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Seasonal variations of the air pollutant concentrations for Krasnoyarsk non-uniform urban territory

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Abstract. In this paper, it is shown that there are great differences in seasonal variations of concentrations of the main atmospheric pollutants in various parts of a large urban territory. The city of Krasnoyarsk is used as an example. For this, an observation method proposed by the authors is used. The detected differences in seasonal variations are a consequence of the microclimatic inhomogeneities of the city territory. They show the effects of breeze and orographic-type circulations on the space-time distribution of atmospheric pollutants. The investigation of the seasonal variability of concentrations of atmospheric pollutants in various parts of the city has made it possible to obtain some useful characteristics for the estimation of population exposure.

1. Introduction

Among the environmental protection problems, the problem of providing the pollution — free atmosphere is especially important. This is due to the fact that the air pollution causes a lot of diseases. Hence, polluted air should be considered as a source of potential danger (risk) for the population and environment. The fact is, many kinds of important human activity associated with social-economic development cause the air environment pollution.

The air pollution in urban conditions is non-uniformly dispersed over the city territory. In many cases, the increased concentrations of pollutants may be observed in the neighborhood of pollution sources. As the motor traffic in cities increases, the most polluted territories are observed in places of compact building. In addition, emissions of a high space-time variability, as well as pollutants with changing conditions of dispersion in the atmosphere, cause variable concentration fields of complex nature in urban conditions.

To obtain a reliable information for the urban air quality management, one needs a comprehensive information about the seasonal and the diurnal variations of pollutant concentration in the sites, where population occurs [1].

1.1. Seasonal variability of pollutant concentrations for an urban territory. The annual variation of pollution vary for different cities due to many factors that affect the pollution composition.

In large European cities, a winter increase in pollutant concentrations is observed. This is caused by increased emissions in the heating season and a recurrence of unfavorable conditions for pollution dispersion in the air surface layer.

For instance, in Stuttgart, a large German city with a population of about 500,000, the seasonal variation in NO concentration is characterized by a winter (November-January) maximum. This is due not only to an increase in the emission volume, but also by a more stable condition of the atmosphere in this period. A minimum of nitrogen oxide in Stuttgart is observed in the summer (June–July) period. At the same time, the annual variation of concentrations of nitrogen dioxide, NO_2, is less pronounced [2].

Seasonal variations with maximum concentrations of NMHC (non-methane hydrocarbon), CO, and NO_x in the winter period and minimum concentrations in the summer period are observed in Kuwait [3]. A similar situation can also be observed in Indian and Japanese cities [4, 5].

An annual variation of sulphur dioxide and CO concentrations with a winter maximum is observed in Venice, Los Angeles, Delhi, in some cities of England, Canada, and Eastern Europe [6–11].

In Hong Kong, increased concentrations of anthropogenic pollutants in the atmosphere in the winter period are also observed. A decrease in the concentrations in the summer period is explained by heavy rains and a well-developed mixing layer [12].

In western regions of the USA [13], in late summer — early autumn, the pollutant concentrations in the atmosphere increase, which is caused by the formation of subsidence inversion, weak breeze winds, and intensive solar radiation. Many researchers indicate to an increase in the concentration of ozone in the urban atmosphere in the summer period.

In Russian cities, several types of the pollutant concentration variations in different seasons are observed [14]. These types are different for suspended and gaseous substances. For instance, in St. Petersburg, a dust concentration maximum is observed in spring, and a maximum of recurrence of increased SO_2 concentrations — in February.

In Arkhangelsk, the concentrations of dust and sulphur dioxide are maximal in winter. In Omsk, under the influence of an increased recurrence of winds from a large industrial complex, the pollution level increases in summer, although more hazardous substances (nearly 30 %) are ejected into the atmosphere in winter.

One can see that starting to investigate on seasonal variations of concentrations in the second half of the last century, so far, researchers have studied only the entire urban territory, but have not considered seasonal variations in different parts of a large urbanized territory.

This is mostly due to the fact that researchers with minor exception have at their disposal only a small number of stations for routine monitoring. These stations do not allow one to evaluate peculiarities of the space-time variability of pollutant concentrations on an urban territory that are necessary for controlling the pollution sources and estimating population exposure. For instance, most Russian cities have about 3–6 permanent stations to control the atmospheric pollution, the biggest cities have about 6–20 stations, and cities with a population less than 250 thousand have only about 1–2 stations. Eight permanent stations are used to control the atmospheric pollution in Krasnoyarsk, a large industrial center with a population of about 1 million.

Some researchers believe that the location of industrial enterprises in the city territory, the pollutant emissions of various kinds, and meteorological conditions — in different seasons of the year play a key role in the annual variation of the pollution composition of the atmosphere. However, some recent investigations have shown that a city microclimate, which is consequence of urbanization, has an ever increasing influence on the pollutant distribution in the atmosphere [15–18].

The study of the seasonal variations of pollutant concentrations in the atmosphere in different parts of the city territory can detect the influence of the city microclimate. Moreover, such information is needed to construct an urban air quality monitoring system, to control pollutant sources, as well as to develop new models of the urban air pollution and to improve the existing models.

1.2. Objectives and tasks. The purpose of this paper is to investigate the seasonal variability of the so-called "classical" air pollutants (CO, NO, NO_2, SO_2, and O_3) in various parts of a large urbanized territory of Krasnoyarsk. These pollutants are most widely distributed in the European Region and pose a risk to human health [1].

