averaged data, one almost always observes anticorrelation of ozone with its precursors (for more details, see the Section Conclusions). It will be revealed most distinctively when considering the daily and seasonal dynamics of the concentration of pollutants.

Results and discussion

Seasonal dynamics of pollutants concentration

The annual course of mean monthly concentrations of pollutants averaged over all regional cities of Belarus is shown in fig. 2. Thus, these curves characterize the seasonal dynamics of pollution of the urban air only. It can be seen that the concentrations of nitrogen oxides, carbon oxide and VOCs rise smoothly towards winter and decrease by summer with insignificant fluctuations. A similar behavior is also characteristic of cities in other countries (Makra et al., 2010; Al-Awadhi, 2014; Laña et al., 2016). One should note that in the Berezinsky Reserve, unlike the cities, a low level of air pollution varies little during the year.

An increase in concentrations of anthropogenic pollutants in the winter is partially due to a gain in their emission because of a heating season. Moreover, meteorological conditions affect quite strongly the seasonal course of their concentrations as well as the concentration of surface ozone. In summer, with the weak vertical stability, the intensive mixing of air layers occurs due to the thermal convection leading to a rapid dispersion of primary pollutants (Cristofanelli et al., 2004). In winter, frequent temperature inversions prevent both the transfer of polluted air to higher layers of the atmosphere and the arrival of air with increased ozone amount from there (Almbauer et al., 2000).

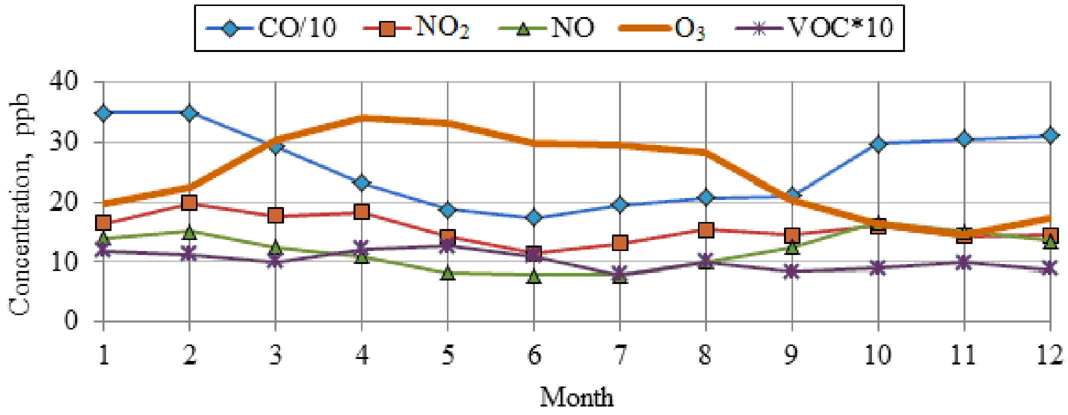

Fig. 2. Seasonal dynamics of average monthly concentrations of anthropogenic pollutants and ozone
Rys. 2. Sezonowa dynamika średnich miesięcznych stężeń antropogenicznych zanieczyszczeń i ozonu
Рис. 2. Сезонная динамика среднемесячных концентраций антропогенных загрязняющих веществ и озона

Another important meteorological factor is the wind, which enhances the transport of pollutants in the horizontal direction and has a significant effect on their concentration. As far as cities with an increased level of air pollution are concerned, the wind here contributes to the reduction of pollutant concentrations (Verma, Desai, 2008). Normally, the average diurnal wind speed is maximum in winter and minimal in summer. A winter increase in the wind speed compensates, to some extent, for intensification of emission sources and inhibition of the convective processes thus contributing to some purification of the urban air.

The seasonal ozone dynamics appears to be opposite to the dynamics of anthropogenic pollution: ozone concentration rises by summer and decreases by winter. A similar behavior is also characteristic of other regions located quite far from Belarus (Khuriganova et al., 2016; Verma et al., 2018). In winter, the atmosphere is more stable, and an increase in ozone concentration due to an air exchange with the free troposphere is minimal. Usually, a dense cloud cover during this period (MATUSZKO, 2012) significantly reduces the intensity of incoming solar radiation. This suppresses a photochemical production of ozone in the surface layer, despite a high reflectivity of the snow cover, a low rate of ozone deposition on the snowy surface and an increased concentration of precursors. Specific conditions for winter ozone generation in Wyoming and Utah (OLTMANS et al., 2014) as well as in Rome (AVINO, 2004) are not typical for Belarus.

In summer, the atmosphere is less stable, and this contributes to ozone arrival from the upper layers of the troposphere (JIANG et al., 2015; ZVYAGINTSEV et al., 2016). The intensity of ultraviolet radiation, enabling to provide generation of ozone in the surface polluted air layer, also increases in summer time. This requires special weather conditions, high concentrations of precursors as well as their specific ratio. In particular, the ozone generation will be most effective if the VOC emission is several times higher than the emission of nitrogen oxides (SILLMAN, 2000). It has been found that in the case of a relatively low NO_x amount and a high VOC concentration, the O_3 concentration rises with increasing NO_x and changes little in response to a gain in the VOC concentration. And for the opposite case, one has the concentration of O_3 falling with increasing NO_x and growing with increasing VOC (SILLMAN, 2003). Normally, in Belarus the concentration of ozone precursors is low in summer, and analyzing averaged characteristics of air and weather conditions, it is difficult to reveal episodes of high ozone concentrations due to anthropogenic pollution.

Diurnal dynamics

In cities, high concentrations of anthropogenic pollution during the day most often appear in the form of short-term big gains in concentrations in regard to a smoother "background" level. To define the regularities in the diurnal course of pollution, we identified and analyzed the frequency of the cases with increased concentrations. All observation data in the six regional centers of Belarus were used for the periods indicated in the Section Material and methods. Observations were selected with the concentrations of individual pollutants exceeding 1.5 times the corresponding average monthly value, and the time of occurrence of such an event was recorded. Further, the number of cases falling in each hour time interval was normalized to their total number. The results for different seasons are shown in fig. 3 with the diurnal course of ozone concentration averaged over all cities.

A high correlation for the time of occurrence of peak concentrations of all the anthropogenic pollutants (carbon oxide, nitrogen oxide and dioxide, and a sum of concentrations of benzene, toluene and xylene) as well as their anticorrelation with ozone is observed.

