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The Relationship between Particulate Air Pollution and Mortality: The Case of Tomsk, Russia

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Abstract—The impact of suspended particles in the urban air on the health of different groups of the population of Tomsk, Russia, is studied. It is shown that women are generally most susceptible to the adverse effects of aerosol air pollution and extreme (high summer and low winter) air temperatures. Women at age of 65–74 are the most vulnerable to the environment hazards. The age-and-sex matched analysis of mortality allows us to determined groups of population (age, causes of death) the most susceptible to high aerosol concentrations and extreme air temperatures: women aged 65–74, cancer of the digestive system, breast cancer, and acute myocardial infarction; women aged 34–50, undetermined causes; women aged 75–87, breast-pang; men aged 53–65, other forms of coronary artery disease; men 78+, male reproductive organ cancer. The general mortality of the population is shown to be mainly due factors not studied in this work. However, the risk of the negative impact of air pollution is significant for the selected groups of population in the region under study.

Keywords: particulate matter, pollution, air, $PM_{2.5}$, PM_{10}, mortality, health, city

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INTRODUCTION

According to the World Health Organization (WHO), air pollution annually leads to premature death of about eight million people worldwide. The main indicator of the atmospheric air quality, according to WHO [1], is the content of fine particles less than 10 (PM_{10}) and 2.5 μm ($PM_{2.5}$) in size. These particles are complex mixtures of solid and liquid organic and inorganic substances, the main components of which are sulfates, nitrates, ammonia, sodium chloride, soot, mineral dust, and water.

Based on numerous studies [1], the WHO states that there is no safe level of aerosol content in the atmosphere, and even low concentrations of particles can pose a threat to human life and health. However, there are air quality standards. Table 1 includes the maximum permissible concentrations (MPC) of suspended particles in the atmospheric air of cities accepted in the Russian Federation and by the WHO in different years.

Particles of different sizes affect the contraction and course of acute and chronic human diseases in different ways: PM_{10} can penetrate deep into the lungs and deposit in them; smaller particles $PM_{2.5}$ directly go to the lung alveoli, where gas exchange between the lungs and blood vessels takes place. During the gas

Table 1. MPCs for particulate matter in urban air

Pollutant, μg/m^3	MPC (period)	Russian Federation, to date [2]	WHO, 2005 [3]	WHO, 2021 [4]
$PM_{2.5}$	MPC_{ot} (20 min)	160	–	–
	MPC_{dm} (24 h)	35	25	15
	MPC_{yr} (1 year)	25	10	5
PM_{10}	MPC_{ot} (20 mean)	300	–	–
	MPC_{dm} (24 h)	60	50	45
	MPC_{yr} (1 year)	40	20	15

“ot” means one-time, “dm” means daily mean, and “yr” means annual MPC.

exchange, $PM_{2.5}$ enters the bloodstream, which provokes different diseases.

Many examples of the harmful impact of particulate matter are described in the scientific literature, which can result in functional disorders in the human body and the occurrence of many diseases, such as panting [5, 6]; destruction of the lung epithelium [7]; cardiac arrhythmia, infarction, and cardiac arrest [8–11]; systemic inflammation [12, 13]; clotting defects [14]; lipid storage disease [15]; vasoconstriction and stroke [16, 17], carcinogenic effect [18], etc.

However, the direct relationship between an increase in the PM concentration and an increase in population morbidity is not always observed. The work by Szyszkowicz et al. [19] showed an increase in the cases of hypertension with the PM_{10} concentration, while no stable relations with $PM_{2.5}$ were found. The authors of [20], on the contrary, showed $PM_{2.5}$ provoked cardiac arrests, but found no relation between those events and PM_{10}. More recent studies have revealed the relation between the atmospheric concentration of particulate matter and the population health to depend on such factors as place of residence, age, gender, and even nationality [21–23].

The harmful effect of aerosols is enhanced if they act along with other pollutants. An enhancement of the negative impact of aerosol by ozone, nitrogen dioxide, and sulfur dioxide was shown in [24–26]; only by ozone, in [27]; by ozone and chlorides, in [28]; by ozone, H_2SO_4, $(NH_4)_2SO_4$, HNO_3, HCHO, and cigarette smoke, in [29]. In summer and winter, the harmful effects of polluted air are enhanced by the negative effect of extreme air temperatures on humans [30]. Boytsov et al. [31] compared an increase in mortality of the Moscow population only due to heat waves in summer 2014 and due to the combined effect of heat waves, high humidity, and high levels of air pollution in summer 2010. They showed a more pronounced increase in mortality under the combined effect of different factors.

