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Detection of Large Fluctuations in Ozone Content in the Middle Atmosphere during Sudden Stratospheric Warmings and Subpolar Latitudes of the Arctic

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Abstract—The results of microwave radiometry studies of the ozone-content dynamics in the middle atmosphere above Peterhof during stratospheric warmings of two winters, 2015–2016 and 2016–2017, are presented. Ground-based observations employed mobile microwave ozone-measuring instrument (operating frequency is 110.8 GHz). The vertical ozone distribution in the altitude range of 22–60 km is estimated. The results are compared to satellite-borne data on the total ozone content, to vertical profiles of the ozone and temperature in the middle atmosphere, and to data from an ozone-measuring sounder. In the middle atmosphere above Peterhof, there have been significant variations (by several times) in the ozone content at heights of 40–60 km due to minor stratospheric warming.

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1. INTRODUCTION

In recent times, there has been growing interest in the interaction of the middle (20–100 km altitude) and upper (over 100 km) atmospheres. Experiments on the artificial effects of a powerful short-wave radiation on the lower ionosphere found that a new physical phenomenon takes place: a decrease in the microwave-radiation intensity of the mesosphere in the ozone line upon ionosphere modification by a SURA heating facility (Kulikov et al., 2012, 2013). There are several hypotheses explaining the observed effect. The first is related to the intensified formation of negatively charged ions in the mesosphere due to the increase in electron temperature upon heating of the lower ionosphere by powerful radiowaves (Kulikov and Frolov, 2010). The second is the effect on the neutral component of the mesosphere, in particular, molecular ozone, which is caused by the inner gravity waves generated in the ionospheric *E*-region during ionospheric heating by powerful radiowaves (Kulikov et al., 2012; Grigor'ev and Trakhtengerts, 1999). The third possible cause is the influence of ion chemistry on the relationship between changes in the mesospheric-ozone content and total electron content in the ionosphere (Pakhomov and Knyazev, 1988; Muscari et al., 2005). Finally, the phenomenon of exchange between the ionosphere and mesosphere can be explained by vertical movements of air masses (Belikovich, 1998).

Disturbances in the ionosphere and mesospheric ozone may also be induced by sudden stratospheric warmings (SSWs). Such an event can be illustrated by warming in 2012–2013 above a vast region of the Northern Hemisphere. Microwave and optical observations in Tomsk revealed significant variations in ozone and temperature at all heights of the middle atmosphere (Marichev et al., 2014; Matvienko et al., 2016). The ozone content at altitudes of 25 to 60 km changed several times. This was a unique warming that caused a 70-K temperature rise relative to the average monthly value at the level of 10 hPa. Notably, the sunrise- and sunset-related diurnal variations in the ozone content at the height of 60 km were as small as ~30%. In addition, the same warming caused variations in the total electron content in the equatorial ionosphere by ~100% (Goncharenko et al., 2013). In the middle and polar latitudes, changes in the total electron content are also attributed to variations in neutral composition during disturbances in the troposphere and stratosphere (Zhirinovsky, 2002; Laticia, 2006; Chernigov kaya et al., 2014). Goncharenko et al. (2012) supposed that warming-driven fluctuations in the middle-atmosphere ozone content can affect the ionosphere via tidal waves. It is known that SSWs are also accompanied by changes in the composition, density, and temperature of the upper thermosphere (400 km above the Earth's surface). The variations in electron density upon warming are the same as those with moderate geomagnetic storms (Pedately et al., 2018).

In the present work we provide the results of microwave observations of ozone in the middle atmosphere above Peterhof (60° N, 30° E) in January–March in 2015–2016 and November–March in 2016–2017 during stratospheric warmings.

2. MOBILE MICROWAVE OZONOMETER AND MEASUREMENT TECHNIQUE

Microwave ground-based radiometry is based on measurements of the rotational radiation spectra of minor gaseous components (including ozone) in the ranges of millimetric and sub-millimetric waves. Microwave observations weakly depend on the weather conditions and aerosol presence in the atmosphere, which constitutes their advantage as compared to observations in the optical and infrared wave ranges. Additionally, microwave observations of ozone can be performed on a 24-hour basis. In the last decade, we have achieved a certain progress in the creation of mobile microwave spectrometers (Krasil'nikov et al., 2003; Kulikov et al., 2007).