Most often, increased concentrations of pollution are registered in the morning and evening, while during the day and night they are likely to occur rather rarely. This peculiarity of the diurnal course is typical for other cities (ALMBAUER et al., 2000; MAKRA et al., 2010; CHEN, TANG, ZHAO, 2015). However, one characteristic feature (at least for Belarus) has not been noticed before: the first, morning peak comes at 5 o'clock GMT (8 a.m. local time) in any city of Belarus, but the time of the second, evening peak depends on a season.

Thinking in a perfunctory manner, one may believe this event to be correlating with the duration of a light day: in winter it occurs earlier, in spring and summer – much later, and in autumn it again shifts to earlier time. However, the observed correlation cannot serve as an explanation for a seasonal shift of the evening peak, since the physical mechanisms of such a shift are not clear. Nor can this explain constancy of the morning peak, which falls on the dark time in winter.

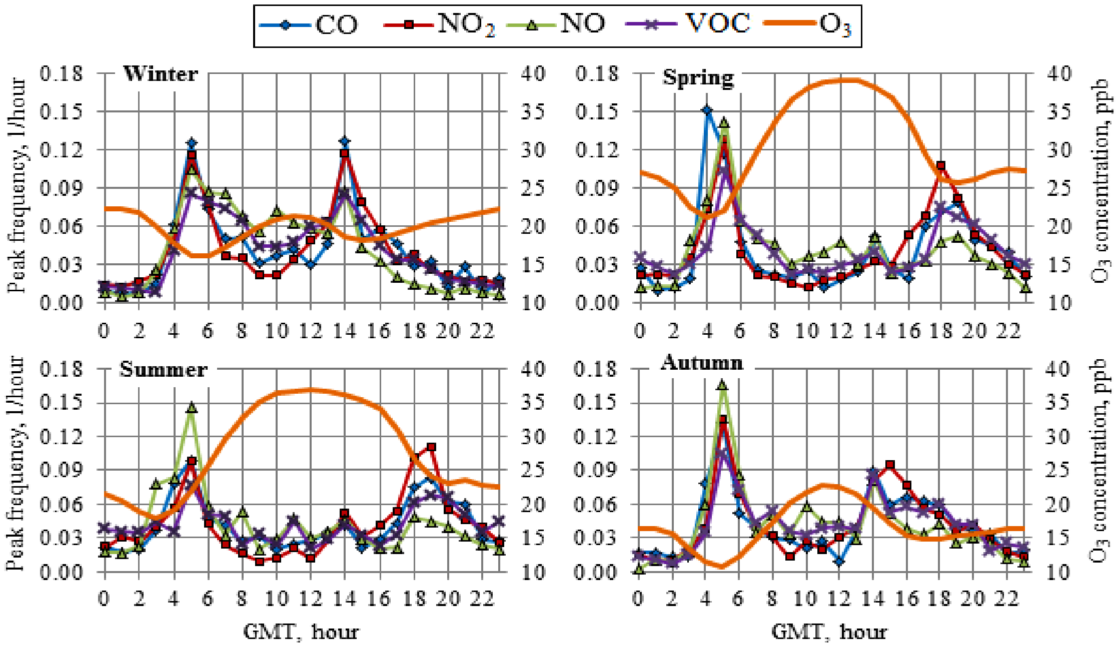

Fig. 3. Frequency distribution of increased concentrations of anthropogenic pollution depending on time of a day and the averaged diurnal variation in ozone concentration in different seasons

Rys. 3. Rozkład częstości podwyższonych stężeń zanieczyszczeń antropogenicznych w zależności od pory dnia i uśrednionych dobowych wahań stężenia ozonu w różnych porach roku

Рис. 3. Распределение частоты появления повышенных концентраций антропогенных загрязнений по времени суток и суточный ход концентрации озона в разные сезоны

It is natural to assume that the appearance of increased concentrations of anthropogenic pollution in the morning and in the evening, the constancy of the morning maximum and the shift of the evening one depending on a season are stipulated by specifics of the diurnal course of the pollution sources intensity. However, meteorological factors also play an important role.

Ozone anticorrelates with precursors, reaching high levels in the daytime and being low at night. The fact, that a gain in the concentration of ozone precursors in morning and evening hours is consistent with a decrease in its concentration at this time, indicates the destruction of ozone in the polluted urban air. This regime refers to a NO$_x$-saturated one (SILLMAN, 2000, 2003) and leads to a decrease of ozone when the NO$_x$ concentration rises.

In winter, the amount of pollutant emissions rises due to a heating season. Conservation of a relatively high ozone concentration at night under favorable conditions (a low rate of the deposition on the snowy surface and the inhibited convection) and its subsequent decrease in the morning is also probably associated with a beginning of processes of morning ozone destruction.

Activity of anthropogenic air pollution sources

The concentration of pollutants in the urban air depends primarily on the intensity of emissions of local sources. Therefore, we may expect that it is the diurnal course of their activity that determines a change in the concentration of pollutants over time (ALMBAUER et al., 2000; MAKRA et al., 2010; AL-AWADHI, 2014). There is convincing evidence of such influence. For example, ALMBAUER et al. (2000), MAKRA (2005) mark a significant decrease in air pollution at the weekend, when the intensity of anthropogenic sources reduces.

The main sources of pollution in large cities are now automobiles, whose contribution to total emissions is over 70%, industrial enterprises and thermal power plants (ADAME et al., 2012). The intensity of automobile emissions rises in the morning, then decreases slightly during daytime, again rises in the evening and reduces with the dark time of a day (Leduc, 2008; van Ruth, 2014; Kleingeld et al., 2017; Klimek, Kotulski, Sedziwy, 2017). A decrease in the traffic intensity (and the intensity of emission of pollutants) during the day depends on a place of observation. For example, in so-called dormitory areas, where there are no industrial production and construction, this decrease is very significant. In areas, where industrial enterprises, construction sites and main highways are located, a considerable reduction in the traffic intensity should not be expected. In particular, the traffic intensity of trucks remains almost constant from morning to evening in Eindhoven (van Ruth, 2014).

Emissions of most industrial enterprises occur during the working day and end after 5–6 p.m. of local time in case of a one-shift operation, or at 11–12 p.m. with a two-shift operation. Few enterprises function in a twenty-four-hour regime. Consequently, the intensity of sources of anthropogenic air pollution decreases at night.

