REVIEWS AND CONSULTATIONS

Ozone Content over the Russian Federation in 2020

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Received January 13, 2021

Revised January 13, 2021

Accepted January 13, 2021

Abstract—The review is based on the results of operation of the total ozone (TO) monitoring system in Russia and neighboring countries that functions in the operational mode at the Central Aerological Observatory. The monitoring system uses data from the national network equipped with M-124 filter ozonometers being under the methodological supervision of the Main Geophysical Observatory. The quality of the functioning of the entire system is operationally controlled using the OMI satellite equipment observations (NASA, USA). Basic TO observation data are generalized for each month of the fourth quarter of 2020, for the fourth quarter, and for the whole year. Data of routine observations of surface ozone in the Moscow region are also presented.

DOI: 10.3103/S1068373921020084

Keywords: Total ozone monitoring in CIS, total ozone anomaly in the fourth quarter of 2020 and for the whole year, Antarctic ozone hole, surface ozone values

The basic results of total ozone (TO) observations for the first three quarters of 2020 were described before in [10–12]. The normals (multiyear means) of TO over Russia and adjoining areas computed for different months of the fourth quarter for the period of 1974–1984 were presented in [4]. The deviations from the normal are given in percent and standard deviation units; the anomalous deviation is the deviation from the normal by 2.5 SD. The low quality of observational data from Samara, Vladivostok, Krasnoyarsk, Nikolaevsk-on-Amur, Voronezh, Karaganda, Almaty, Semipalatinsk, Arkhangelsk, Murmansk, Bol'shaya Elan', and Chardzhou stations does not allow their use for analyzing the TO field for the whole year. In addition, observational data from Khanty-Mansiysk and Gur'ev stations were not used to analyze the TO fields for the fourth quarter of 2020 for the same reason.

The quarterly mean TO values in the fourth quarter of 2020 were close to the multiyear means for 1974–1984 (Fig. 1a). The maximum deficiency of quarterly mean TO values was registered in Yakutsk and amounted to 8% or 2.0 SD. The maximum exceeding over the normal was registered in Tomsk (8% or 2.4 SD). The lowest quarterly mean TO values (272–310 DU) in the fourth quarter of 2020 were observed over the European part of Russia, over the Ural, the northern regions of Western and Central Siberia, and over western Kazakhstan. The highest values (355–366 DU) were registered over the Magadan oblast and Kamchatka. Over the rest of the territory under control the TO values were 310–355 DU.

Table 1 presents data on the anomalous deviations from the normal of daily TO values recorded at the ozonometric stations in the fourth quarter of 2020.

Fig. 1. The field of deviations (%) of total ozone from the multiyear mean in (a) October–December, (b) October, (c) November, and (d) December as well as (e) for the whole 2020.

In October 2020 the monthly mean TO values were close to the normal over the territory under control (Fig. 1b). The maximum deficiency of monthly mean TO values was recorded at Kotel'nyi Osland station and amounted to 7% or 1.1 SD. The normal was maximally exceeded in Tomsk: by 9% or 2.1 SD.

In November the monthly mean TO values were basically close to the normal over the territory under control (Fig. 1c). The monthly mean TO values below the normal (by 10–20%) were observed over the north of the Krasnoyarsk krai, over Yakutia and the Magadan oblast. The anomalous deficiency of monthly mean TO values was registered in Yakutsk (20% or 2.9 SD). The maximum exceeding over the normal was registered in Moscow: 8% or 1.5 SD.

In December the monthly mean TO values were close to the normal over the territory under control (Fig. 1d). The quarterly mean TO values below the normal (by 10–16%) were observed over the north-western regions of European Russia. The maximum deficiency of monthly mean TO values was recorded in St. Petersburg: 16% or 2.3 SD. The maximum exceeding of the normal was registered at Nagaevo station (11% or 1.9 SD).

