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Tropospheric Ozone Concentration in Russia in 2022

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Abstract—We consider the distribution of tropospheric ozone on the territory of Russia in 2022 using data from 33 stations located in different physical and geographical zones, as well as its vertical distribution from results of aircraft sensing. It was shown that measurements at all measurement sites exceeded the maximum permissible daily average concentrations, determined by the national hygienic standard. In some regions, the excess over the maximum permissible concentrations of the working zone and over the maximum one-time hourly average concentrations is recorded, so that the population should be broadly warned about the monitoring results and measures should be taken to reduce the level of ozone concentration in the surface air layer.

Keywords: atmosphere, air, concentration, ozone, maximum permissible concentration, surface layer, troposphere

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INTRODUCTION

Owing to its physicochemical properties [1–5] and its effect on biological beings and environmental entities, ozone in all developed countries is considered as the number one air pollutant. This is primarily because air pollution and, in particular, air pollution by ozone entails premature mortality which, as indicated in work [6], can reach 3.3 million deaths per year on the planet.

Besides its effect on human health, ozone in large concentrations strongly depresses plant life activity. In response to increased ozone concentration, plants reduce their productivity and sometimes even die [7, 8]. Ozone reduces the ability plants to absorb carbon dioxide, which can lead to an increase in the radiative forcing of the planet [9, 10]. It is also the strongest oxidant, capable destroying rubber, and oxidizing many metals, even from the platinum group [11–15]. Its contribution to the radiative effect exceeds 8% of the total air heating due to the absorption of solar radiation by greenhouse gases [16]. Most probably, the ozone concentration will increase [17–19] under the conditions a warming climate. Hydroxyl is formed in air during the production of tropospheric ozone; therefore, this process will be accompanied by an increase in the oxidizing potential of the atmosphere [20].

In view of such various possible negative consequences of increasing tropospheric ozone concentrations for both humans and the environment, trends of variations in ozone concentrations in the surface air require increased attention. The data from work [18] indicate that there were more than 10 thousand stations for monitoring ozone and its precursors in Europe as early as 2003. Very importantly, the information is made available to the population and used by administrative decision makers. The United States and Europe have already succeeded in reducing ozone concentration in air [21–23]. Much progress in this direction is also observed in China [24–26]. However, even given so much attention to the problem in the developed countries, the authors of work [27] nevertheless argue that the efforts are still insufficient to solve the problem because precursor gases are transported from neighboring countries and regions, thus increasing the ozone background. They suggest that a body of the type of the Intergovernmental Panel on Climate Change be created to justify political decision making regarding the tropospheric ozone problem.

In the former Soviet Union and in today's Russia, ozone monitoring and measures to reduce its content are not given due attention. The Hydrometeorological Center of Russia, which was made responsible for controlling the atmospheric air quality, carries out a technological modernization of the observational network, so that surface ozone is measured in a small number of big and industrial cities only. The two biggest megalopolises, i.e., St. Petersburg and Moscow, own monitoring systems of surface ozone and other pollutants, comparable to foreign analogs. Moscow since 2002 has operated the ecological monitoring network in State Nature Organization Mosecomonitoring, specially certified to carry out the State ecological monitoring [28]. The surface ozone concentrations are measured at 15 automatic air pollution control stations (AAPCS) hourly and around-the-clock. The annual report publishes analytical materials on the environmental state in Moscow [29]. They are partly included in reviews [30, 31].

However, so far the state reports do not provide the data on the surface ozone content on the territory of Russia [32, 33]. On the remaining territory of the Russian Federation the ozone observations are arranged on an initiative basis, basically by scientific organizations of or higher-education institutions. The informal consortium of these organizations, thus formed, started publishing the yearly reviews, presenting information on ozone content in the troposphere over the territory of Russia [34–36]. This paper continues the above-mentioned series of reviews. Its aim is to collect in a single publication the data on ozone content in the surface air layer in 2022 in different regions of Russia, carry out the comparative analysis of these data, and to compare these with the national hygienic standards [37].

1. NETWORK OF STATIONS AND THEIR LOCATIONS

The list of the most stations and the instrumentation installed on them, and their operation mode were presented in the previous reviews [34–36]. The number of the stations increases with time. Table 1 lists the stations, the data from which are included in this review. The average ozone characteristics were determined using the AAPCS Mosecomonitoring data (Table 2).

Table 1 shows that the stations measuring the surface ozone concentration (SOC) are located on the territory of just 13 federal subjects. This is less than a sixth of the total number of subjects in the Russian Federation. That is insufficient for such a vast country as Russia. By the type of the environment, the stations can be divided into urban (9) and background (7); two stations refer to suburban, and one to high-mountain stations. The westernmost station, carrying out measurements in the surface layer, is the OPTEC-PR, the easternmost station is the Ulan-Ude, the northernmost station is the Apatity, and the southernmost station is the Karadag.

The locations of the stations on the territory of Russia are shown in Fig. 1a. Due to "clumping" character of their locations, more detailed insets are given for the stations in four regions, i.e., St. Petersburg, Moscow, Tomsk, and the Baikal region. Figure 1b shows separately the locations of the Mosecomonitoring stations.

From Fig. 1a, it can be seen that, still, ozone monitoring measurements cover only about a third of the territory of the Russian Federation. There are no measurements in such vast regions as Krasnoyarsk krai, Yakutia, Chukotka, Kamchatka, the Far East, and the northern regions of the European territory of Russia (ETR) and western Siberia. At the same time, the operational stations are very sparse. This is untrue only for Moscow (Fig. 1b), where the stations are comparable in number to those in the total for Russia.

2. RESULTS OF MONITORING OF SURFACE OZONE CONCENTRATION

2.1. Annual Average Data

Figure 2 presents the annual average ozone concentrations measured at the stations listed in Table 1, in 2022. The observations at the Ulan-Ude and Boyarsky sites were carried out one after the other; therefore, data from these stations are merged into a single time series called "Buryatia." Error bars indicate the standard deviations.

From Fig. 2 it can be seen that the annual average SOCs differed by more than a factor of three on the territory of Russia. The largest values were recorded at the Kislovodsk high-mountain scientific station (KHMSS), in Buryatia, Listvyanka, and Large Aerosol Chamber (LAC). The smallest values were observed in the Peo-

