

## LONG-TERM MICROWAVE MEASUREMENTS OF THE MIDDLE ATMOSPHERE OZONE ABOVE APATITY (67N, 33E) IN WINTER-SPRING SEASONS

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### Abstract

We perform continuous ozone measurements above Apatity, Kola Peninsula with ground-based a mobile ozonemeter (observation frequency 110.8 GHz) in the polar middle atmosphere covering from 2017 to 2024. The instrument allow to measure a spectrum of the emission ozone line for time about 15 min with a precision of  $\sim 2\%$ . On the measured spectra were appreciated of ozone vertical profiles in the layer of 22-60 km which compared to satellite data MLS/Aura. This work is directed on understanding the possible action of highly altered dynamics of sudden stratospheric warming and polar vortex on ozone variations in the Arctic middle atmosphere. The present study improves our representation of influence of solar activity on ozone and, hence, on a climate of the Earth.

### 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 a 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 wave range are given in [1, 2].

### The temperature variations in the polar middle atmosphere during winter-spring from 2017 to 2024

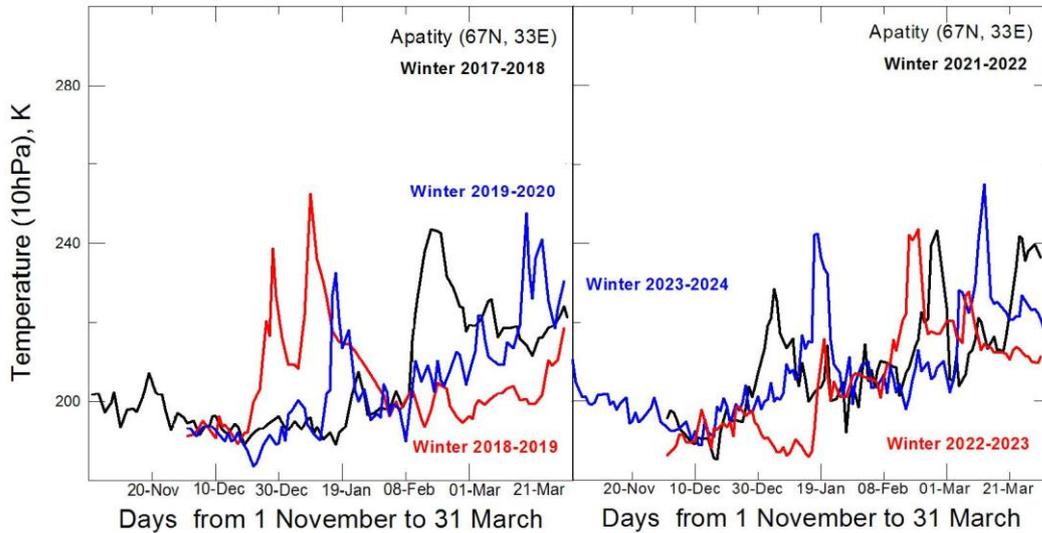
For a better understanding of the nature of ozone variations, it is necessary to have a data of temperature changes at altitudes of the middle atmosphere. Temperature changes indicate the influence of the sudden stratospheric warming (SSW) on the structure of the middle atmosphere. For this purpose, a height level of 10 hPa is usually chosen, at which remote airborne and ground-based can be compared with contact measurements. In Fig. 1, data for six winters 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. For each of these seasons temperature disturbances were registered. Temperature disturbances were caused by sudden stratospheric warming (SSW).