A microwave ozonometer consists of (1) a heterodyne, noncooled receiver tuned to a fixed frequency of 110836.04 MHz, which corresponds to the rotational transition of ozone molecule 6_{06}–6_{15}, and (2) a multichannel spectral analyzer. The module at the receiver input has an antenna (scalar amplifier) and a commutation switch to calibrate the intensity of the received atmospheric radiation in the ozone line. The width of the diagram of the amplifying antenna directivity on the level of 3 dB is 5.4°. The single-band noise temperature of the receiver is 2500 K; the receiver mode in a single band is provided by a beyond-cutoff filter with direct losses of 0.5 dB and mirror -suppression of more than 20 dB. The spectral analyzer consists of 31 filters with bandpasses of 1–10 MHz and with a full analytical band of 240 MHz.

The parameters of this instrument allow the measurement of the 15-min spectrum of the ozone radiation line within an accuracy of ~2%. The spectra of atmospheric thermal radiation are measured via calibration on two "black-body" standards, which are at the boiling point of liquid nitrogen and at the temperature of the surrounding air.

Data on the ozone content is contained in the measured spectrum of the integrated radio emission of the middle atmosphere. Data on vertical ozone distribution (VOD) in the atmosphere can be obtained via inversion of the obtained spectra. The criterion of the reliability of the inverse problem is the best match of the ozone spectral line, which is calculated on the restored profile of the ozone concentration, to the initial experimental spectrum. The error of VOD measurements for the spectra measured by the described instrument is no more than 10–15%.

One of these mobile ozonometers was installed in 2007 at the laboratory of the Physical Faculty of the St. Petersburg University at Peterhof (Timofeev et al., 2008). To date, there have been continuous microwave ozone observations of the middle atmosphere with this instrument.

3. OBSERVATION RESULTS AND THEIR DISCUSSION

Figure 1 presents the data from satellite-borne temperature measurements at the level of 10 hPa (approximately corresponds to the altitude of 30 km) above Peterhof obtained by the MLS/Aura instrument (millimetric wavelength range) for two winter periods of 2015–2016 and 2016–2017. These periods were marked by minor stratospheric warmings almost at the same time, at the end of the second third of January (January 19). The thin and thick curves correspond to the data for January 2016 and January 2017, respectively. Every warming lasted about 10 days, and the maximum deviation of temperature from its background value was ~40 K. To compare, the minor warming above Peterhof in winter of 2013–2014 lasted ~2.5 months, i.e., as long as dynamic disturbances in the stratosphere, at altitudes of above 20 km (Bochkovskii et al., 2016).

First, we decided to study the character of changes in ozone content in these winter seasons based on the observations by orbital and ground-based instruments. Figure 2 demonstrates the variations in ozone content in January 2015–March 2016 (left panel) and in November 2016–March 2017 (right panel) above Peterhof. The solid line in the left-hand panel indicates the total ozone content (TOC) measured by the satellite-borne OMI/Aura instrument (http://disc.sci.gsfc.nasa.gov/aura/). The average TOC value for the period of January 1 to March 31, 2016 was 339 ± 5 DU. The maximum TOC value reported for this period was 482 DU (March 18, 2016), and the minimal value was 249 DU (March 3, 2016). The analogous average TOC values for the period of November 1, 2016 to March 31, 2017 (right panel) was 324 ± 4 DU. In this period, there were two peak TOC values of 447 and 467 DU (on January 15 and March 24, 2017, respectively), and the minimal TOC value was 228 DU (November 22, 2016).

The lower parts of both left and right panels of Fig. 2 show temporal changes in the ozone content in the altitude layer of 22–50 km based on data from the MLS/Aura X^{MLS} instrument (22–50 km) (solid line) and in the ozone content in the layer above 22 km based on data from the X^{MMB} microwave ozonometer (≥22 km) (crosses). The MLS/Aura instrument uses limb scatter measurements of the atmospheric parameters (Waters et al., 2006). We chose the ozone and