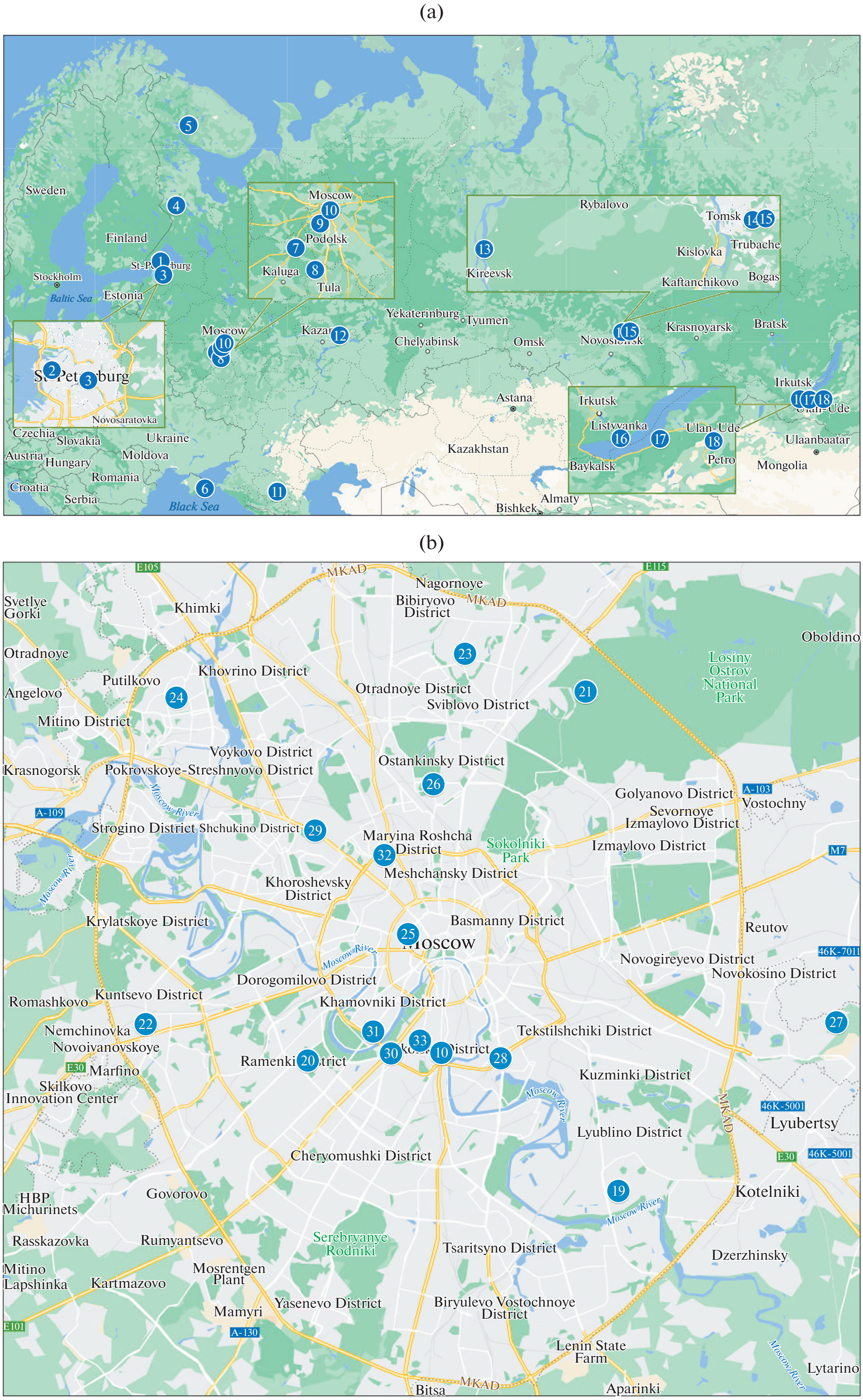
Table 1. Stations, carrying out ozone monitoring in the surface air layer in Russia

No.	Station	Region	Coordinates		Altitude, asl, m	Type
			latitude	longitude		
1	OPTEC-PR	Leningrad Oblast	60°42′59″	30°03′24″	40	Background
2	OPTEC-P	St. Petersburg	59°56′27″	30°15′14″	8	Urban
3	OPTEC-N	St. Petersburg	59°55′23″	30°23′17″	1	Urban
4	OPTEC-Karelia	Republic of Karelia	63°44′41″	31°56′33″	185	Background
5	Apatity	Murmansk Oblast	67°34′14″	33°23′51″	180	Urban
6	SBEM Karadag	Republic of Crimea	44°56′24″	35°14′12″	180	Background
7	Obninsk	Kaluga Oblast	55°05′48″	36°36′36″	175	Urban
8	Tarusa	Kaluga Oblast	54°43′36″	37°10′40″	128	Urban
9	Troitsk	Moscow	55°28′37″	37°18′44″	193	Suburban
10	RUDN	Moscow	55°42′37″	37°36′78″	149	Urban
11	KHMS IAP RAS	Stavropol Krai	43°43′59″	42°39′40″	2096	High-mountain
12	Vyatskiye Polyany	Kirov Oblast	56°13′33″	51°03′56″	74	Background
13	Fonovaya	Tomsk Oblast	56°25′07″	84°04′27″	80	Background
14	TOR	Tomsk Oblast	56°28′41″	85°03′15″	133	Urban
15	LAC	Tomsk Oblast	56°28′49″	85°06′08″	120	Suburban
16	Listvyanka	Irkutsk Oblast	51°50′48″	104°53′58″	670	Background
17	Boyarsky	Republic of Buryatia	51°50′22″	106°03′50″	516	Background
18	Ulan-Ude	Republic of Buryatia	51°48′48″	107°37′20″	523	Urban

Table 2. Mosecomonitoring stations

No.	Station	Coordinates		Type
		latitude	longitude	
19	Maryino	37°45′72″	55°39′11″	Urban
20	MSU	37°31′26″	55°42′25″	Urban
21	Losiny Ostrov	37°43′41″	55°51′32″	Urban
22	Tolbukhina street	37°24′18″	55°43′19″	Urban
23	Polyarnaya street	37°38′20″	55°52′30″	Urban
24	Turistskaya street	37°25′41″	55°51′25″	Urban
25	Spiridonovka street	37°35′49″	55°45′32″	Urban
26	Ostankino	37°36′58″	55°49′16″	Urban
27	Kozhukhovo	37°54′43″	55°43′23″	Urban
28	Kozhukhovo proezd	37°39′54″	55°42′29″	Urban
29	MADI	37°31′44″	55°48′07″	Roadside
30	Gagarina ave	37°35′06″	55°42′36″	Roadside
31	Khamovniki	37°34′19″	55°43′08″	Roadside
32	Nizhnyaya Maslovka street	37°34′48″	55°47′31″	Roadside
33	Shabolovka	37°36′22″	55°42′54″	Roadside

ples' Friendship University (RUDN) in Moscow, Tarusa, St. Petersburg (OPTEC-N), and Troitsk. The first, except KHMSS, can be referred to the background or suburban stations, and the second can be classified as urban stations. Seemingly, under the urban conditions the annual average SOC is influenced by ozone neutralization in vehicle engine exhausts, manifested most strongly at nighttime hours.


(a)

(b)

Sweden
Finland
Stockholm
Baltic Sea
Estonia
St-Petersburg
St-Petersburg
Novosaratovka
Moscow
Podolsk
Kaluga
Tula
Kazan
Yekaterinburg
Tyumen
Chelyabinsk
Omsk
Novosibirsk
Rybalovo
Tomsk
Kislovka
Trubache
Kireevsk
Kaftanchikovo
Bogas
Krasnoyarsk
Bratsk
Irkutsk
Listvyanka
Ulan-Ude
Baykalsk
Petro
Ulaanbaatar
Mongolia
Astana
Kazakhstan
Almaty
Bishkek
Czechia
Slovakia
Ukraine
Austria
Hungary
Moldova
Romania
Croatia
Serbia
Black Sea
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15
16
17
18
E105
MKAD
E115
Svetlye Gorki
Khimki
Nagornoye
Bibiryovo District
Otradnoye
Putilkovo
Khovrino District
Otradnoye District
Sviblovo District
Oboldino
Losiny Ostrov National Park
Angelovo
Mitino District
Voykovo District
Krasnogorsk
Pokrovskoye-Streshnyovo District
Ostankinsky District
Golyanovo District
A-103
Vostochny
Severnoye Izmaylovo District
A-109
Moscow River
Strogino District
Shchukino District
Maryina Roshcha District
Sokolniki Park
Izmaylovo District
M7
Khoroshevsky District
Meshchansky District
Krylatskoye District
Basmanny District
Reutov
Moscow
46K-7011
Novogireyevo District
Novokosino District
Dorogomilovo District
Romashkovo
Kuntsevo District
Khamovniki District
Nemchinovka
Novoivanovskoye
Tekstilshchiki District
E30
Marfino
Ramenki District
Kuzminki District
Skolkovo Innovation Center
46K-5001
Lyubertsy
Lyublino District
46K-5001
Cheryomushki District
HBP Michurinets
Govorovo
Kotelniki
Rasskazovka
Rumyantsevo
Serebryanye Rodniki
Tsaritsyno District
Dzerzhinsky
Mitino
Lapshinka
Kartmazovo
Mosrentgen Plant
Yasenevo District
Biryulevo Vostochnoye District
Mamyri
E101
A-130
Lenin State Farm
Lytarino
Bitsa
Aparinki
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Fig. 1. Locations of ozone monitoring stations: (a) on the territory of Russia, (b) in Moscow (see Tables 1 and 2 for the station numbers).

