Russian Federation National Report for the 12th WMO/UNEP Ozone Research Managers' Meeting (22 - 24 April 2024, Geneva, Switzerland)

1. OBSERVATIONAL ACTIVITIES

1.1. Column measurements of ozone and other gases/variables relevant to ozone loss

In the Russian Federation, regular measurements of total column ozone (TCO) are provided and interaction with the WMO is effected by the Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet).

Roshydromet continues to carry out TCO measurements at 28 ozonometer stations that are part of the Global Ozone Measuring Network (GAW WMO). Methodological and metrological support of the network is provided by the staff of A.I. Voeykov Main Geophysical Observatory (MGO). The ozone measuring stations are equipped with M-124 filter ozonometers. Guided by the MGO, TCO measurements proceed at 5 ozonometer stations in Kazakhstan.

Accumulated 50-year homogeneous TCO data series allow to analyze long-term trends and assess the current state of the ozone layer. Annually, reviews of ozone layer state over the territory of the Russian Federation are prepared, including updated analyses of long-term trends and features of the ozone field over the past year.

In Antarctica, TCO measurements are also made with M-124 ozonometers by specialists of the Arctic and Antarctic Research Institute (AANI) at the Russian polar stations: Novolazarevskaya, Mirny, and Vostok, as well as aboard the Russian Antarctic research vessels.

Work is continued to retrofit the network with automated equipment. During test operation of UFOS spectrometers designed for automated complex measurements of the spectral composition of total UV radiation (UVR) and TCO, the software, calibration methods, and calculation of TCO have been improved. Separate components of the instruments have been upgraded. Series of observations using some instruments, made simultaneously with M-124 ozonometers, have been accumulated, which demonstrate satisfactory consistency and uniformity of the data series.

A new climate-resistant modification of the automatic zenith spectrometer-ozonometer has been developed. Such spectrometers are significantly smaller and cheaper than UFOS spectrometers, which is advantageous for network devices (ease of transportation and possibility of purchasing more devices to provide an exchange fund in order to ensure observation series continuity). In 2022-2023, both field and laboratory tests of 6 such spectrometers were fulfilled.

Since 2009, under the guidance of specialists from the Central Aerological Observatory (CAO), a TCO and total NO_2 measurement network has been created using automatic Mini-SAOZ spectrophotometers manufactured in France, which are installed in areas where negative TCO anomalies are often observed at 6 stations: Anadyr, Zhigansk, Salekhard, Murmansk, Irkutsk, Dolgoprudny, in winter and spring. The Mini-SAOZ data from Salekhard station (67° N 67° E) is available at: http://saoz.obs.uvsq.fr. Regular observations are carried out at CAO (Dolgoprudny). The measurement data archive is available at: http://www.cao-rhms.ru/saoz.

During 2020-2023, at Obninsk measuring station (55°06' N 36°37' E) (the Global Atmospheric Observation Service (GAW) identifier – OBN, the number in the database of the World Ozone and Ultraviolet Data Center – 307) specialists of Scientific Production Association (SPA) "Typhoon" carried out systematic measurements of:

- TCO using Brewer MKII spectrophotometer No. 44;
- integral CH_4 and H_2O content in the atmospheric column by a spectroscopy method.

TCO measurements are carried out at the high-altitude research station of A.M. Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences (RAS), in the North Caucasus (43.7° N 42.7° E), in the zone of alpine meadows at an altitude of 2070 m a.s.l. Most time, observation conditions at the station can be taken as background, since polluted air from the nearest city of Kislovodsk, 18 km north, situated at an altitude of 750-900 m, does not reach the station. TCO by direct solar radiation was measured at the station, using spectrometer based on the MDR-3 monochromator, from 1981 to 1989, and based on the Brewer MkII #043 spectrophotometer, from 1989 until the present. When the Sun is overclouded, TCO is measured with the Brewer MkII #043 by radiation scattered at the zenith.

Since 2009, regular measurements of TCO and gases that destroy ozone (CFC-11, CFC-12, HCFC-22) and those involved in various ozone cycles (HCl, $ClONO_2$, HNO_3, etc.) have been carried out at St. Petersburg State University's station in Peterhof (59.88°N, 29.82°E), using a Bruker IFS 125HR, high-spectral resolution Fourier spectrometer measuring solar IR radiation transmitted through the atmosphere in the range of 650-5400 cm^{-1}.

The monitoring of TCO and analysis of the data obtained with the Fourier spectrometer IKFS-2 installed on the Russian satellite Meteor-M No. 2 are being continued.

Surface ozone

Two of Russia's largest megacities, St. Petersburg and Moscow, have got systems for monitoring surface ozone and other pollutants, which are comparable with foreign analogues. Since 2002, the environment monitoring network of the State Budgetary Institution for Environment Protection "Mosecomonitoring", a specially authorized organization for environmental monitoring, has been operating in Moscow [https://mosecom.mos.ru]. Regular hourly measurements of surface ozone concentrations are made around the clock at 17 automatic air pollution control stations (ASCS). Average values for 20-minute intervals are recorded in the database. The measurements are performed by three types of gas analyzers based on the ultraviolet photometry method: Casella Monitor ME 9810B, Environnement S.A. O3 42M, HORIBALtdAPXA-370 mod. APOA-370, and one OPSIS AB AR500 device based on differential optical absorption spectroscopy method. The devices are included in the State Register of Measuring Instruments and verified by the State Metrological Service. The annual report publishes analytical materials on the state of the environment in Moscow [https://www.mos.ru/eco/documents/doklady/view/] which are also partially included in quarterly reviews by specialists of the Central Aerological Observatory and the Hydrometeorological Center of Russia [e.g. Ivanova et al., 2021, 2022].

In 2022, measurements of surface ozone concentrations were carried out at 10 observation points in St. Petersburg and Leningrad region. Ozone concentrations are measured in 4 cities (Angarsk, Baikalsk, Irkutsk, Shelekhov) of Irkutsk region, 3 cities (Gusinoozersk, Selenginsk, Ulan-Ude) of the Republic of Buryatia, 2 cities (Magnitogorsk, Chelyabinsk) of Chelyabinsk region , 1 city (Chita) on the Trans-Baikal Territory, 1 city (Krasnoyarsk) on the Krasnoyarsk Territory, 1 city (Lipetsk) in Lipetsk region, 1 city (Nizhny Tagil) in Sverdlovsk region, 1 city (Cherepovets) in the Vologda region, 1 city (Novokuznetsk) in Kemerovo region, and 1 city (Norilsk) in Taimyr Autonomous District. A brief analysis of surface ozone observations in these cities in 2022 is published in the annual report "The state of atmospheric pollution in cities in Russia for 2022" [MGO, 2023].

The average annual ozone concentration was 1.6 MPC in Lipetsk, 1.5 MPC in Nizhny Tagil and Baikalsk, 1.3 MPC in Gusinoozersk, Magnitogorsk and Selenginsk, 1.2 MPC in Ulan-Ude and Chelyabinsk, 1.1 MPC in Norilsk and St. Petersburg, in Krasnoyarsk, Irkutsk, Cherepovets, Novokuznetsk, Shelekhov, Chita and Angarsk the values did not exceed the MPC.

Also, annual reviews of the results of observations of ozone concentration in the troposphere in Russia, conducted mainly by scientific or university organizations [Andreev et al., 2021, 2022, 2023], are published. According to these reviews, measurements of ground-level ozone continue at Kislovodsk high-altitude research station of Obukhov Intitute of Atmospheric Physics of the RAS, in the Karadag State Nature Reserve in the Crimea, on a 300-meter tower in Obninsk (Kaluga region, SPA "Typhoon"), at 2 stations in St. Petersburg: ORTES-N and ORTES-P, ORTES-PR station in Leningrad region, at the station of monitoring ground-level ozone and its precursors at the Peoples' Friendship University of Russia with the participation of the A.M. Prokhorov Institute of General Physics of the RAS in Moscow, at Vyatskiye Polyany station in the south of Kirov region, at TOR station and Fonovaya Observatory in Tomsk Region, and in Ulan-Ude. The Apatity station in Murmansk Region, where the DASIBI 1008AH ozonometer is employed, and Boyarsky station in

Buryatia have been additionally set up. In 2021, measurements were restored at Listvyanka (Irkutsk region) and Tarusa (Kaluga region) stations; also, OPTEK station was opened in Karelia. The stations are equipped with the network instruments recommended by the Global Atmosphere Service (GAW WMO). All the instruments underwent regular calibration.

The monitoring of surface ozone in Moscow atmosphere in 2020 and 2021 was analyzed under stringent conditions associated with the COVID-19 pandemic [Stepanov et al., 2022]. The two years differed significantly in weather conditions and anthropogenic impact on the environment. In 2020, surface O_3 concentrations were relatively low for the megalopolis, with an average annual value of 28 μg/m^3 and a 185 μg/m^3 maximum for the year. That was due to the combination of relatively cool summer weather with the low amount of pollutants in the atmospheric air. In the summer of 2021, intense heat waves were observed under the conditions of a blocking high with daytime temperatures up to 35°C. Combined with enhanced air pollution, this led to abnormally high O_3 concentrations, with an annual mean of 48 μg/m and an annual maximum of 482 μg/m.

In central Russia, abnormally low ozone concentrations in the surface atmosphere were recorded in the spring of 2020 [Kotelnikov et al., 2021]. The ozone content increase that is normal for spring due to seasonal increases in temperature and illumination changed to a monotonous decrease. The monthly mean daily maxima observed in April 2020 were 3 times as low as compared with those in 2019. Both a regional background ozone concentration decrease in the surface atmosphere and a decrease in photochemical ozone formation intensity were observed. The authors consider the most likely reason for the occurrence of the observed phenomenon to be the decreased emissions of combustion products into the atmosphere in China, Europe, and Russia, due to the introduction of restrictions associated with the COVID-19 pandemic.

Instruments and methods

The atmospheric air monitoring station in Vyatskiye Polyany in the south of Kirov Region (56°13'33" S, 51°03'56" E), 74 m a.s.l.. part of A.M. Prokhorov Institute of General Physics of the RAS, has regularly measured surface ozone concentrations since 2010. The town of Vyatskiye Polyany is located at sufficient distances from the nearest industrial centers - Naberezhnye Chelny (97 km), Kazan (131 km), Izhevsk (148 km), and Kirov (277 km). The population of the town with the neighboring regions is about 50,000 people. There are no industrial enterprises producing gas emissions in the town or its surroundings. The regional air pollution background in the town is formed by local and regional transport. Thus, this station can be referred to a group of lowland stations in rural areas, and its data can characterize the state of atmospheric pollution at a regional level. To measure surface ozone concentrations, a commercial chemiluminescent gas analyzer Model 3.02 P-A manufactured by OPTEK CJSC, St. Petersburg, Russia, with international certification from the U.S. Environmental Protection Agency, https://archive.epa.gov/nrmrl/archive-etv/web/pdf/vs_optecfeb2008.pdf).

Once a year, the manufacturer calibrates the instrument, using the 1st category working standard of the unit of a molar ozone fraction in ozone-air mixtures RE 154-1-33-2008, stored at the instrument-making enterprise "OPTEK". The instrument also undergoes monthly calibration, using the GS-024-2 generator developed and manufactured by "OPTEK CJSC". The gas analyzer operates as part of an automated measuring system that provides data collection, storage, preprocessing, and transmission, as well as remote control and data visualization. The measuring system is installed on the fifth floor of a building in a park area. The intake of an air sample to be analyzed is done via a Teflon tube at a 10-m height above the ground surface. The measurement results are published in annual reports in the journal "Optics of the Atmosphere and Ocean".

At Obninsk station, specialists from the SPA "Typhoon" (Kaluga Region) carry out systematic measurements of surface ozone concentration, using an optical ozonometer F-105, measurements of surface concentrations of CO, CH_4, and other gaseous constituents involved in the ozone cycle, as well as simultaneous measurements of meteorological parameters in the boundary layer of the atmosphere.