Anthropogenic emissions of air pollutants in cities significantly reduce during the weekend, and the daily course of pollutant concentrations well confirms this fact. Fig. 4 presents the diurnal course of pollution concentration averaged over individual seasons and regional cities on weekdays and weekends. In contrast to the previous case (fig. 3), here we deal with concentrations, and not a frequency of registration of increased concentrations. Therefore, the morning and evening maxima are not revealed so clearly.

The difference between weekdays and weekends is due solely to a decrease in the activity of air pollution sources on weekends. However, there are still morning and evening

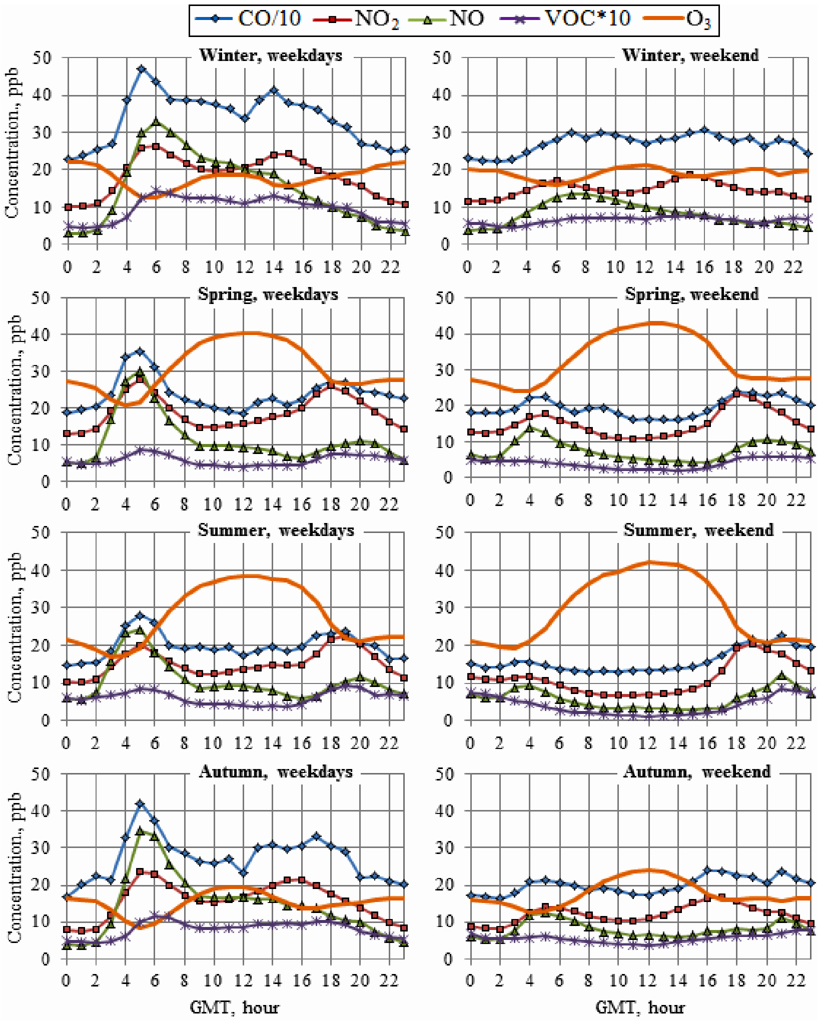

Fig. 4. Daily course of concentration of anthropogenic pollutants and ozone on weekdays and weekends

Rys. 4. Dzienny przebieg stężeń antropogenicznych zanieczyszczeń i ozonu w dni powszednie i weekendy

Рис. 4. Суточный ход концентрации антропогенных загрязняющих веществ и озона в будние и выходные дни peaks of the concentration of pollutants in spring and summer at the weekend, while in autumn and winter these are very weak.

It seems appropriate to reveal the results of observations in the Berezinsky Biosphere Reserve located far enough from anthropogenic sources. The diurnal variation in the concentrations of some anthropogenic pollutants and ozone, averaged over the seasons in 2014 and 2015, is shown in fig. 5.

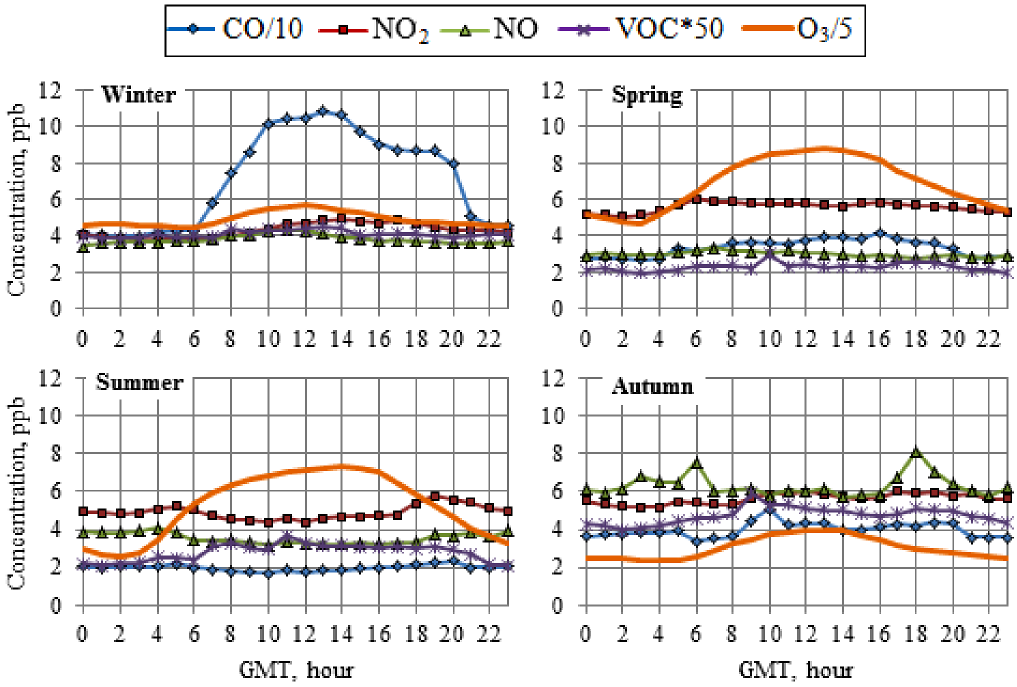

Fig. 5. Diurnal course of pollutant concentrations at the Berezinsky Biosphere Reserve in different seasons
Rys. 5. Dobowy przebieg stężeń zanieczyszczeń w Rezerwacie Biosfery Berezyński w różnych porach roku
Рис. 5. Суточный ход концентраций загрязнений в Березинском биосферном заповеднике в разные сезоны

The concentrations of pollution in the Reserve are much lower than those in cities, and they are mainly determined by the wind transfer of polluted air. Therefore, their diurnal course is practically missing, despite the diurnal course of atmospheric stability and wind speed being identical to those in cities. The vertical mixing does not lead to changes due to vertical homogeneity of the composition of the troposphere in the well-mixed air. Thus, the wind bringing air with the same concentrations of pollutants does not make any changes.