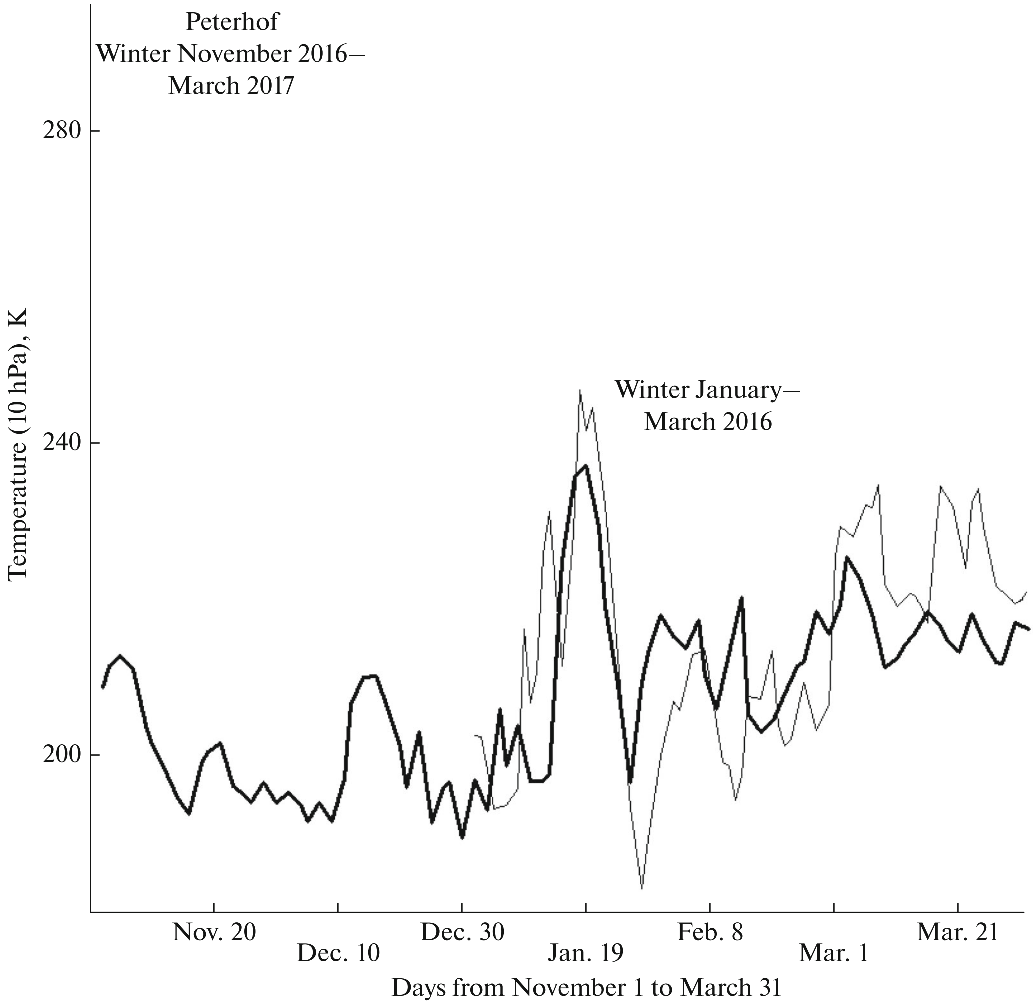

Fig. 1. Time variations at the 10-hPa level above Peterhof based on the data from the MLS/Aura instrument. The thick line corresponds to the period of November 2016–March 2017; the thin line shows the winter period (January–March) of 2016.

temperature data corresponding to the time of satellite passage above Peterhof. For this purpose we chose the domain with coordinates (60 ± 1.5)° N and (30 ± 5)° E for Peterhof. The X^{MMB} data correspond to ozone contents for diurnal and nocturnal spectra; notably, they are almost the same. In the period of January 1 to March 31, 2016, the average X^{MLS} and X^{MMB} contents (left panel) were 158.6 ± 2.7 and 155.0 ± 3.0 DU, respectively, with the maximum X^{MLS} value of ~199 DU observed on March 13, 2016, and the minimal value of ~117 DU observed on March 3, 2016. The maximum-to-minimum ratio was 1.7. According to ground-based microwave observations, the maximum X^{MMB} value of ~203 DU was recorded on March 14, 2016, while the minimum value of ~113 DU was recorded on February 3, 2016; their maximum-to-minimum ratio was 1.79. In the winter season from November 1, 2016 to March 31, 2017 (right panel), the respective average X^{MLS} and X^{MMB} values were 160.0 ± 4.0 and 148.9 ± 2.5 DU. The maximum X^{MLS} value was ~208 DU (January 17, 2017), and the minimum value of 123 DU was recorded in the second half of November 2016. The maximum-to-minimum ratio was 1.7. According to ground-based microwave observations, the maximum X^{MMB} value of ~197 DU was recorded on January 17, 2017, and the minimal value of ~118 DU was recorded on November 25, 2016. The respective maximum-to-minimum ratio was 1.6. The behavior of the ozone content based on data from both satellite-borne and ground-based instruments indicates a weak relationship with warming on January 19, 2016. In January 2017, stratospheric warming increased the TOC to 447 DU and increased the ozone content in the atmospheric layer above 22 km X^{MLS} and X^{MMB}. The character of variations in ozone content obtained by both instruments (Fig. 2) is virtually the same. This comparison shows that the results of ground-based measurements of ozone content are representative.