1.2. Measurements of the vertical distribution of ozone and other minor gaseous constituents responsible for ozone depletion (Profile measurements of ozone and other gases/variables relevant to ozone loss)

In 2021-2023, specialists from the Polar Geophysical Institute of the RAS (Apatity) and the Institute of Applied Physics of the RAS (Nizhny Novgorod) studied ozone concentrations changes in the middle atmosphere observed, using a ground-based microwave radiometry method. This method is based on measuring thermal radiation of the atmosphere near the ozone line in the range of millimeter and submillimeter waves. Microwave observations are but slightly dependent on weather conditions and the presence of aerosols, which is an advantage, compared to observations in the optical and infrared wavelength ranges. In addition, microwave ozone monitoring can be carried out around the clock. The instrument consists of an uncooled heterodyne receiver tuned to a fixed frequency of 110,836.04 MHz, corresponding to the rotational transition of ozone molecules $6_{0,6}$– $6_{1,5}$, and a multichannel spectrum analyzer. The ozonometer is installed at the Apatity Department of the Polar Geophysical Institute. Measurements were carried out in the periods from December 2021 to March 2022, from December 2022 to June 2023, and from October 2023 to December 2023. The results of the analysis of ozone measurements in Apatity are presented in the publications by Kulikov Yu. et al. 2022, 2023.

At Obninsk station, specialists of the SPA "Typhoon" carry out lidar measurements of high-altitude profiles of ozone concentration in an altitude range from 12 to 35, using the AK-3 lidar developed at the SPA "Typhoon". Also, this lidar measures the vertical profiles of temperature (in an altitude range from 26 to 72 km) and aerosol (from 10 to 40 km), the parameters that are critical for ozone measurement data interpretation.

Along with the measurements of the ozone content, observations of other minor gas constituents affecting the state of the stratospheric ozone layer are carried out. Regular measurements of the vertical distribution and total content of nitrogen dioxide at heights up to 45 km by scattered solar radiation at dusk have been performed at Zvenigorod research station since 1990 and at Kislovodsk high-altitude research station of Obukhov Institute of Atmospheric Physics of the RAS since 2014. The measurements are made with spectrophotometers based on LOMO MDR-23 and Oriel-MS260i monochromators, respectively. In 2016, NO_2 measurements at Zvenigorod research station use a Shamrock-303i spectrophotometer. The station is part of the international Network for the Detection of Atmospheric Composition Change (NDACC). Measurement data from this station is available on the NDACC website (http://www.ndacc.org).

Nitrogen dioxide is also one of the key components of the photochemistry of ozone in the lower troposphere. Reactions with its participation lead, in particular, to an increase in surface ozone content as well as nitric acid formation and precipitation of acid rain. Regular measurements of the vertical distribution (VRS) of NO_2 in the lower troposphere have been performed by ELISA, using the MAX-DOAS method, at Zvenigorod since 2012, Kislovodsk since 2022, and in Tomsk they were performed during 2012-2022. At IFA, the first experiments on comprehensive sensing of tropospheric NO_2 from satellites were fulfilled in 2016-2017, using measurements of the GSA spectrometers installed on space platforms of Resurs-P series. Based on the survey, the first world-class algorithm of determining integral NO_2 content in the troposphere with spatial resolution of about 2.4 km on a 120-m grid, with a measurement error of 1015 molec/cm$_2$, typical of satellite methods, was developed [Zakharova et al. 2021]. Based on the obtained distribution fields, using chemical transport modeling, emissions from an individual enterprise in China were estimated [Davydova et al. 2021].

The vertical distribution of ozone in the troposphere was measured with the instrumentation [Belan et al., 2022] installed on board the aircraft laboratory Tu-134 "Optik". Monthly flights were fulfilled over the southern regions of Western Siberia. In September 2022, an experiment was conducted to measure air composition in the meridional direction. The flight route started near 56° N and ended over the waters of the Kara Sea, where the research vessel "Akademik Mstislav Keldysh" additionally provided measurements at sea surface level.

During the cold seasons of 2020-2023, regular daily measurements of ozone profiles in the stratosphere and mesosphere over Moscow region, using a microwave (142.2 GHz) radiometer, proceeded at the P.N. Lebedev Physical Institute of the RAS (LFI, Moscow). The relation between ozone variations at 15-55 km and the dynamics and temperature regimes of the stratosphere, with sudden stratospheric warming events, is being investigated.

Together with the Institute of Microstructure Physics of the RAS (IMP RAS, Nizhny Novgorod), a statistical analysis of ozone profiles in the stratosphere and lower mesosphere above Moscow obtained from radiometric measurements at LFI in 1996-2017 [Gaikovich et al., 2020, Gaikovich et al., 2021], was fulfilled.

Variations of mesospheric ozone over Moscow region were measured during the partial solar eclipse of October 25, 2022 [Rozanov et al., 2023].

Lidar measurements of high-altitude ozone concentration profiles around 12 - 35 km are carried out at Obninsk station, using the AK-3 lidar developed at the SPA "Typhoon". The lidar measures the vertical profiles of temperature (in an altitude range from 26 to 72 km) and aerosol (between 10 and 40 km) – the parameters critical for the interpretation of ozone measurements.

A mobile, fully automated ground-based spectral radiometer system with a 110,836 GHz central frequency, designed for continuous monitoring of the structure of the ozone layer, has been constructed and put into operation at the Institute of Applied Physics of the RAS. Distinctive features of the system are: a wide reception and analysis bandwidth (0.8 GHz), an interface with a digital spectrum analyzer with 60 kHz resolution, noise temperature <1500 K, low power consumption and weight (less than 10 kg), and calibration of the measured signal by an electronically controlled internal standard. The application of a statistical (Baeis) approach to solving incorrect inverse problems allows to satisfactorily retrieve the vertical profile of ozone concentration in an altitude range between 20 and 75 km.

The vertical distribution of ozone has been measured with the Brewer MkII #043 spectrophotometer since 1989 at the high-altitude research station of Obukhov Institute of Atmospheric Physics of the RAS, located near the city of Kislovodsk.

At the Siberian lidar station of V.E. Zuev Institute of Atmospheric Optics, Siberian Branch of the RAS (IAO SB RAS) in Tomsk (56,5° N, 85° E), ground-based remote measurements are being carried out, using laser sensing and spectrophotometry of the aerosol and gas composition and temperature of the atmosphere. The scattering characteristics of the stratospheric aerosol layer, the vertical distribution and TCO, as well as the vertical temperature distribution from the troposphere up to the mesosphere, are measured [Dolgii et al., 2022].

At St. Petersburg State University station in Peterhof (59.88° N and 29.82° E), measurements of ozone content in various atmospheric layers, up to 4 ones, including ozone content in the tropospheric layer [Virolainen et al., 2023c], as well as measurements of nitric acid content in 2 atmospheric layers, are carried out using a ground-based spectroscopic IR method [Virolainen et al., 2023b].

1.3. UV measurements

Measurements of erythemic UV radiation, using M-124 ozonometer with a special corrective nozzle have continued at 12 stations of Roshydromet. Automated monitoring of the global UV radiation proceeds at 10 stations. At 4 stations, the UV index is recorded, using UV indicators; at 8 ones, the spectral composition of UV radiation is recorded using UVOS spectrometers.

In 2022, specialists from the Main Geophysical Observatory and the Arctic and Antarctica Research Institute initiated joint work to establish a network of regular automated UV observations with high time resolution at polar stations in the Arctic and Antarctica and research vessels; the network is to include 5 stations.

Systematic measurements of surface UV irradiance are carried out in the UV-B range, using the Brewer MKII spectrophotometer No. 044 at SPA "Typhoon" (Obninsk, Kaluga Region).

The monitoring of biologically active erythemic UV radiation (UVR) has proceeded at the Meteorological Observatory of Lomonosov Moscow State University since 1999. Measurements of long-wavelength 300-380 nm UV radiation have continued since 1968, this being the world's longest series of UFR measurements. In 2021, a new system under the BSRN standard was established, including measurements of erythemic UVR and UVR in the region of 315-400 nm [Chubarova et al. 2022]. The results of the analysis of UFR trends and comparison with the results of the reconstruction model are given in [Chubarova et al., 2023]. It is shown that the long-term interannual UVR variability for 1968-2019 period had a pronounced positive trend, especially that of erythemic UVR (about 5% per decade) since the late 1970s. However, in recent years this positive trend has slowed down. The increase in UVR is due to simultaneous decrease in cloud amount and total ozone content and, to some extent, a decrease in the optical thickness of aerosol, while the slighter trend for UVR in the range of 300-380 nm results from the insignificant ozone effect on long-wavelength ultraviolet radiation [Chubarova et al., 2023].

Spectral UV radiation in the range of 290-325 nm has been measured in 0.5 nm increments, using the Brewer MkII #043 spectrophotometer, at Kislovodsk high-altitude station since 1991.

1.4. Calibration activities

The M-124 filter ozonometers used in the Russian Federation (as well as at Russian scientific stations in Antarctica and 5 stations in Kazakhstan) are linked to the world scale by regular calibration by the working standard of Roshydromet ozonometer network (Dobson Spectrophotometer #108) located in the Main Geophysical Observatory's actinometric pavilion in Voeykovo near St. Petersburg. Dobson spectrophotometer No. 108 regularly participated in comparisons with the European regional standard. The last intercalibration (MOHp2019) took place in July 2019 at the Regional European Center for Calibration of Brewer and Dobson Spectrophotometers in Germany (Hohenpeissenberg). The deviation from the regional standard (Dobson # 64) was less than 1%.

The last intercalibration of the Brewer spectrophotometer MKII No. 044 (SPA "Typhoon", Obninsk, Kaluga region) was carried out in summer 2018 in Switzerland (Aros Climate Observatory). The calibration of the F-105 ozonometer was carried out in 2022.

In August 2017, Brewer MkII #043 spectrophotometer used at Kislovodsk high-altitude station failed. In April 2018, it was repaired, and regular monitoring was resumed. In 2019, the staff of the station restored the functionality of the Brewer internal calibration module, using a standard (halogen) lamp. Routine maintenance of Brewer spectrophotometer MkII #043 follows the WMO requirements. Its last calibration was carried out by Brewer MkII #017 standard in Obninsk in 2012 with the WMO support. The repairs and calibration of the spectrophotometers MDR-3, MDR-23, and Oriel 256i are performed by specialists of Zvenigorod research station of A.M. Obukhov Institute of Atmospheric Physics of the RAS.

Dobson #14 and Brewer #049 spectrophotometers are not currently employed at the Institute of Atmospheric Optics (IAO) of the Siberian Branch of the RAS. Dobson spectrophotometer No. 14 is not operated due to the lack of an agreement between the WMO and the Institute. So, it is impossible to obtain a statement from the Federal Service for Technical and Export Control (FSTEC of the Russian Federation) on the use of foreign technical means of surveillance and control (ITSC) on the territory of Russia. Brewer spectrophotometer #049 which failed after a severe thunderstorm was restored. However, calibration is required, since the last one was performed in 2012.

Brewer MKIII # 222 spectrophotometer installed in the Central Aerological Observatory (Dolgoprudny) in 2014 is not currently operated and requires calibration.

