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BEHAVIOR OF THE MIDDLE ATMOSPHERE OZONE IN THE WINTER 2023-2024 DURING HEIGHTENED SOLAR ACTIVITY. THE FIRST OBSERVATION OF DAILY CYCLE OF MESOSPHERIC OZONE DURING POLAR DAY (MIDNIGHT SUN)

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Abstract
We present data continuous series of microwave observations of the middle atmosphere ozone in winter 2023-2024 above Apatity (67N, 33E). Measurements were carried out with the help of mobile microwave ozonemeter (observation frequency 110.8 GHz). The instrument allow to measure a spectrum of the emission ozone line for time about 15 min with a precision of ~ 2%. On the measured spectra were appreciated of ozone vertical profiles in the layer of 22 – 60 km which were compared to satellite data MLS/Aura. Besides we have executed continuous observations of ozone content within June, 14-15, 2023. Changes mesospheric ozone (60 km) during a summer solstice represented a quasi – periodic dependence on time with amplitude about 15%. In too time daily cycle of mesospheric ozone (altitude 60 km), connected with photochemical processes, and are not observed.

Microwave ground-based equipment used in the experiment
Method ground-based microwave radiometry is based on measurements of thermal atmospheric radiation in vicinity the ozone line in the range of millimeter and submillimeter waves. Microwave observations are weakly dependent on weather conditions and the presence of atmospheric aerosols, and this is an advantage compared with observations in the optical and infrared wavelength ranges. In addition, the microwave ozone observations can run around the clock. In recent years it is managed to make a significant step forward towards the creation of a new generation of mobile microwave spectrometers. The device consists of an uncooled heterodyne receiver tuned to a fixed frequency 110836.04 MHz corresponding to a rotational transition of ozone molecules $6_{0,6} – 6_{1,5}$, and multichannel spectrum analyzer. In front of receiver is s module that includes an antenna (scalar horn) and a switch to calibrate accepted intensity of atmospheric ozone radiation. Information about the content of the ozone is contained in the measured radio emission spectrum of the middle atmosphere. The error of estimating the vertical distribution of ozone from the measured spectra by above described device does not exceed 10-15%. A detailed description of the spectrometer and the method of measuring ozone of the middle atmosphere in the millimeter wavelength range are given in [1, 2].

The temperature variations in the middle atmosphere during winter 2023 – 2024
For a better understanding of the nature of ozone variations, it is necessary to have a data of temperature changes at altitudes of the middle atmosphere. Temperature changes indicate the influence of the sudden stratospheric warming (SSW) on the structure of the middle atmosphere. For this purpose, a height level of 10 hPa is usually chosen, at which remote airborne and ground-based can be compared with contact measurements. In Figure 1, data for two winter seasons are given for temperature measurements over Apatity by MLS/Aura satellite instrument at a level of 10 hPa, which approximately corresponds to an altitude of 30 km. In each of these seasons, SSWs were recorded. In this figure, the bold solid line shows the temperature changes in the winter of 2023 – 2024. In a winter season 2023 - 2024 it was registered two temperature disturbances - in the first decade of January and last decade March.

Influence of proton events in February 2024 on mesospheric ozone
Solar proton events were marked in middle of February, 2024 according to satellite GOES-18. Duration of events from February, 09 till February, 21. Detectors (10, 50 and 100 MeV) of satellite have registered three burst of proton flux: 09.02. – 14 UT; 12.02. – 07 UT; 16.02. – 11 UT.

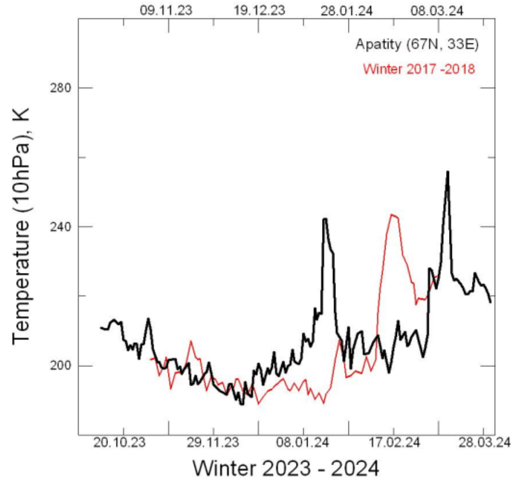

Figure 1. Time course of the temperature at the level 10 hPa above Apatity according to MLS/Aura for winter seasons: black solid thick line, October – March 2023 – 2024; red line, November – March 2017 – 2018.

In **Table** the ozone density are given in mol/cm^3, averaged over 4 hours near noon and midnight at an altitude of 60 km in February for three time intervals up to in time and after proton events. The last column of Table shows the average amplitude of the daily variations ozone density during proton events in February 2024. These amplitudes did not differ from similar for February in mesosphere over Apatity.