Let us consider the relationships between ozone and temperature variations at specific heights of the

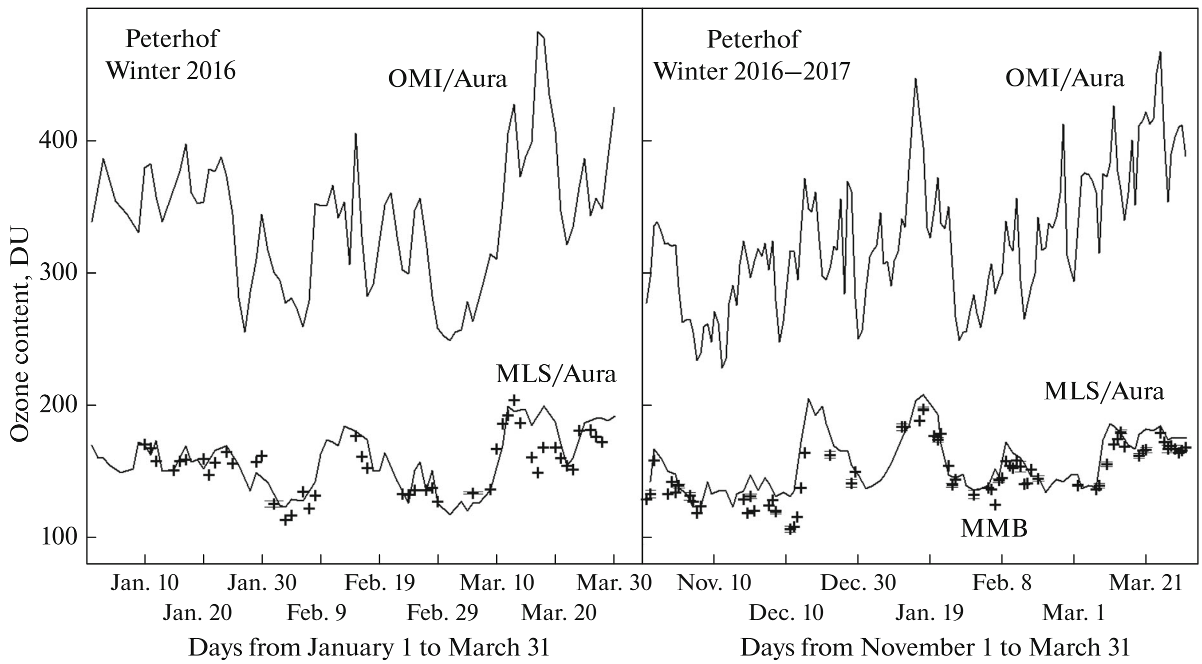

Fig. 2. Variations in ozone content above Peterhof in winter of 2016–2017 based on data from satellite measurements and a ground-based microwave spectrometer. The left panel corresponds to the winter period (January–March) of 2016; the right panel shows November 2016–March 2017. The upper solid line in both panels denotes the total ozone content as inferred from the OMI/Aura satellite-borne instrument; the lower solid line shows the ozone content in the 22- to 50-km layer based on microwave measurements with the MLS/Aura satellite-borne instrument. Crosses denote the ozone contents for the heights above 22 km (MMB) based on ground-based microwave measurements.