The deviations of annual mean TO values from the normal in 2020 (Fig. 1e) at most stations in Russia are negative and are in the range from –14 to 3% for all analyzed stations. The largest deviations were registered on the Arctic Ocean islands, in the north of the Krasnoyarsk krai and Yakutia, which was an effect of the large and durable ozone anomaly in the winter-spring period [11, 12]. The maximum deficiency of an-

Table 1. Total ozone deviations from the normal in the fourth quarter of 2020

Station	October			November			December		
	Date	TO		Date	TO		Date	TO	
		%	SD		%	SD		%	SD
Below the normal									
Aral Sea	19	19	2.7						
Yekaterinburg	10	24	2.8						
St. Petersburg							22	37	2.8
Turukhansk	11	28	2.9						
Yakutsk				29	33	2.6			
Above the normal									
Irkutsk	9	20	2.6						
	10	21	2.6						
Moscow	21	27	3.0						
Nagaevo							25	30	2.9
Omsk	22	26	3.1	12	27	2.7			
	23	24	2.9						
Tomsk	24	35	3.9				26	37	3.0
	28	28	3.0						

nual TO means (14%) was registered at Tura, Olenek, and Kotel'nyi Island stations. The maximum exceeding of annual mean TO values over the normal (3%) was observed in Tsimlyansk.

During 2020, some considerable deviations of daily TO values from the normal were registered in January–May. For example, the daily TO values were below the normal:

- by 35–46% on January 27–29 over the northern regions of European Russia (190–232 DU);
- by 30–45% on February 5–6 over the northern regions of the Krasnoyarsk krai and Evenkia (238–322 DU);
- by 28–43% on February 9–10 over the northern regions of the Krasnoyarsk krai, Evenkia, and Yakutia (255–332 DU);
- by 27–60% on February 18 and March 15 over the northern regions of the Krasnoyarsk krai, Yakutia, Evenkia, and the Magadan oblast (187–367 DU);
- by 19–51% on March 17–May 14 over the north of European Russia, the Arctic Ocean islands, Western Siberia, the northern regions of the Krasnoyarsk krai, Yakutia, Evenkia, the Magadan and Irkutsk oblasts (221–361 DU);
- by 17–27% on May 18–27 over Western Siberia, the northern regions of the Krasnoyarsk krai, Yakutia, Evenkia, the Ural, and northern Kazakhstan (265–346 DU).

As noted in [11, 12], such anomalies in the winter-spring seasons in the northern regions of Russia were recorded earlier in 1997 and 2011. However, in 2020 the series of negative anomalies was especially durable and finished a month later than the anomaly in 2011. In 2011, the maximum TO deficiency was registered at Kotel'nyi Island station on March 20 and made up 50%. The maximum TO deficiency in 2020 (60%) was registered on March 2 at Kotel'nyi Island station as well. Such significant TO reduction affected the UV irradiance of the earth surface in the areas of the TO anomaly. However, due to a very low position of the sun in the high latitudes in this season, the values of the UV index [7–9] did not reach the levels dangerous for the population and did not exceed 1. In the second half of May 2020, when the TO decrease reached 24% over the northern regions of the Krasnoyarsk krai, Yakutia, and Evenkia, the exceeding of UV-B irradiance of the territory as compared to the normal made up about 80%, and the UV index in the anomaly zone was below 4 (the level of UV radiation is considered dangerous for humans at the index values equal to 6 and more [16]).

Fig. 2. The interannual variability of annual mean TO values in the latitude range of (1) 60–90° N and (2) 30–60° N as well as at (3) Yakutsk (62° N, 130° E), (4) Yekaterinburg (57° N, 61° E), and (5) St. Petersburg (60° N, 30° E) stations.

The variations in annual mean TO values during the period from 1997 at three stations of the Russian ozonometric network and in two latitude zones of the Russian Federation are shown in Fig. 2. The annual mean TO values were calculated from satellite data (<http://ozonewatch.gsfc.nasa.gov>) for the latitude zones and from operational data of M-124 filter ozonometers for the stations. The considerable depletion of the ozone layer was observed from the early 1980s till the middle of the 1990s, whereas its relative stabilization has been observed since the late 1990s (see Fig. 2). Against a background of high interannual variability, it is difficult to state clearly the significant TO trends in the middle and high latitudes. In 2020 all TO anomalies in the Russian Federation were negative, considerable, and totally rather durable. This led to a significant decrease in average annual TO values at the stations situated in the anomaly zones. Most such stations in Russia are located in the high latitudes. The low TO values were also recorded at the Arctic and subarctic stations of Canada and West European countries in the winter-spring period of 2020 [14]. Therefore, there is a dramatic decrease in the annual mean TO values in the latitude zone of 60–90° N and in the trend calculated from the presented data. According to Fig. 2, the trend in annual mean TO values in the latitude zone of 60–90° N is positive and is equal to 0.34 DU per decade. It is much smaller than the trend calculated from data for 1997–2019. A weak TO growth in the Northern Hemisphere high latitudes is also mentioned in [3, 5, 15]. The trend in annual mean TO values in the latitude zone of 30–60° N remains negative, its absolute value increased as compared to the trend computed from the data for 1997–2019 and is equal to –0.42 DU per decade.