With regard to one of the pollutants – carbon oxide – it should be noted that in the winter time the Reserve has its own source of this pollutant – emissions from heating stoves in villages located within the territory of or nearby the Reserve. This explains the increase in CO concentration in winter and its specific diurnal variation.

Vertical stability of the atmosphere

The state of the atmosphere (or stratification), in which minor vertical movements in the atmosphere propagate onwards, taking up new layers of air, is called unstable. On the contrary, if the movements that have begun, do not evolve, but rather die down, one speaks of a stable stratification. These propagations are more intense at large vertical temperature gradients, $-\partial T/\partial h$ (T is the temperature, h is the height), and rapidly dampen in isothermal and inversion layers.

In Belarus, measurements of the vertical temperature profile are not currently conducted. At the National Hydrometeorological Center, the global numerical model of the UKMO (United Kingdom Meteorological Office) is used to estimate a magnitude of the vertical temperature gradient in the boundary layer of the troposphere. Data have been taken from Met Office, 2018. Based on UKMO data, it is possible to estimate the vertical temperature gradient in the boundary layer of the atmosphere for two layers: from a height of 2 m to an air pressure level of 925 hPa and from a level of 925 hPa to 850 hPa (pressure values approximately correspond to heights of 800 and 1500 m).

The minimum value of the temperature gradient for the two given layers is further used as a parameter characterizing the efficiency of the vertical mixing. This choice ensues from the fact that the vertical exchange is restrained by a layer of air that has the highest stability, that is, the lowest vertical temperature gradient.

In other words, it does not matter where the temperature inversion was formed, it is important that as a result, vertical movements are abruptly slowed down, and this prevents the mixing of the surface air with the air from the upper layers of the lower troposphere and the dispersion of pollutants.

In some other publications, the height boundary of the mixing layer is preferred (ALMBAUER et al., 2000; GEIß et al., 2017; MAKRA et al., 2010; SCHÄFER et al., 2014). Although this height is not coupled by a clearly defined functional dependence with the above minimum gradient, the named characteristics should qualitatively well correlate with one another, proceeding from physical considerations.

According to the foresaid, the lower is the value of the gradient, the more stable is the atmosphere, and the stronger the vertical movements of air are slowed down. Fig. 6 shows the diurnal variation of the vertical temperature gradient in different seasons in the regional cities of Belarus. The results are obtained by averaging the calculations for each of the seasons of 2013–2015 in Minsk and Viciebsk, for 2014–2016 in Gomel and Grodno, and for 2013–2016 in Brest and Mogilev. It can be seen that the stability of the atmosphere in winter is the highest. Furthermore, it depends little on the time of a day. In spring and summer, the stability rises at night and falls during daytime. A minimum of the stability (a maximum of the vertical temperature gradient) usually arises in the afternoon (about 12 hours GMT). In the autumn period, the stability parameter holds an intermediate position between winter and spring-summer values.

The frequency peaks of increased pollutant concentrations (grey areas on the graphs) correspond to the lower but not the minimum, even slightly rising in winter, values of the vertical temperature gradient in all seasons. Therefore, one cannot positively state that this parameter has a decisive influence on the seasonal shift of the evening maximum of pollution and on constancy of the morning one. This is also confirmed by a minor change in the gradient value during the day in winter.

In autumn and winter, the morning peak of anthropogenic air pollution falls at the minimum of the vertical temperature gradient, and in spring and summer it comes when the gradient rapidly grows. Since a significant change in the gradient does not affect in any way the time of the morning maximum, we may conclude that the vertical stability of the atmosphere is not the determining factor in explaining the constancy of the morning maximum time and the evening peak shift.

Fig. 6 displays a very weak variability of the minimum temperature gradient in the boundary layer of the troposphere over the country. Among the possible reasons, one might assume a low spatial resolution of calculations, but analysis of diurnal (not averaged over the seasons and years) data refutes this assumption: the results show a significant difference in the vertical temperature gradient depending on a region on individual days (fig. 7).

Consequently, closeness of the curves in fig. 6 is the result of averaging over the aggregate of days and years. In other words, in Belarus normals of the diurnal course of the vertical temperature gradient remain almost the same, despite possible significant differences of the gradient between individual regions on a particular day of a particular year.