Spectrophotometer / Organization	Status / The year of the last calibration
Dobson spectrophotometer #108 / MGO	in use / 2019 at the Regional European Center in Germany.
Brewer spectrophotometer MKIII # 222 / CAO	not used, requires calibration
Dobson spectrophotometer # 107 / CAO	not used, requires calibration / 2010.
Dobson spectrophotometer #14 / Institute of Atmospheric Optics SB RAS	not used due to no agreement between the WMO and the Institute and thus, no permission for its use in Russia
Brewer spectrophotometer #049 / Institute of Atmospheric Optics SB RAS	in use, requires calibration / 2012
Brewer spectrophotometer MKII # 044 / SPA "Typhoon", Obninsk	in use, requires calibration / 2018 in Switzerland
Brewer MkII #043 spectrophotometer, high-altitude station of Obukhov Institute of Atmospheric	in use, requires calibration / by Brewer MkII #017 standard in 2012 in Obninsk with the WMO support

Physics RAS, Kislovodsk	

2. Results of observations and analysis

The duration of homogeneous TCO data series for most Roshydromet stations is more than 45 years. Daily, after initial critical review by a CAO specialist, operational data from the Russian ozonometric network are sent to the WMO server and used to build daily combined TCO maps. Annually, after thorough inspection and rejection by the network's methodologist at the MGO, data arrays for 21-23 stations are sent to the WMO World Data Center (WOUDC).

An original algorithm for solving the inverse problem was proposed, implemented and validated to obtain TCO from the spectra measured by Fourier spectrometer IKFS-2 on the Russian satellite Meteor-M No.2 [Timofeyev et al., 2021, Polyakov et al., 2021b, 2023b]. The algorithm is based on the method of artificial neural networks, the method of principal components and TCO measurements by the OMI uinstrument on the Aura satellite. The error in determining the TCO is less than 3%, the method allows one to analyze the global distribution of TCO, including that in the absence of solar radiation, for example, during the polar nights. The database of the TCO global distribution fields for 2015-2020 is included in the database registry [Polyakov et al., 2023].

The analysis of ICFS-2 TCO measurements jointly with the analysis of ERA5 reanalysis data on temperature and potential vorticity made it possible to study in detail the evolution of the polar stratospheric vortex and ozone mini-holes in the Northern Hemisphere in March and April 2020 [Polyakov et al., 2021b]. Total ozone measurements for 2015-2020 [Polyakov et al., 2023b] were used to analyze ozone distribution fields in the Arctic and Antarctic in spring.

Another method of interpreting spectral measurements of ICFS-2 is also proposed, based on the construction of an inverse operator characterizing the relation between reference ground-based measurements of the TCO (Dobson and Brewer instruments) and satellite measurements of the thermal radiation of the planet [Timofeyev et al., 2023]. As exemplified by TCO measurements nearby St. Petersburg, the estimate of the TCO measurement accuracy was about 3%.

The DOAS differential spectroscopy technique was applied to interpret the measurement results of the ground-based ultraviolet ozone spectrometer UVOS to determine the TCO [Ionov, Privalov, 2021]. Comparisons of the calculated TCO values with the data of independent measurements revealed systematic discrepancy between them, which can be eliminated with a more thorough adaptation of the DOAS algorithm to the problem conditions and the characteristics of the UVOS instrument.

An improved technique for processing ground-based spectral measurements of the Bruker 125HR Fourier spectrometer (FS) in the vicinity of St. Petersburg to obtain information about TCO and other stratospheric gases is presented [Virolainen et al., 2021]. The time variability of the TCO of stratospheric gases HCl, HF, HNO_3, $ClONO_2$ has been studied, including that during periods of the stratospheric polar vortex over St. Petersburg, and feasibility of using ground-based IR measurements to interpret processes occurring in the ozonosphere has been demonstrated [Virolainen et al., 2021, 2023f].

The results of ground-based measurements of the TCO near St. Petersburg for the period 2009-2020 were compared with the Dobson spectrophotometer, the M-124 filter ozonometer and the Bruker 125HR FS (Nerobelov et al., 2022b). The spread of data between different ensembles of TCO measurements did not exceed the measurement errors of the methods.

Ground-based measurements were supplemented by satellite measurements (OMI, TROPOMI and IKFS—2) as well as data from model calculations (EMAC and IWM RAS-RGGMU) and reanalysis (ERA5 and EAC4) [Nerobelov et al., 2022a]. All data sets demonstrated a pronounced seasonal variation of TCO in the St. Petersburg area, with a maximum in spring and a minimum in autumn. For the period 2004-2021, all data sets were harmonized, and on the basis of a single TCO ensemble, a statistically significant positive TCO trend was obtained near St. Petersburg (+0.4 ± 0.1 DU per year).

In addition to the TCO analysis, 2018-2020 measurements of ozone content profiles in the atmosphere of St. Petersburg using Bruker 125HR ground-based FS and satellite microwave instrument (MLS) were compared, and the vertical variation of the differences between the two methods of measuring the ozone profile was investigated [Bordovskaya et al., 2022].

The informativeness of the microwave (MKV) method for determining the profiles of ozone content in the stratosphere, based on measurements of the MKV ozonometer developed at the Institute of Applied Physics of the RAS, was investigated. It is shown that, using optimal a priori information and inverse operator, it is possible to determine ozone content in a 20-60 km layer with an accuracy of 3-8% [Bordovskaya et al., 2023].

The variability of ozone content in the 0-8 km troposphere layer at the St. Petersburg State University station in Peterhof was analyzed; correlations of tropospheric ozone content with measurements of surface ozone concentrations (SOC) were investigated [Virolainen et al. 2023c]. Validation of satellite measurements of tropospheric ozone by IASI and IASI/GOME2 instruments was carried out; reliable estimates of the decrease in ozone content in the 0-8 km layer in the vicinity of St. Petersburg for 2012-2021, amounting to 5-6% over a decade, were obtained [Virolainen et al. 2023d]. Validation of satellite measurements was extended to two more stations of the IRWG-NDACC ground observation network-Kiruna and Izaña [Virolainen et al. 2023e].

To analyze changes in the ozone content in the troposphere in the St. Petersburg area, the WRF-Chem (Weather Research and Forecasting - Chemistry) high spatial resolution numerical model, version 4.1.2, of weather forecast and composition of the troposphere and lower stratosphere was adapted to the Gulf of Finland region, including the territories of the cities of St. Petersburg and Helsinki (Finland). Numerical experiments on the transport of ozone and its precursors in the troposphere and lower stratosphere were carried out for the period 2016 - 2019. Tropospheric ozone modeling data are presented in the form of a database [Nerobelov et al., 2023a]. Comprehensive validation of the ozone content in the troposphere was fulfilled, using data from SOC measurements in both cities, as well as ground-based remote measurements of the tropospheric ozone content (in a layer up to ~8 km), using the Bruker 125HR IR FS. Correlations for surface ozone concentrations and tropospheric ozone were about 0.5 and 0.6-0.7, respectively. The data of modeling the spatial distribution of tropospheric ozone over an area of ~1000x1000 km2 centered in St. Petersburg were compared with satellite measurement data by the IASI instrument. It was found out that using the WRF-Chem model, it is possible to describe the space and time change in tropospheric ozone by seasons [Nerobelov et al., 2023b, 2023c].

Research on monitoring ozone-depleting gases was conducted using ground-based remote measurements of the atmospheric content of various gases by the FTIR method. Methods for measuring ozone-depleting anthropogenic gases such as CCl_3F, CCl_2F_2, $HCClF_2$ (CFC-11, 12, HCFC-22), [Polyakov et al., 2021, Polyakov et al., 2023a], HNO_3 [Virolainen et al., 2023a] have been improved. Measurements of gases related to ozone photochemistry such as HCl, $ClONO_2$, HNO_3, HCl, HF (stratospheric dynamics indicator) are regularly performed [Akishina et al. 2023a, 2023b, Virolainen et al., 2023b] As the time series of data on the content of these gases continues, the analysis of their temporal variability on various scales, from daily to long-term trends, is being refined. A statistically significant decrease in the total content of chlorine components in the atmosphere was demonstrated in 2009-2022 [Polyakov et al., 2021, Virolainen et al., 2023f, Akishina et al., 2023a, 2023b] ($ClONO_2$: -1.64%, HCl: -0.22%, CFC-11: -0.4%, CFC-12: -0.49% in year), testifying to successful implementation of the Montreal Protocol and its subsequent amendments.

Based on the analysis of systematic measurements of total ozone content, surface ozone concentration, and surface UV irradiation in Obninsk (Kaluga region) obtained by specialists of the SPA "Typhoon", the following conclusions can be drawn:

• The range of the TCO values (250 - 450 DU) experimentally observed over many years is generally maintained. Critically low values below 200 DU corresponding to the "ozone hole" were not observed. Total ozone decreases noticeable both in magnitude (up to 50 DU) and duration were recorded in mid-April and early August 2023 [Korshunov 2023];

• The nature of seasonal changes in the level of surface UV irradiation with a maximum in summer is generally preserved. The level of surface UV irradiation, and hence the level of negative solar exposure, even in the warmest summer period, remained moderate.

According to lidar measurements in 2020-2023, variations within ± 8 DU (± 3%) in the integral mean annual ozone content in the layer from 12 to 35 km were observed. In August 2023, a negative anomaly of stratospheric ozone content of -18 DU was noted, which was a record for the month of August during observations since 2012.

The results of the measurements of stratospheric and tropospheric NO_2 performed at Zvenigorod Research Station (ZRS) of A.M. Obukhov Institute of Atmospheric Physics of the RAS are used in the validation of GOME-2, OMI, and TROPOMI satellite equipment [Verhoelst et al., 2021] and assessment of the quality of improved algorithms [Chan et al., 2022].

3. Theory, modeling, and other ozone related research

Estimates of the chemical destruction of the ozone layer in the winter season 2019-2020 have been calculated, which became a record for all years of observation in terms of the strength of the destruction of the ozone layer in the Arctic stratosphere [Tsvetkova et al. 2021]. The chemical destruction of ozone inside the stratospheric polar vortex in the Arctic using satellite and balloon measurements has been assessed on a regular basis in the CAO since 2000.

Using numerical modeling, specific features of the chemical destruction of the ozone layer in the Arctic in 2019-2020 winter season were revealed and analyzed [Smyshlyaev et al., 2021]. It is suggested that the underestimated propagation of wave activity from the troposphere to the stratosphere, which caused a strong stable stratospheric polar vortex and, as a result, severe destruction of the ozone layer, could be associated with significant positive surface temperature anomalies observed in Siberia during the winter months.

The dynamic features of an abnormally stable stratospheric polar vortex in the Arctic in the winter of 2019-2020 were investigated using Lagrangian methods [Lukyanov et al., 2021]. Variations of the horizontal dynamic structure of the vortex, obtained by a method of filling space with reverse trajectories, and those of the vortex force, represented as an M-function, depending on time and altitude, were studied. Estimates of ozone variation and thermodynamic parameters, averaged over an ensemble of trajectories inside the vortex were obtained.

A new model of the SOCOLv4 terrestrial system [Sukhodolov et al., 2021] including interactive ocean, dynamic vegetation, atmospheric chemistry and microphysics of sulfate aerosol was the basis of studying the behavior of the ozone layer at St. Petersburg State University. Calculations of changes in the ozone layer during the historic period were carried out using the observed parameters for all impact factors such as: concentrations of greenhouse gases and ozone-depleting substances, emissions of gases from sources, solar radiation, and volcanic eruptions. The calculated trends were compared with the results of analyzing ozone changes obtained from the data of the multisensor composites BASIC and MSRv2, and the data of the MERRA-2 and ERA-5 rieanalysis. The trends were analyzed separately for the periods of depletion (1985-1997) and recovery of the ozone layer (1998-2018). In the period 1998-2018, SOCOLv4 shows statistically significant positive trends in ozone content in the mesosphere, upper and middle stratosphere and a steady increase in tropospheric ozone. The results of SOCOLv4 [Karagodin-Doyennel et al., 2022] also indicate some negative trends in the lower layers of the tropical and mid-latitude stratosphere, which, however, do not agree with the BASIC data in magnitude and statistical significance. Despite the somewhat lower significance and scale of the simulation results, it is concluded that modern CCM, such as SOCOLv4, are generally capable of reproducing the observed changes in ozone.