The observations of the Antarctic ozone hole (AOH) were continued. The detailed description of the AOH development in August–September 2020 is given in [10]. The basic volume of data on the AOH characteristics is obtained from satellite observations using the equipment produced in the USA and Western Europe. The area where $TO < 220$ DU, is considered as the area occupied by AOH. The quantitative parameters of AOH and Figs. 3 and 4 were taken from the NASA website (<http://ozonewatch.gsfc.nasa.gov>).

In 2020 the Antarctic ozone hole appeared in early August (as well as in 2017–2019), which corresponds to the average time of its occurrence, and disappeared on the last days of December (Fig. 3), which is almost three weeks later than the mean dates of its disappearance. The AOH area reached the maximum ($24.8 \cdot 10^6$ km²) on September 20 and then started decreasing very slowly. By November 7, it decreased to $20.7 \cdot 10^6$ km² (the mean value for this day is $12.4 \cdot 10^6$ km²). From November 18 to December 2 and from December 8 to the end of the anomaly, its area exceeded the previously registered maxima.

The content of polar Antarctic ozone (the mean TO value in the zone south of 63° S) was below the multi-year means since the end of April. At the end of August, it was above the normal for three days only, started decreasing rapidly afterwards, and reached the minimum of 170 DU on September 27, 2020. The minimum value for this day is 167 DU, and the absolute minimum of the polar Antarctic ozone is 157 DU. In October, polar ozone content started growing and reached 214 DU on October 13; after that it decreased to 189 DU by October 28 (the previously registered minimum of polar Antarctic ozone for this day is 184 DU). After that, the gradual growth started, but the pattern was repeated: having reached the local maxima of 226 DU on November 8, the value of polar ozone content dropped again to 202 DU on November 14. On November 13–30 and December 12–25, the values of polar Antarctic ozone updated the previous minima for these days.

The monthly mean values of polar ozone in the Antarctic in November and December 2020 were minimal of all previously registered monthly mean values for these months (212.67 and 263.04 DU, respec-

Fig. 3. The major characteristics of the Antarctic ozone hole in 2020 from the NASA (USA) satellite data: (a) the area occupied by $TO < 220$ DU (10^6 km²), (b) minimum TO (DU), and (c) minimum stratospheric temperature at the level of 50 hPa south of 50°S (K). The areas between the minimum and maximum values observed in 1979–2020 are gray; the light lines inside these areas indicate the mean values for this period.

Fig. 4. (a) The mean area of the Antarctic ozone hole (10^6 km²) in September 7–October 13 and (b) the mean value of minimum TO in it (DU) in September 21–October 16 according to the NASA (USA) satellite data for 1979–2020. Figures 3 and 4 were taken from the NASA website: <http://ozonewatch.gsfc.nasa.gov>. The extremes of the mentioned parameters reached in the previous years are marked separately (data for 1995 are absent).

tively). The monthly mean value for November almost coincided with the value of polar Antarctic ozone for August–November 2020 (212.72 DU). The minimum mean value of polar Antarctic ozone over all years of the mentioned period was recorded in 1998 and amounted to 210.9 DU. In 1999 and 2006, the mean values of polar Antarctic ozone over the mentioned period were below the value registered in 2020 (212.5 and 211.1 DU, respectively) [13]. In the next years, the minimum mean value of polar Antarctic ozone for August–November was observed in 2015 (213.5 DU). Figure 5 presents the polar Antarctic ozone values in August–December 2015 and 2020 and, for comparison, variations in the multiyear means and in the multiyear means minus 2.5 SD. It is clear that a unique event occurred in the Antarctic at the end of December 2020. For the first time over all observation years, a negative anomaly of polar Antarctic

Fig. 5. The variations in polar Antarctic ozone in August–December in (1) 2020 and (2) 2015, as well as (3) its multiyear means $\bar{X}$ and (4) the difference $\bar{X} - 2.5 \text{ SD}$.