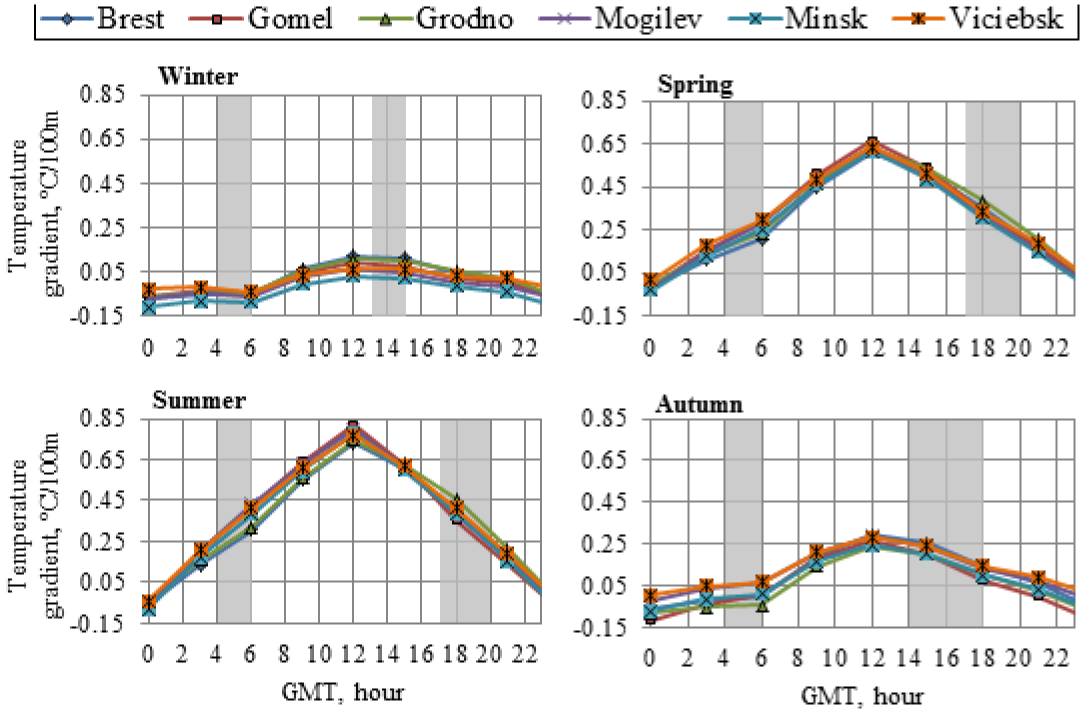

Fig. 6. Average daily variation of the vertical temperature gradient in the boundary layer of the troposphere in different seasons. The intervals of time corresponding to the highest frequency of occurrence of the increased concentrations of anthropogenic pollution have been filled with a grey color

Rys. 6. Średnie dobowe zmiany pionowego gradientu temperatury w warstwie granicznej troposfery w różnych porach roku. Przedziały czasu odpowiadające największej częstości występowania zwiększonych stężeń zanieczyszczeń antropogenicznych wypełniono szarym kolorem

Рис. 6. Средний суточный ход вертикального градиента температуры в пограничном слое тропосферы в разные сезоны. Закрашены интервалы времени, отвечающие наибольшей частоте появления повышенных концентраций антропогенных загрязнений

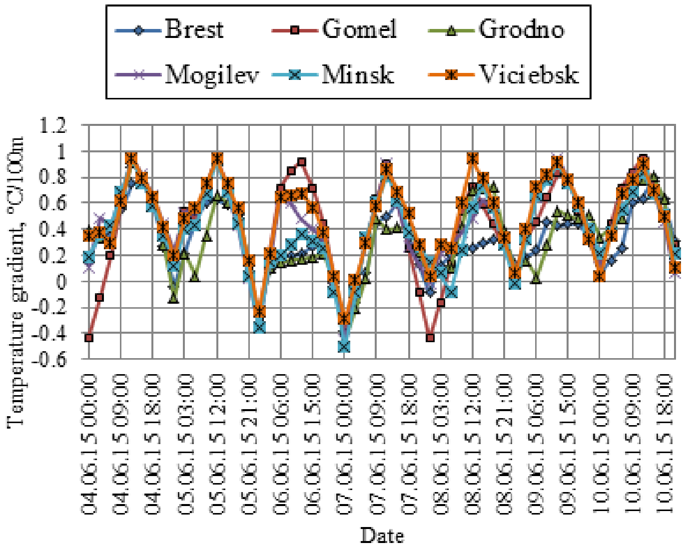

Fig. 7. Diurnal course of the vertical temperature gradient covering several days of June, 2015 in the regional centers of Belarus

Rys. 7. Dobowy przebieg pionowego gradientu temperatury w miastach obwodowych Białorusi obejmujący kilka dni czerwca 2015 r.

Рис. 7. Суточный ход вертикального градиента температуры в областных городах Беларуси за несколько дней июня 2015 г.

Wind speed

A dynamic climatic normal (Vinnikov, Robock, Basist, 2002; Vinnikov et al., 2004; Vinnikov et al., 2006; Bloomer, Vinnikov, Dickerson, 2010) of the wind speed was determined for the regional cities of Belarus, depending on a season and time of a day, on the basis of observations conducted at the city weather stations covering the period of 1985–2015. In contrast to the classical definition of WMO, the dynamic normal enables to determine not only the annual course of a meteorological parameter, but also its long-term trend.

The normal of the diurnal variation of the wind speed in all cities, despite differences in an absolute magnitude, turns out to be increasing in the daytime and reducing by the night (fig. 8). Just like in a case of the vertical temperature gradient, in winter these changes are minor, while in other seasons they are rather significant.