To solve this problem, we use the receptor-aided techniques to measure pollutant concentrations in the atmosphere in an inhomogeneous urbanized territory.

2. Methods

In this study, a mobile gas-analysis laboratory manufactured by Thermo-Environmental Instruments Inc. (USA) was exploited to measure pollutant concentrations in the Krasnoyarsk territory.

Throughout the world, mobile laboratories are used to solve many problems. These are: checking the capability of stationary observation points; a precise determination of the boundaries of sanitary protection zones of enterprises, detection of the episodic emissions; investigate motor-traffic pollution; and experimentally estimate the environment protection effectiveness of city design elements [15].

An effective use of mobile automated gas-analysis systems to investigate atmospheric pollution in an urban area is possible only if a good strategy for selecting observation points is developed. Such a strategy is necessary to make the best use of the observation time and to determine the number of points and their locations [19–22].

2.1. Krasnoyarsk territory zoning. In this paper, to choose observation points and to perform measurements, Krasnoyarsk territory zoning with allowance for the building density was made (Figure 1). In the zoning, the height of city building elements relative to the local terrain was taken into account.

In addition to the building density (P^B) and the height of terrain terraces, the zones obtained (Figure 1) have different functional types. They are characterized by an average height of buildings (H) and a width of urban roadways crossing the zone (w).

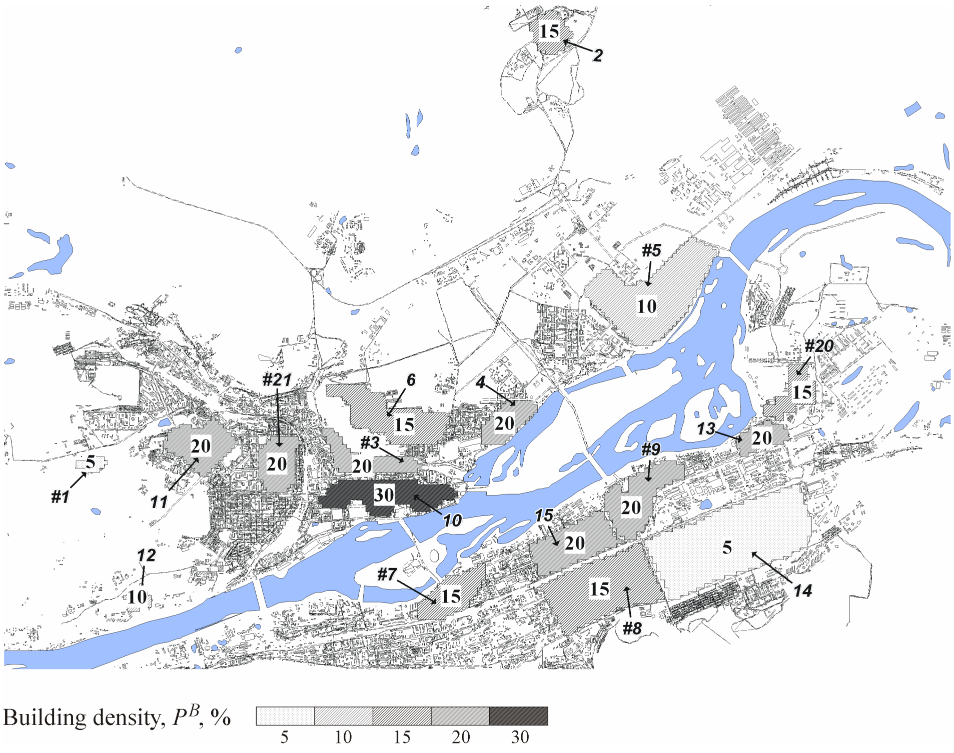

Figure 1. Zones of the Krasnoyarsk territory. A number in the zone center shows the building density (%). Numbers of zones with stationary air pollution observation stations of the State Center for Hydrometeorology and Environmental Monitoring are denoted by the symbol #, the zone number and the station number being the same

Table 1. Characteristics of measurement zones for the city of Krasnoyarsk

No	Zone number (Figure 1)	Height above sea level, m	Building density, P^B, %	Building height, H, m	Roadway width, w, m	Traffic* intensity, I, ths. vehicle/day	Functional type of zone**
1	#1	220	5	5	10	6	Residential
2	14	140	5	10	25	20	Industrial
3	12	260	10	15	30	10	Residential
4	#5	200	10	30	30	40	Commercial
5	6	260	15	5	20	7	Residential
6	#8	140	15	15	25	35	Residential, industrial
7	2	320	15	30	35	10	Residential
8	#7	140	15	30	35	85	Commercial
9	#20	140	15	30	35	8	Residential, industrial
10	13	140	20	10	30	40	Commercial
11	11	200	20	15	25	35	”
12	#3	140	20	15	25	35	”
13	4	160	20	15	50	60	”
14	#9	140	20	15	35	60	”
15	15	140	20	15	25	40	”
16	#21	180	20	15	20	55	”
17	10	140	30	15	25	30	”

*In all the zones, observations of traffic intensity were made. According to the observations results on major roadways, an average diurnal traffic intensity I (vehicle/day, averaged over 24 hours) was calculated. An analysis of the seasonal variations of traffic intensity in the Krasnoyarsk territory has shown that no significant differences in traffic intensity in the winter and in the summer seasons were observed on the roadways in all above zones.
**The major traffic flows of Krasnoyarsk are redistributed in commercial zones.