At nine stations, the monitoring has been carried out for three years. Figure 3 demonstrates how annual average ozone concentration varied in 2020–2022.

From Fig. 3 it follows that SOC at separate sites changes by 20–30% from year to year, reaching the twofold difference in Moscow (RUDN). The ozone concentration at KHMSS decreased in the period from 2020 to 2022. In 2021, the ozone concentration decreased at the background stations Vyatskiye Polyany, Tropospheric Ozone Research (TOR), OPTEC-PR, and Fonovaya Observatory, and increased at urban stations OPTEC-N, RUDN, and OPTEC-P. It is difficult to comment on this ozone behavior.

The annual maxima are distributed on the territory of Russia in a different way (Fig. 4). Error bars indicate the uncertainty (error) of one-time measurement.

From Fig. 4 it can be seen that the largest ozone concentrations, exceeding the maximum permissible one-time concentration ($MPC_{m.o}$) [37], were observed in 2022, mainly at the background stations OPTEC-PR, Boyarsky, Vyatskiye Polyany, TOR, LAC, and Listvyanka. As a rule, they are located in forested regions, where increased content of organic compounds of vegetation origin is usually observed [38].

The interannual differences between absolute maxima are presented in Fig. 5.

A concentration maximum in 2021 in Moscow (RUDN) is clearly identified in Fig. 5. It is attributed to smog that was observed in the city during summer. This was favored by the uniquely long-lasting blocking anticyclone in the period of maximal summertime temperatures [36]. In 2022, the largest ozone concentrations were recorded at the station OPTEC-PR.

Figures 2–5 illustrate the physical-geographical features of the regions where measurements were carried out. We can identify the terrains with high daily

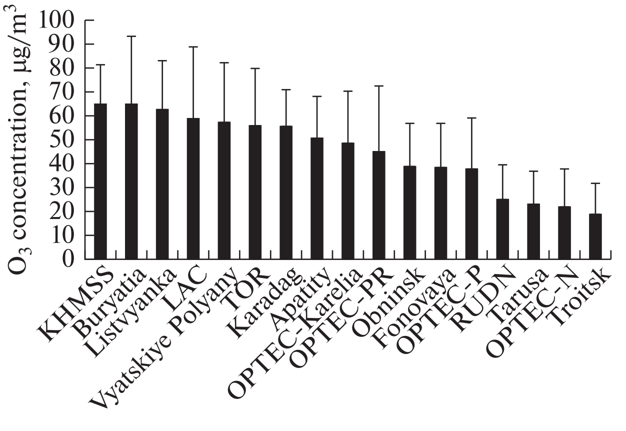

Fig. 2. Annual average ozone concentrations in 2022.

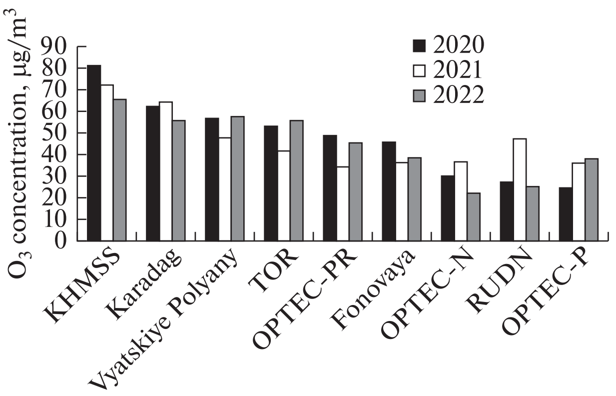

Fig. 3. Annual average ozone concentrations in 2020–2022.

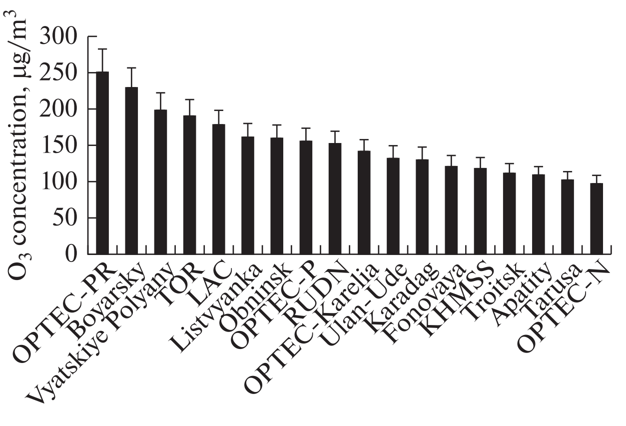

Fig. 4. Annual maxima of ozone concentration in 2022.

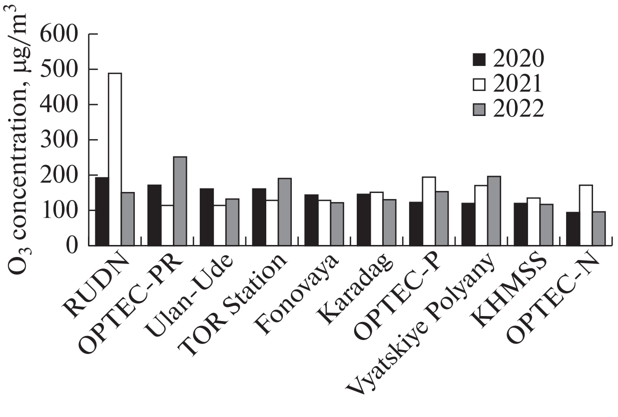

Fig. 5. Annual maxima of ozone concentration in 2020–2022.

average or maximal one-time ozone concentrations. Obviously, they may strongly differ for such a large country as Russia. This is also characteristic for other large countries [39–41].

2.2. Annual Behavior

Figure 6 presents the annual behavior of ozone concentration in the surface air layer at different stations. Stations are arranged in the order of decreasing annual ozone concentration in accordance with the data in Fig. 1. Here also the horizontal lines indicate the levels of the limiting daily average concentrations ($\mathrm{MPC_{d.a}}$) to estimate the periods when hygienic standards were exceeded. The quantitative characteristics of theses excesses are presented below.

An unusual annual behavior can be seen at KHMSS, being in air from the free atmosphere most of the time. The mountainous relief favors the transport of ozone-rich air from the stratosphere to the free atmosphere and the associated increase in the admixture concentration, observed at the station. From the beginning of surface-ozone measurements in 1989, the KHMSS observations usually showed two (spring and summer) local maxima of the monthly average ozone concentrations and a minimum in fall–winter [42]. A prominent feature of 2022 had been a poorly defined local springtime maximum. In the period of the 2022 summer maximum, the absolute hourly average contents reached 117 $\mu g/m^3$ on August 27–31 and 110 $\mu g/m^3$ on July 31–August 1. These values are lower than the maxima in excess of 140 $\mu g/m^3$, recorded in 2020 and 2021 [34–36]. Under the high-mountain conditions at KHMSS, high ozone concentrations can be associated with stratospheric intrusions to the free troposphere, and with a subsequent mixing in the zone of orographic disturbances [43]. Usually, these events are short-term, lasting from one to a few hours. Moreover, the increased concentrations may be associated with ozone production in polluted air during long-range transport.