Fig. 6. The deviations from the multiyear means: (1) for polar Arctic ozone from January 1 to April 20, 2020; (2, 3) for polar Antarctic ozone from August 22 to December 9 in 2020 and 2015, respectively. N is the number of the day.

ozone was recorded (assuming that the anomaly is the deviation from the mean by 2.5 SD). Its deficiency exceeded 2.5 SD on December 17 and 19–24 and exceeded 3 SD on December 20 and 21. Paradoxically, all polar ozone anomalies (if they are considered in the above sense as unlikely events) that were recorded in the Antarctic during the period of 1979–2019 were positive.

It should especially be noted that the change in polar Antarctic ozone in the winter-spring season of 2020 followed to some extent the variation in polar Arctic ozone in the Northern Hemisphere winter-spring season. On both poles in the mentioned period, the negative deviations of polar ozone from the multiyear means were gradually increasing and, having reached the absolute maxima, were disappearing very slowly and for a long time [10–12]. For comparison, Figure 6 presents the deviations of polar Arctic ozone from the multiyear means from January 1 to April 20, 2020 and the deviations of polar Antarctic ozone from the multiyear means in 2015 and 2020 from August 22 to December 9 (110 days). The ozone loss in the Antarctic during AOH in 2020 is close to the maxima, and the ozone loss in the Arctic at the beginning of 2020 is more significant and longer than in the Antarctic. The monthly mean values of Arctic polar ozone in February, March, and April in 2020 were minimal over all observation years (340.2, 330.4, and 344.3 DU, respectively). The coefficient of correlation between the deviations from the mean values of polar Arctic ozone in 2020 and the respective deviations of polar Antarctic ozone in the same year presented in the figure is equal to 0.83. The coefficient of correlation between polar Antarctic ozone in 2015 and 2020 during the period from August 22 to December 9 is 0.81.

According to satellite data, the minimum TO value southward of 40° S during AOH in 2020 updated the previously registered minima several times: on October 20, 21, 27, November 2, 4–7, 10–28, December 9–25, 27, 28; the minimum TO (94 DU) was recorded on October 6, 2020.

During the whole period of the 2020 AOH, the ozone mass deficit exceeded the multiyear means for 1979–2019. The maximum ozone mass deficiency in 2020 was registered on October 8 and made up

Fig. 7. (1) The interannual variability of the mean value of polar Antarctic ozone for August–November and (2) the trend curve.

35.93 10^6 t, which is almost 40% higher than the multiyear mean maximum. From November 11 to December 2 and from December 8 till the complete disappearance of AOH on December 28, the ozone mass deficit exceeded the maxima previously observed at that time.

The zonal mean temperature in the latitude zone of 60–90° S at the level of 70 hPa in October was rising at first, but stopped rising in the second half of the month; it varied within 202–204 K till November. On October 27–29 and November 1, temperature updated the previous minima for these days, but remained close to the previous minima slightly exceeding them (below the multiyear means by 8–10 K). From November 11 to December 26 (except for December 8 and 9), temperature continued rising but was below the previously registered minima.

The area of stratospheric NAT clouds (formed of nitric acid trihydrate solid particles), as well as the area of ice stratospheric clouds at the isentropic level of 460 K in 2020 during almost their whole lifetime was above the multiyear means. The area of stratospheric NAT clouds on October 3 and from October 18 till their complete dissipation at the end of the first ten days of November updated the previous maxima. Their formation started close to the average long-term dates, and the dissipation was delayed for almost three weeks due to low stratospheric temperature. The dissipation of ice stratospheric clouds finished at the end of the first ten days of October (almost two weeks after the mean date of dissipation), and their area exceeded the previous maxima on September 30 to October 2.

Zonal wind at the level of 70 hPa at 60° S in August and September 2020 updated the previously recorded maxima (August 5–7 and September 23–26). Its maximum speed of 58 m/s was reached on September 25. In October, the wind started decreasing gradually, most of the time its speed exceeded the multiyear means. Then, on October 30, the wind dramatically strengthened to 55 m/s and started weakening, but was close to the previous maxima and even updated them on October 31, November 1, 9, 10, 18, 19, 25–27, December 10, 13–21, 23, and 24.