Let us consider in more detail some characteristics of the zones obtained for the Krasnoyarsk territory (Table 1). Table 1 shows detailed characteristics of the zones. It is seen that the zones differ in the building characteristics. The zones with building heights up to 15 m (zones #3, 4, #9, 10, 15, and #21) have a greater building density than “modern” neighborhood units with building heights of 30 m and higher (zones 2, #5, #7, and #20). Zones #1 and 14 have the least building density.

In contrast to European cities, which typically have building densities from 14 to 58 % [23], the zones marked to measure the air pollution concentrations for the city of Krasnoyarsk have building densities from 5 to 30 %.

All zones obtained for the Krasnoyarsk territory were partitioned according to their functions. Zones 10, #3, 4, #5, #21, 11, #7, 15, #9, and 13 obtained for the Krasnoyarsk territory are mostly of the traffic type, and the major flows of private, passenger, and cargo traffic pass though these zones.

Zones #1, 2, 6, 12, and #20 can be considered as residential. These zones have a low traffic intensity and no industrial enterprises. Zones #8 and 14 can be considered as residential-industrial. These are zones with industrial enterprises and apartment buildings.

2.2. Observation procedure. The measurements under consideration were made in the Krasnoyarsk territory from 2001 to 2005. Systematic route measurements during the day and at night were made in the zones obtained above. The observation program included estimation of traffic intensity on roadways inside each zone. The meteorological conditions were estimated using temperature–wind sounding data. The observations were made in the following models:

- Measurements on the city's major roadways with a spacing of 100 and 500 m during the day and night;
- Twenty-four-hour and systematic measurements in the city apartment buildings area at fixed observation points.

Three to five observation points were chosen in each Krasnoyarsk zone with a "homogeneous" building density. On the whole, there were more than 500 observation hours in each zone.

2.3. Processing of measurements. To investigate the seasonal variations of CO, NO, NO_2, SO_2, and O_3 concentrations in the Krasnoyarsk territory, some statistical indicators of the concentrations were calculated in each zone from October to March (the winter season) and from April to September (the summer season). The data were processed according to the measurement data statistical processing in 1997 WHO Report [24].

To analyze types of pollutant concentration variations in different seasons in the Krasnoyarsk territory, the authors proposed a parameter D. In order to determine this parameter in each zone and for each pollutant, the following ratio was calculated: $\Delta = \dfrac{C_\text{w}}{C_\text{s}}$, where C_w and C_s are average pollutant concentration levels for the winter and the summer periods, respectively.

The parameter D is determined as follows:

$$D = \begin{cases} 1, & \Delta > 1, \\ -1, & \Delta < 1, \\ 0, & \Delta \approx 1. \end{cases}$$

In other words, D is 1 if the winter pollution level is higher than the summer one, -1 if the summer pollution level is higher than the winter one, and 0 if a difference between the average pollution levels in the winter and in the summer periods is statistically insignificant. Thus, D is a parameter that characterizes types of pollutant concentration variations.

The correlation between the types of pollutant concentration variations was investigated. To estimate the correlation "strength", the Goodman γ-statistic was used [25, 26]. Investigation of a simultaneous variation of the parameter D for the pollutants under consideration was made with the use of a method of analysis of contingency tables [27].

3. Results

3.1. Variations of CO, NO, and NO_2 concentration. Let us consider variations of CO, NO, and NO_2 concentrations in different seasons in the Krasnoyarsk territory. These pollutants are major components of vehicle emissions. Therefore, it is convenient to consider them simultaneously.

Analysis of an average concentration of CO, NO, and NO_2 in different seasons in various city zones has made it possible to obtain the following types of concentration variations (Figure 2):

(a) Pollution maximum in the winter period and a minimum in the summer period, $D(1, 1, 1)$;

(b) Pollution maximum in the summer period and a minimum in the winter period, $D(-1, -1, -1)$;

(c) Uniform pollution level in summer and in winter, $D(0, 0, 0)$;

(d) a mixed type, $D(1, 0, -1)$.