Future changes in the ozone layer were estimated using the SOCOLv4 and scenarios for changes in the concentration of greenhouse and ozone-depleting substances, source gas emissions, solar radiation, and volcanic eruptions [Karagodin-Doyennel et al., 2023]. The simulation was performed based on two IPCC scenarios: SSP2-4.5 and SSP5-8.5. The model shows a decrease in tropospheric ozone in the future, which will begin in SSP2-4.5 in the 2030s and in SSP5-8.5 after the 2060s, and is associated with a decrease in concentrations of ozone precursors such as NO_x and CO. The results also indicate a very likely increase in ozone content in the mesosphere, upper and middle stratosphere, as well as in the lower stratosphere at high latitudes. According to SSP5-8.5, the increase in ozone content in the stratosphere is higher due to stronger cooling (> 1° K per decade) caused by greenhouse gases (GHGs), which slows down the cycles of catalytic destruction of ozone. In the tropical lower stratosphere, ozone concentrations decrease, but increase over the middle and high latitudes of both hemispheres due to increased meridional transport which is stronger for the SSP5-8.5 scenario. There were no signs of a decrease in ozone levels in the lower stratosphere at mid-latitudes. It is expected that in the future, the TCO will be noticeably higher in the middle and high latitudes, but will decrease in the tropics, which causes a decrease/increase in the surface level of UV radiation.

The generally optimistic estimates of the future changes in the ozone layer contrast sharply with the hypothetical situation where measures to protect the ozone layer would not have been taken. New estimations made using the SOCOLv4 [Egorova et al., 2023], which includes an interactive ocean and dynamic vegetation, confirmed the dramatic destruction of the ozone layer in this case, calculated earlier with less complex models. The introduction of restrictions on the production of ozone-depleting substances has made it possible to prevent additional warming of the global climate by more than 2°C.

Interesting results regarding factors likely to affect the ozone layer were also obtained by Sedlacek et al. (2023), Józefiak et al. (2023) and Karagodin-Doyennel et al. (2021). Using an alternative IPCC scenario of solar activity, assuming a decrease in solar radiation in the future, it was shown that the expected decrease will not significantly affect the restoration of the ozone layer [Sedlacek et al. 2023]. Józefiak et al. (2023) assessed the consequences of a possible change in oxygen content in the atmosphere and found ozone maximum to occur at present-day oxygen concentration. A further increase in oxygen concentration leads to changes in circulation that prevent an increase in ozone content. Karagodin-Doyennel et al. (2021) analyzed the effect of iodine-containing minor species and showed that only a strong (more than two-fold) increase in the emission of these gases would significantly threaten the ozone layer, which does not seem realistic. Therefore, the basic version of the SOCOLv4 was used to calculate the evolution of the ozone layer from 1980 to 2100 [Sukhodolov et al., 2021] without taking iodine-containing minor species into account.

Much attention has been paid to the impact of space-related factors on the ozone layer. It has been shown that the weakening of the magnetic field can lead to the destruction of 5% of the ozone layer due to the weakening of galactic cosmic ray shielding [Cooper et al. 2021]. This value is comparable with the effect of emissions of anthropogenic halogen-containing substances and can cause environmental disasters. Mironova et al. (2022) and Grankin et al. (2023) showed that energetic electron precipitation from the magnetosphere can greatly influence ozone. Modeling of the consequences of an extreme event over Moscow in December 2009 showed almost complete destruction of the ozone layer in the mesosphere and lower thermosphere of the northern hemisphere. Grankin et al. (2023) examined the precipitation of energetic electrons over the city of Apatity and calculated changes in concentrations of ozone, electrons, nitrogen oxides and hydrogen caused by these events. For the events of 9.10.1998 and 01.09.2000, the calculated decreases in ozone concentration at an altitude of 75 km were 14 and 30 %, respectively. The results indicate a potentially significant effect of energetic electrons on atmospheric chemistry.

The development of numerical global models of the ionosphere, ozonosphere, temperature regime and circulation for altitudes up to 130 km continued at the CAO (Krivolutsky et al. 2021).

Using calculations of the climate model of the Marchuk Institute of Numerical Mathematics (INM) of the RAS from 2015 to 2100 for moderate and severe scenarios of the increase in greenhouse gas concentrations (SSP2-4.5 and SSP5-8.5), a possibility of an increase in air masses with temperatures sufficient for the formation of polar stratospheric clouds of the 1st type (PSC NAT) in the 2nd half of the XXI century was shown. A stronger increase was revealed under the SSP5-8.5 scenario. Such an increase may lead to significant ozone depletion in certain winter seasons [Vargin et al., 2022].

Analysis of ensemble calculations of the SOCOLv4 chemical and climatic model for future climate conditions according to the SSP2-4.5 and SSP5-8.5 scenarios shows that in the 2nd half of the XXI century winters are likely to occur with negative anomalies of total ozone content close to 100 DU. in March in the Arctic (8 such winters were revealed), which is comparable to the anomalies observed in 2011 and 2020 [Vargin et al., 2023]. An increase in the isolation of the stratospheric polar vortex and an increase in the volume of air masses are revealed, with temperatures sufficient for the formation of the PSC NAT that are necessary for activation of ozone-depleting compounds in March; this is indicative of intensification of the vortex at the end of the winter season by the end of the XXI century and possible severe destruction of the ozone layer, despite a decrease in the content of ozone-depleting compounds in the atmosphere.

On the whole, the results suggest that the evolution of stratospheric ozone over the XXI century will be largely determined not only by a decrease in halogen concentrations, but also by future greenhouse gas emissions (and associated circulation changes). Therefore, although the problem of anthropogenic halogen emissions has been brought under control today, future ozone changes on a global and regional scale are still unclear and largely dependent on future human activities.

Using temperature and ozone data from OMI/MLS instruments installed on the Aura satellite (USA), a study of the features of the ozone anomaly in the Arctic in spring 2020 was conducted [Bazhenov 2021].

A comparison of the specific features of changes in the ozone layer in winter seasons, with the most dramatic ozone destruction observed in the winter seasons of 2010-2011 and 2019-2020, was performed using TEMIS and OMI/MLS data [Bazhenov 2022]. A detailed correlation analysis showed that deviations of water vapor and ozone concentrations, water vapor and temperature, ozone and temperature from the long-term means correlated better in 2020 than in 2011. The correlations diminished towards the periphery of the vortex due to the exchange of air masses between the Arctic and middle latitudes, and became of little significance outside the Arctic Circle.

Also, based on the OMI/MLS satellite data, the dependence between the content of ozone and chlorine oxide was revealed. The close correlation of the fluctuations of these parameters at approximately the same heights, as well as between the total content of O_3 and ClO calculated from the profiles of these parameters, indicates their close relationship. Therefore, the concentration and total content of ClO can be used as indicators of ozone depletion in the Arctic stratosphere [Bazhenov 2023].

CAO specialists, jointly with their colleagues from St. Petersburg State University and Kazan Federal University, investigated the peculiarities of the Arctic stratosphere circulation and their impact on the troposphere and the state of the ozone layer during the winter seasons of 2020-2021 [Vargin et al., 2021] and 2021-2022 [Vargin et al., 2022].

Using five 50-year calculations of the INM RAS climate model for present-day climate conditions, the influence of surface temperature anomalies in the equatorial and northern Pacific on the stability of the stratospheric polar vortex in the Arctic was studied [Vargin et al., 2021]. It is shown that winter seasons with El Niño events are characterized by higher temperatures of the Arctic stratosphere compared to seasons with La Niña. Winter seasons with positive temperature anomalies in the North Pacific correspond to lower temperatures of the Arctic stratosphere compared to seasons with negative anomalies.

The first ever full-scale measurements of the center of the atmospheric ozone intrinsic emission line near 110.836 GHz, with record-high accuracy (~12 kHz), were carried out [Kulikov et al., 2023]. Processing of the long-term series of brightness temperature spectra has made it possible to determine the central frequency of the line to be 110,835,909 ± 0.016 MHz. It is shown that the Doppler frequency shift by the horizontal wind, as well as variations in tropospheric absorption, do not affect the result obtained. The value obtained is 130 kHz less than that measured in the laboratory and differs considerably from the calculations of modern models, but is close to the results of early semi-empirical calculations conducted more than 40 years ago. The ozone transition frequency J = 61.5 - 60.6 obtained can be used as a reference point for the creation of new microwave equipment aimed at measuring the ozone profile and the zonal wind profile in the mesopause region as well as testing modern semi-empirical and quantum chemical methods and models.

The quality of the retrieval of the daily distributions of O, H, OH, NO_2 and the rate of chemical heating at 77-100 km altitudes was analyzed based on the long-term (2003-2015) database of SABER/TIMED satellite measurements using the photochemical equilibrium condition of daytime ozone [Kulikov et al., 2022a]. It was found that the generally accepted rejection of $H + O_3 \rightarrow OH + O_2$ reaction in this condition leads to underestimation (up to 35-40%) of O concentration of and chemical heating and significant overestimation (up to ~50-85%) of HO_2 and OH.

An improved model of excited OH with constants corresponding to published data was used to reconstruct the daily distributions of O, H, OH, NO_2 from the same SABER/TIMED data [Kulikov et al., 2022b]. It was found that changing the parameters of the recovery procedure leads (1) to a noticeable (up to 80%) increase in the concentration of O below 85-86 km, (2) to a significant (up to 170%) increase in concentrations of H, OH, and NO_2 below 90 km and a noticeable (up to 40%) decrease near 100 km.

A nonlinear photochemical response to diurnal variations in solar illumination at the second subharmonic of this effect was first experimentally recorded in the Earth's atmosphere [Kulikov et al., 2021]. As a result of a theoretical study of two-day photochemical oscillations in the evolution of components of the odd oxygen families Ox (O, O(1D), O3) and hydrogen HOx (H, OH, HO_2) at mesopausal altitudes (80-90 km), indicators of the presence of this phenomenon in rocket and satellite sensing data were determined using models of varying complexity. The most pronounced feature of these oscillations is a significant (by several orders of magnitude) difference between two consecutive values of H concentration at the end of the night. The necessary conditions for the manifestation of these oscillations in the H profile before sunrise are certain restrictions on the lifetime of the family of NOx and O at these local time moments. The processing of SABER/TIMED satellite data has made it possible to obtain the first experimental evidence of the existence of two-day photochemical oscillations at mesopause heights.

A modified derivation of the criterion for the chemical equilibrium of night ozone (CRNO) in the mesopause region is presented [Kulikov et. al., 2023a]. According to the calculations of the 3D chemical transport model, the improved criterion reproduces the lower bound of this equilibrium much better than its earlier version. Processing of 2021 SABER/TIMED satellite sensing data shows that the modified criterion raises the CRNO boundary by ~0.1–1.7 km, depending on latitude and season. In addition, a general theory of the photochemical/chemical equilibrium of chemically active minor atmospheric species is presented and a cascade of conditions is strictly mathematically derived, showing that a particular species must be near its instantaneous equilibrium value. The proposed method of determining the state of chemical equilibrium is of a general nature and can be used to analyze the equilibrium of a lot of minor gaseous species of the stratosphere and troposphere and used in various practical applications.

Based on the results of three-dimensional chemical transport modeling of the mesopause region (80-100 km), a simple and practical characteristic is proposed that allows tracking the altitude position of the transition zone which separates fundamentally different modes of behavior of photochemistry of Ox-HOx components; its variations largely determine the variability of many physico-chemical phenomena at these heights, e.g., atmospheric luminescence of oxygen and hydroxyl excited states. Analysis of the global long-term evolution of the night ozone equilibrium boundary, based on 2002-2021 SABER/TIMED satellite sensing data, has found this characteristic to be a sensitive indicator of the dynamics of the mean atmosphere with different spatial and temporal scales. In particular, it is sensitive to the SSW and elevated (up to ~80 km) stratopause phenomena; in its annual variations at low and middle latitudes, a clear (with an anticorrelation coefficient close to -1) signal of the 11-year solar cycle is observed.