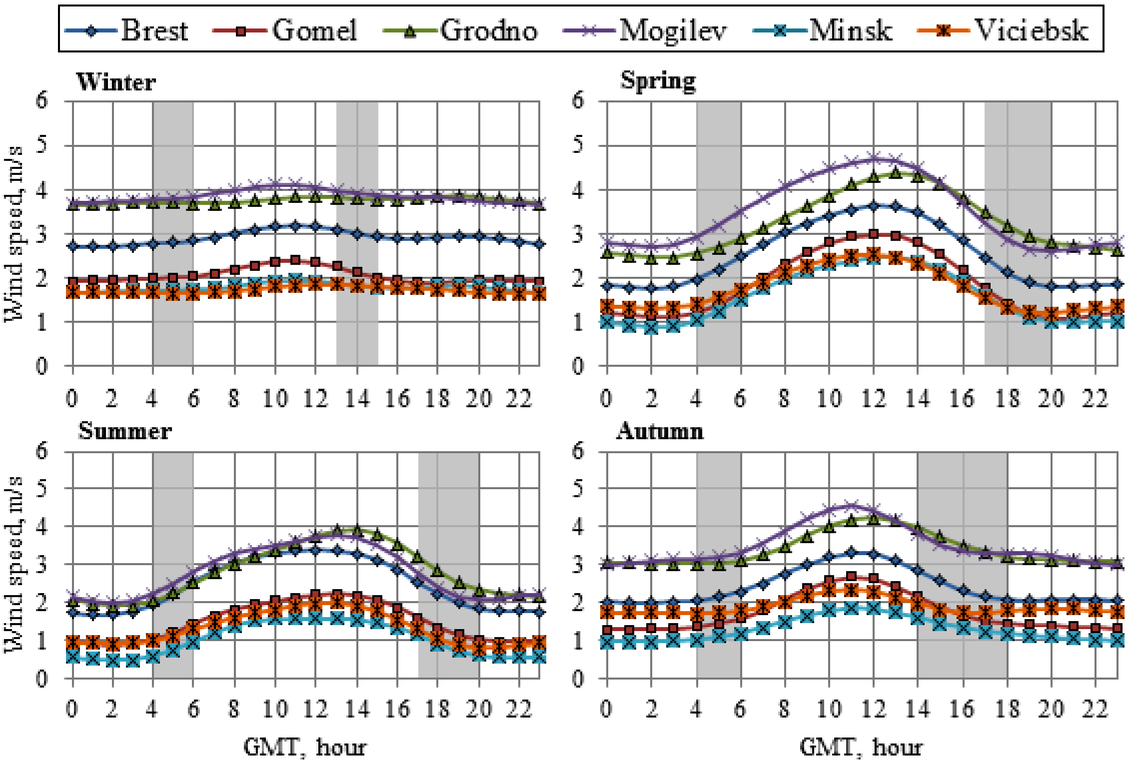

Fig. 8. Climatic normals of the diurnal course of the wind speed in the regional centers of Belarus
Rys. 8. Klimatyczne normy dobowego przebiegu prędkości wiatru w miastach obwodowych Białorusi
Рис. 8. Климатические нормы суточного хода скорости ветра в областных центрах Беларуси

Thus, the diurnal course of the wind speed and the vertical stratification of the boundary layer of the troposphere contribute to the dispersion of pollutants and the reduction of their concentrations in the surface layer of air during daytime. The time of the evening peak of the frequency of increased pollutant concentrations follows the seasonal shift of the minimum wind speed. The curves are plotted for the dates of January 15, April 15, July 15, and October 15. It is well seen that in spring and summer an evening decrease in the wind speed occurs somewhat later if compared to winter and autumn.

Conclusions

In cities of Belarus, the concentration of anthropogenic air pollution is usually significantly higher, and ozone is lower in comparison with rural areas. The magnitude of air pollution grows in autumn and winter and decreases in the spring-summer time. The seasonal course of surface ozone is revealed as the opposite to the course of concentrations of anthropogenic pollution. This behavior is most likely due to the vertical stability of the atmosphere varying during a year and intensifying or slowing down the dispersion of anthropogenic pollution and the inflow of ozone from the upper layers of the troposphere.

The daily course of pollutant concentrations is more strongly affected by the wind, whose speed reaches a maximum in the afternoon. This conclusion results from the correlation between the shift in the time of the evening peak of pollution and the minimum of the wind speed.

If one assumes the intensity of anthropogenic pollution sources to be constant during the day, then the increased vertical stability of the atmosphere and the wind dying down at night should contribute to a growth of the pollution concentrations in the air in comparison with the daytime. However, we positively know that the intensity of sources falls at night, and the concentrations of pollutants in the air, as the observations show, do decrease. And in the daytime effective mechanisms for the dispersion of pollutants are activating and their concentration again decreases. Therefore, the effects of inhibition of the pollution dispersion emerge only in the morning and in the evening, when there are good reasons for a dispersion slowdown, and the intensity of sources is already (in the morning) or still (in the evening) great. In other words, a decrease in urban air pollution after the evening maximum results from a reduction in emissions, despite a weakening of the efficiency of pollution dispersion. Similarly, an increase in pollution in the morning should be attributed to an increase in the activity of emission sources, where the enhancing dispersion processes finally form the morning peak, ensuring a subsequent decrease in the concentrations of anthropogenic pollution.

To a lesser extent this conclusion is valid for the winter season, where the daily variation of the vertical stability of the atmosphere and the wind speed are insignificant, and they act in an antiphase: the stability is high and the wind speed is also high, yet, the morning and evening peaks are observed (STURM, 2003), although their amplitudes are noticeably lower. Perhaps, only during this period the observed morning and evening maxima of anthropogenic pollution are stipulated mainly by the daily course of the traffic intensity.

This leads us to the implication that human activity appears to be the main reason for occurrence of the morning and evening peaks of air pollution in cities, and its beginning and damping correlate with the time of maximum concentrations of air pollution. The diurnal course of the efficiency of the processes of pollution dispersion plays an important role in the formation of these peaks. The influence of meteorological conditions on the level of urban air pollution most distinctively reveals in the morning and in the evening, contributing much to the termination of a growth of the morning concentrations and to the beginning of an evening increase.

The seasonal dynamics of ozone precursors depends on the anthropogenic activity. The heating season in winter yields an increase in the concentration of pollutants in the atmosphere. The seasonal dynamics of pollutants is also consistent with the annual course of meteorological factors enhancing their dispersion. Those factors are the wind, transporting pollution in the horizontal direction, and the convection with the intense vertical air mixing.

Surface ozone is a secondary air pollutant which can be produced in the presence of primary ones due to the solar radiation activity. On the territory of Belarus, the following processes affect the observed concentration of surface ozone: atmospheric convection, wind transport, destruction and generation in the presence of nitrogen oxides, carbon oxide and VOCs, and deposition on the surface. The polluted air of cities suppresses ozone. This is confirmed by anticorrelation of ozone with precursors in both annual and daily courses. Air pollution increasing in the morning and evening hours leads to a fall in the ozone concentration. A decrease in pollution at weekends correlates with a growth of surface ozone.

Only in the cold period does the ozone concentration remain at night almost the same as during the day, due to a low rate of destruction on the snowy surface, inhibited convection and the lowered solar radiation which initiates chemical processes involving ozone. In the annual course, the level of ozone is high in spring and summer because of an increase in the intensity of the ozone generation and thermal convection.

While studying the problem, one has not revealed high ozone episodes in city air related to a VOC-saturated regime. Probably, this is due to a low level of the air pollution and a composition of pollution. In addition, such episodes are usually short-lived, and for their detection some other techniques are required employing a detailed analysis of the daily course of meteorological conditions, concentrations of anthropogenic pollutants and ozone (AVINO, 2004).

The results obtained are based solely on the statistical characteristics of the annual and diurnal course of pollutant concentrations and the meteorological parameters defining efficiency of their dispersion. At this point, one can assume that the effect of the revealed physical mechanisms controlling the concentration of anthropogenic pollution of urban air also shows itself only in a statistical sense. However, these mechanisms are by no means of a statistical nature, despite the fact that a statistical approach has been used with averaging over seasons and a number of years to detect their effect on the air pollution. The intensity of emission sources and the meteorological conditions, varying both with every day and during the day, can bring significant changes into the described average picture: a new powerful source of pollution, destruction of inversion or wind intensification rapidly lead to a change in the level of the urban air pollution on any day of a year and at any time of a day. In this case, the course of pollution concentrations differs from the mean diurnal one, but the intensity of emissions, wind and thermal convection are still the reasons for its change.