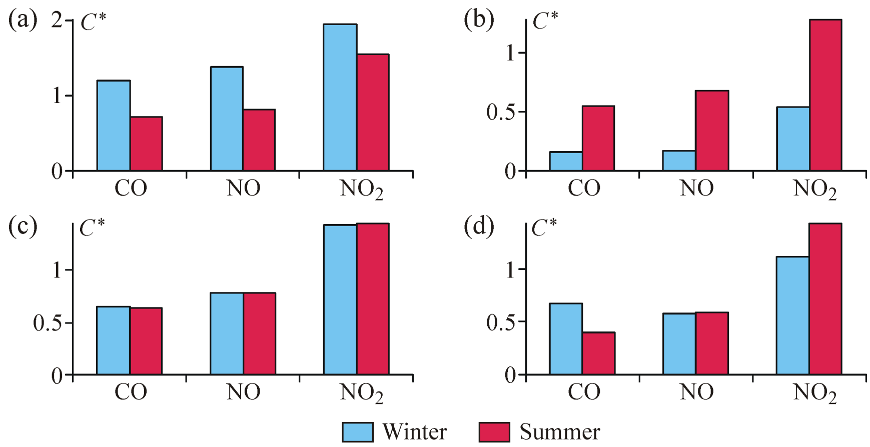

Figure 2. Types of CO, NO, and NO_2 concentration variations in Krasnoyarsk territory; (a) type $D(1, 1, 1)$ in zone #7; (b) type $D(-1, -1, -1)$ in zone 12; (c) type $D(0, 0, 0)$ in zone #15; (d) type $D(1, 0, -1)$ in zone #8. $C^* = C/\mathrm{MAC}$, where MAC is a maximum allowable concentration, the Russian standard of the air quality: $\mathrm{MAC_{CO}} = 5$ mg/m^3, $\mathrm{MAC_{NO}} = 0.4$ mg/m^3, $\mathrm{MAC_{NO_2}} = 0.085$ mg/m^3

Let us consider the distribution of various types of CO, NO, and NO_2 concentration variations for different seasons in the Krasnoyarsk territory (Table 2). One can see that predominance of the winter pollution level over the summer one for CO ($D_{CO} = 1$) is observed in more than half of the city zones. For NO, only 30 % of the territory has the type of pollutant concentration variations $D_{NO} = 1$, and the rest 70 % in equal proportion have the type $D_{NO} = 0$ (the pollution level does not change) and $D_{NO} = -1$ (the summer pollution level predominates). For nitrogen dioxide, the type of pollutant concentration variations $D_{NO_2} = -1$ is observed for the most part of the area under investigation.

Table 2. Distribution of types for CO, NO, and NO_2 concentration variations, %

D	CO	NO	NO_2
−1	12	35	65
0	35	35	18
1	53	30	17

Table 3. Correlation between types of pollutant concentration variations

Pollutants	Correlation
CO–NO	0.75
CO–NO_2	0.55
NO–NO_2	0.93

Now let us consider a correlation between the types of CO, NO, and NO_2 concentration variations (Table 3). To estimate the correlation strength, the Goodman γ-statistics was used [25, 26]. One can see that the strongest correlation is between the types of NO and NO_2 concentration variations. The variations of CO concentration in different seasons have also a strong positive correlation with NO concentration.

Table 4. Contingency for types of CO, NO, and NO_2 concentration variations, %

D_{CO}	D_{NO}	D_{NO_2}			D_{CO}	D_{NO}	D_{NO_2}			D_{CO}	D_{NO}	D_{NO_2}		
		−1	0	1			−1	0	1			−1	0	1
−1	−1	12	0	0	0	−1	12	0	0	1	−1	12	0	0
−1	0	0	0	0	0	0	12	12	0	1	0	12	0	0
−1	1	0	0	0	0	1	0	0	0	1	1	5	5	18

To investigate the simultaneous variations of CO, NO, and NO_2 concentration in different seasons, the following contingency table was made up (Table 4). One can see that if the CO and NO concentration variations have the type 1, the probability that NO_2 concentration variation also has the type 1 is greatest. When CO concentration variation has the type 0, the following three types of NO and NO_2 concentration variations are possible: $(-1, -1)$, $(0, -1)$, and $(0, 0)$. If the type of CO concentration variation is -1, NO and NO_2 concentration variations also have the type -1.

Let us consider the location of zones with various types of CO, NO, and NO_2 concentration variations in the Krasnoyarsk territory (Figure 3).

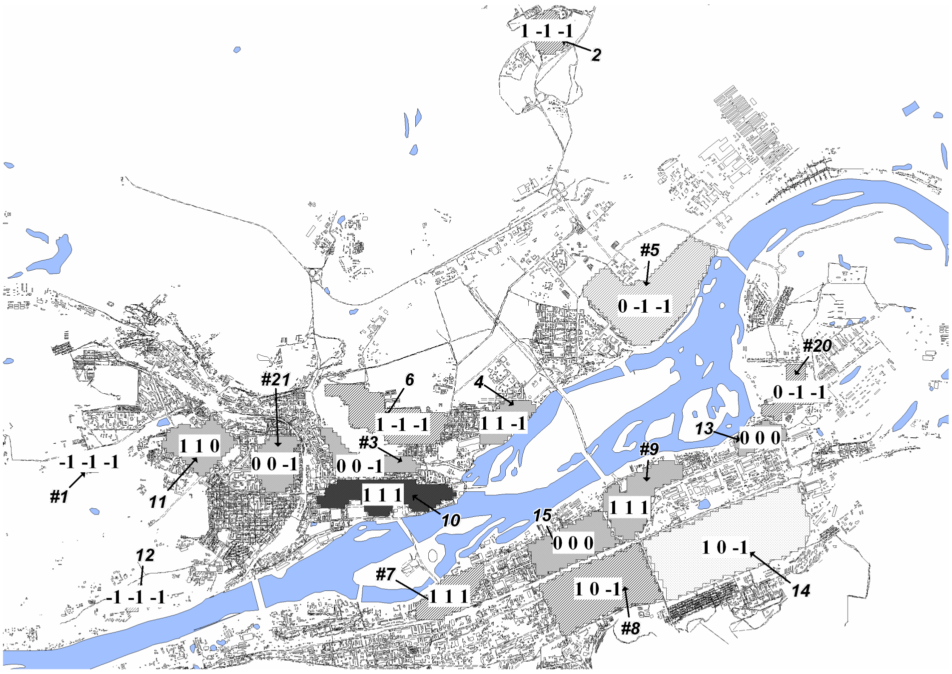

Figure 3. Variations of CO, NO, and NO_2 concentrations in the Krasnoyarsk territory

The type $D(1, 1, 1)$ of CO, NO, and NO_2 concentration variations is observed in zones 10, #7, and #9. This can be explained by the fact that they are located on the lowest terrace, at a height of 140 m above the sea level, and are subject to the influence of breeze circulation [28, 29], which results from a temperature difference between the river that does not freeze in winter and the riverside area.