middle atmosphere (25, 40, and 60 km) during SSWs. The respective results are shown in Figs. 3 and 4. Figure 3 illustrates the satellite-borne temperature measurements by the SABER instrument (operated in infrared wave range) and by the MLS/Aura instrument (operated in millimetric wave range) in January–March 2016. Although both instruments have recorded similar noticeable temperature disturbances in the height interval of 40–60 km, we should emphasize there are certain differences in measured temperature values, which are sometimes up to 10–20 K. There are clear disturbances in temperatures of the middle atmosphere (height interval of 40–60 km), as recorded by the SABER and MLS/Aura. Temperature changes ranging in amplitude from the minimal to maximal (~20 K) and with a quasi-period of about two weeks were observed at 60 km in the period after January 30, 2016. These variations lasted about two months (from January 25 to March 31, 2016). From January 13 to 24, 2016, satellite-borne instruments recorded the minimal temperature at the 60-km level (it was 219.8 ± 3.2 K based on MLS/Aura and 224.7 ± 1.9 K based on SABER). A disturbance in the ozone concentration was observed at the same time. According to the ground-based microwave observations, there was twofold increase in the ozone concentration at 60 km in comparison to the background values in the first third of January 2016 and a threefold increase as compared to the relatively "quiet" period in January and March. The maximum ozone concentration on January 15–17, 2016, was 2.3×10^{10} mol/cm^3, with the average concentration during the undisturbed period corresponding to J daytime observations (empty circles in the upper panel of Fig. 3) and $(7.8 \pm 0.3) \times 10^{09}$ mol/cm^3 for nocturnal observations (filled circles). Thus, the diurnal variations in ozone concentration at 60 km (nocturnal exceedance of the ozone concentration above its daytime values) in February–March 2016 reached 70% in amplitude. One can clearly see two temperature peaks in the middle panel of Fig. 3 (which corresponds to a height of 40 km): one of them occurred on February 6–7 with a value of 275 K, and the other one occurred on March 4–5 with a value of 285 K. Both temperature disturbances lasted for about a week. Notably, we recorded the maximum ozone content for this season, $\sim(6.6 \pm 0.1) \times 10^{11}$ mol/cm^3, in the initial period of observations, when the background temperature at 40 km was undisturbed. The first temperature peak was marked by a minimum ozone concentration of $\sim(3.30 \pm 0.08) \pm 10^{11}$ mol/cm^3, and the variations in the ozone concentration during February–March were insignificant. It should be noted that the duration of disturbance in ozone concentration at the 60 km is significantly less than that at 40 km. The lower panel of Fig. 3 shows the temperature variations at 25 km based on the data from the satellite-borne MLS/Aura and SABER instruments. The mid-January minor warming was accompanied by a temperature growth at this level of more than 20 K.

The polar cyclone intensively deformed in this time; it had a heterogeneous height structure (http://cdsespri.ipsl.fr/etherTypo/index.php?id=1663&L=1). The upper stratospheric layers above Peterhof, which were beyond the cyclone limits until mid-January, appeared in its inner part after January 20 and remained there until mid-March, when the cyclone disintegrated. The recorded abrupt ozone drop at the heights of 40 and 60 km was likely caused by the time evolution of the polar cyclone, the inner parts of which were characterized by lower ozone concentrations. The height of 25 km appeared to be beyond the cyclone limits during the observation period: as a result of cyclone deformation on February 16–17 and during its breakdown on March 10–15. In these periods we observed significant growth in the ozone content (Fig. 3, lower panel). The trajectory analysis (https://ready.arl.noaa.gov/HYSPLIT) shows that in the air in the observation area the noted days moved from the ozone-rich regions, i.e., from eastern Siberia (http://exp-studies.tor.ec.gc.ca/cgi-bin/selectMap). To compare, in the remaining days of February and March, the trajectories of air masses fell within the limits of the polar cyclone, and the ozone concentration slowly grew as cyclone power weakened. We revealed an almost twofold increase in the ozone content at the height of 25 km; however, it should be noted that such increase was also recorded by a number of arctic stations.

Figure 5 shows the variations in ozone density at 25 km in the period of January 1–March 31, 2016. They were obtained via ground-based microwave radiometry at Peterhof (filled circles). Additionally, Fig. 5 provides the data from direct VOD measurements in observatories located to the north of the North Polar Circle: Sodankylä (67° N, 27° E; empty squares), Summit (73° N, 38° W; filled triangles), and Salekhard (67° N, 67° E; crosses). At the first two stations, balloon ozone sounders are regularly launched. Based on data from the analysis of multiannual satellite-borne ozone measurements (Finger et al., 1995), the character of the relationship between ozone and temperature in the stratosphere indicates that there is a positive correlation between the ozone content and temperature in the lower stratosphere and a negative one at heights over 30 km. The ground-based microwave observations of stratospheric ozone at polar latitudes during stratospheric warmings found a positive correlation between ozone and temperature changes at 20–30 km. Strong warmings were accompanied by a positive correlation at all stratosphere heights (Kulikov et al., 2002a, 2002b, 2005, 2007).