According to WHO estimates, daily mortality due to all causes increases by 0.2–0.6% after even a short-term increase in PM_{10} concentration by 10 μg/m^3. Under a long-term increase in the $PM_{2.5}$ concentration, an increase by every 10 μg/m^3 is associated with an increase in the long-term risk of mortality from diseases of the cardiovascular and respiratory systems by 6–13% [3]. Due to the fact that high atmospheric concentrations of particulate matter are often accompanied by other pollutants and extreme air temperatures, the problem arises of differentiating the impact of each factor on the human health. Revich et al. suggested a model for estimating the contribution of each component and their joint impact on an increase in the population mortality in Moscow as an example [32]. The same group of Russian researchers showed a relative increase by 0.47% in the mortality of the Moscow population due to all natural causes per an increase in the daily average PM_{10} concentration by every 10 μg/m^3 [30].

Despite a large number of works devoted to the effect of aerosol air pollution on human health, a number of issues remain poorly studied, including those related to the effect of air pollution on different gender, age, and other groups. The purpose of this work is to assess the effect of particulate matter in urban air on the mortality in Tomsk and to identify the population groups most susceptible to this effect.

1. SOURCE DATA

Depersonalized mortality records for Tomsk in 2011–2019 were provided by the Federal State Statistics Service [33]; they included the date of death, sex, age, and cause of death encoded according to the International Classification of Diseases, 10th Edition (ICD-10). During the period under study, the number of residents in Tomsk increased by almost 37 500 people; therefore, the actual number of deaths was considered during the analysis within a year, and the number of deaths per 100 thousand people (*D*) was considered in the interannual study. Figure 1 shows the age dependence of the annual average natural mortality in Tomsk for 2011–2019.

The analysis of the statistical parameters of the age dependence of the mortality allowed us to determine several groups of men and women. The first group (a) is characterized by a small increase in mortality with age and a low SD (standard deviation) over the period under study. The second group (b) is characterized by a sharp increase in mortality with age and a low SD. The third group (c) is characterized by the absence of a pronounced increase in mortality with age and a high SD. The fourth group (d) consists only of women and is characterized by a sharp increase in mortality with age and a high SD. The fifth group (e) is characterized by a sharp decrease in mortality with an increase in age and a low SD. These groups, in our opinion, can indicate a stronger or weaker sensitivity to the external adverse factors. A low SD over the period under study points to mainly constant mortality in an age group. A high SD can indicate a significant addition to natural mortality due to external factors, such as atmospheric parameters. Thus, four age groups were formed for men: (a) 42–52, (b) 53–65, (c) 66–77, and (e) 78+ years old, and five groups for women: (a) 34–50, (b) 51–64, (c) 65–74, (d) 75–87, and (e) 88+ years old.

The mass concentration of suspended particles (*m*) in the Tomsk atmosphere was calculated on the basis of measurements of the total particulate count. The particle density was set equal to 1.5 g/cm^3. Hourly measurements were carried out at the TOR station on the eastern outskirts of Tomsk. The technical characteristics of the TOR station and its modernization over the past 25 years are described in [33]. To estimate the

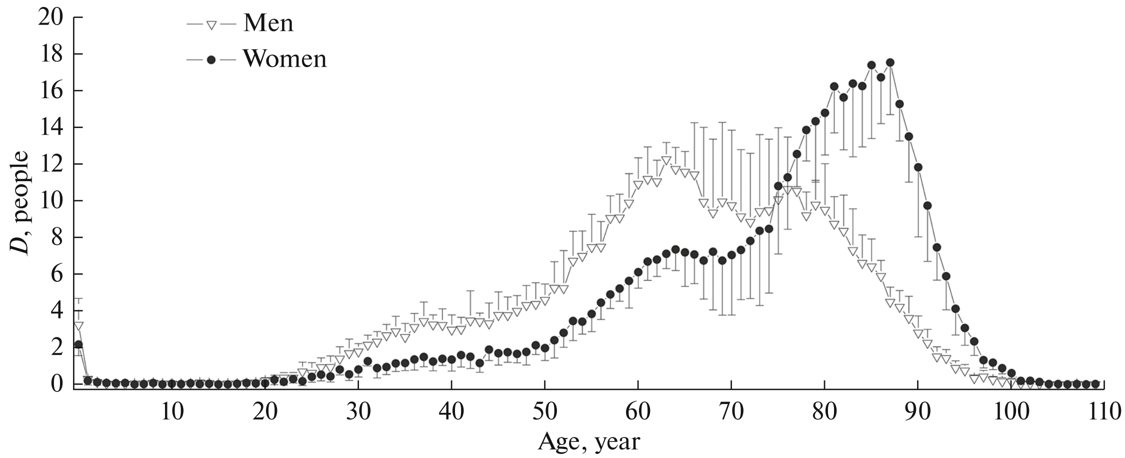

Fig. 1. Age dependence of the annual average mortality of the population of Tomsk due to all natural causes for 2011–2019.

correctness of extrapolation of atmospheric parameters measured at one station to the entire city, we used the atmospheric measurements with an AKV-2 mobile station in Tomsk [35–37].