A trajectory analysis of air masses, arrived at the KHMSS, was carried out to estimate the contribution of long-range transport to the observed extreme values. The method for calculating the 7-day back trajectories was described in the overview of the 2020 observations [34–36]. The 2022 calculations modeled 22479 trajectories. To mitigate the effect of local factors, we excluded from analysis the back trajectories for days, characterized by high (more than 85%) humidity and by the presence of fog at the trajectory end point (at the KHMSS), which were strictly not associated with the long-range transport. After that, 20619 trajectories were left in the dataset. This dataset was processed to select two sets of trajectories, corresponding to the extreme negative and extreme positive ozone anomalies, respectively, in the first and last deciles of the distribution function of ozone anomalies, calculated with respect to the second-order polynomial fit. For extreme ozone concentrations of both signs we estimated the probability fields (P, %) of air particle transport from spatial cells with the size of 1° × 1° to the KHMSS. Figure 7 shows the fields of the annual average probability of air particle transport for extremely low and extremely high ozone concentrations at the KHMSS.

On the whole, the 2022 probability fields are similar to the 2020 and 2021 estimates: extremely low (high) surface ozone concentrations at the KHMSS in 2022 were associated with the air transport from the northwestern (southern) directions. As in 2020–2021, the 2022 trajectories, associated with extremely low surface concentrations, passed with the largest probability over Krasnodar krai, the Azov Sea, and Ukrainian Azov region. As in 2021, the extremely high values in 2022 are explained by the sources in the southeastern cluster: the air masses with the largest probability moved over Azerbaijan and the South Caspian Sea. As in 2020 and 2021, the second cluster of high values is associated with the arrival of air masses from Turkey and from the Middle East. Both clusters are the regions with intense extraction and processing of oil and gas, in the plume of which, under the conditions of high temperatures and solar illumination, volatile organic compounds oxidize to produce ozone. Passage of air masses over these regions, in addition to mixing in the zone of orographic disturbances, may be the cause for the recorded increased values [44].

At the Boyarsky station the measurements were mostly carried out in warm period. As at the KHMSS, at the Boyarsky station the daily average SOCs are in the range of 1–3 $\mathrm{MPC_{d.a}}$, reaching 5 $\mathrm{MPC_{d.a}}$ on separate days. The annual behavior is difficult to quantify because the annual cycle is incomplete in this work.

At the stations Listvyanka, LAC, Vyatskiye Polyany, and TOR, the annual behavior is typical for background regions, with the maximum in springtime period and minimum in fall. At all sites, the ozone content is within 2–4 $\mathrm{MPC_{d.a}}$ (1–2 $\mathrm{MPC_{d.a}}$) in the first (second) half-year.

At the Karadag station, the annual behavior of the SOC during 2022 markedly differs from previous years [34–36], when concentration in this region was maximal during fall. During 2022 fall (September and October), no measurements were carried out because of the repairs and annual scheduled verification of the gas analyzer in the D.I. Mendeleev All-Russian Institute for Metrology, St. Petersburg. Most probably, this

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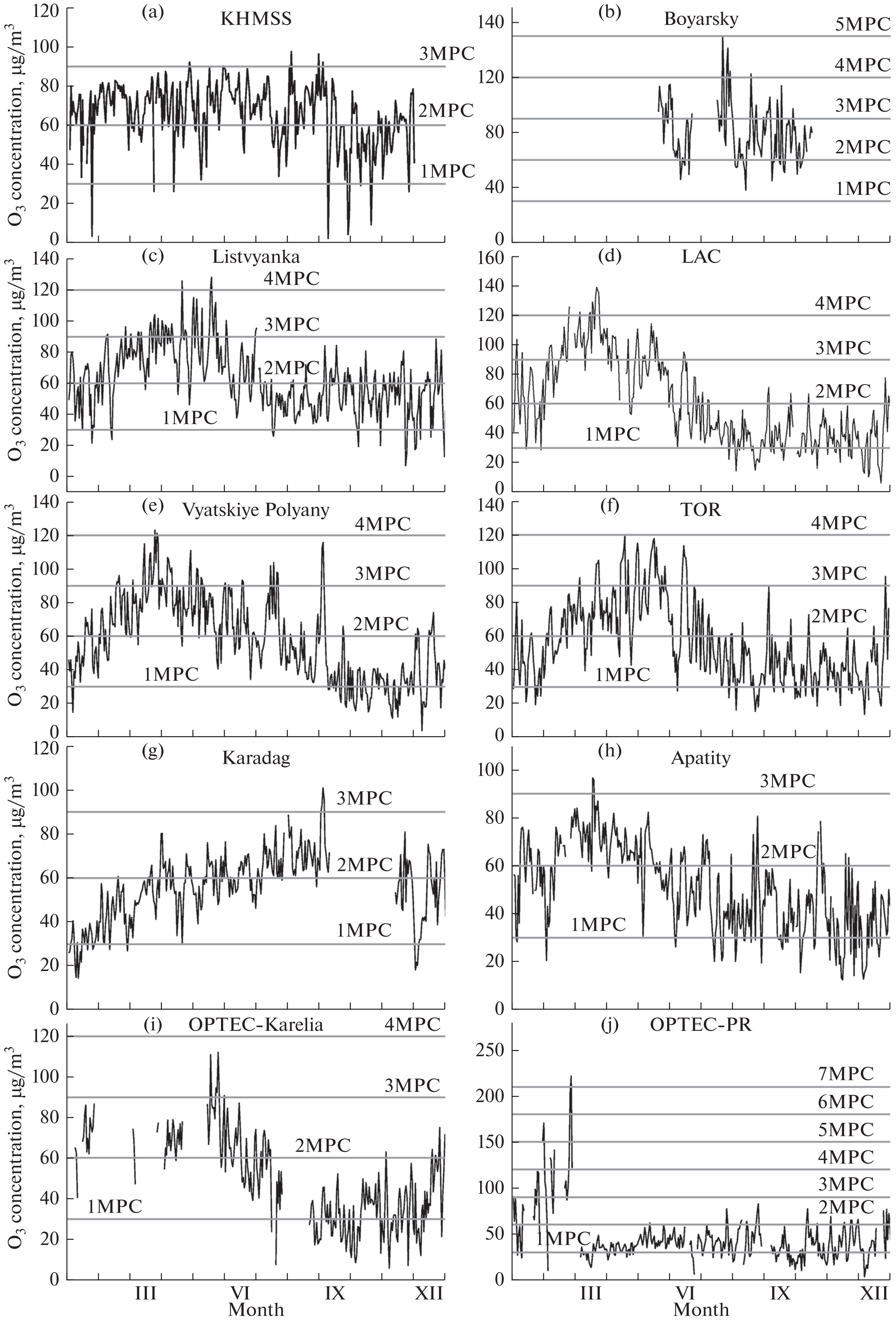
Fig. 6. Annual behavior of the daily average ozone concentration in 2022.