Table. The numerical data of diurnal mesospheric ozone cycle.

Data	10:00 – 14:00	22:00 – 02:00	A
07 – 09.02.2024	**(6.07 ± 0.04)·10^{09}**	**(7.51 ± 0.12)·10^{09}**	**24%**
12 – 16.02.2024	**(5.53 ± 0.20)·10^{09}**	**(6.41 ± 0.19)·10^{09}**	**16%**
18 – 21.02.2024	**(5.84 ± 0.29)·10^{09}**	**(6.88 ± 0.23)·10^{09}**	**18%**

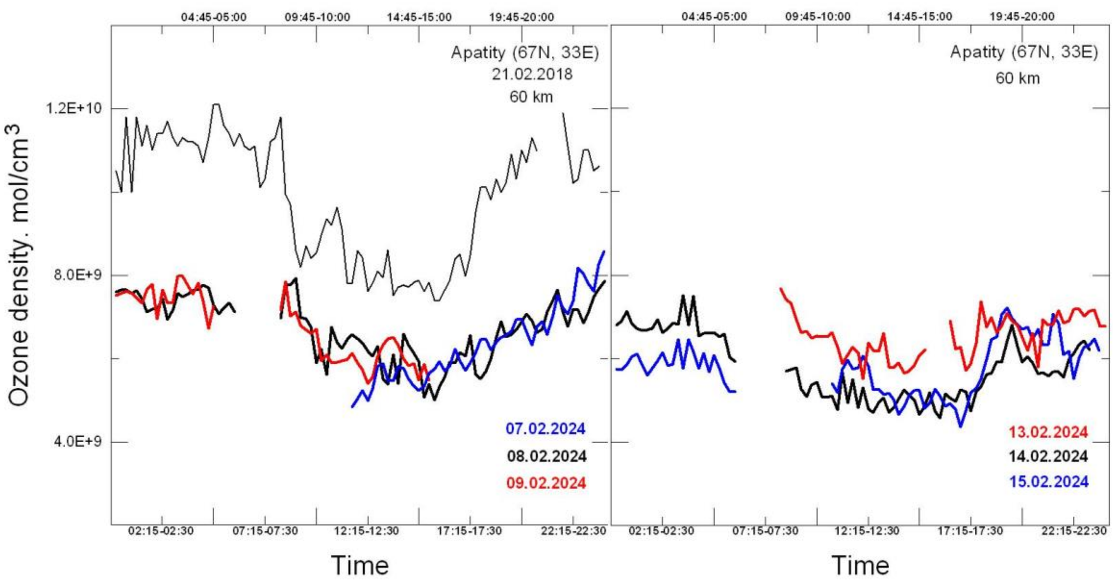

Figure 2. Diurnal variations of mesospheric ozone density (60 km) from MM-measurements during proton events in February 2024. Left panel (before proton events) – daily cycle of ozone density in February 7 (dark blue line), 8 (black line) and 9 (red line). The right panel (during proton events) – daily cycle of ozone density in February 13 (red line), 14 (black) line and 15 (blue line). Also on the left panel the daily cycle O_3 for February, 2018 after major warming is shown.

In Figure 2 the daily variations of ozone density at altitude 60 km which were obtained from continuous microwave observations in February 2024 with temporal resolution 15 min are shown. On the basis of the given data follows, that decreasing of mesospheric ozone (60 km) during proton events has composed (10 ± 2)%.

Influence of proton events in March 2024 on mesospheric ozone

Solar proton events were marked last decade March, 2024 according to satellite GOES-18. Duration of events from March, 23 till March, 21. Detectors (10, 50 and 100 MeV) of satellite have registered burst of proton flux: 23.03. – 04 UT; March 27 – ending of proton events. Geomagnetic storm accompanied by large Forbush decrease in galactic cosmic ray intensity was recorded in March, 24, 2024. More precisely, on 24 March 2024, a G4 (according to the NOAA Space Weather Scale for Geomagnetic Storms) geomagnetic storm was registered, with the corresponding geomagnetic indices K_p and Dst equal to 8 and – 130 nT, respectively. On the same day the majority of ground-based neutron monitor station recorded an unusual Forbush decrease (FD). It is supposed, that FD can cause changes in a structure of a middle atmosphere ozone [3]. In Figure 3 the daily variations of ozone density at altitude 60 km which were obtained from continuous microwave observations in March 2024 with temporal resolution 15 min are shown. It is necessary to note that last decade March there was a significant SSW (see. Figure 1), which could disguise changes of ozone because of the charged particles. As we see, there is no changes mesospheric ozone during proton events.