The results of ground-based microwave measurements of the evolution of the vertical ozone content in the middle atmosphere over Nizhny Novgorod (NN) (56°20' N, 44° E) in the winter of 2017-2018 were obtained [Belikovich et al., 2021]. They were compared with the data of the MLS/Aura satellite instrument and those of the ERA5 reanalysis. The degree of the ozone content dependence in the stratosphere on the position of the polar vortex boundary, relative to the observation point at different altitudes, was established. Starting from January 2018, the vortex approached NN, and further on until its collapse (on February 12), its boundary had been oscillating over the city, so that different high-altitude echelons alternately appeared either inside or outside the vortex. Such vortex dynamics most noticeably influenced the evolution of the stratospheric maximum of ozone content, whose position followed the change in the vortex boundary and quasi-periodically varied in an altitude range of 30-35 km. The results of ground-based microwave sensing, on average, give a lower relative ozone content than the MLS data, with a maximum systematic difference of ~0.8 ppm per 38-39 km. Nevertheless, ground-based measurements recorded a clearer ozone response to changes in the vortex structure over NN than in the case of satellite and reanalysis data.

In 2021-2023, the Hydrometeorological Center of Russia (HCR) carried out work on modeling pollutants, using chemical transport models (HTM) [Kuznetsova et al., 2022a,b] and on the use of machine learning methods to correct numerical forecasts of ground-level ozone with a discreteness of 1 hour [Borisov, Kuznetsova 2023]. The time and quantitative changes in atmospheric emissions of pollutants, used in the calculation of HTM in the EMER cadastre [Borisov et al., 2023], were analyzed. The technology is being employed, and daily calculations of the concentration fields of pollutants, including ground-level ozone, are carried out for 48 hours ahead for Moscow region, based on two HTMS - CHIMERE and COSMO-Ru2ART, with a horizontal grid pitch of about 2 km [Kuznetsova et al., 2022b]. Quarterly data analysis of the automated ground-level ozone monitoring at the stations of the State Budgetary Institution "Mosecomonitoring" in Moscow is fulfilled. The results of the analysis are included in the quarterly reviews "Ozone content over the territory of the Russian Federation" published in the journal "Russian Meteorology and Hydrology".

Specialists of the HCR participated in the preparation of the review "Tropospheric ozone concentration in Russia in 2022" published in the journal "Optics of the Atmosphere and Ocean" [Andreev et al., 2023].

A study of 2014-2021 ozone variations over Obninsk, Kaluga region, was fulfilled. Ozone variations in three layers at 13-18, 18-23 and 23-30 km altitudes were considered based on lidar and satellite measurements. In the lower stratosphere, at 13 to 23 km, maximal ozone content is observed in winter and spring, while in the overlying 23-30 km layer it occurred in summer. A statistical regression analysis of the deviations of ozone content from the seasonal variation was carried out. It was revealed that the influence of different factors on ozone varies depending on the season and the height of the layer. For a 23-30 km layer in the I and II quarters and a 18-23 km layer in the I quarter, ozone concentration increased in the eastern phase of the QBO. In the II quarter, ozone concentration in the 13-18 km layer increased in the western phase of the QBO. Ozone depletion in the PSC region in the winter-spring period has a noticeable effect on ozone variations. The time-delayed effect of PSC and QBO is found in the IV quarter in 13-18- and 18-23 km layers. In the III quarter, ozone variations were found to be related to the AO index. This indicates that the influence of the vertical movements in the stratosphere associated with synoptic processes becomes noticeable at this time of the year. The negative effect of aerosol on ozone is manifested in the III and IV quarters, when aerosol content in the lower stratosphere increases. The results obtained are generally consistent with the current knowledge about the dynamic and microphysical mechanisms that determine ozone content in the stratosphere of middle latitudes.

At the Russian Federation State Hydrometeorological University (RSMU) in St. Petersburg, research on the ozone layer is carried out, using the chemical and climatic model (CCM) of the ozonosphere developed at the University in collaboration with the Marchuk Institute of Numerical Mathematics of the RAS. The model takes into account the variability of 74 chemically active atmospheric gases which, in a varying degree, affect the variability of ozone content, as well as dynamic and radiative processes affecting ozone transport in the atmosphere.

In 2021-2023, the RSMU carried out investigations of the factors that had determined the periodic formation of areas with low ozone content in the Arctic in the spring of 2020 [Smyshlyaev et al., 2021], of the causes of total ozone content variability in St. Petersburg area [Nerobelov et al., 2022], as well as the influence of the ocean surface temperature variability on the Arctic ozone content [Jakovlev et al., 2023], using the CCM of the ozonosphere.

V.L. Talrose Institute of Energy Problems of Chemical Physics of N.N. Semenov Federal Research Center for Chemical Physics of the RAS has obtained the following results:

- estimates of changes in biologically active UV radiation at the end of the XXI century as compared to 1980, including data related to the formation of erythema and vitamin D in humans, have been obtained; it has been shown that the parameters of biologically active radiation may change by the end of the 21st century as compared to 1980, but pose no significant threat to human health [Larin 2023];

- using the interactive two-dimensional SOCRATES model for the conditions of June and January 2020, at 50° N in an altitude range of 50-90 km, data on the rate of ozone depletion in the catalytic cycles of Ox, HOx, NOx, ClOx, and BrOx in the mesosphere as well as data on the length of the reaction chains in HOx, NOx, ClOx and BrOx cycles have been acquired [Larin 2022].

- using the interactive two-dimensional SOCRATES model and one-dimensional ATMO model for the conditions of June and January 2000, at 50° N in an altitude range of 0-50 km, data on the length of the reaction chains in the ClOx, BrOx and IOx catalytic cycles of ozone depletion have been are obtained and presented [Larin 2022];

- using the SOCRATES model, estimates of changes in the chemical composition of the high-latitude middle atmosphere of the Northern Hemisphere, including the troposphere, stratosphere, and mesosphere, for the 21st century are obtained; it is shown, in particular, that for June 2100, compared to June 2000, the relative change (in %) in the total content of the components of ClO_x family in the stratosphere would be -57.5%, +4.0% for O_x family, – 25.7% for BrO_x, + 13.9% for NO_x, and – 4.1% for HO_x families. In January, the corresponding data for ClO_x was -59.1%, for O_x – +7.3%, for BrO_x – -26.2%, for NO_x – +7.1% and for HO_x – -3.6% [Larin 2022];

- estimates of the global warming effect on the ozone layer and the intensity of midday surface UV radiation for 2100 compared with 2000 were obtained; changes in the ozone layer were calculated for 50° N, January and June, using a one-dimensional photochemical model and the SOCRATES model. It is shown that during the transition from 2000 to 2100, the upper level of UV radiation in January, as a result, diminishes by 3.49% and 5.66% under scenarios RCP 4.5 and RCP 6.0, respectively; in June, it decreases by 1.88% and 3.40% under scenarios RCP 4.5 and RCP 6.0, respectively [Larin 2021].

4. Dissemination of results

The data of systematic measurements of total ozone, ground-level UV irradiation, as well as information about maximal values of UV index from Obninsk station are archived and stored in the database of SPA "Typhoon". Measurement results are regularly transmitted to the World Data Center (WOUDC) in Canada and provided to the Russian Federation Hydrometcenter to be used in the work under Roshydromet programs.

The data of systematic lidar measurements of ozone concentration at altitudes between 12 and 35 km from Obninsk station are archived and stored in the database of SPA "Typhoon".

Every year, analytical materials are submitted by the Voeikov Main Geophysical Observatory (MGO) for the annual review of the state and pollution of the environment and the annual report on climate peculiarities on the territory of the Russian Federation. Conventionally, the materials reflect the features of the ozone layer state during the year as well as long-term trends and variations of total ozone content for the territory of the Russian Federation. Information about the fluid and its impact is published at http://voeikovmgo.ru

Daily measurement data on UV-B radiation with midday values from 12 stations of Roshydromet are transmitted to the Hydrometeorological Center of Russia, Central Aerological Observatory, and Roshydromet.

Total ozone data from the Russian Antarctic stations is transmitted in real time to the WMO for publication in the bulletins on the state of the ozone layer in Antarctica: http://www.wmo.int/pages/prog/arep/gaw/ozone/index.html

4.1. Presentation of observation data

The data of observations from the stations using ozonometer M-124 is transmitted in real time to CAO, MGO, and HCR. Operationally, this data is downloaded, archived, and transmitted to WOUDC. Together with the data from other countries it is used there for daily representation of total ozone fields. At CAO, maps of TCO distribution over the territory of Russia and the neighboring countries are operationally builds, anomalies are revealed, and the causes of their occurrence are analyzed. In the case of significant anomalies in TCO and UV radiation fields, CAO promptly informs Roshydromet about the events. At MGO, the data undergoes more thorough quality control resulting in conclusions about the quality of performance of separate instruments and stations and subsequent correction of the data, followed by the corrected data transmission to WOUDC.

Also regularly transmitted to WOUDC are TCO and UV radiation data obtained with Brewer spectrophotometer at the stations of Kislovodsk and Obninsk.

The data from systematic measurements of total ozone, ground-level UV irradiation, maximal values of UV index at the station of Obninsk are archived and stored in the database of the SPA "Typhoon".

The data are regularly transmitted to WOULDS (Canada), and is also provided to the Russian Federation Hydrometcenter to be used in the realization of the Roshydromet programs.

The data of systematic lidar measurements of ozone concentration at altitudes between 12 and 35 km from Obninsk station are archived and stored in the database of SPA "Typhoon".

The data of regular measurements of total ozone and NO_2 in the vertical atmospheric column in St. Petersburg, since 2004, using a spectrophotometer developed on the basis of the domestic scanning monochromator MDR-12 (LOMO), is available at http://troll.phys.spbu.ru/Personal_pages/ionov/welcome.html.

The data of regular measurements (since 2009) of the vertical profiles and total content of ozone and related gases: Hcl, HF, $ClONO_2$, HNO_3, CFC-11, CFC-12, HCFC-22, fulfilled with a Fourier spectrometer, produced by Bruker IFS 125HR, at the station of NDACC in St. Petersburg, is readily available at the site https://www-air.larc.nasa.gov/missions/ndacc/data.html.

The measurement data on NO_2 content in the stratospheric column and atmospheric boundary layer, obtained at Zvenigorod research station of Obukhov Institute of Atmospheric Physics, is regularly transmitted to NDACC and is readily available at http://www.ndacc.org.

4.2. Public information

Quarterly reviews with the current analyses of the ozone layer state over Russia are published in the journal "Russian Meteorology and Hydrology" (with English language version by Springer).

Similar information is published in the annual Reports on the peculiarities of climate on the territory of the Russian Federation and Reviews of the state and pollution of the environment in the Russian Federation, prepared by Roshydromet.

Forecasts of the high values of UV index for the current and the following day, indicating the territory with a hazardous event and recommending protective measures to be taken by various groups of the population are available at the site of the HCR (http://meteoinfo.ru).

4.3 Related scientific publications

Reviews of scientific publications:

Andreeva V.V., Bazhenov O.E., Belan B.D., Vargin P.N., Gruzdev A.N., Elansky N.F., et al. Russian Studies of Atmospheric Ozone and Its Precursors in 2019–2022. – *Izvestiya, Atmos. Oceanic Phys.*, 2023, V. 59, Suppl. 3, pp. S439–S463.