Figure 4 presents the temporal variations in the ozone concentration (diamonds, ground-based microwave sounding) and temperature (solid line, MLS/Aura data) at the middle atmosphere heights (25, 40, and 60 km) above Peterhof in the winter of 2016–2017. In addition, the lower panel provides the results of ozone measurements at the Sodankylä station (empty squares). During this winter season, the polar cyclone

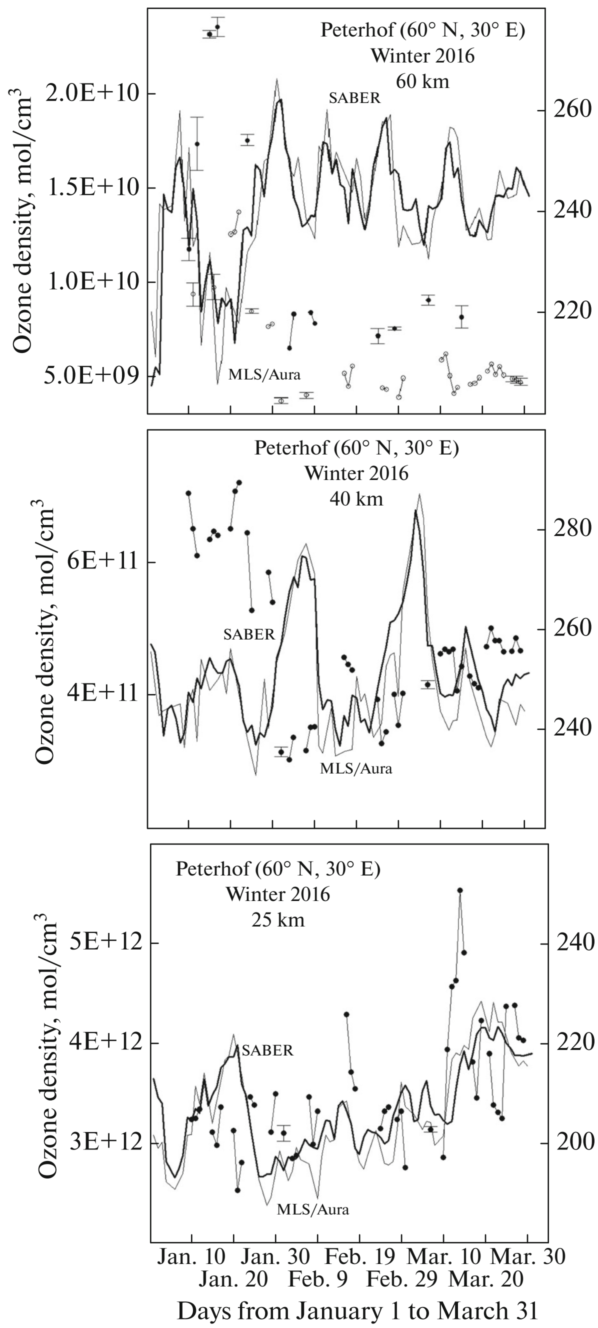

Fig. 3. Variations in the ozone concentration (circles) and temperature (thick and thin solid lines) at the heights of 25, 40, and 60 km in the winter period (January–March) of 2016. The thick solid line denotes the data from the satellite-borne SABER instrument; the thin solid line shows data from the satellite-borne MLS/Aura instrument. The filled and empty circles in the upper panel (the ozone concentration at a height of 60 km) correspond to data inferred from the processed daytime and nocturnal observations, respectively.