(a) KHMSS
3MPC
2MPC
1MPC
(b) Boyarsky
5MPC
4MPC
3MPC
2MPC
1MPC
(c) Listvyanka
4MPC
3MPC
2MPC
1MPC
(d) LAC
4MPC
3MPC
2MPC
1MPC
(e) Vyatskiye Polyany
4MPC
3MPC
2MPC
1MPC
(f) TOR
4MPC
3MPC
2MPC
1MPC
(g) Karadag
3MPC
2MPC
1MPC
(h) Apatity
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1MPC
(i) OPTEC-Karelia
4MPC
3MPC
2MPC
1MPC
(j) OPTEC-PR
7MPC
6MPC
5MPC
4MPC
3MPC
2MPC
1MPC
O_3 concentration, μg/m^3
0
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40
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80
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120
140
160
250
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VI
IX
XII
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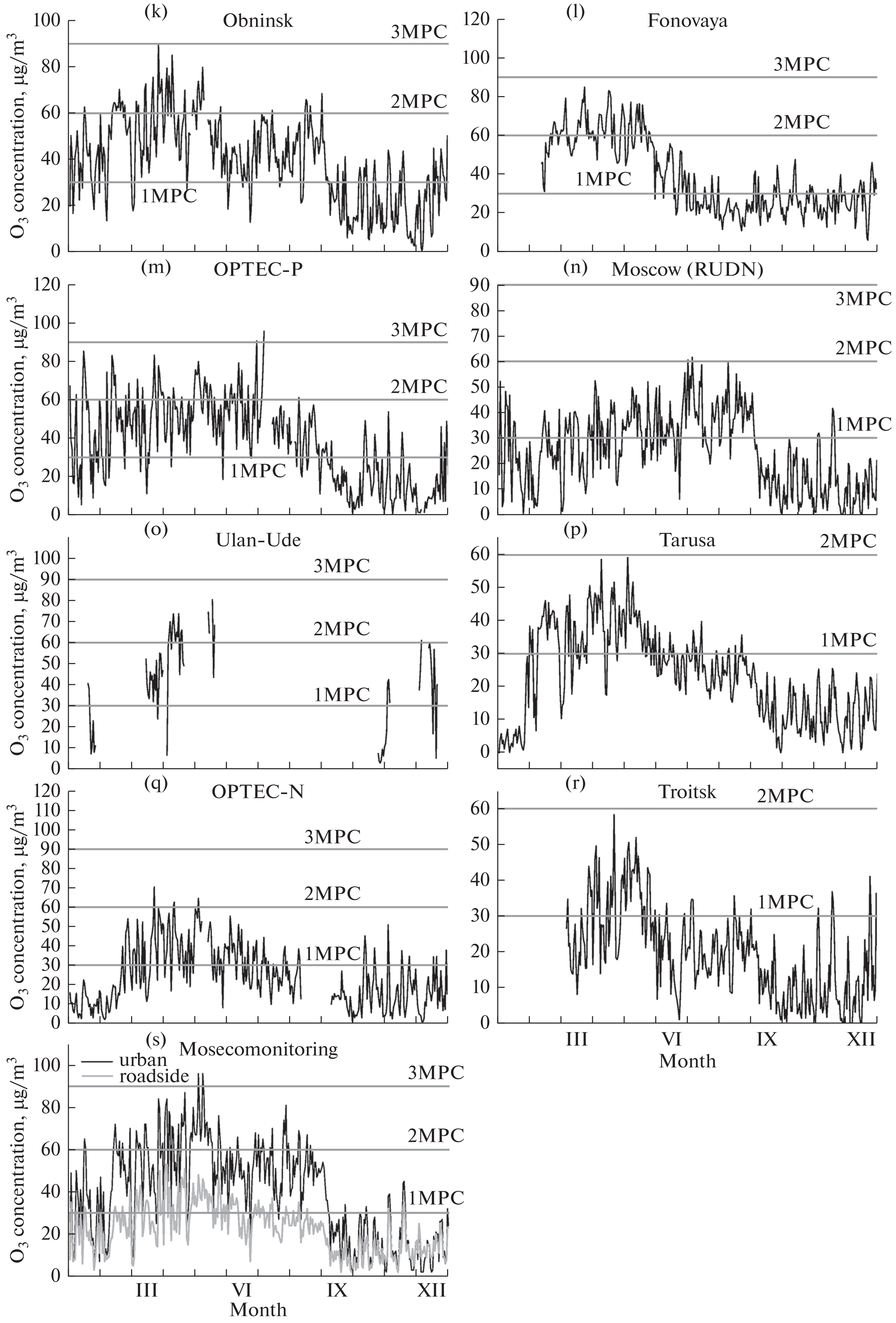
(k) Obninsk
3MPC
2MPC
1MPC
O3 concentration, µg/m3
0
20
40
60
80
100
(l) Fonovaya
3MPC
2MPC
1MPC
0
20
40
60
80
100
120
(m) OPTEC-P
3MPC
2MPC
1MPC
O3 concentration, µg/m3
0
20
40
60
80
100
120
(n) Moscow (RUDN)
3MPC
2MPC
1MPC
0
10
20
30
40
50
60
70
80
90
(o) Ulan-Ude
3MPC
2MPC
1MPC
O3 concentration, µg/m3
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20
30
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50
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70
80
90
100
(p) Tarusa
2MPC
1MPC
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50
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(q) OPTEC-N
3MPC
2MPC
1MPC
O3 concentration, µg/m3
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(r) Troitsk
2MPC
1MPC
0
10
20
30
40
50
60
III
VI
IX
XII
Month
(s) Mosecomonitoring
urban
roadside
3MPC
2MPC
1MPC
O3 concentration, µg/m3
0
20
40
60
80
100
III
VI
IX
XII
Month

Fig. 6. (Contd.)

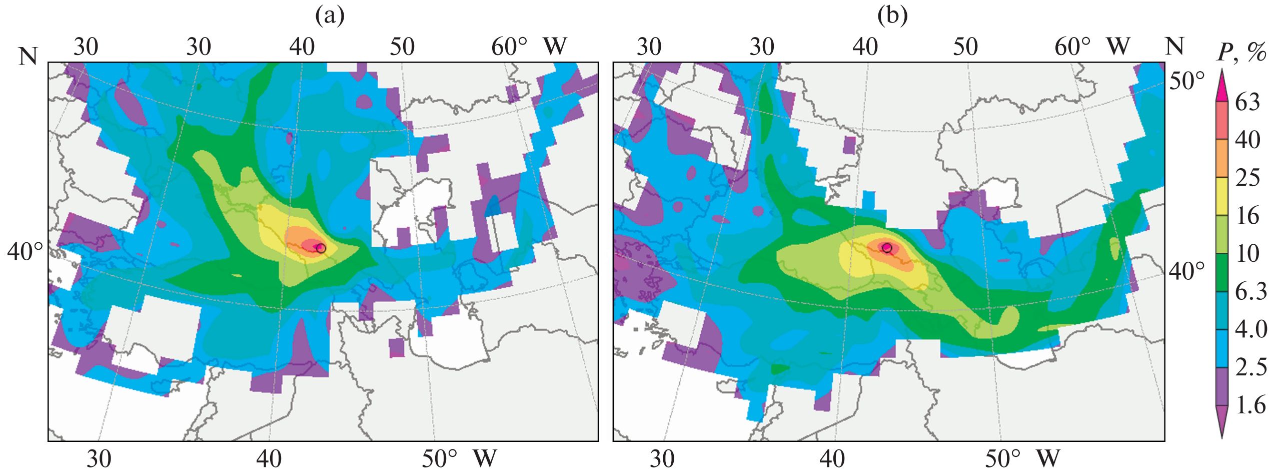

Fig. 7. Probability of passage of elementary air masses, associated with (a) 10% of the lowest and (b) 10% of the highest anomalies of the surface ozone concentration at the KHMSS in 2022 over different territories.

anomaly (autumn maximum) was due to a cold spring and a cold early summer.

Seemingly, the annual behaviors in Apatity and Karelia can be considered as typical for the northern regions of ETR. On this territory, the maximum is observed during spring, and the minimum occurs during fall for relatively low ozone concentrations within 1–3 $MPC_{d.a}$.