2. RESULTS AND DISCUSSION

2.1. Mass Concentration of Aerosols in the Atmosphere of Tomsk

Route measurements of aerosol concentration in urban air with the AKV-2 mobile station were carried out in different seasons, days, and weather conditions. Table 2 presents the average mass concentration of aerosols in the atmosphere of Tomsk calculated from measurements at the TOR and mobile stations. The average mass concentration of aerosols for the TOR station was calculated as the average over a nine-year series of measurements (2011–2019) in a season specified, and at the mobile station, as the average over all routes within the city or its environs in a season specified. The maximum for the TOR station was calculated via averaging the seasonal maxima over the nine years, and for the mobile station, as the average over experimental maxima inside the city or in its vicinity in a season specified.

The mass concentration of aerosols measured with the mobile station inside the city is evidently comparable to the values of the TOR station. In our study, we use data on the mortality in Tomsk without taking into account the place of residence; therefore, we believe that it is possible to use air pollution measurements only from the TOR station.

Figure 3 shows the statistical parameters of the mass concentration of aerosols in the air of Tomsk calculated on the basis of measurements. One can see that the average annual values meet the WHO air quality standards. The only exception is 2012, when the high air temperatures in combination with a lack of precipitation in summer resulted in numerous wildfires on the territory of Tomsk region and neighboring areas, due to which the settlements were shrouded in smoky haze [38]. The first signs of a smoky haze were recorded in Tomsk on June 19, and the maximal particulate matter concentrations, on July 25–28. The total number of days when the concentrations were higher than the daily average MPC was 33 days. Such a long-term aerosol exposure in Tomsk was unprecedented for the period under study.

Table 2. Average mass concentrations of aerosols in the atmosphere of Tomsk measured at the TOR and with mobile stations

Season	Pollutant	Parameter	TOR station	Mobile station	
				city	environs
Winter	$PM_{2.5}$	Mean	9.78	13.87	9.65
		Max	41.51	92.03	20.76
	PM_{10}	Mean	12.56	16.95	11.24
		Max	79.33	98.73	26.65
Summer	$PM_{2.5}$	Mean	9.26	14.66	6.10
		Max	73.44	135.83	17.19
	PM_{10}	Mean	15.48	32.67	11.26
		Max	105.82	496.75	35.92

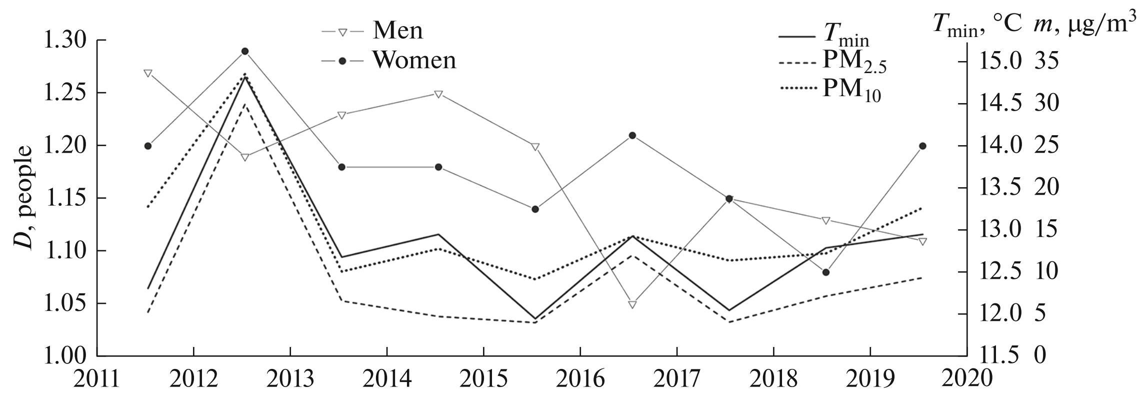

Fig. 2. Comparison between the daily average mortality per 100 thousand people due to all natural causes and atmospheric parameters ($PM_{2.5}$, PM_{10}, and T_{min}) during summer in Tomsk.

In total, 111 (3.6% of the period under study) and 60 (2%) days with $PM_{2.5}$ and PM_{10} higher MPCot, respectively, were recorded in Tomsk. For brevity, Table 4 includes only the periods when the daily average $PM_{2.5}$ and PM_{10} concentrations exceeded the MPCdm for two or more days together. A long period with PM concentrations above MPC in the air of Tomsk was observed only in summer 2012; all other periods were short. Therefore, for summer 2012, we analyzed both the instantaneous and delayed responses of the human body to the PM exposure. For all other cases, we analyzed only the immediate response.