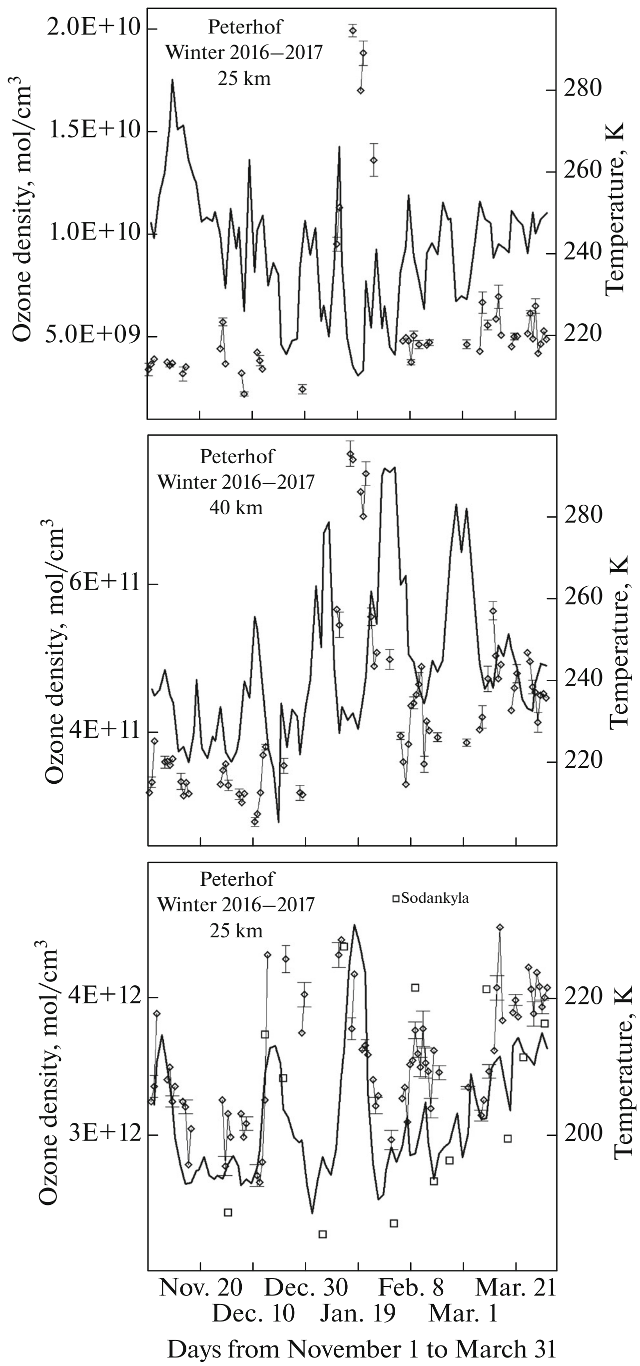

Fig. 4. Variations in the ozone concentration (diamonds) and temperature (solid line) in the middle atmosphere heights of 25, 40, and 60 km. The ozone data are obtained from observations by ground-based microwave radiometry; the temperature data are taken from the satellite-borne MLS/Aura instrument. The squares in the lower panel present the results of direct ozone measurements at a height of 25 km at the Sodankylä station in November 2016–March 2017.

underwent repeated deformations accompanied by significant temperature variations at all stratospheric heights. At 25 km, we can see three intensive temperature surges, while there are four at 40 km. The data shown in Fig. 4 suggest that variations in the ozone concentration in the stratosphere were also recorded in this period. One can see that the variations in the ozone content and temperature at the level of 25 km were synchronous according to both ground-based microwave sounding and data from the balloon ozone sounders of the Sodankylä station. It should be pointed out that the very low ozone concentrations obtained at this station (less than 2×10^{12} mol/cm^3) correspond to the time at which it was located within the limits of the polar cyclone. We repeatedly observed similar values during microwave ozone measurements at Apatity station (Kulikov et al., 2002b, 2005), which is located at the same latitude as Sodankylä. The ozone variations at 40–60 km in the winter of 2016–2017 were of higher amplitude than those for the winter of 2015–2016. Notably, a surge in ozone content also occurred around January 19, 2017. In the upper panel of Fig. 4, the presented temporal variations in the ozone concentration (empty diamonds) at 60 km are based on daytime observations only. The maximum average ozone concentration of January 17–21, 2017, was $(1.86 \pm 0.07) \times 10^{10}$ mol/cm^3, while the average concentrations for the undisturbed periods of November–December 2016 and February–March 2017 were $(3.66 \pm 0.18) \times 10^{09}$ and $(5.10 \pm 0.15) \times 10^{09}$ mol/cm^3, respectively. Similar fluctuations in the ozone concentration at 60 km were recorded at subpolar latitudes (Peterhof) in the winter of 2013–2014 (Bochkovskii et al., 2016). Remarkably, the value of the disturbance in the ozone concentration at 40–60 km exceeds the ozone variations at 25 km. It should be noted that the ozone variations in the middle atmosphere in this particular season are related to the deformation and movement of the polar cyclone, e.g., it strongly deformed in mid-December 2016, and the entire European part of Russia appeared to be beyond its limits. The trajectory analysis (https://ready.arl.noaa.gov/HYSPLIT) showed that the state of the ozone layer at 25 km in this period was determined by horizontal air transfer from Siberian region, where a higher ozone content was observed (see the ozone field maps (http://exp-studies.tor.ec.gc.ca/cgi-bin/selectMap)). One can see (Fig. 4) that a higher ozone concentration was observed in the last third of December at the height of 25 km based on microwave data. The same increase was found at Sodankylä station (direct O_3 measurements). The ozone content barely changed at 40 and 60 km; an analogous pattern was observed in mid-January 2017, when Peterhof again appeared beyond the polar cyclone. At that time, the circulation regime in the stratosphere above the observation point had changed: the air masses from the inner closed region of the cyclone were replaced by those from the North Atlantic, where a higher ozone content was observed. During the entire second half of January, we noticed an increased ozone content at all altitude levels (Fig. 4). The variations in the content of stratospheric ozone in February were similar to those in December and were caused by the change in circu-