Low stratospheric temperatures, that were observed in the Antarctic for a long time in the winter-spring season of 2020 thus leading to the formation of the great number of long-lived stratospheric clouds, and strong zonal winds, caused the significant and durable depletion of polar Antarctic ozone. Figure 7 presents the values of polar Antarctic ozone averaged over August–November in 1979–2020 and the trend curve indicating that the minimum was passed, and, starting from the early 21st century, there has been an increase in polar Antarctic ozone values. The estimate of the trend in polar Antarctic ozone averaged over August–November obtained a year ago [13] was apparently overestimated, which was expected due to a high variability of the values. The results for 2020 made substantial correction, the trend decreased but remained positive (0.23 DU per year if taking a derivative for 2020 and 1.09 DU if estimating the linear trend based on data since 1997).

In 2020, the monitoring of surface ozone in Moscow continued. The routine measurements of surface ozone in Moscow are carried out at the Mosekomonitring environmental monitoring network (<https://mosecom.mos.ru/vozdux/>). The surface ozone measurements are performed at 17 automatic air pollution control stations located in residential areas and close to major highways. In 2020, surface ozone values in the Moscow region were basically within the range of variability of seasonal long-term values [2, 6]; however, in April to September, the monthly mean surface ozone values were 10–15% lower as compared to the preceding 2019 [13]. The surface ozone maximum commonly observed in April [2] was poorly pro-

Fig. 8. The average daily surface ozone value in Moscow in 2020 ((1) averaged over measurements at urban stations; (2) averaged over measurements at near-highway stations; the circles are the maximum surface ozone values in the city; the single maximum permissible concentration ($MPC_{m.s.}$) and average daily MPC ($MPC_{a.d.}$) are presented).

nounced. The monthly mean surface ozone value in April was close to that in March. The second seasonal surface ozone maximum, that is most often observed in July or August, was not formed.

The peculiarities of the seasonal distribution of surface ozone in 2020 were associated with several factors. Firstly, the essential influence on surface ozone was exerted by weather anomalies. Secondly, the low surface ozone values could be an effect of reduced emissions of pollutants to the atmosphere during the coronavirus pandemic and the self-isolation regime. In the first half-year of 2020 as compared to the respective period in 2019, the concentrations of carbon oxide, nitrogen dioxide and oxide, and sulfur dioxide in air over Moscow were lower by 11, 22, and 36%, respectively; in April, the concentration of nitrogen dioxide was smaller by 47% (www.mosecom.mos.ru).

The effect of positive temperature anomaly in 2020 was evidently not manifested due to the excess precipitation. In general, the year 2020 was record warm over the whole 130-year history of regular meteorological observations; in Moscow, average annual air temperature was 3 °C above the normal and was equal to 8.0 °C (<https://meteoinfo.ru/>). The prevalence of cloudy rainy weather during the period of long-term seasonal maxima of surface ozone impeded the inflow of ultraviolet radiation required for the ozone generation [1]. The annual precipitation normal in Moscow (691 mm) was reached already during 8 months, and monthly total precipitation in May–July exceeded the multiyear means by 2–3 times.

The most dramatic variations in surface ozone, as usual, were observed in January and February, on some days surface ozone values increased to 70–90 $\mu\text{g}/\text{m}^3$ (Fig. 8). In March and April, the highest surface ozone values in the year were observed (0.1–0.12 $\mu\text{g}/\text{m}^3$). In May, June, as well as in August and September, the monthly mean surface ozone value was below the multiyear means by 0.05–0.1 $\mu\text{g}/\text{m}^3$ due to weather anomalies. The annual minimum of surface ozone, as usual, fell on November–December. As a display of ozone destruction in polluted air [1], most of the year surface ozone values in the near-highway areas were 10–15% lower than in the residential areas of the city.

In 2020, the number of cases of surface ozone approaching the maximum permissible level was smaller than in the previous years. On June 18–19, the surface ozone growth to 0.15–0.155 $\mu\text{g}/\text{m}^3$ was recorded; on July 7, surface ozone exceeded $MPC_{m.s.}$ and reached 0.167 $\mu\text{g}/\text{m}^3$. The dramatic increase in surface ozone in these short-term episodes occurred in the afternoon, when temperature rose to 30 °C. At 8 of 17 environmental monitoring stations in Moscow, the average annual surface ozone value exceeded the standard for the average daily concentration accepted in Russia and equal to 0.03 $\mu\text{g}/\text{m}^3$.

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