The measurements made in the observation period have shown that a maximum temperature difference between the river and the riverside area reaches 5 °C in the winter period and −3 °C in the summer period.

In the winter period, as a result of the development of thermal convection, there occurs a pollutant flow from outskirts (periphery) of the city to the near-shore areas. In the summer period, a reverse circulation takes place, which purifies the riverside area.

The type $D(1, 1)$ of CO and NO concentration variations in zones 4 and 11 can be explained by the fact that these zones have local boiler houses with low (lower than 50 m) chimneys, and in the winter period the emission of these pollutants increases.

The type $D_{NO_2} = -1$ in zone 4 can be explained as follows: in the summer period, when NO emission of a boiler house in this zone decreases, there is a seasonal increase in the solar radiation, the ozone concentration in the atmosphere increases, and the intensity of NO conversion into NO_2 also increases. This leads to an increase in the nitrogen dioxide concentration in the atmosphere in zone 4, which is of the traffic type and has an average traffic intensity of 60000 vehicles/day, because nitrogen oxide emitted by the traffic is intensively converted into nitrogen dioxide.

In traffic zone 11, the type $D_{NO_2} = 0$ is observed. This can be explained by the fact that in the winter period in this zone there is much NO but little ozone. In the summer period, the situation changes: the level of NO emission decreases, but the intensity of NO conversion into NO_2 increases considerably in comparison to the cold period. All this provides a permanent level of nitrogen dioxide concentration in zone 11 during the year.

The type $D(-1,-1,-1)$ is observed in zones #1 and 12. This can be explained by the orographic factor and the atmospheric circulation. Zones #1 and 12 are located on the elevated terrain. Zone #1 is at a height of 220 m above the sea level, and zone 12 — at a height of 260 m above it.

The industrial (point) sources of the air pollution closest to zones #1 and 12 are located on the opposite shore at a height of 140 m above the sea level. With the east-direction winds, which are observed in the summer period, there is a pollutant flow directed from the sources to the zone due to differences in heights. This leads to the flow deformation and, as consequence, to an increase in the pollutant concentration in the areas of these zones.

The types $D(1,-1,-1)$ and $D(0,-1,-1)$ are observed in zones 6, 2, and #5. This fact can also be explained by the atmospheric circulation over an orographically complex territory. These zones are located on the elevated terrain. Zone 6 is located at a height of 260 m above the sea level, zone 2 — at a height of 320 m above it, and zone #5 — at a height of 200 m above the sea level. Thus, one can see that increased pollutant concentrations in the atmosphere are observed in the Krasnoyarsk territory on the elevated terrain. This is due to the change in atmospheric circulation that takes place in the summer period.

One can also see that in most zones of the Krasnoyarsk territory, the type -1 is observed for NO_2 concentrations. This is due to an increase in the solar radiation intensity that takes place in the summer period [30].

The types $D(0,0,0)$, $D(0,0,-1)$, $D(0,-1,-1)$, and $D(1,0,-1)$ are observed in zones 15 and 13, #3, N21, N20, and in zones #8 and 14. This fact cannot be easily explained without use of mathematical models that can describe the atmospheric boundary layer and the atmospheric circulation over an orographically and thermally inhomogeneous territory.

3.2. Variations of SO_2 and O_3 concentration. Let us consider the distribution of various types of sulphur dioxide and ozone concentration variations in different seasons in the Krasnoyarsk territory (Table 5).

One can see that a general regularity in the variations for most city zones is an increase in ozone (O_3) concentration in the atmosphere in the summer period, and in sulphur dioxide (SO_2) concentration in the winter period (Figure 4).

Table 5. Distribution of types for SO_2 and O_3 concentration variations, %

D	SO_2	O_3
−1	23	82
0	18	12
1	59	6

The type of ozone concentration variations $D_{O_3} = 0$ is observed in zone 12. This can be explained by the fact that there is an intensive decrease in the ozone concentration in the atmosphere filled with nitrogen oxide. In zone 12, the concentration of ozone in the summer period does not increase, since at the same time the nitrogen oxide concentration increases in this zone, $D_{NO} = -1$.

The type $D_{O_3} = 1$ is observed only in one zone, #20. In this zone, the increased (in comparison to all other territories) ozone concentrations are observed throughout the year. This is due to the influence of a high-voltage power line that passes through this zone.

The type $D_{SO_2} = 1$ is observed in the territory of most zones. This fact is due to an increase in the emission from boiler houses and heat stations that takes place in the heating season. The types $D_{SO_2} = 0$ and -1 are observed in some zones. This can be due to the atmospheric circulation over the orographically complex area of Krasnoyarsk.