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References

Adame J. A., Hernández-Ceballos M. A., Bolívar B. De la Morena J. P., 2012: Assessment of an air pollution event in the southwestern Iberian Peninsula. Atmospheric Environment, 55: 245–256. https://doi.org/10.1016/j.atmosenv.2012.03.010.

Al-Awadhi J. M., 2014: Measurement of Air Pollution in Kuwait City Using Passive Samplers. Atmospheric and Climate Sciences 4, 253–271. http://dx.doi.org/10.4236/acs.2014.42028.

Almbauer R. A., Piringer M., Baumann K., Oettl D., Sturm P. J., 2000: Analysis of the daily variations of wintertime air pollution concentrations in the city of Graz, Austria. Environmental Monitoring and Assessment, 65: 79–87. https://doi.org/10.1023/A:1006464225727.

Avino P., 2004: Mechanism of smog photochemical formation in the urban area of Rome. In: Zerefos C. S. (ed.): Proceedings of the Quadrennial Ozone Symposium, Kos (Greece): 936–937.

Bian L., Ye L., Ding M., Gao Z., Zheng X., Schnel R. C., 2018: Surface ozone monitoring and background concentration at Zhongshan Station, Antarctica. Atmospheric and Climate Sciences, 8: 1–14. https://doi.org/10.4236/acs.2018.81001.

Bloomer B. J., Vinnikov K. Y., Dickerson R. R., 2010: Changes in Seasonal and Diurnal Cycles of Ozone and Temperature in the Eastern U.S. Atmospheric Environment, 44: 2543–2551. https://doi.org/10.1016/j.atmosenv.2010.04.031.

Brönnimann S. T., Neu U., 1997: Weekend-weekday differences of near-surface ozone concentrations in Switzerland for different meteorological conditions. Atmospheric Environment, 31, 8: 1127–1135. https://doi.org/10.1016/S1352-2310(96)00311-1.

Chen W., Tang H., Zhao H., 2015: Diurnal, weekly and monthly spatial variations of air pollutants and air quality of Beijing. Atmospheric Environment, 119: 21–34. https://doi.org/10.1016/j.atmosenv.2015.08.040.

Clapp L. J., Jenkin M. E., 2001: Analysis of the relationship between ambient levels of O_3, NO_2 and NO as a function of NO_x in the UK. Atmospheric Environment, 35: 6391–6405.

Cristofanelli P., Bonafë U., Bonasoni P., Colombo T., Stohl S., 2004: Vertical exchange of ozone between the boundary layer and the free troposphere. In: Zerefos C. S. (ed.): Proceedings of the Quadrennial Ozone Symposium, Kos (Greece): 862–863.

Finardi S., Pellegrini U., 2004: Systematic analysis of meteorological conditions causing severe urban air pollution episodes in the Central Po valley. In: Institut für Meteorologie und Klimaforschung. Proceedings of the 9th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Garmisch-Partenkirchen (Germany): 250–254. http://www.harmo.org/conferences/Proceedings/_Garmisch/publishedSections/6.13.pdf.

Geiß A., Wiegner M., Bonn B., Schäfer K., Forkel R., von Schneidemesser E., Münkel C., Chan K. L., Nothard R., 2017: Mixing layer height as an indicator for urban air quality? Atmospheric Measurement Techniques. 10: 2969–2988. https://doi.org/10.5194/amt-10-2969-2017.

Han L, Zhou W., Li W., Meshesha D. T., Li L., Zheng M., 2015: Meteorological and urban landscape factors on severe air pollution in Beijing. Journal of the Air & Waste Management Association, 65: 782–787, https://doi.org/10.1080/10962247.2015.1007220.

IPCC, 2006. Precursors and Indirect Emissions. In: Eggleston H. S. et al. (eds.): Guidelines for National Greenhouse Gas Inventories V. 1 General Guidance and Reporting, Japan, IGES: 16 p.

Jenkin, M., Clemitshaw K. C., 2000: Ozone and other secondary photochemical pollutants: chemical processes governing their formation in the planetary boundary layer. Atmospheric Environment, 34: 2499–2527.

Jiang Y.C., Zhao T. L., Liu J., Xu X. D., Tan C. H., Cheng X. H., Bi X. Y., Gan J. B., You J. F., Zhao S. Z., 2015: Why does surface ozone peak before a typhoon landing in southeast China? Atmospheric Chemistry and Physics, 15: 13331–13338. https://doi.org/10.5194/acp-15-13331-2015.

Khuriganova O., Obolkin V., Akimoto H., Ohizumi T., Khodzher T., Potemkin V., Golobokova L., 2016: Long-Term Dynamics of Ozone in Surface Atmosphere at Remote Mountain, Rural and Urban Sites of South-East Siberia, Russia. Open Access Library Journal, 3, 4: 1–9. http://dx.doi.org/10.4236/oalib.1102578.

Kleingeld E., van Hove B., Elbers J., Jacobs C., 2017: Carbon dioxide fluxes in the city centre of Arnhem, A middle-sized Dutch city. Urban Climate, 24: 994–1010. https://doi.org/10.1016/j.uclim.2017.12.003.

Klimek R., Kotulski L., Sedziwy A., 2017: Behavioural patterns from cellular data streams and outdoor lighting as strong allies for smart urban ecosystems. Frontiers in Artificial Intelligence and Applications, 298: 109–121. https://doi.org/10.3233/978-1-61499-804-4-109.

Laña, I., Del Ser J., Padró A., Vélez M., Casanova-Mateo C., 2016: The role of local urban traffic and meteorological conditions in air pollution: A data-based case study in Madrid, Spain. Atmospheric Environment, 145: 424–438. http://doi.org/10.1016/j.atmosenv.2016.09.052.

Leduc G., 2008: Road Traffic Data: Collection Methods and Applications. In: Working papers on energy, transport and climate change, N.1. European Commission, Joint Research Centre, Institute for Prospective Technological Studies, Seville (Spain): 55 p.

Logan J. A., 1989: Ozone in rural areas of the United States. Journal of geophysical research. 94 (D6): 8511–8532. https://doi.org/10.1029/JD094iD06p08511.