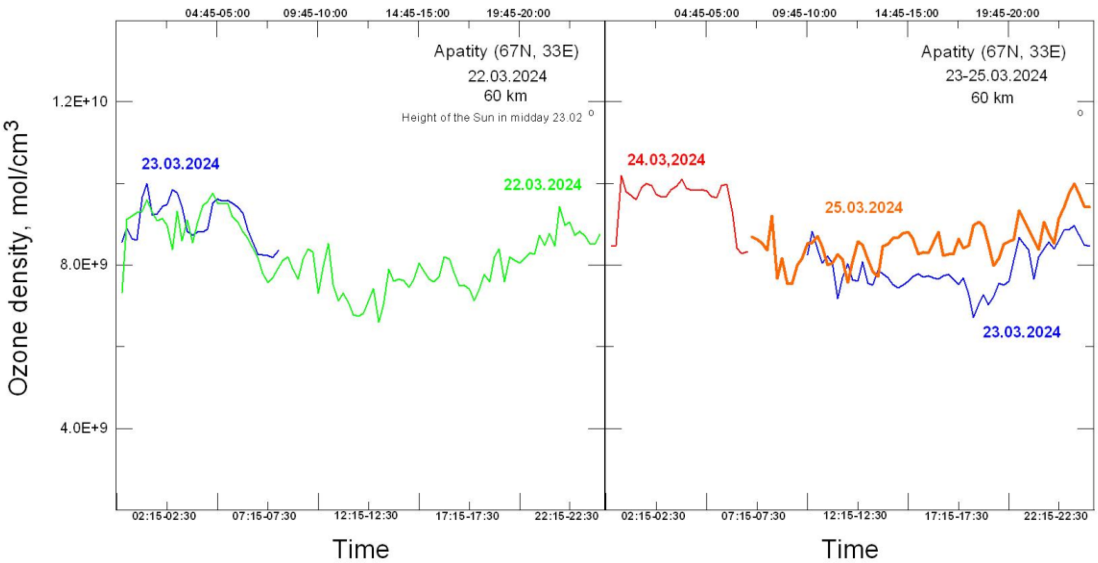

Figure 3. Diurnal variations of mesospheric ozone density (60 km) from MM-measurements during proton events and FD in March 2024. Left panel (before proton events and FD) – daily cycle of ozone density in March 22 (green line) and 23 (short dark blue line). The right panel (during proton events and FD) – daily cycle of ozone density in March 23 (continuation of a dark blue line), 24 (red line) and 25 (orange line).

Daily variations of mesospheric ozone during a summer solstice

June, 14-15 2023 near to a summer solstice continuous microwave measurements with temporal resolution 15 min of diurnal variations of mesospheric ozone (60 km) were executed. The amplitude of the diurnal variation of the O_3 density on June 14 – 15, 2023 was about zero (see Figure 4). The height of the Sun in midnight had size about + 1°. Almost periodic changes of ozone density with amplitude about 15 %, which, apparently, are caused by planetary waves, are well appreciable. For comparison in the bottom part of figure daily changes of ozone near to a winter solstice are shown (red line for December 25, 2022 and dark blue line for December 25, 2021). In December (polar night) the amplitude of a daily cycle of the mesospheric ozone in different years made from 6 % up to 20 %.

Conclusion

• One of the important results of this paper is the successful use of radiophysical method for diagnosing ozone in the middle atmosphere, that is, ground-based radiometry in the millimeter wavelength range.

• Changes in mesospheric ozone at altitude 60 km are not found out during proton events in February and March 2024 together with Forbush effect.

• For the first time MM-measurements of a daily cycle of the mesospheric ozone are executed during a summer solstice.

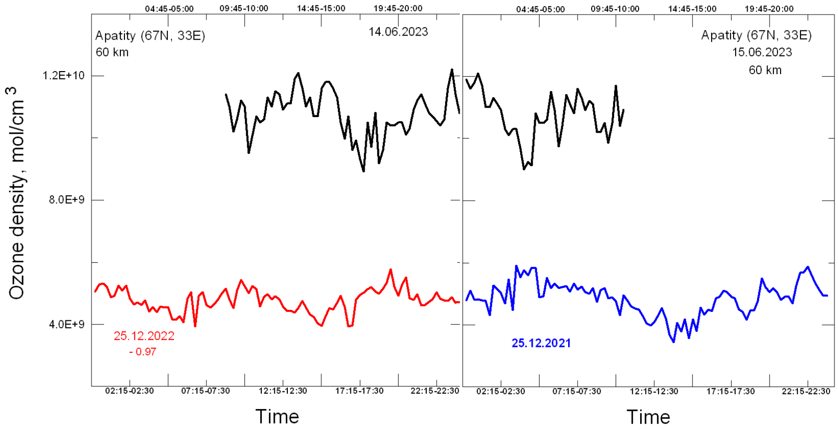

Figure 4. The diurnal variation of mesospheric ozone over Apatity is June 14 – 15, 2023 (black line).

Acknowledgments

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