The annual behavior at the OPTEC-PR station is quite peculiar in character. The concentration rapidly grows up to 7 $MPC_{d.a}$ at the beginning of the year, followed by almost neutral behavior in the range of 1–2 $MPC_{d.a}$ from May through the end of the year.

Though belonging to urban stations, Obninsk shows the annual behavior typical for background regions, with the maximum during spring and minimum during fall. The ozone content was within 1–3 $MPC_{d.a}$ throughout the year and decreased to 1 $MPC_{d.a}$ and lower by the end of the year.

At the Fonovaya Observatory the annual behavior is typical for regions remote from industrial centers, with the concentration maximizing in spring and minimizing in fall and winter. In contrast to other background stations, the ozone concentration was relatively low: 2–3 $MPC_{d.a}$ at the maximum and less than or equal to $MPC_{d.a}$ at the minimum.

The other six stations are among urban ones and, as such, show minimal annual average ozone concentrations (see Fig. 2). At the stations OPTEC-P, Moscow (RUDN), and Ulan-Ude, the annual behavior is typical for urban conditions, with a maximum in summertime. The SOC values are within 1–3 $MPC_{d.a}$. The three remaining stations refer to the regions, in which the smallest ozone concentrations are minimal, i.e., below or slightly above $MPC_{d.a}$. Seemingly, these cities have no major anthropogenic emissions of ozone-forming compounds. This can be concluded not only from low SOCs, but also from the character of annual behavior, which corresponds to background conditions.

We conclude this section by considering the Moscow-average characteristics, presented in Fig. 6u. This figure presents the daily average ozone concentrations averaged over nine urban and six roadside stations. The annual average ozone concentration in the surface air in residential regions of Moscow was 39 $\mu g/m^3$ (32–45 $\mu g/m^3$ at urban AAPCS) and 22 $\mu g/m^3$ near highways (19–26 $\mu g/m^3$ on traffic type AAPCS), reflecting the inhomogeneity of the surface ozone field, characteristic for the megalopolis. The SOC measurements from monotypic stations at different separations from the pollution sources and with specific landscape features correlate well; the correlation coefficient between urban AAPCSs was 0.9–0.96 (R = 0.82 between AAPCSs in Tolbukhina and MSU). In the annual behavior, the ozone concentration showed a maximum in spring and an annual minimum in October–December. The ozone concentrations, averaged over summer months, turned out to be comparable to the average SOC in March and were about 10 $\mu g/m^3$ smaller than in April–May.

From 6u it can be seen how efficiently ozone is extinguished in motor vehicle exhausts. The ozone content at roadside stations throughout the year is almost half that at urban stations. But, even at these AAPCSs, the SOC exceeds the daily average $MPC_{d.a}$.

2.3. Maximal Concentrations

Figure 8 shows the annual (2022) behavior of the hourly maximal SOCs at different stations. According to Fig. 4, the hourly maximal SOCs were recorded in those same regions where the annual average ozone

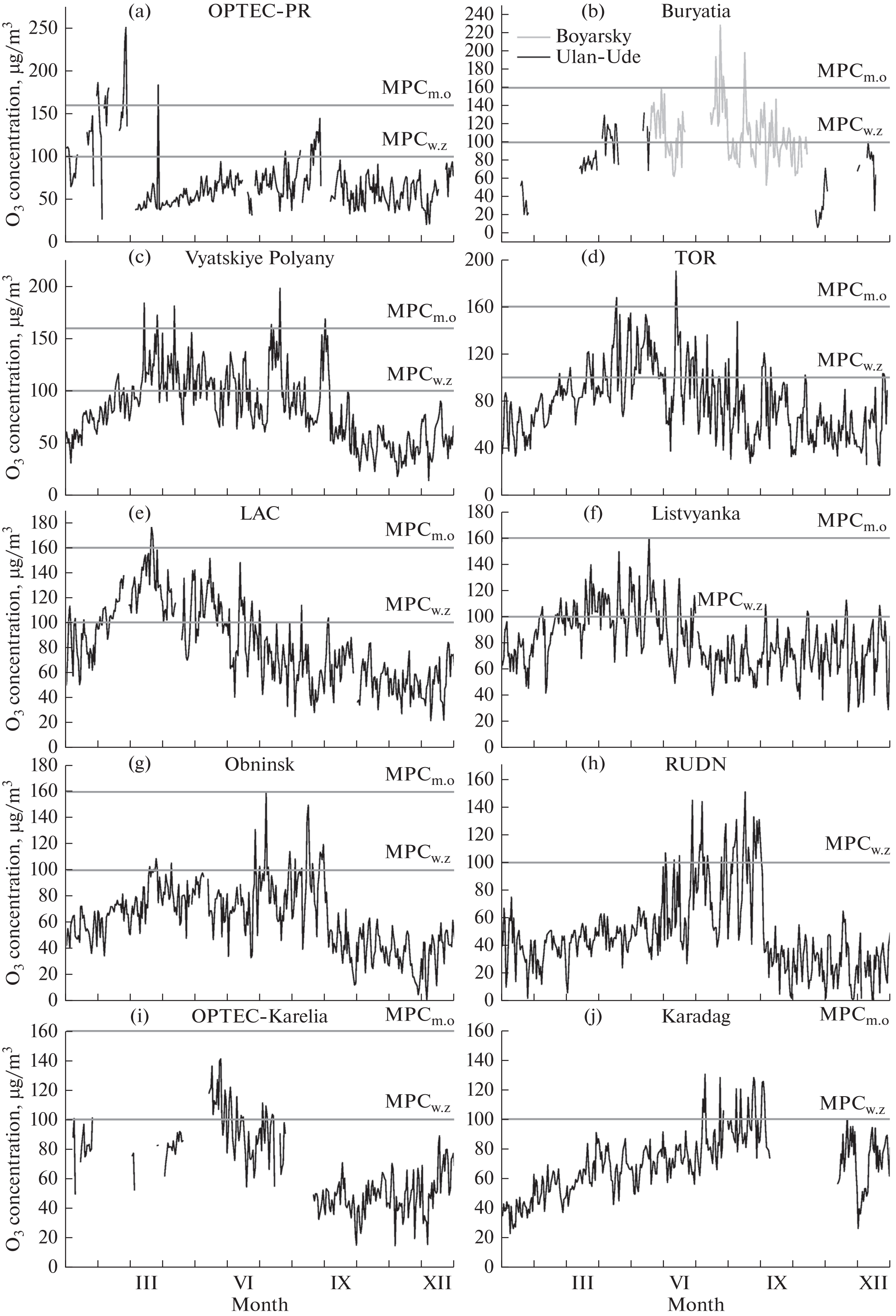

Fig. 8. Annual behavior of hour-maximal ozone concentration in 2022.