Makra L., 2005: The Role of Traffic in Modifying Air Quality in a Medium-Sized City, Szeged, Hungary. Epidemiology, 16: 62–72. https://journals.lww.com/epidem/Fulltext/2005/09000/

Makra L., Mayer H., Mika J., Sánta T., Holst J., 2010: Variations of traffic related air pollution on different time scales in Szeged, Hungary and Freiburg, Germany. Physics and Chemistry of the Earth, 35: 85–94. https://doi.org/10.1016/j.pce.2010.03.005.

Matuszko D., 2012. Influence of the extent and genera of cloud cover on solar radiation intensity. International Journal of Climatology, 32: 2403–2414. https://doi.org/10.1002/joc.2432.

Met Office. http://www.metoffice.gov.uk, 2018. [Online; accessed January 2018].

Oltmans S., Schnell R., Johnson B., Pétron G., Mefford T., Neely R. III, 2014: Anatomy of wintertime ozone associated with oil and natural gas extraction activity in Wyoming and Utah. Elementa: Science of the Anthropocene, 2, 24, 15 p. http://doi.org/10.12952/journal.elementa.000024.

Order of the Ministry of Health of the Republic of Belarus "On the Approval and Enforcement of Standards for Maximum Permissible Concentrations of Pollutants in the Atmospheric Air and Approximately Safe Levels of Impact of Pollutants in the Atmospheric Air of Settlements and Places for Mass Recreation of the Population and the Recognition of Some Orders of the Ministry of Health of the Republic of Belarus as Invalid of 08.11.2016, № 113" [Postanovlenie ministerstva zdravoohraneniya Respubliki Belarus "Ob utverzhdenii i vvedenii v deystvie normativov predelno dopustimyih kontsentratsiy zagryaznyayuschih veschestv v atmosfernom vozduhe i orientirovochno bezopasnyih urovney vozdeystviya zagryaznyayuschih veschestv v atmosfernom vozduhe naselennyih punktov i mest massovogo otdyiha naseleniya i priznanii utrativshimi silu nekotorykh postanovleniy Ministerstva zdravoohraneniya Respubliki Belarus ot 08.11.2016, № 113"], Minsk, 2016. http://pravo.by/document/?guid=3961&p0=W21631467p (in Russ.)

Schäfer K. et al., 2014: Influences of meteorological parameters and mixing layer height upon air pollutant concentrations in urban area. In: Proceedings of the 9th international conference on air quality science and application, Garmisch-Partenkirchen (Germany): 11 p. https://www.umwelt.sachsen.de/umwelt/download/KlausSchaefer.pdf.

Sillman S., 2000: Ozone production efficiency and loss of NOx in power plant plums: photochemical model and interpolation of measurements in Tennessee. Journal of geophysical research 105 (D7): 9189–9202. https://doi.org/10.1029/1999JD901014.

Sillman S., 2003: Tropospheric ozone, smog and ozone-NOx-VOC sensitivity. Treatise on Geochemistry, 9: 407–431. https://doi.org/10.1016/B0-08-043751-6/09053-8.

Solberg S., Simpson D., Jonson J. E., Hjellbrekke A. G., Derwent R., 2004: Ozone. Chapter 6. In: Lövblad G. et al. (eds.): EMEP Assessment Report – Part I, Oslo (Norway): 77–106. http://emep.int/publ/reports/2004/assessment/Part1_087-116_06-Ozone.pdf

Stockwell W. R., Lawson C. V., Saunders E., Goliff W. S., 2012: A review of tropospheric atmospheric chemistry and gasphase chemical mechanisms for air quality modeling. Atmosphere, 3: 1–32. https: //doi.org/10.3390/atmos3010001.

Sturm P. J., 2003: Air Pollutant Emissions in Cities. Chapter 3. In: Moussiopoulos N. (ed.): Air Quality in Cities. Springer, Berlin, Heidelberg: 31–50. https://doi.org/10.1007/978-3-662-05217-4_4.

THE_ROLE_OF_TRAFFIC_IN_MODIFYING_AIR_QUALITY_IN_A.150.aspx

Van Ruth F., 2014: Traffic intensity as indicator of regional economic activity. Statistics Netherlands, Discussion Paper, 21: 1–27. https://www.cbs.nl/nl-nl/achtergrond/2014/34/traffic-intensity-as-indicator-of-regional-economic-activity.

Verma N., Satsangi A., Lakhani A., Kumari K. M., 2018: Characteristics of surface ozone in Agra, a suburban site in Indo-Gangetic Plain. Journal of Earth System Science, 127 (3): 1–16. https://doi.org/10.1007/s12040-018-0934-3.

Verma S. S., Desai B., 2008: Effect of Meteorological Conditions on Air Pollution of Surat City. Journal of International Environmental Application & Science, 3 (5): 358 –367.

Vinnikov K. Y., Robock A., Basist A., 2002: Diurnal and Seasonal Cycles of Trends of Surface Air Temperature. Journal of Geophysical Research: Atmospheres, 107 (D22): 4641–4661. https://doi.org/10.1029/2001JD002007.

Vinnikov K. Y., Robock A., Grody N. C., Basist A., 2004: Analysis of Diurnal and Seasonal Cycles and Trends in Climatic Records with Arbitrary Observation Times. Geophysical Research Letters, 31 (6): 5 p. https://doi.org/10.1029/2003GL019196.

Vinnikov K. Y., Grody N. C., Robock A., Stouffer R. J., Jones P. D., Goldberg M. D., 2006: Temperature Trends at the Surface and in the Troposphere. Journal of Geophysical Research: Atmospheres 111, (D3): 14 p. https://doi.org/10.1029/2005JD006392.

Zhang Y., Wang Y., 2016: Climate-driven ground-level ozone extreme in the fall over the Southeast United States. Proceedings of the National Academy of Sciences of the USA, 113: 10025–10030. https://doi.org/10.1073/pnas.1602563113.

Zvyagintsev A. M., Kuznetsova I. N., Shalygina I. Yu., Lapchenko V. A., Brusova N. E., Arkhangelskaya A. A., Tereb N. V., Lezina E. A., 2016. Causes and factors of positive surface ozone anomalies in the Moscow region and on the southeastern coast of the Crimea. Atmospheric and Oceanic Optics, 29 (6): 551–560. https://doi.org/10.1134/S1024856016060178.

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