Larin I.K. History of ozone. Moscow. Russian Academy of Sciences, 2022. 478 p. [in Russian] https://new.ras.ru/work/publishing/monographs/istoriya-ozona/

Research publication (original papers):

1. Akishina S.V., Polykov A.V., Virolainen Y.A. Investigation of HCl and HF content in atmosphere by ground based IR Fourie spectroscopy. - *Proc. Inter. Symp. on Atmospheric Radiation and Dynamics (ISARD-2023)*, St.-Petersburg, p. 158-161, 2023a [in Russian]

2. Akishina S.V., Polykov A.V., Virolainen Y.A. Measurements of halogen-containing gases in the atmosphere at the NDACC station St. Petersburg. - *Proc. Conf. "Problems of Geokosmos-2022"*, St.-Petersburg, p. 136–144. DOI 10.53454/978598620_136. – EDN EWSOAR., 2023b [in Russian]

3. Andreev V.V., Arshinov M.Yu., Belan B.D., et al. Surface Ozone Concentration in Russia in the Second Half of 2020. – *Atmos. Oceanic Optics*, 2021, V. 34, No. 4. pp. 347–356

4. Andreev V.V., Arshinov M.Yu., Belan B.D., et al. Tropospheric Ozone Concentration on the Territory of Russia in 2021. – *Atmos. Oceanic Optics*, 2022, V. 35. No. 06. pp. 741–757.

5. Andreev V.V., Arshinov M.Yu., Belan B.D. et al. Tropospheric Ozone Concentration in Russia in 2022 – *Atmos. Oceanic Optics*, 2023, V. 36. No. 6. pp. 741. DOI: 10.1134/S1024856023060040

6. Bazhenov O. E. Chlorine oxide as an indicator of ozone destruction in the winter-spring stratosphere of the Arctic according to satellite (Aura MLS) observations – *Atmos. Oceanic Optics, 2023,* V.36, No 11. p. 904–909. DOI: 10.15372/AOO20231105. [in Russian]

7. Bazhenov O.E., Nevzorov A. B., Smirnov S. V., Elnikov A.B., Loginov V. A. Comparison of ground based and satellite total column ozone over Tomsk from 2006 to 2020 – *Atmos. Oceanic Optics.* 2023. V. 36. No 2. p. 111–115. DOI: 10.15372/AOO20230205. [in Russian]

8. Bazhenov O.E., Nevzorov A.A., Nevzorov A.V., Dolgii S.I., Makeev A.P. Disturbance of the Stratosphere over Tomsk prior to the 2018 Major Sudden Stratospheric Warming: Effect of ClO Dimer Cycle – *Optical Memory and Neural Networks*. 2021. V. 30. N. 2. P. 146–1156. https://doi.org/10.3103/S1060992X21020065

9. Bazhenov O. E. Ozone Anomaly during Winter–Spring 2019–2020 in the Arctic and over the North of Eurasia Using Satellite (Aura MLS/OMI) Observations. – *Atmos. Oceanic Optics*. 2021. V.34. No.6. P.P. 653-658. DOI: 10.1134/S102485602106004X

10. Bazhenov O.E., Ozone Anomalies in the Stratosphere of the Arctic and North Eurasia: Comparison of the 2011 and 2020 Events Using TEMIS and Aura MLS Data. – *Atmos. Oceanic Optics*, 2022, V. 35, No. 5, pp. 517–523. DOI: 10.1134/S1024856022050086;

11. Belan B. D., Ivlev G. A., Kozlov A. V., Pestunov D. A., Sklyadneva T. K., Fofonov A. V. Solar Radiation Measurements at the Fonovaya Observatory: Part I: Methodical Aspects and Specifications. – *Atmos. Oceanic Optics*. 2023. V. 36. No. 1. P. 47–53. DOI: 10.1134/S1024856023020045.

12. Belan B.D., Ivlev G.A., Sklyadneva T.K. The Relationship of Ultraviolet Radiation, Meteorological Factors and Atmospheric Turbidity: Part II–Role of Surface Albedo. – *Atmos. Oceanic Optics*. 2021. V. 34. No. 2. P. 128–133. DOI: 10.1134/S1024856021020020

13. Belan B. D., Ivlev G. A., Kozlov A.V., et al. Solar Radiation Measurements at the Fonovaya Observatory: Part II: Results from 2021 Measurements. – *Atmos. Oceanic Optics*. 2023. V. 36. No. 1. P. 54–60. DOI: 10.1134/S1024856023020057

14. Belan B.D., Ancellet G., Andreeva I.S., et al. Integrated airborne investigation of the air composition over the Russian sector of the Arctic. – *Atmos. Meas. Tech.*, 2022, v.15, No 13, p.3941–3967.

15. Belikovich M.V., Ryskin V.G., Kulikov M.Yu., Krasilnikov A.A., Shvetsov A.A., Feigin A.M. Microwave observations of atmospheric ozone over Nizhny Novgorod in winter of 2017-2018. – *Radiophysics and Quantum Electronics*, V. 63, p.191–206, https://doi.org/10.1007/s11141-021-10045-3, 2021.

16. Bordovskaya, Y.I., Timofeyev, Y.M., Poberovsky, A.V. et al. Analysis of the Ground-Based Microwave Method for Measuring the Ozone Vertical Profile. - *Atmos. Oceanic Optics*. 2023. V. 36. P. 512–516. https://doi.org/10.1134/S1024856023050196

17. Bordovskaya Yu.I., Virolainen Ya.A., Timofeyev Yu.M. Comparison of ground-based and satellite methods for determining vertical ozone profiles. - *Sovremennye Problemy Distantsionnogo Zondirovaniya Zemli iz Kosmosa*, 2022, V. 19, No. 2, P. 225-231, doi: 10.21046/2070-7401-2022-19-2-225-231 [In Russian].

18. Borisov D.V., Kuznetsova I.N. Postprocessing numerical forecasts of ground-level ozone concentrations using machine learning. - *Hydrometeorological Research and Forecasting*. 2023. No 4 (390). p. 86-104. DOI: https://doi.org/10.37162/2618-9631-2023-4-86-104 [In Russian].

19. Borisov D.V., Kuznetsova I.N., Nakhaev M.I. Changes in cadastral data on emissions of pollutants into the atmosphere in the Moscow region. - *Hydrometeorological Research and Forecasting*. 2023. No 2 (388). p. 156-173. DOI: https://doi.org/10.37162/2618-9631-2023-2-156-173 [In Russian].

20. Cooper A., Turney C., Palmer J., Hogg A., McGlone M., Wilmshurst J., et al. Response to Comment on "A global environmental crisis 42,000 years ago". Science. 2021, 374 (6570): eabi9756. doi: 10.1126/science.abi9756. Epub 2021 Nov 18. PMID: 34793203.

21. Chan K. L., Valks P., Heue K.-P., Lutz R., Hedelt P., Loyola D., et al. Global Ozone Monitoring Experiment-2 (GOME-2) Daily and Monthly Level 3 Products of Atmospheric Trace Gas Columns. – *Earth Syst. Sci. Data Discuss.* 2022, doi:10.5194/essd-2022-315.

22. Chan, K. L., Valks, P., Heue, K.-P., Lutz, R., Hedelt, P., et al. Global Ozone Monitoring Experiment-2 (GOME-2) daily and monthly level-3 products of atmospheric trace gas columns, *Earth Syst. Sci. Data*, 2023, 15, 1831–1870, doi:10.5194/essd-15-1831-2023.

23. Chubarova N.E., Rosental V.A., Zhdanova E.Yu., Poliukhov A.A. New radiation complex at the Moscow State University meteorological observatory of the BSRN standard: methodological aspects and first measurement results. – *Atmos. Oceanic Optics*, 2022, v.35, 8, p.670-678, DOI: 10.15372/AOO20220811

24. Chubarova N., Nezval' Y., Zhdanova Y. Trends and causes of long-term changes in erythemal UV irradiance and UV 300-380 nm in Moscow, Russia. – *AIP Conf. Proc.* 18 January 2024; 2988 (1): 090009. https://doi.org/10.1063/5.0182777

25. Davydova M.A., Elansky N.F., Zakharova S.A., Postylyakov O.V. Application of a Numerical-Asymptotic Approach to the Problem of Restoring the Parameters of a Local Stationary Source of Anthropogenic Pollution. *Doklady Mathematics, 2021, Vol. 103, No. 1, 26–31. doi: 10.1134/S1064562421010026)*

26. Dolgii S.I., Nevzorov A.V., Nevzorov A.A., Gridnev Yu.V., Romanovskii O.A., Kharchenko O.V. Influence of Absorption Cross-Sections on Retrieving the Ozone Vertical Distribution at the Siberian Lidar Station. – *Atmosphere*. 2022. V.13. Issue 2. P. 293. https://doi.org/10.3390/atmos13020293

27. Egorova, T., Sedlacek, J., Sukhodolov, T., Karagodin-Doyennel, A., Zilker, F., Rozanov, E. Montreal Protocol's impact on the ozone layer and climate. – *Atmos. Chem. Phys.*, 2023, V. 23, p. 5135–5147, https://doi.org/10.5194/acp-23-5135-2023.

28. Gaikovich K.P., Kropotkina E.P., Rozanov S.B. Statistical analysis of 1996-2017 ozone profile data obtained by ground-based microwave radiometry. - *Remote Sensing*, 2020, V.12, No.20, p. 3374; DOI: 10.3390/rs12203374.

29. Gaikovitch K.P., Kropotkina E.P., Rozanov S.B. Statistical parameters of the ozone profile over Moscow and their trends in 1996-2017 according to radiometric measurements – *J. Radioelectronic*, 2021, No 8, https://doi.org/10.30898/1684-1719.2021.8.14 [in Russian]

30. Grankin D., Mironova I., Bazilevskaya G., Rozanov E., Egorova T. Atmospheric Response to EEP during Geomagnetic Disturbances. – *Atmosphere*, 2023, V. 14, 273. https://doi.org/10.3390/atmos14020273.

31. Józefiak I., Sukhodolov T., Egorova T., Chiodo G., Peter T., Rieder H., Sedlacek J., Stenke A., Rozanov E. Stratospheric dynamics modulates ozone layer response to molecular oxygen variations. –*Front. Earth Sci.*, 2023, 11:1239325. doi: 10.3389/feart.2023.1239325

32. Ionov, D.V., Privalov, V.I. The Differential Spectroscopy Technique DOAS in the Problem of Determining the Total Ozone Content from Measurements of Ground-Based UV Spectrometer UFOS. - *Atmos. Oceanic Optics*, 2022, V. 35, P. 1–7. https://doi.org/10.1134/S1024856022010079

33. Ivanova, N.S. A Model of Mean Long-term Values of Atmospheric Aerosol Optical Depth at a 354 nm Wavelength in Russia in the Warm Season. – *Russ. Meteorol. Hydrol.* 2023, V.48, p.210–220. https://doi.org/10.3103/S1068373923030032

34. Ivanova N.S., Kruchenitsky G.M., Kuznetsova I.N., Shalygina I. Ju., Lezina E.K. Ozone Content over the Russian Federation in 2020. - *Rus. Meteor. Hydrol.*, 2021, V. 46 (2), p. 129-137 doi: 10.3103/S1068373921020084 [in Russian]

35. Ivanova N.S., Shalygina I. Ju., Lezina E.K. Ozone Content over the Russian Federation in 2021. - *Rus. Meteor. Hydrol.*, 2021 V. 46. No. 11. P. 136-142 [in Russian]

36. Ivanova N.S. A Statistical Model of Winter/Spring Polar Ozone. -*Russ. Meteor. Hydrol.*, 2021, V. 46 (5), p. 295-301, DOI: 10.3103/S1068373921050022

37. Ivanova N.S., Kuznetsova I.N., Lezina E.K. Ozone Content over the Russian Federation in 2022. - Rus. Meteor. Hydrol., 2023, V. 48 (2), p. 179-187, DOI: 10.3103/S1068373923020115 [in Russian]

38. Ivanov V.N., Zubachev D.S., Korshunov V.A., Sakhibgareev D.G. Network lidar AK-3 for sensing the middle atmosphere: device, measurement methods, results. - *Proc. of Voeykov Main Geophysical Observatory*, Sankt-Petersburg, 2020. Is. 598. p.155-187. [in Russian]

39. Jakovllev A. R. Smyshlyaev S.P. The Impact of the Tropical Sea Surface Temperature Variability on the Dynamical Processes and Ozone Layer in the Arctic Atmosphere, *Meteorology, preprint*, DOI: 10.20944/preprints202311.1229.v1, 2023

40. Korshunov V.A. Stratospheric Ozone Content Variations Over the City of Obninsk from Data of Lidar and Satellite Measurements. - *Izvestiya, Atmos. Oceanic Phys.*, 2023, V. 59, No. 5, p. 585–594

41. Kotelnikov S.N., Stepanov E.V. Anomalous dynamics of ozone content in the troposphere in the spring of 2020 in central Russia – Brief communications on Physics, *Lebedev Physical Institute*. 2021. V. 48. No 3. p. 44-51 [in Russian]

42. Krivolutskii. A.A., Vyushkova, T.Y., Cherepanova, L.A. *et al.* Numerical Global Models of the Ionosphere, Ozonosphere, Temperature Regime, and Circulation for Altitudes of 0–130 km: Results and Prospects. *Russ. Meteorol. Hydrol.* 2021, V. 46, p. 596–605. https://doi.org/10.3103/S1068373921090053

43. Kulikov M.Yu., Krasil'nikov A.A., Belikovich M.V., Ryskin V. G., Shvetsov A.A., Skalyga N.K., Kukikn L.M., Feigin A.M. High precision measurements of resonance frequency of ozone rotational transition J = $6_{1,5}$ - $6_{0,6}$ in the real atmosphere. – *Remote Sensing*, 2023, V. 15, 2259. https://doi.org/10.3390/rs15092259.