The data in Tables 3 and 4 show that high pollutant concentrations are mainly associated not with the life activity of the city, but with atmospheric changes all over the region, for example, due to summer wildfires. Therefore, the highest mass concentrations of aerosols are characteristic of summer periods in Tomsk, and the analysis has been carried out mainly for this season.

2.2. Air Temperature in Tomsk

Table 3 presents the statistical characteristics of the air temperature in summer in Tomsk. This is necessary to assess the synergistic effect of air pollution and high temperatures on humans. Summer 2012 was characterized not only by the highest atmospheric concentrations of harmful substances over the period under study, but also by the highest air temperatures, both maximum and minimum. Summer 2016 followed with the second highest level of air pollution with PM; however, it was characterized by a comfortable air temperature. Summer seasons in 2014 and 2015 were hot, but with low air pollutant concentrations.

2.3. Mortality in Tomsk versus Atmospheric Parameters

The analysis of the impact of the summer maximal, minimal, and average air temperatures on humans showed the most pronounced correlation between mortality and a high nighttime T_{min}. This can be explained by the fact that houses in Siberia are rarely equipped with air conditioners. Therefore, at high nighttime temperatures, buildings have no time to cool down after a hot day and a human body does not receive the necessary rest from the heat. Figure 2 shows the total mortality of the population of Tomsk per 100 thousand people due to all natural causes and atmospheric parameters in the summer of each year. Women are evidently more susceptible to the both adverse effects, of atmospheric pollution with particulate matter and of high nighttime temperatures, in general. Table 5 shows the correlation coefficients between the mortality of men and women in summer and atmospheric parameters along with levels of significance.

Women 65–74 years old are the most vulnerable group among all age groups of women. Figure 3 shows the mortality accumulated over 30 days per 100 thousand people due to all natural causes, the average mortality over 2011–2019, the moving average (averaging period of 30 days corresponds to the period of accumulated mortality) $PM_{2.5}$ and PM_{10}, and the daily minimal air temperatures in Tomsk over the period May 1–August 31, 2012. A noticeable increase in mortality in this subgroup is seen at about 10 days after the increase in the PM concentration in the atmosphere in the first 10 days of June. The peak of the moving average aerosol concentration falls on July 4 (averaging period is from July 4 to August 4), the peak of accumulated mortality falls on July 14 (averaging period is from July 14 to August 14), which corresponds to the period of maximal smoke in the atmosphere in Tomsk. The noticeable drop in mortality after the increase in aerosol concentrations at the end of July suggests no long-term delayed response in this age group. A dip (~1 month) in the time variation in the accumulated mortality is seen after the peak associated with aerosol pollution. Then, the accumulated mortality curve approaches its average value. This can be an evidence

Table 3. Statistical parameters of mass concentrations of aerosols and air temperature in Tomsk

Parameter			Year								
			2011	2012	2013	2014	2015	2016	2017	2018	2019
Winter	$PM_{2.5}$	Mean	12.67	12.96	7.20	8.47	7.19	10.44	7.03	12.25	9.83
		Max	44.76	43.54	24.03	53.14	24.57	51.69	22.03	73.54	36.27
		$N > 25$	4	7	0	4	0	8	0	8	4
	PM_{10}	Mean	15.66	17.95	8.66	11.63	9.05	12.77	7.41	14.33	15.61
		Max	43.84	72.46	112.79	72.22	32.24	55.41	41.43	83.24	200.37
		$N > 50$	0	2	1	2	0	1	0	1	4
Spring	$PM_{2.5}$	Mean	7.01	7.28	3.30	5.66	4.82	5.03	4.29	4.38	4.32
		Max	19.63	28.55	8.16	23.78	14.75	14.24	16.65	12.27	9.95
		$N > 25$	0	2	0	0	0	0	0	0	0
	PM_{10}	Mean	20.06	14.87	4.54	11.06	14.15	11.03	6.20	6.91	9.29
		Max	368.43	64.28	12.39	35.68	290.68	40.70	52.95	21.05	68.57
		$N > 50$	2	1	0	0	3	0	1	0	2
Summer	$PM_{2.5}$	Mean	5.29	29.99	6.60	4.76	4.03	12.05	4.09	7.18	9.36
		Max	16.35	330.37	51.44	12.26	11.33	95.90	9.25	70.99	63.04
		$N > 25$	0	33	3	0	0	15	0	5	8
	PM_{10}	Mean	18.01	33.41	10.13	12.77	9.29	14.28	11.48	12.25	17.69
		Max	71.13	333.79	65.61	34.25	27.40	99.92	110.75	74.62	134.89
		$N > 50$	2	15	2	0	0	2	1	3	6
	T	T_{max}	22.38	25.99	23.07	23.57	24.41	23.13	22.02	22.97	23.78
		T_{min}	12.31	14.82	12.68	12.95	11.95	12.93	12.05	12.79	12.95
		T_{dm}	17.34	20.35	17.80	18.34	18.30	17.97	17.01	17.93	18.39
Autumn	$PM_{2.5}$	Mean	5.94	3.80	3.71	4.85	4.55	9.31	4.27	3.56	4.65
		Max	20.42	9.38	10.15	17.39	15.44	60.80	14.73	11.13	18.62
		$N > 25$	0	0	0	0	0	9	0	0	0
	PM_{10}	Mean	22.38	4.80	9.05	8.25	9.07	10.18	8.24	5.35	14.55
		Max	447.50	11.18	41.31	27.64	48.15	64.31	64.40	13.01	278.07
		$N > 50$	4	0	0	0	0	1	1	0	2
Year	$PM_{2.5}$	Mean	**7.65**	**13.76**	**4.86**	**6.11**	**4.97**	**9.28**	**5.16**	**7.03**	**6.73**
	PM_{10}	Mean	**19.00**	**18.20**	**7.63**	**11.07**	**10.21**	**12.17**	**8.53**	**9.95**	**13.92**