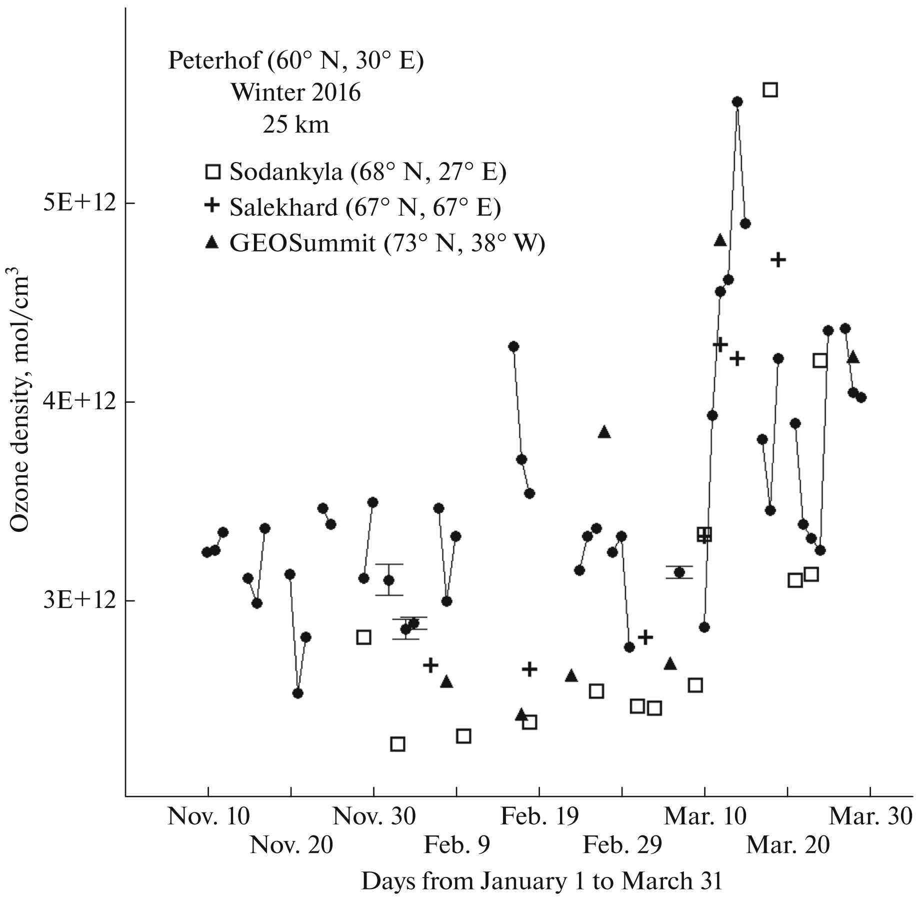

Fig. 5. Comparison of the data from ground-based microwave observations above Peterhof and direct ozone measurements at a height of 25 km in the Arctic region in the winter period (January–March) of 2016.

lation only in the lower part of the stratosphere; in turn, this change was caused by the deformation and movement of the polar cyclone (https://ready.arl.noaa.gov/HYSPLIT). Finally, in the beginning of March 2017, this cyclone considerably weakened and disintegrated (http://cds-espri.ipsl.fr/etherTypo/index.php?id=1663&L=1). This was the period in which there was a moderate increase in the ozone content due to the horizontal advection of air from eastern Siberia.

The present work notes the increased ozone content observed in the height range of 40–60 km during SSWs. Fluctuations in the ozone content can cause additional heating of the stratosphere and mesosphere due to the absorption of ultraviolet solar radiation by ozone molecules. The change in temperature regime of this region can generate different types of wave activity. Yasyukevich et al. (2018) noted the relationship between the increases in the stratospheric ozone content, the thermospheric O/N_2, and the ionospheric electron content at middle latitudes for a quite long-term period (up to 20 days) after the SSW peak. Similar research at the polar latitudes is planned for the future.

4. CONCLUSIONS

Long-term microwave observations above Peterhof revealed significant variations in the ozone content at the heights of 40–60 km in two winter seasons; they emerged during minor SSWs in mid-January in 2016 and 2017.

We revealed for the first time that extent of changes in the ozone concentrations at the heights of 40–60 km exceeds the respective changes at the height of 25 km in a period of minor warming.

All documented changes in the ozone layer of the middle atmosphere occurred as a result of the change in the circulation regime in the stratosphere above the station performing the microwave observations. These changes were largely caused by the deformation and movement of the polar cyclone.

5. FUNDING

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