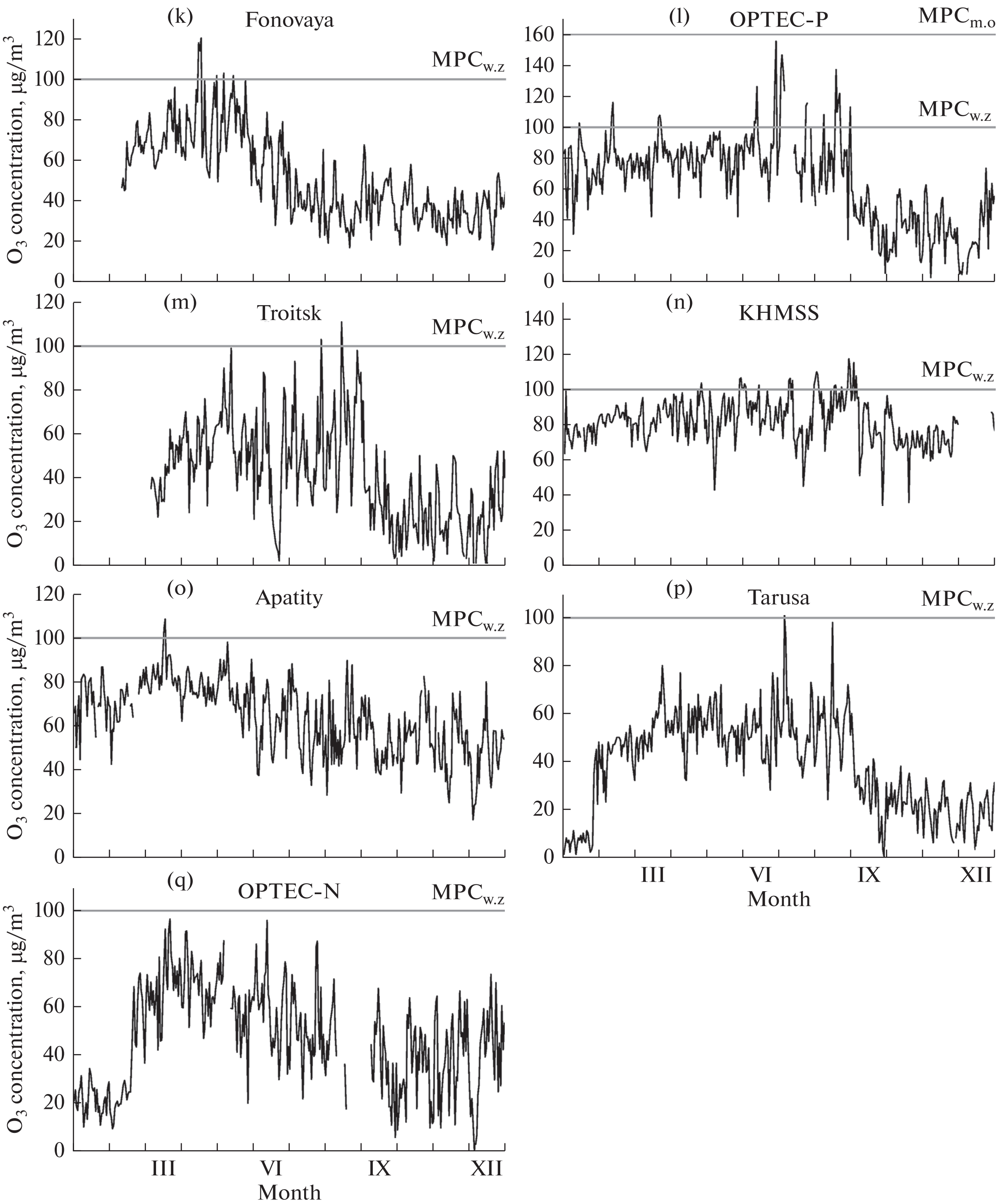

Fig. 8. (Contd.)

concentrations were the largest. Therefore, the stations in Fig. 8 are arranged in the order of decreasing values, presented in Fig. 4. The data for Boyarsky and Ulan-Ude are given together in a single plot. In this figure the horizontal lines indicate the maximum one-time hourly MPC (MPC$_{m.o}$) and the MPC of the working zone (MPC$_{w.z}$).

From Fig. 8 it can be seen the hourly MPC$_{m.o}$ values are exceeded at six stations (background or suburban). At nine stations the 100 μg/m^3 level was exceeded, which is the basis for determining MPC$_{w.z}$. Recall that, based on work [37], this concentration should be recorded for no less than eight successive hours. At two stations (Tarusa and OPTEC-N) the

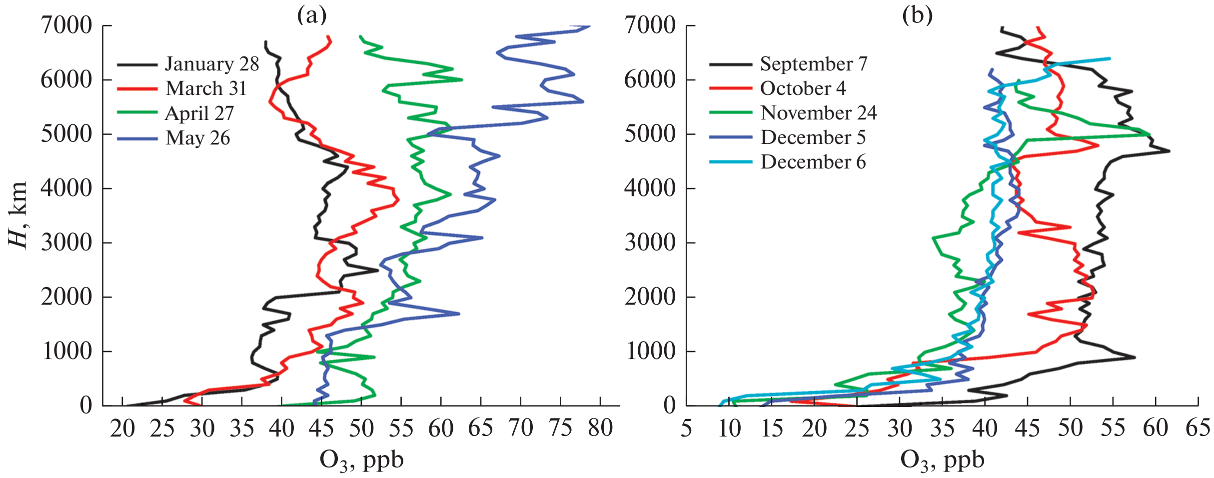

Fig. 9. Ozone vertical distribution over the southwestern Siberia (Novosibirsk) in 2022.

maximal ozone concentration in the surface air layer did not reach 100 μg/m^3. In section 4 we present the qualitative values of excesses over MPC.

At the background stations (OPTEC-PR, Vyatskiye Polyany, TOR, LAC, and Listvyanka) in annual behavior the concentrations are maximal during spring, during their main growth. There are secondary maxima at Vyatskiye Polyany, LAC, and TOR in summertime. Possibly, this is due to anthropogenic activity in the station surroundings. The main maximum is recorded at summertime at just one station, namely, Boyarsky.

At the urban stations (Obninsk, RUDN, OPTEC-P, Troitsk, Tarusa, and OPTEC-N) the concentrations are maximal during summer, probably signifying the ozone production from anthropogenic emissions during increased air temperatures [44–47].

At two background stations (OPTEC-Karelia and Fonovaya) ozone in background air layer was maximal in late spring, possibly due to meteorological conditions in these regions.

In Karadag, the annual behaviors of diurnally averaged and maximal concentrations markedly differ. The ozone concentrations in the surface air layer are maximal in summer months (July, August). The concentrations in 2022 were the largest on July 8 and August 22 on clear-sky and calm days (130 and 128 μg/m^3 respectively). The ozone concentration during summer was maximal for the southern and southeastern directions of air mass motion.

At the KHMSS the burst of the maximal ozone concentrations was recorded in late summer, while the annual behavior was quite neutral in the other periods.

Poorly defined dynamics of maximal concentrations in the annual behavior was also recorded in Apatity.

If we compare the above-mentioned diurnal average and maximal ozone concentrations in surface air layer in Russia against the data from other countries, they are comparable to SOCs from the United States and Europe [48–50] and somewhat lower than those from China [51].