$N > 25$and $N > 50$ are the number of days when the MPC_{ot} was exceeded by mass concentrations of aerosols in air; MPC_{ot} = 25 μg/m^3 for 2.5 and 50 μg/m^3 for PM_{10}. The winter of a year is from December of the previous year to February of the current year; T_{max}, T_{min}, and T_{dm} are the season average temperatures over the maximum, minimum, and daily average temperatures.

of the fact that aerosol pollution of this level reduces life time by a few months for the group under study. No similar dependence was found for other age groups.

We also analyzed the mortality of people grouped not only in age and sex, but also in the main disease types by ICD-10. The following groups showed the highest sensitivity to high aerosol concentrations and extreme air temperatures: women aged 65–74, malignant neoplasms of the digestive organs (ICD-10 codes C15–C26), malignant neoplasm of the mammary gland (ICD-10 code C50), and acute myocardial infarction (ICD-10 code I21); women aged 34–50, unspecified causes (ICD-10 codes R00–R99); women aged 75–87, angina pectoris (ICD-10 code I20); men aged 53–65, other forms of acute coronary heart disease (ICD-10 code I24); men aged 78+, malignant neoplasms of the male genital organs (ICD-10 codes C60–C63).

Figure 4 shows the accumulated and actual total mortality in the selected population groups per 100 thousand people, the moving averages of $PM_{2.5}$ and PM_{10}, and the daily minimum air temperature in

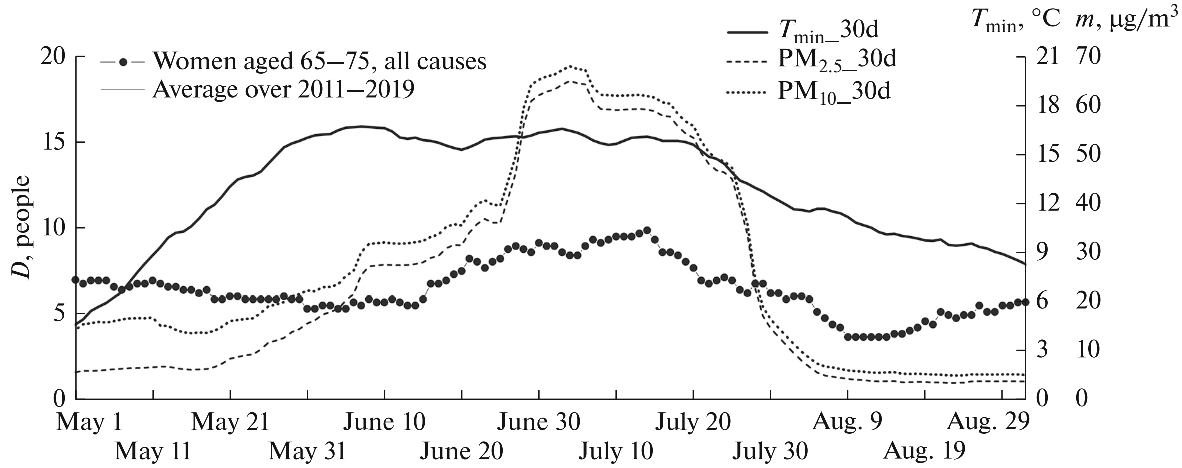

Fig. 3. Accumulated (over 30 days) mortality of women aged 65–74 per 100 thousand people due to all natural causes, moving averages of $PM_{2.5}$ and PM_{10}, and air temperature minimum in Tomsk in May 1–August 31, 2012.