44. Kulikov M.Yu., Belikovich M.V., Grygalashvyly M., Sonnemann G.R., Feigin A.M. Retrieving daytime distributions of O, H, OH, HO2, and chemical heating rate in the mesopause region from satellite observations of ozone and OH* volume emission: The evaluation of the importance of the reaction H+O3 ->O2+OH in the ozone balance. – *Adv. Space Res.*, 2022a, V. 69 (9), p. 3362-3373. https://doi.org/10.1016/j.asr.2022.02.011

45. Kulikov M.Y., Belikovich M.V., Grygalashvyly M., Sonnemann G.R., Feigin A.M. The revised method for retrieving daytime distributions of atomic oxygen and odd-hydrogens in the mesopause region from satellite observations. – *Earth, Planets and Space*, 2022b, 74, 44. https://doi.org/10.1186/s40623-022-01603-8

46. Kulikov M.Y., Belikovich M.V., Feigin A.M. The 2-day photochemical oscillations in the mesopause region: the first experimental evidence? – *Geophys. Res. Lett.*, 2021, V. 48. e2021GL092795. https://doi.org/10.1029/2021GL092795.

47. Solomatnikova A.A., Volokhina D. Y., Jukova M.P. 2.3.3.1. Features of the state of the ozone layer over the regions of the Russian Federation – *Review of the state and pollution of the environment in the Russian Federation for 2021*, 2022, p. 36-39 [in Russian]
https://www.meteorf.gov.ru/product/infomaterials/90/?year=2021&ID=90

48. Solomatnikova A.A., Volokhina D.Y., Jukova M.P. State of the ozone layer over the Arctic regions of the Russian Federation – *Review of the state and pollution of the environment in the Russian Federation for 2021*, 2022, p. 182-183 ISBN 978-5-9631-0987 [in Russian]

49. Karagodin-Doyennel A., Rozanov E., Sukhodolov T., Egorova T., Saiz-Lopez A., Cuevas C., Fernandez P., Sherwen T., Volkamer R., Koenig T., Giroud T., Peter T. Iodine chemistry in the chemistry–climate model SOCOL-AERv2-I. – *Geosci. Model Dev.*, V. 14, p. 6623–6645, 2021. doi: 10.5194/gmd-14-6623-2021.

50. Karagodin-Doyennel A., Rozanov E., Sukhodolov T., Egorova T., Sedlacek J., Ball W., Peter T. The historical ozone trends simulated with the SOCOLv4 and their comparison with observations and reanalyses. – *Atmos. Chem. Phys.*, 2022, 23, 15333–15350. doi:10.5194/acp-22-15333-2022.

51. Karagodin-Doyennel A., Rozanov E., Sukhodolov T., Egorova T., Sedlacek J., Peter T. The future ozone trends in changing climate simulated with SOCOLv4. – *Atmos. Chem. Phys.*, V. 23, p. 4801–4817, https://doi.org/10.5194/acp-23-4801-2023, 2023.

52. Kulikov Yu.Yu., Kirillov A.S., Poberovskii A.V., Imchasin Ch.Ch. Microwave monitoring of middle atmosphere ozone in Apatity and Peterhof in the winter of 2021/2022. – *Russ. Meteor. Hydrol.*, 2022, v.47, No 12, p.969-975.

53. Kulikov Yu.Yu., Andriyanov A.F., Demin V.I., Demkin V.M., Kirillov A.S., Ryskin V.G., Shishaev V.A. Long-term microwave observations of middle atmospheric ozone in Apatity during three winters. – *Geomagnetism and Aeronomy*, 2023, v.63, No 5, p.608-619

54. Kulikov M.Yu., Belikovich M.V., Chubarov A.G., Dementeyva S.O., Fegin A.M. Boundary of nighttime ozone chemical equilibrium in the mesopause region: improved criterion of determining the boundary from satellite data. – *Adv. Space Res.*, 2023a, V. 71 (6), p. 2770-2780. https://doi.org/10.1016/j.asr.2022.11.005

55. Kulikov M.Yu., Belikovich M.V., Chubarov A.G., Dementeyva S.O., Fegin A.M. Boundary of nighttime ozone chemical equilibrium in the mesopause region: long-term evolution from 20-year satellite observations. – *Atmos. Chem. Phys.*, 2023b, V. 23, p. 14593–14608, https://doi.org/10.5194/acp-23-14593-2023

56. Kuznetsova I.N., Rivin G.S., Borisov D.V., Shalygina I.Yu., Kirsanov A., Nakhaev M.I. Modeling Surface Air Pollution with Reduced Emissions during the COVID-19 Pandemic Using CHIMERE and COSMO-ART Chemical Transport Models. - *Rus. Meteor. Hydrol.*, 2022a, V. 47, No. 3, p. 174–182. DOI: 10.3103/S1068373922030025

57. Kuznetsova I.N., Nakhaev M.I., Kirsanov A.A., Borisov D.V, Tkacheva Y.V., Rivin G.S., Lezina E.A. Testing and prospects of air pollution forecasting technology using chemical transport models CHIMERE и COSMO-Ru2ART. - *Hydrometeorological Research and Forecasting*, 2022b. No 4 (386), p. 147-170. DOI: https://doi.org/10.37162/2618-9631-2022-4-6-29 [in Russian]

58. Larin, I.K. On the Influence of Global Warming on the Ozone Layer and UV-B Radiation. – *Izv. Atmos. Ocean. Phys.* 2021, V. 57, p. 110–115. https://doi.org/10.1134/S0001433821010096

59. Larin I. K. Chemical Composition of the High Latitude of the Middle Atmosphere of the Northern Hemisphere and its Changes in the 21st Century. – *Russ. J. Physical Chemistry B*, 2022, V. 16, No. 3, p. 492-498 DOI: 10.1134/S1990793122030083

60. Larin, I.K. Chain Lengths of Haloid Catalytic Cycles of Ozone Destruction. – *Izv. Atmos. Ocean. Phys.* 2022, V. 58, p. 391–400. https://doi.org/10.1134/S0001433822040089

61. Larin, I.K. On Ozone Depletion in the Mesosphere. – *Izv. Atmos. Ocean. Phys.* 2022, V. 58, p. 150–157. https://doi.org/10.1134/S0001433822020074

62. Larin, I.K. Biologically Active UV Radiation in the 21st Century. – *Russ. J. Phys. Chem. B*, 2023, V. 17, p. 244–250. https://doi.org/10.1134/S1990793123010074

63. Lukyanov A.N., Vargin P.N., Yushkov V.A. Lagrange Studies of Anomalously Stable Arctic Stratospheric Vortex Observed in Winter 2019–2020. – *Izvestiya, Atmos. Ocean. Phys.* 2021, V. 57, No 3, p. 247-253. https://doi.org/10.1134/S0001433821030075

64. Mironova, I., M. Sinnhuber, G. Bazilevskaya, M. Clilverd, B. Funke, V. Makhmutov, E. Rozanov, M. Santee, T. Sukhodolov, and T. Ulich, Exceptional middle latitude electron precipitation detected by balloon observations: implications for atmospheric composition. – *Atmos. Chem. Phys.*, 2022,V. 22, p. 6703–6716. doi:10.5194/acp-22-6703-2022

65. Moiseenko K.B., Vasileva A.V., Skorokhod A.I., Shtabkin Yu.A., Belikov I.B., Repin A.Yu. Photostationary Equilibrium in the O_3–NO_x System and Ozone Generation According to ZOTTO Tall Tower Data. - *Atmos. Ocean. Opt.* 2022. V. 35, N S1. P. S125–S132. DOI: 10.1134/S1024856023010128.

66. Nerobelov G., Timofeyev Y., Virolainen Y., Polyakov A., Solomatnikova A., Poberovskii A., Kirner O., Al-Subari O., Smyshlyaev S., Rozanov E. Measurements and Modelling of Total Ozone Columns near St. Petersburg, Russia. - *Remote Sensing*, 2022a, V. 14, No. 16, P. 3944, doi: 10.3390/rs14163944

67. Nerobelov G., Al-Subari O., Timofeyev Yu.M., Virolainen Ya.A., Poberovskii A.V., Solomatnikova A.A. Comparison of Ground-Based Measurement Results of Total Ozone near St. Petersburg. - *Izvestiya, Atmos. Oceanic Phys.*, 2022b, V. 58, No. 5, P. 494–499, doi: 10.1134/S0001433822050073

68. Nerobelov G.M., Virolainen Y.A., Ionov D.V. Database of numerical modeling of ozone distribution in the troposphere of St. Petersburg and adjacent regions (TROPOZ) – *Certificate of state registration of databases*, 2023a, № RU 2023621780 от 01.06.2023 [in Russian]

69. Nerobelov G., Virolainen Y., Ionov D., Polykov A. WRF-Chem modeling of tropospheric ozone in the St. Petersburg region. – *Proc. International Symposium on Atmospheric Radiation and Dynamics (ISARD-2023)*, Sankt-Petersburg, p. 163–164. 2023b

70. Nerobelov G.M., Virolainen Y.A., Ionov D.V., Polykov A.V. Modeling of tropospheric ozone content in cities on the coast of the Gulf of Finland using WRF-Chem. - *Proc. 21th Inter. Conf. "Modern problems of remote sensing of the earth from space"*, Moscow, Institute of Space Research of RAS, 13-17.11.2023c [in Russian]

71. Nevzorov A.A., Nevzorov A.V., Kharchenko O.V., Makeev A.P. Development of mobile lidar system for monitoring of tropospheric ozone and aerosol. – *Proc. SPIE*. 2022. V.12341.

72. Nevzorov A.A., Nevzorov A.V., Kravtsova N.S., Kharchenko O.V., Romanovskii Ya.O. Mobile Lidar for Sensing Tropospheric Ozone. – *Atmos. Oceanic Optics*, 2023, V. 36. No. 05, p. 562. https://doi.org/10.1134/S1024856023050123

73. Nevzorov A. A., Nevzorov A. V., Nadeev A. I., Zaitsev N. G., Romanovsky Ya. O., Kharchenko O. V., Kravtsova N. S. Algorithm for processing data from lidar sounding of ozone in the atmosphere. – *J. Applied Spectroscopy*, V. 90, No. 4, 2023. DOI: 10.1007/s10812-023-01601-y

74. Petkov B. H., Vitale V., Di Carlo P., Drofa O., Mastrangelo D., Smedley A. R., Solomatnikova A.A., Pavlova K. G. et.al. An unprecedented Arctic ozone depletion event during spring 2020 and its impacts across Europe. – *J. Geophys. Res., Atmos.*, 2023, 128, e2022JD037581 https://doi.org/10.1029/2022JD037581

75. Polykov A.B., Virolainen Y.A., Nerobelov G.M., Timofeev Y.M., Krukovskikh E.P., Uspensky A.B., Kozlov D.A. Global Atmospheric Ozone Distribution Database (GLOBOZ). *Certificate of state registration of databases*, 2023, №RU 2023621767 от 01.06.2023

76. Polyakov A., Virolainen Ya., Nerobelov G., Timofeyev Yu., Solomatnikova A. Total ozone measurements using IKFS-2 spectrometer aboard Meteor M N2 satellite in 2019–2020. – *Int. J. Rem. Sens.*, 2021, V. 42, 22, p. 8709–8733, https://doi.org/10.1080/01431161.2021.1985741.