3. OZONE VERTICAL DISTRIBUTION IN THE TROPOSPHERE

The ozone vertical distribution in the troposphere was measured onboard *Optik* Tu-134 aircraft laboratory [52]; its current instrumentation was presented in [53]. Monthly flights over the southern regions of western Siberia were carried out throughout the period considered here. A unique experiment, aimed to measure the composition of air including ozone, was carried in September 2022. Its purpose was to carry out sensing with a profile variable in altitude in the meridional direction. The route started near 56° N and ended in the Kara Sea basin near 75° N, where synchronous near-water measurements onboard the research vessel (RV) *Akademik Mstislav Keldysh* were carried out. The measurements over the south of western Siberia are presented in Fig. 9. Figure 9a displays the profiles in the period of increasing ozone concentration in the troposphere; and Fig. 9b gives an idea on the ozone vertical distribution in the period of decreasing concentration.

From Fig. 9a it can be seen that, in the winter period and in early spring, the ozone concentration was small (20–30 ppb) in the lower layer, increased to 40–50 ppb in the middle troposphere, and decreased again in the upper troposphere. This vertical profile indicates that the exchange processes between the troposphere and stratosphere were insignificant in that period of time.

In the middle and late spring, the ozone concentrations in the boundary layer increased to 40–50 ppb due to intensification of the photochemical processes. High concentrations in the lower troposphere indicate the intensification of exchange processes with the stratosphere.

Under the conditions of moderate air exchange between the troposphere and stratosphere (Fig. 9b), the ozone content reaches 50–55 ppb in the lower troposphere in the second half-year due to photochemical ozone production. In November–December the concentration dropped throughout the troposphere.

Figure 10 presents the data obtained during meridional flight. The legend lists the sites over which the aircraft laboratory descended. The southernmost site was the Novosibirsk airport; and the northernmost site was RV *Akademik Mstislav Keldysh*. It can be seen that, despite the large distance between the measurement sites (56°–74° N), the ozone concentrations in the period of the experiment in the lower and middle troposphere differed little. The maximal differences in this atmospheric layer reached 20 ppb.

There were high-altitude frontal zones in the upper troposphere over the southern and northern regions. From Fig. 10 it can be seen that, over Novosibirsk and Salekhard, the aircraft crossed the tropopause, signified by the rapid growth of ozone concentration; over the Kara Sea it evidently crossed the tropopause "fold."

Thus, if we compare the vertical distributions, presented in Figs. 9 and 10, with previous results for this same region [54–56], we can conclude that they are in the middle of the possible multiyear variability range. A similar result was also obtained by our Chinese colleagues [57]. The low values in the Arctic are possibly associated with the depletion of tropospheric ozone [58].

4. CORRESPONDENCE OF OZONE CONCENTRATION IN RUSSIA TO HYGIENIC STANDARDS

Table 3 presents the quantitative indices of ozone concentrations exceeding the hygienic standards, accepted in the Russian Federation in [37].

From Table 3 it follows that the daily average surface ozone surface concentrations may exceed the $MPC_{d.a}$ on the entire territory of Russia covered by measurements. Importantly, the excess strongly varies in space and can be from 20 to 100%. Moreover, except Troitsk and Tarusa, the threshold of 2 $MPC_{d.a}$ can be exceeded everywhere: from 0.5 to 82%. The threshold of 3 $MPC_{d.a}$ is also often exceeded at the most (13 out of 18) stations. Even concentrations exceeding 5 MPC are recorded in St. Petersburg and Boyarsky.

The notion of the MPC of the working zone for ozone is extended somewhat because ozone is not injected by certain anthropogenic sources, but is formed directly in the atmosphere from precursor gases that can come to air outside the zone itself. Nonetheless, $MPC_{w.z}$ in Tomsk oblast was exceeded 53 times in the region of LAC and 26 times in the region of the TOR station. The $MPC_{w.z}$ in 2022 was exceeded sixteen times in St. Petersburg (OPTEC-PR), nine times in Karelia, twelve times in Listvyanka, nineteen times in Boyarsky, and eight times in Vyatskiye Polyany. The RUDN station in Moscow should be mentioned separately. At this station, $MPC_{w.z}$ was exceeded 145 times in 2021 and only once in 2022, highlighting how the situation can differ in different years.

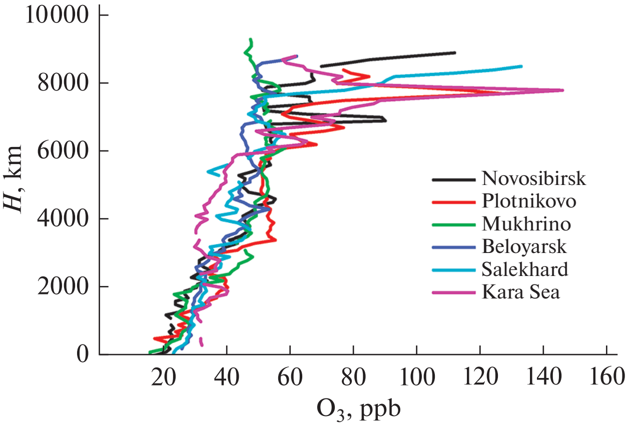

Fig. 10. Ozone vertical distribution on September 8–11, 2022 along meridian.

The number of stations, at which the maximum one-time $MPC_{m.o}$ = 160 μg/m^3 was exceeded, remained almost unchanged. They were as many as five in 2021 and six in 2022. It is important to stress that two stations were added in 2022. The $MPC_{m.o}$ was exceeded three and two times in the region of Tomsk, 10 times in St. Petersburg, once in Listvyanka, five times in Boyarsky, and six times in Vyatskiye Polyany. In Moscow the $MPC_{m.o}$ was exceeded 402 times in the period of summer smog in 2021 and not even once in 2022.

Thus, our study shows that nature protection measures should be taken in many regions of Russia to reduce the level of the tropospheric ozone concentration.

CONCLUSIONS

The analysis of the number and locations of ozone monitoring stations shows that they still cover only a third of the territory of Russia. Therefore, it is very important to increase the country's area covered by the monitoring sites and especially in background and southern regions.

The ozone surface concentration was at the moderate level in 2022 in Russia, comparable to its content in a number of developed countries. Nonetheless, the maximum permissible daily average concentrations, determined by the national hygienic standards, were exceeded at all measurement sites. In separate regions,

Table 3. Concentrations exceeding the maximum permissible concentrations of ozone in Russia in 2022

Station	>1MPC, %	>2MPC, %	>3MPC, %	>5MPC, %	MPC$_{w.z}$, number of cases in excess of MPC	MPC$_{m.o}$, number of cases in excess of MPC	Number of days of measurements
LAC	84.8	41.4	19.2		53	3	355
TOR station	87.6	38.7	9.4		26	2	362
Fonovaya	54.8	19.1					325
OPTEC-N	30.6	1.1					360
OPTEC-P	61.6	18.2	0.6				352
OPTEC-PR	76.1	17.3	6.3	1.6	16	10	318
OPTEC-Karelia	76.7	32.7	2.9		9		245
Karadag	94.3	42.0	1.0				300
KHMSS	97.3	68.6	1.8				334
Listvyanka	95.6	50.8	10.7		12	1	364
Apatity	85.4	34.3	0.6				356
Boyarsky	100.0	82.0	28.7	0.8	19	5	122
Ulan-Ude	74.0	24.7	1.4				73
Moscow (RUDN)	39.5	0.5			1		365
Troitsk	20.3						301
Tarusa	31.0						365
Vyatskiye Polyany	86.3	46.8	11.2		8	6	365
Obninsk	69.4	13.3	0.3				360

the maximum permissible concentrations of the working zone and the maximum one-time hourly average concentrations were exceeded. In this situation, the population should be broadly informed about the monitoring results and the possible consequences from concentrations exceeding the hygienic standard; also, nature protection measures should be elaborated to reduce the level of ozone concentration in the surface air layer.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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