Table 4. Periods of two and more days when daily average concentrations of particulate matter were higher than MPC_{ot}

$PM_{2.5}$				PM_{10}			
period	N	mean	max	period	N	mean	max
January 7–8, 2011	2	32.17	34.79				
February 20–21, 2012	2	36.84	43.54				
June 19–August 4, 2012	33	52.44	330.37	July 4–August 2, 2012	15	67.84	333.79
February 10–13, 2014	4	41.75	53.14	August 11–12, 2014	2	67.73	72.22
				April 20–23, 2015	3	127.75	290.68
January 20–24, 2016	4	33.12	51.69	July 23–24, 2016	2	80.26	99.92
February 15–16, 2016	2	27.52	29.82				
July 17–30, 2016	12	38.54	95.90				
August 18–21, 2016	3	28.45	38.49				
September 17–27, 2016	8	30.65	60.80				
January 3–4, 2018	2	31.11	31.47				
February 3–4, 2018	2	55.46	73.54				
July 22–26, 2018	5	50.61	70.99	July 23–25, 2018	3	65.09	74.62
				February 2–5, 2019	4	122.72	200.37
				May 8–9, 2019	2	59.80	68.57
July 20–26, 2019	7	51.25	63.04	July 19–26, 2019	6	69.92	134.89
				September 15–16, 2019	2	241.65	278.07

Table 5. Correlation coefficients between the mortality in Tomsk and atmospheric parameters in summer and their significance levels

Parameter	Men	Women	
	correlation coefficient	correlation coefficient	significance level
T_{min}	−0.11	0.72	0.05
$PM_{2.5}$	−0.20	0.76	0.05
PM_{10}	−0.01	0.81	0.01