77. Polyakov A.V., Poberovsky A.V., Makarova M.V., Virolainen Y.A., Timofeyev Y.M., Nikulina A.L. Measurements of CFC-11, CFC-12, and HCFC-22 total columns in the atmosphere at the St. Petersburg site in 2009-2019. - *Atmos. Measurement Techniques*, 2021a, V. 14, No. 8, P. 5349–5368, doi: 10.5194/amt-14-5349-2021.

78. Polyakov A., Virolainen Y., Nerobelov G., Timofeyev Y., Solomatnikova A. Total ozone measurements using IKFS-2 spectrometer aboard Meteor-M N2 satellite in 2019–2020. - *Inter. J. Remote Sensing*, 2021b, V. 42, No. 22, P. 8709–8733, doi: 10.1080/01431161.2021.1985741

79. Polyakov A.V., Nikulina A.L., Poberovsky A.V., Kozlov D.A., Makarova M.V., Virolainen Y.A. Determination of Total Column of Trichlorofluoromethane in the Atmosphere Considering the Effect of Amorphous Water Ice Precipitation on the Spectrometer Detector. - *J. Applied Spectroscopy*, 2023a, V. 90, No. 1, P. 66–71, doi: 10.1007/s10812-023-01504-y]

80. Polyakov A., Virolainen Y., Nerobelov G., Kozlov D., Timofeyev Y. Six years of IKFS-2 Global Ozone Total Column Measurements. - *Remote Sensing*, 2023b, V. 15, No. 9, P. 2481, doi: 10.3390/rs15092481.

81. Yearbook "State of air pollution in cities in Russia for 2022", Voeykov Main Geophysical Observatory, 2023. http://voeikovmgo.ru/index.php/home/27-sobytiya/1168-ggo-opublikovan-ezhegodnik-sostojanie-zagrjaznenija-atmosfery-v-gorodah-na-territorii-rossii-za-2022-g [in Russian]

82. Rozanov S., Ignatyev A., Zavgorodniy A. Ground-based Microwave Measurements of Mesospheric Ozone Variations over Moscow region during the Solar Eclipses of 20 March 2015 and 25 October 2022. - *Remote Sensing*, 2023, V.15, No.15, p.3440; DOI: 10.3390/rs15133440.

83. Sedlacek J., Sukhodolov T., Egorova T., Karagodin-Doyennel A., Rozanov E. Future climate under CMIP6 solar activity scenarios. – *Earth Space Science*, 2023, 10, e2022EA002783. doi:/10.1029/2022EA0027830

84. Shapovalov S.N., Solomatnikova A.A., Ryabinin I.O. Monitoring of the UV-Index at the AARI polar stations, – ААНИИ, *Proc. Conf. «Solar and Solar-Earth Physics – 2023»,* p.357-360 https://doi.org/10.31725/0552-5829-2023-357-360 SSN 0552-5829 [in Russian]

85. Shishigin S.A. Model calculations of ozone content in the atmosphere based on the outgoing radiation of the Earth. - *Exploring the Earth from Space*, 2023, No 2, p. 84-92 [in Russian]

86. Smyshlyaev S.P., Vargin P.N., Motsakov M.A. Numerical modeling of ozone loss in the exceptional Arctic stratosphere winter-spring of 2020. – *Atmosphere*, 2021, 12, 1470, https://doi.org/10.3390/atmos12111470

87. Stepanov E.V., Andreev V.V., Konovaltseva L.V., Kasoev S.G. Surface Ozone in the Atmosphere of Moscow during the COVID-19 Pandemic. – *Atmos. Oceanic Optics*, 2022, V. 35. No. 6. p. 732–740.

88. Sukhodolov T., Egorova T., Stenke A., Ball W., Brodowsky C., Chiodo G. et al. Atmosphere-Ocean-Aerosol-Chemistry-Climate Model SOCOLv4.0: description and evaluation. – *Geosci. Model Dev.*, 2021, 14, p. 5525–5560, doi: 10.5194/gmd-14-5525-2021.

89. Timofeyev Yu.M., Nerobelov G.M., Polyakov A.V., Virolainen Ya.A. Satellite Monitoring of the Ozonosphere. - *Russ. Meteorol. Hydrol.*, 2021, V. 46, No. 12, p. 849–855, doi: 10.3103/S1068373921120062

90. Timofeyev Yu.M., Nerobelovu G.M., Kobzaru G.V. et al. New Technique for Satellite Observation Interpretation Based on Standard Ground-Based Measurements of the Total Ozone Column. - *Atmos. Oceanic Optics*, 2023, V. 36, P. 207–212. https://doi.org/10.1134/S1024856023030181

91. Tsvetkova N.D., Vargin P.N., Lukyanov A.N., Kirushov B.M., Yushkov V.A., Khattatov V.U. Investigation of chemistry ozone destruction and dynamical processes in Arctic stratosphere in winter 2019-2020. – *Russ. Meteor. Hydrol.*, 2021, 46, No 9, p. 597–606. https://link.springer.com/article/10.3103/S1068373921090065

92. Vargin P. N., Fomin B. A., Semenov V. A. Influence of ozone mini-holes over Russian territories in May 2021 and March 2022 revealed in satellite observations and simulation. – *Atmos. Oceanic Optics*. 2023. V. 36. No 4, p. 320–330. DOI: 10.15372/AOO20230409.

93. Vargin, P.N.; Kostrykin, S.V.; Volodin, E.M.; Pogoreltsev, A.I.; Wei, K. Arctic Stratosphere Circulation Changes in the 21st Century in Simulations of INM CM5. – *Atmosphere*, 2022, *13*, 25. https://doi.org/10.3390/atmos13010025

94. Vargin P., Kostrykin S., Koval A., Rozanov E., Egorova T., Smyshlyaev S., Tsvetkova N. Arctic stratosphere changes in the 21st century in the Earth system model SOCOLv4. – *Front. Earth Sci.*, 2023, 11:1214418. doi: 10.3389/feart.2023.1214418

95. Vargin P.N.., Guryanov V.V., Lukyanov A.N., Vyzankin A.S. Arctic stratosphere dynamical processes in the winter of 2020-2021. – *Izvestiya, Atmos. Oceanic Physics*. 2021, V. 57, No 6, p. 568-580. https://link.springer.com/article/10.1134/S0001433821060098

96. Vargin P.N., Koval A.V., Guryanov V.V. Arctic Stratosphere Dynamical Processes in the Winter 2021–2022. – *Atmosphere*. 2022, V. 13, 1550. https://doi.org/10.3390/atmos13101550

97. Vargin P.N., Kolennikova M.A., Kostrykin S.V., Volodin E.M. Influence of equatorial and north Pacific SST anomalies on Arctic stratosphere in INM RAS climate model simulations. - *Russ. Meteor. Hydrol.*, 2021, V. 46, No 1, p.1-9. https://doi.org/10.3103/S1068373921010015

98. Verhoelst T., Compernolle S., Pinardi G., Lambert J.-C., Eskes H. J., Eichmann K.-U., et al., Ground-based validation of the Copernicus Sentinel-5P TROPOMI NO_2 measurements with the NDACC ZSL-DOAS, MAX-DOAS and Pandonia global networks. – *Atmos. Meas. Tech.*, 2021, V. 14, p. 481–510, https://doi.org/10.5194/amt-14-481-2021

99. Virolainen Ya.A., Polyakov A.V., Timofeyev Yu.M. Analysis of the Variability of Stratospheric Gases Near St, Petersburg Using Ground-Based Spectroscopic Measurements. - *Izvestiya, Atmos. Oceanic Phys.*, 2021, V. 57, No. 2, P. 148–158, doi: 10.1134/S0001433821010138

100. Virolainen Ya. A., Yu. M. Timofeyev, A. V. Poberovsky, A. V. Polyakov. Information Content of the Ground-Based FTIR Method for Atmospheric HNO_3 Vertical Structure Retrieval. - *Atmos. Oceanic Optics*, 2023a, V. 36, No. 1, p. 24–29, DOI: 10.1134/S102485602302015X

101. Virolainen Y.A., Timofeyev Y.M., Polyakov A.V., Poberovsky A.V. Ground-Based FTIR Measurements of Atmospheric Nitric Acid at the NDACC St. Petersburg Site. - *Izvestiya, Atmos. Oceanic Phys.*, 2023b, V. 59, No. 2, p. 167–173, doi: 10.1134/S000143382302007X

102. Virolainen Ya.A., Ionov D.V., Polyakov A.V. Analysis of Long-Term Measurements of Tropospheric Ozone at the St. Petersburg State University Observational Site in Peterhof. - *Izvestiya, Atmos. Oceanic Phys.*, 2023c, V. 59, No. 3, p. 287–295, doi: 10.1134/S000143382303009X

103. Virolainen Ya.A., Nerobelov G.M., Polyakov A.V. Comparison of satellite and ground-based measurements of tropospheric ozone columns in the vicinity of St. Petersburg. - *Izvestiya, Atmos. Oceanic Phys.*, 2023d, V. 59, No. 4, P. 411–420, doi: 10.1134/S000143382304014X

104. Virolainen Y., Nerobelov G., Polyakov A., Akishina S. Comparison of satellite and ground-based measurements of tropospheric ozone. – *Proc. of SPIE, 29th Inter. Symp. on Atmos. and Ocean Optics: Atmospheric Physics*, 2023e, V. 12780, 127804X, doi: 10.1117/12.2688764.short

105. Virolainen Y., Polyakov A., Timofeyev Y., Poberovsky A. FTIR measurements of stratospheric gases at the St.Petersburg site. - *Springer Proc. in Earth and Environmental Sciences, ICS 2022: Problems of Geocosmos—2022*, 2023f, P. 43–53, doi: 10.1007/978-3-031-40728-4_4

106. Zakharova S., Davydova M., A. Borovski A., Shukurov K., Mukhartova Y., Makarenkov A., Postylyakov O. Experiments on high-detailed mapping of tropospheric NO_2 using GSA/Resurs-P observations: results, validation with models and measurements, estimation of emission power, - *Proc. SPIE 11859, 1185905, 2021; doi:10.1117/12.2600316*

5. PROJECTS, COLLABORATION, TWINNING AND CAPACITY BUILDING

(e.g., national projects, international projects, other collaboration (nationally, internationally))

6. IMPLEMENTATION OF THE RECOMMENDATIONS OF THE 10th OZONE RESEARCH MANAGERS MEETING (e.g., specifics on progress towards such implementation, difficulties encountered, near-term plans, etc.)

7. FUTURE PLANS

Further observations of the atmosphere state with measurements of TCO, other minor gas constituents, surface UV irradiation, and surface ozone concentration (SPA "Typhoon").

Currently, AK-3 lidars are installed at 7 Roshydromet sensing stations on the territory of the Russian Federation. It is planned to operate them and perform regular measurements.

St. Petersburg State University is developing a methodology to obtaining data on the ozone content in the troposphere layer, using the Russian satellite-borne instrument IKFS-2; in the near future, it is planned to study the space and time variability of tropospheric ozone on both global and regional scales in the period 2015 - 2022.

8. NEEDS AND RECOMMENDATIONS