### Influence of solar activity on mesospheric ozone

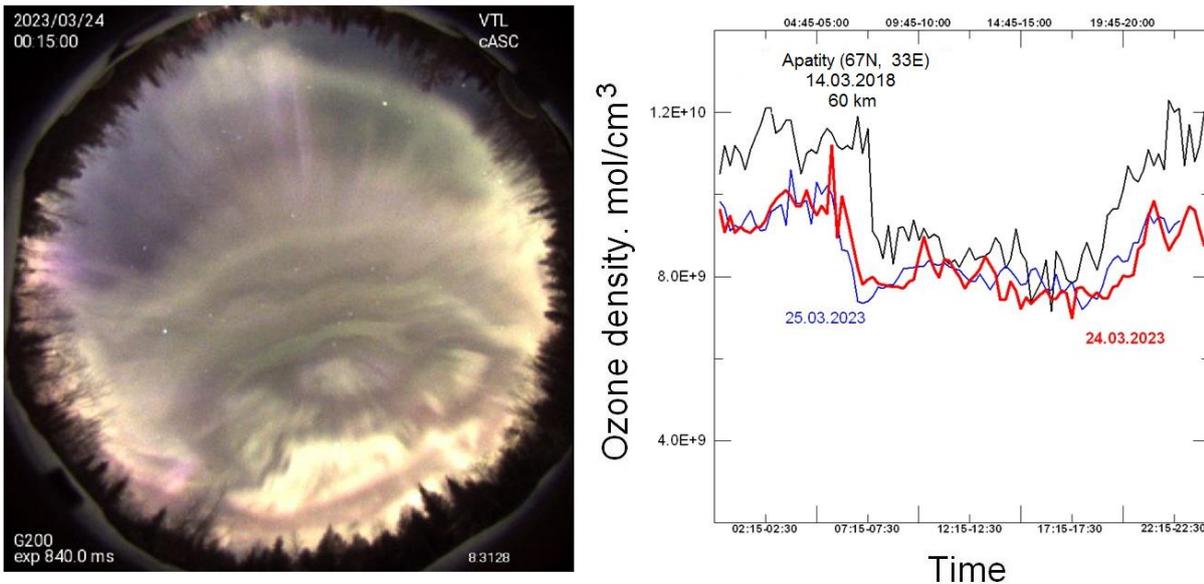
Polar ozone in the middle atmosphere is affected by dynamic processes associated with both the development of SSW or the activation of a polar vortex [3, 4] and by solar activity products, i.e. proton events and auroral electron precipitation [5-7].

In March 2023 (23-24), Earth's geomagnetic observatories recorded a recent-year high planetary-scale magnetic storm. The main phase of the storm began at 17:30 UT on Marc23; the storm intensity peak (7.7) was at 21:30 UT. The variability of the magnetic field was up to 1500 nT, and it was mainly observed in auroral latitudes [8]. Figure 2 (Right panel) shows the diurnal variations in  $O_3$  density (60 km) according to continuous ground-based microwave observations from March 21 to 26, i.e., before and after the magnetic storm. Ozone variations are plotted with 15-min resolution. No significant difference in diurnal ozone variations is seen. Variations in mesospheric  $O_3$  (60 km) associated with sunrise and sunset dominate over the variations due to the solar wind. Figure 2 also shows the diurnal

ozone cycle (black curve) on March 14, 2018, formed after major SSW in mid-February 2018. The difference the SSW effects on mesospheric O<sub>3</sub> density in winter 2022-2023 and 2017-2018 is pronounced.



**Figure 1.** Time course of the temperature at the level 10 hPa above Apatity according to satellite data (MLS/Aura) for winter-spring season: left panel – 2017-2020, right panel – 2021-2024.



**Figure 2.** Left panel: Display from observatory Verchne-Tulomskaya (69N, 32E) camera all-sky (KBH-22) on March 24, 2023; Right panel: Daily cycle of mesospheric ozone (60 km) during the storm of March 23-24, 2023; variations in O<sub>3</sub> density during the storm (March 24, red line) and after the storm (March 25, blue line), as well as the cycle mesospheric O<sub>3</sub> during March 14, 2018, after SSW effect on the middle atmosphere (black line).

**Influence of proton events on mesospheric ozone**

Solar proton events were marked in middle of February and last decade March, 2024 according to satellite GOES-18. Duration of events was 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. Duration of events was from March, detectors 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 March 24, 2024, a G4 (according to the NOAA Space Weather Scale for Geomagnetic Storms) geomagnetic storm was registered, with the corresponding geomagnetic indices K<sub>p</sub> and Dst equal to 8 and

–130 nT, respectively. On the same day 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 [9]. It is necessary to note that last decade March there was a significant SSW (Figure 1, right panel), which could disguise changes of ozone because of the charged particles. As we See, there is no changes mesospheric ozone during proton events.

In Table 1 the ozone density are given in mol/cm<sup>3</sup>, 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 1.** The numerical data of diurnal mesospheric ozone cycle.

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

On the basis of the given data follows, that decreasing of mesospheric ozone 60 km during proton events has composed  $(10 \pm 2)\%$ .

### Mesospheric ozone (60 km) during polar night at low and high solar activity

In the present section of article the behaviour mesospheric ozone in December (polar night) is discussed during change of solar activity. Why for such analysis month December is chosen? The basic attention we give changes of ozone density within day at altitude of 60 km. Polar mesospheric ozone is affected by photochemical processes (sunset and sunrise), by dynamic processes associated with both development of SSW or the activation of a polar vortex and by solar activity products, i.e., proton events and auroral electron precipitation. In December, as a rule, SSW are absent and can not affect a vertical structure of ozone. The height of the Sun about time of a winter solstice (Apatity) is equal concerning horizon – 1°.