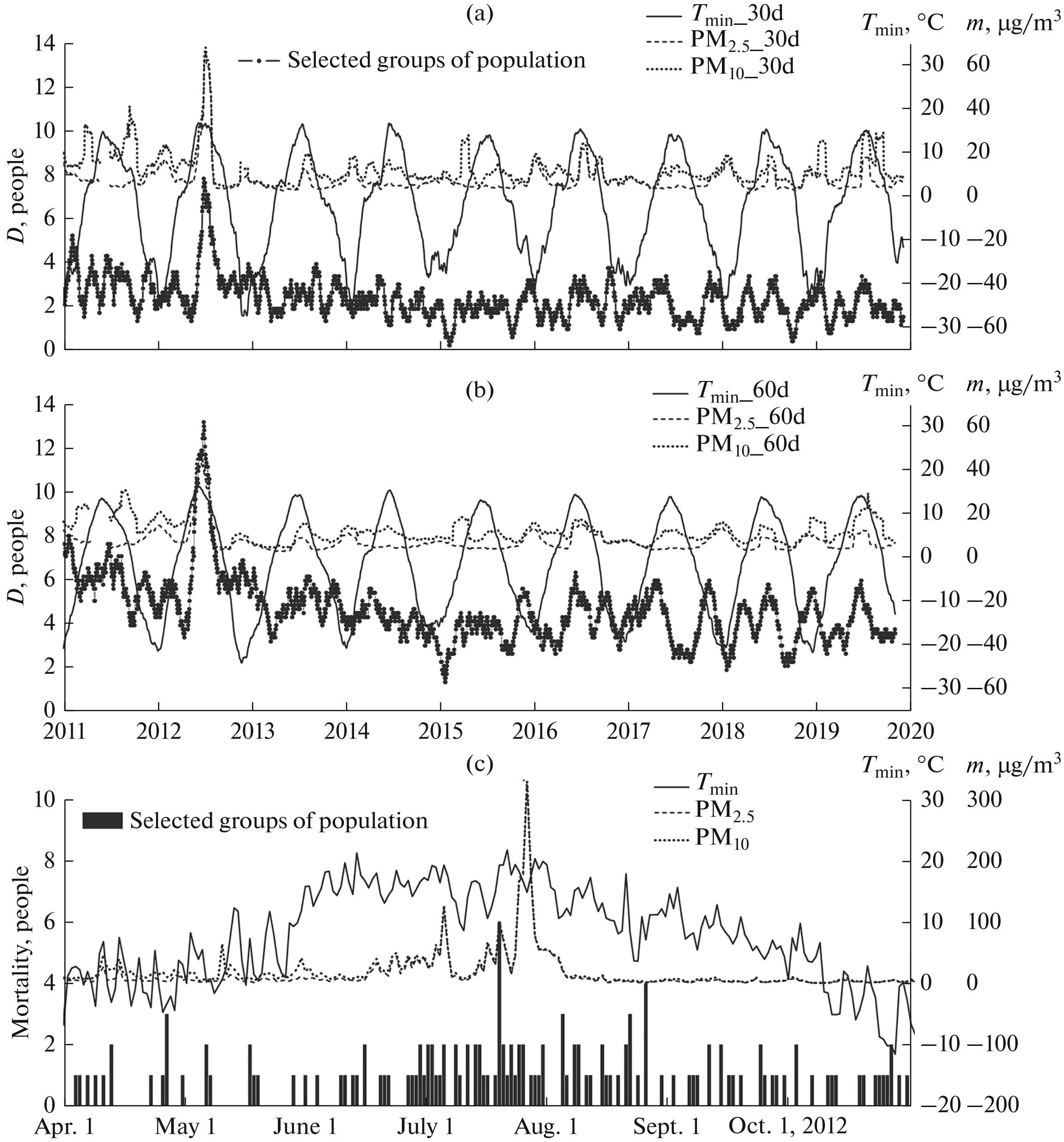

Fig. 4. Accumulated and actual mortality of selected groups of population per 100 thousand people (women aged 65–74, malignant neoplasms of the digestive organs, breast, acute myocardial infarction; women aged 34–50, unspecified causes; women aged 75–87, angina pectoris; men aged 53–65, other forms of acute ischemic heart disease; men 78+, malignant neoplasms of the male genital organs), moving averages of $PM_{2.5}$ and PM_{10}, and air temperature minimum in Tomsk: (a) over 30 days; (b) over 60 days, and (c) actual (April 1–November 1, 2012)).

Table 6. Correlation coefficients between the mortality in selected groups and atmospheric parameters and their significance levels

Parameter	Summer		Winter		All seasons	
	correlation coefficient	significance level	correlation coefficient	significance level	correlation coefficient	significance level
T_{min}	0.85	0.01	−0.79	0.05	−0.14	–
T_{max_night}	0.85	0.01	−0.84	0.01	−0.15	–
$PM_{2.5}$	0.91	0.001	0.47	–	0.71	0.001
PM_{10}	0.92	0.001	0.49	–	0.68	0.001