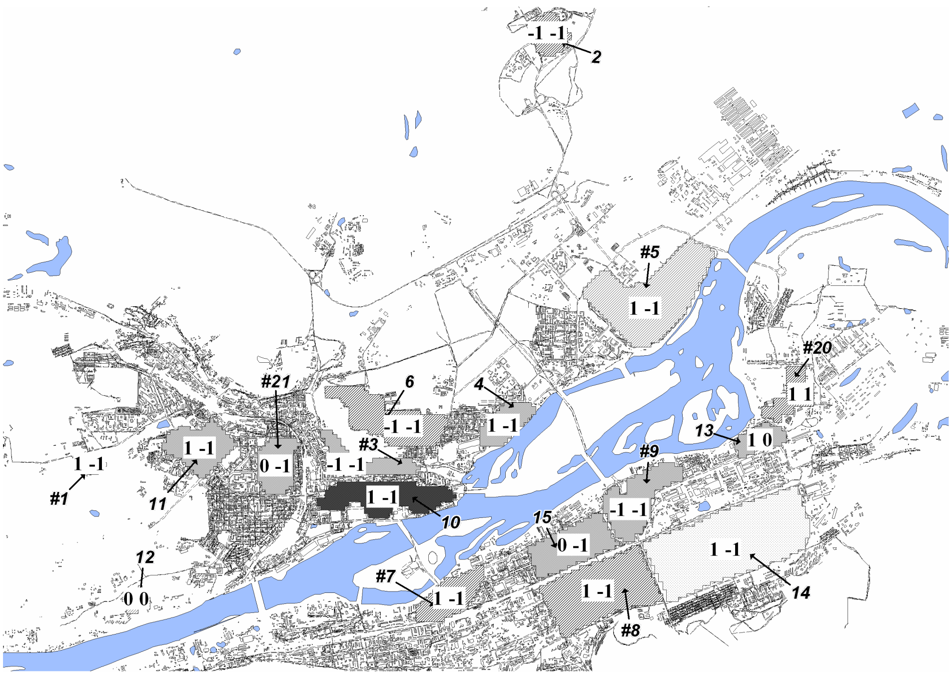

Figure 4. Variations of SO_2 and O_3 concentration in the Krasnoyarsk territory

3.3. The behavior of pollutant concentration variations in the Krasnoyarsk territory. One can see that the air pollutant concentration variations in different seasons in various parts of a large urbanized territory are not the same. Let us consider how these pollutant concentration variations affect the air quality. To compare the concentrations, let us use the Russian standards of air quality for residential areas. These are the standards $\mathrm{MAC_{ind}}$ (a maximum allowable individual concentration) and $\mathrm{MAC_{d.a.}}$ (a maximum allowable daily average concentration).

The air quality of populated areas in Russia is regulated by sanitary requirements, i.e., maximum allowable concentrations (MAC) of atmospheric pollutants (chemical and biological substances). Meeting these requirements ensures the absence of a direct or an indirect effect on the population's health and living conditions [31].

For instance, an unfavorable effect of pollution on human health when the human organism receives atmospheric pollutants for a long time is insignificant if $\mathrm{MAC_{d.a.}}$ are met. The $\mathrm{MAC_{d.a.}}$ is calculated for all population types and for an indefinitely long period of action. It is common practice to compare this standard with concentrations averaged over all observation points in the territory under control during the entire year.

The irritating action and reflex phenomena of the population, as well as a strong effect of atmospheric pollutants on human health in the periods of short-term increases in concentrations are insignificant if the $\mathrm{MAC_{ind}}$ standard is met. The $\mathrm{MAC_{ind}}$ is used to create scientific and technical regulations—maximum allowable pollutant emissions. During pollutant dispersion in the atmosphere at boundaries of sanitary protection zones of enterprises, the pollutant concentrations at any time must not exceed the $\mathrm{MAC_{ind}}$. The $\mathrm{MAC_{ind}}$ considers 20-min averaged concentrations.

3.4. Variations of CO and NO concentrations. Let us consider the variations of CO concentrations in the Krasnoyarsk territory (Figure 5). One can see that the greatest pollution of the air by carbon oxide is observed in the traffic type zones.

In the winter and in the summer periods, maxima of CO concentrations are in zones 4, #21, #7, and #9. This is due to the fact that the major traffic flows of Krasnoyarsk are redistributed in these zones.

In zone #9, the winter pollution level is about 70 % higher than the summer one, and in zones #7 and 4 it is about 60 % higher. In this case, in zone 12, the summer level of CO concentration in the atmosphere is three times higher than the winter one. Zones #9, #7, 21, and 4 are considered to be most unfavorable for the population's health.