In Table 2 average day and night of ozone density above Apatity in December for six winter seasons and their relation night / day are submitted.

**Table 2.** Daily cycle mesospheric ozone density during polar night, mol/cm<sup>3</sup>.

	Low solar activity		
	2017/2018	2018/2019	2019/2020
Day	$(4.24 \pm 0.05) \cdot 10^{09}$	$(4.64 \pm 0.11) \cdot 10^{09}$	$(4.44 \pm 0.07) \cdot 10^{09}$
Night	$(5.24 \pm 0.70) \cdot 10^{09}$	$(5.87 \pm 0.20) \cdot 10^{09}$	$(4.94 \pm 0.09) \cdot 10^{09}$
N/D	1.24	1.26	1.11
	High solar activity		
	2021/2022	2022/2023	2023/2024
Day	$(4.35 \pm 0.09) \cdot 10^{09}$	$(4.38 \pm 0.09) \cdot 10^{09}$	$(4.23 \pm 0.13) \cdot 10^{09}$
Night	$(5.17 \pm 0.09) \cdot 10^{09}$	$(4.66 \pm 0.13) \cdot 10^{09}$	$(4.68 \pm 0.09) \cdot 10^{09}$
N/D	1.19	1.06	1.11

The analysis of the data which are given in Table 2, specifies high repeatability of day and night of ozone density in December during six winter-spring seasons in comparison with other months. In December (polar night) the amplitude of a daily cycle of the mesospheric ozone in different years made from 6 % up to 20 %. At high solar activity the average night of ozone density decreases on of 10 %, and day less than 5 %.

## 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 wave range.
- The planetary geomagnetic storm 23-24 March, 2023 did not render influence on mesospheric ozone (60 km) above Apatity.
- In ground-based microwave observations of a middle atmosphere ozone above Apatity during proton events in February and March 2024 decrease of mesospheric ozone was no more than 10%.

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## References

1. Kulikov Y.Y., Krasilnikov A.A., Ryskin V.G., Shanin V.N., Shchitov A.M. Ground-based microwave instrument to research of stratospheric ozone (some results of observations). Proc. XXX Annual Seminar, Apatity, pp. 218-221, 2007.
2. Krasilnikov A.A., Kulikov Y.Y., Mazur A.B., Ryskin V.G., Serov N.V., Fedoseev L.I., Shvetsov A.A. Detection of «ozone clouds» in the upper stratosphere of the Earth by means of microwave radiometry technique. *Geomagnetism and Aeronomy* (Eng. Transl.), V. 37, P. 385-391, 1997.
3. Kulikov Y.Y., Andriyanov A.F., Demin V.I., Demkin V.M., Kirillov A.S., Ryskin V.G., Shishaev V.A. Long-term microwave observations of middle atmosphere ozone in Apatity during three winters. *Geomagnetism and Aeronomy*, V. 63, P. 608-619, 2023.
4. Kulikov Y.Y., Demin V.I., Demkin V.M., Kirillov A.S., Losev A.V., Ryskin V.G. Dynamic phenomena in stratospheric and mesospheric ozone of polar atmosphere in February-March 2023. *Atmospheric and Oceanic Optics*, V. 38, P. 283-289, 2025.
5. Jackman C.H., Fleming E.L., Vitt F.M., Considine D.V. The influence of solar proton events on the ozone layer. *Adv. Space Res.*, V. 24, No. 5, P. 625-630, 1999.
6. Jackman C.H., March D.R., Vitt F.M., Garcia R.R., Randall C.E., Fleming E.L., Frith S.M. Long-term middle atmosphere influence of very large solar proton events. *J. Geophys. Res.*, V. 114, No. D11, DOI: 10.1029/2008jD011415, 2009.
7. Andersson V.E., Verronen P.T., Rodger C.J., Clilverd M.A., Seppälä A. Missing driver in the Sun-Earth connection from energetic precipitation impacts mesospheric ozone. *Nat. Commun.*, V. 5, Art. 5194, DOI: 10.1038/ncomms6197, 2014.
8. Pancheva D., Mukhtarov P., Bojilova R. Response to geomagnetic storm on 23-24 March, 2023 long lasting longitudinal variations of the global ionospheric TEC. *Advance in Space Research*, V. 73, No. 12, P. 6006-6028, DOI: 10.1016/j.asr.2024.03.023, 2024.
9. Fedulina I., Lastovička J. Effect of Forbush decreases of cosmic ray flux on ozone at higher middle latitudes. *Advance in Space Research*, V. 27, No. 12, P. 2003-2006, 2001.