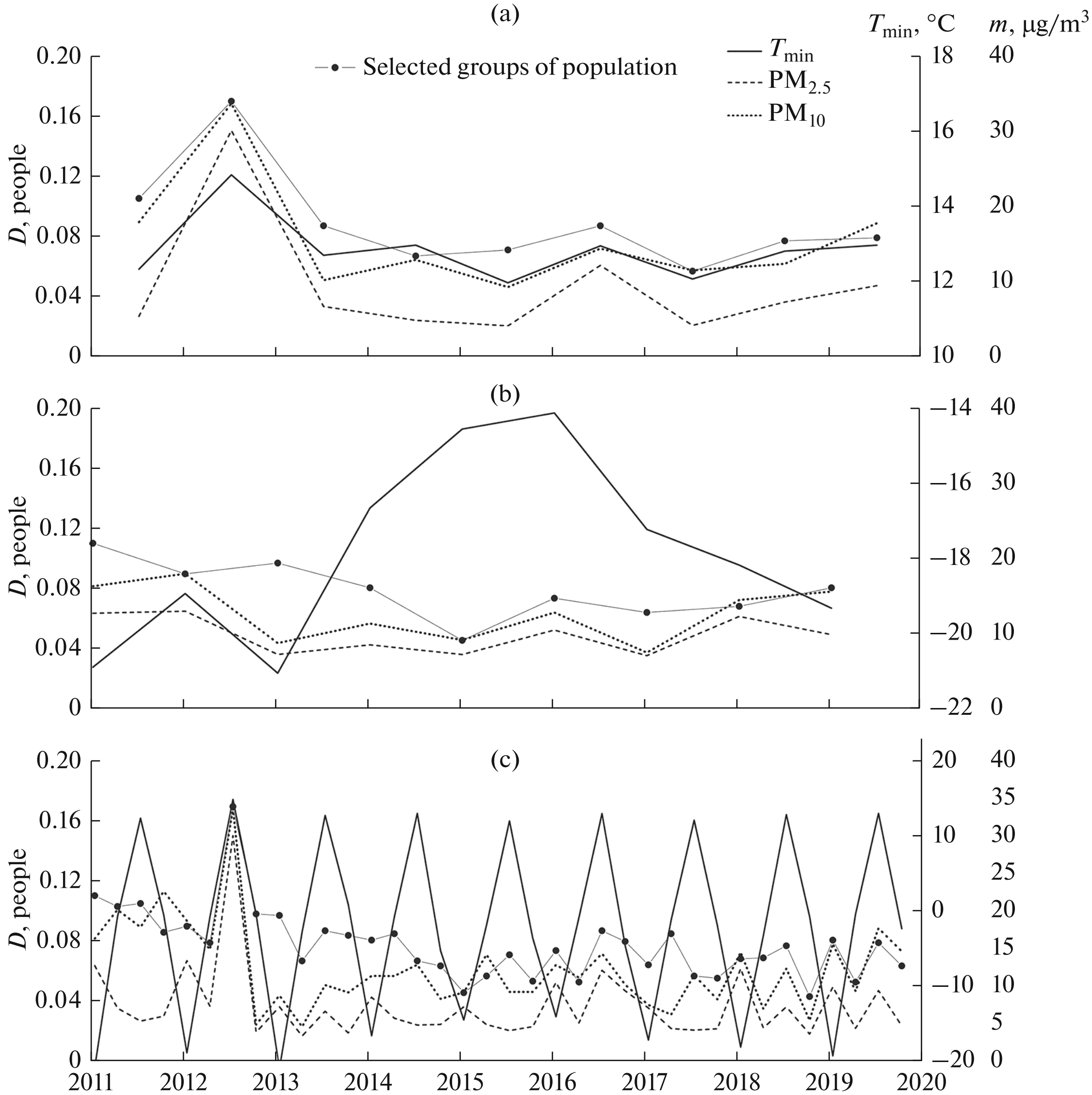

Fig. 5. Daily average mortality in the selected groups of population per 100000 people: (a) in summer, (b) in winter, (c) in all seasons.

Tomsk. The mortality in the selected groups increased three times in summer 2012 as compared to the average mortality over nine years. The increase in mortality begins on June 27, 2012, i.e., eight days after the smoky haze arrived in Tomsk. It is important to note that the daily average mass concentrations were 25.4 μg/m^3 for $PM_{2.5}$ and 31.1 μg/m^3 for PM_{10} in those eight days. Those conditions can be characterized as critical for a noticeable increase in the mortality. It is also possible to note an increase in mortality by 1.7 times from the average in the next six months after the episode of summer fires in 2012 (see Figs. 4a and 4b).

Figure 5 shows the long-term dynamics of the average mortality in the selected population groups and atmospheric parameters for summer and winter, characterized by extreme temperatures. Table 6 presents the correlation coefficients of these dependences and their significance levels. A strong correlation between the mortality in the selected groups and atmospheric parameters can be seen in summer, and the correlation coefficient between mortality and aerosol content is higher than between mortality and air temperature. In winter, the correlation between mortality and aerosol content is weak and unreliable (correlation coefficient is 0.47–0.49), although low air temperatures in the cold season significantly affect the mortality in selected groups of the population (correlation coefficient is 0.84, with a probability of random coincidence of 1%). This can be explained both by a lower average level of atmospheric pollution and by short periods of continuous excess over MPC in winter.

It should be noted that the average contribution of the mortality of the selected groups of population to the total mortality in Tomsk was only 3% over the nine years under study. In summer 2012, that contribution increased to 6.7%. The general mortality of the population in Tomsk does not correlate with high levels of atmospheric pollutants and extreme temperatures. This can be explained by the fact that, on average, the atmosphere of Tomsk is not heavily polluted and the climate is not harsh, and the total mortality of the population is mainly influenced by factors not studied in this work. Nevertheless, the risk of a negative impact of pollutants is significant for the most susceptible groups of the population identified in the region under study.

CONCLUSIONS

The analysis of the effect of atmospheric parameters on the mortality of different groups of the population showed that women are generally most susceptible to the adverse effects of both atmospheric pollution with particulate matter and extreme (high summer and low winter) temperatures. The following groups showed the highest sensitivity to high aerosol concentrations and extreme air temperatures: women aged 65–74, with causes of death "malignant neoplasms of the digestive organs" (ICD-10 codes C15–C26), "malignant neoplasm of the mammary gland" (code ICD-10 C50), "acute myocardial infarction" (ICD-10 code I21); women aged 34–50, unspecified causes (ICD-10 codes R00–R99); women aged 75–87, "angina pectoris" (ICD-10 code I20); men aged 53–65, "other forms of acute coronary heart disease" (ICD-10 code I24); men 78+, "malignant neoplasms of the male genital organs" (ICD-10 codes C60–C63).

The correlation analysis of atmospheric parameters and mortality has shown that the atmosphere of Tomsk is not heavily polluted and the climate is not harsh, and the total mortality of the population is mainly influenced by factors not studied in this work. The risk of negative impact of pollutants is significant for the most susceptible groups of population identified in the region under study.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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