The behavior of the nitrogen oxide NO concentration variation in different seasons in the Krasnoyarsk territory is similar to the variations of CO. A non-uniform distribution of NO concentration over the city territory is

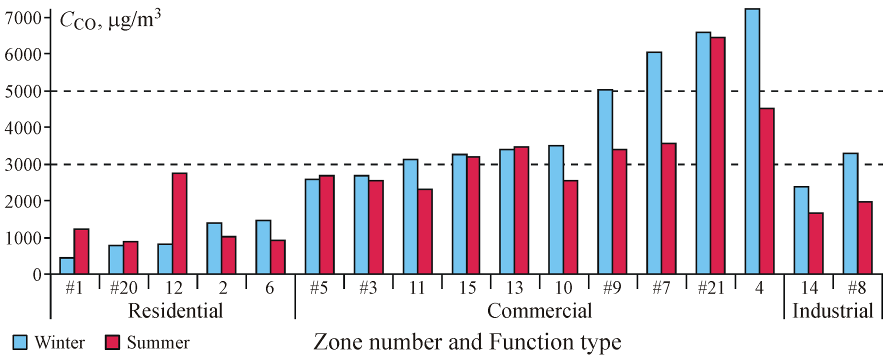

Figure 5. Variations of CO concentrations. Dash lines show the levels of $MAC_{ind,CO} = 5000$ μg/m³ and $MAC_{d.a.,CO} = 3000$ μg/m³

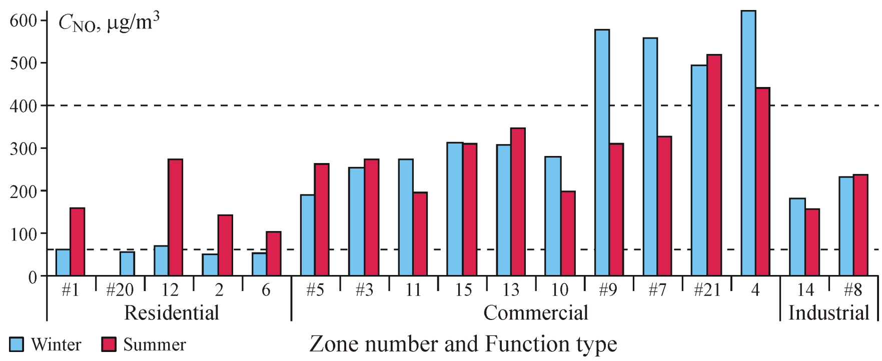

Figure 6. Variations of NO concentrations. Dash lines show the levels of $MAC_{ind,NO} = 400$ μg/m³ and $MAC_{d.a.,NO} = 60$ μg/m³

observed (Figure 6). The concentration maxima are located not in industrial zones but in the traffic type zones. This behavior can be explained by the existence of a strong correlation between CO and NO concentrations, because they are major constituents of vehicle emissions.

In zone #9, the winter level of NO is by a factor of 1.5 higher than the summer level, in zone #7 by 60 %, and in zone 4 by 70 %. In contrast to this, one can see that in residential area 12, the summer level of atmospheric pollution by nitrogen oxide is almost by a factor of 4 higher than the winter one, in zones #1 and 2 by a factor of 2.5, and in zone 6 by a factor of 2.

3.5. Variations of NO_2 and O_3 concentrations. The winter maxima of NO_2 concentrations are also in traffic zones. Among these zones, #21, 4, #7, and #9 are most prominent. The average concentration of NO_2 in the winter period is not greater than MAC_{ind} only in seven zones (among 17 zones) (Figure 7).

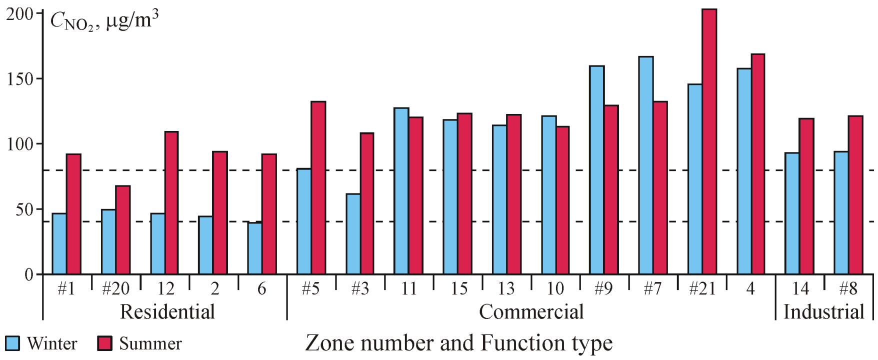

Figure 7. Variations of NO_2 concentration. Dash lines show the levels of $MAC_{ind,NO_2} = 85$ µg/m^3 and $MAC_{d.a.,NO_2} = 40$ µg/m^3. Russian standard $MAC_{d.a.,NO_2}$ coincides with a criterion for NO_2 recommended by WHO for European countries [1]

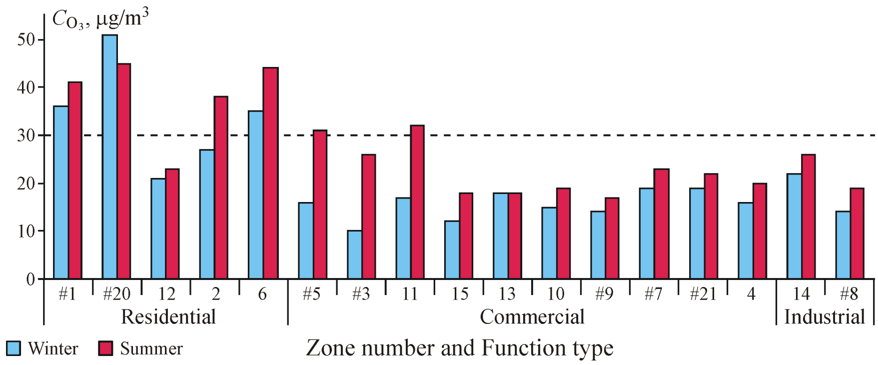

Figure 8. Variations of O_3 concentrations. Dash line shows the level of $MAC_{d.a.,O_3} = 30$ µg/m^3 ($MAC_{ind,O_3} = 160$ µg/m^3)

In the summer period, when the intensity of photochemical reactions increases [30], NO_2 concentrations also increase. As a result, the spatial distribution of nitrogen dioxide concentrations over the Krasnoyarsk territory becomes more uniform. Maximum concentrations are observed in zones #21 and 4. Here in all the zones except for one (zone #20), an average concentration of NO_2 is higher than MAC_{ind}.

An analysis of the ozone concentration variations shows that in the winter period the concentration maxima are in residential zones #1, #20, 12, 2, and 6. In this case, a concentration minimum of O_3 is observed in zones of the traffic and industrial types (Figure 8).

In the summer period, the ozone concentrations increase, but the spatial distribution of the concentrations does not considerably change. Concentration maxima are observed in residential zones and minima — in zones of the traffic and industrial types. Here, the highest values of ozone concentrations in the Krasnoyarsk territory throughout the year are observed in zone #20.

3.6. Variations of SO_2 concentrations. In the winter period, the concentration maxima of SO_2 are in zones 4, 10, #7, #8, and 14. In the summer period, a redistribution of the maxima takes place. At this time, maximum concentrations are observed in zones 10, #21, 6, and #20 (Figure 9).

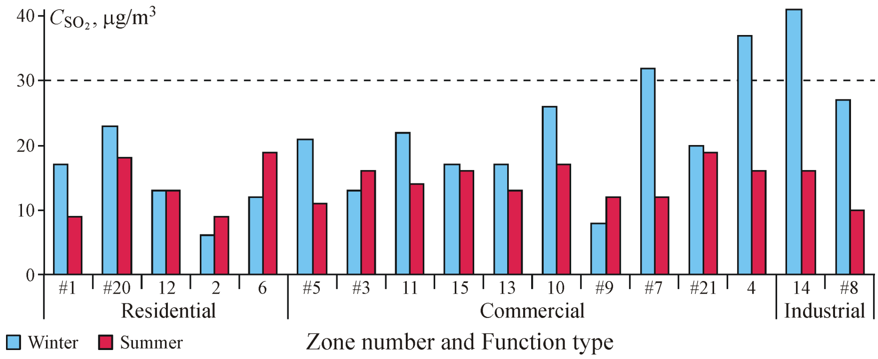

Figure 9. Variations of SO_2 concentrations. Dash line shows the level of $MAC_{d.a.,SO_2} = 50$ µg/m^3 ($MAC_{ind,SO_2} = 500$ µg/m^3)

Analysis of the sulphur dioxide concentration variations shows that the main source of SO_2 in the Krasnoyarsk territory is not the motor traffic but industrial enterprises, boiler houses, and heat stations. We found this by analyzing the traffic intensity on roadways in these zones. A maximum traffic intensity is observed in zones #7 (about 80,000 vehicles/day), 4, and #9 (about 60,000 vehicles/day) and in zone #21 (about 55,000 vehicles/day). Here, a maximum concentration of SO_2 in the winter period is observed in zone 14 with a traffic intensity of about 20,000 vehicles/day.

The sulphur dioxide concentrations in the winter and the summer periods in the Krasnoyarsk territory do not reach the MAC.

4. Discussion

The above investigation of CO, NO, NO_2, SO_2, and O_3 concentration variations in different seasons in the Krasnoyarsk territory have shown that the pollution level of air in various parts of the large urbanized area depends on a great number of factors. One of these factors is the existence in the city territory of numerous line (vehicles), point (local boiler houses), and area (industrial enterprises, heat stations) sources of the atmospheric pollution. Another factor is temperature inhomogeneity of the territory, which results in various local circulations (such as breeze). The orographic inhomogeneity of the territory also leads to changes in the distribution of pollutant concentrations in the atmospheric surface layer of the city during the year.

The effects of all these factors separately on the city atmosphere pollution were studied by many researches. However, complex investigations of the city atmosphere with the use of measurement stations should be performed to study a combined effect of these factors.

The results obtained in this paper are of importance to solve the problem of controlling the quality of the air to decrease harmful effects of pollutants on the health of the population in an inhomogeneous urbanized territory. The importance of such investigations and results is obvious, because the existing mathematical models for the pollutants dispersion in the urban atmosphere cannot still satisfactorily reproduce the observed peculiarities and characteristics of the space-time variability of pollutant concentrations in urban conditions.

The above investigation of pollutant concentration variations in different seasons in the Krasnoyarsk territory has also shown that the proposed observation method, which is based on zoning the city territory with respect to the building density, is an effective instrument of research. This study may simply be useful for carrying out population exposure investigations using receptor-aided techniques, since the building density is also a characteristic of the population density.

5. Conclusion

The complex pattern of the air pollutant concentration variations in different seasons in an inhomogeneous urbanized territory is a consequence of the inhomogeneity caused by local microclimate. Finding the causes of the variations observed above will make it possible to determine the physical mechanisms of the city microclimate. A combination of instrumental observations in the territory (measurement of the meteorological parameters and concentrations) and mathematical modeling should be used to solve this problem.

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