

A Double Portrait: The Contributions G.S. Golitsyn and P.J. Crutzen Made to Studying the Physics and Chemistry of the Atmosphere

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Abstract—This is the introductory article for the special issue of *Izvestiya, Atmospheric and Oceanic Physics* dedicated to the 2019 Lomonosov Gold Medal of the Russian Academy of Sciences awarded to Academician Georgy Golitsyn “for making an outstanding contribution to the study of atmospheric physics of the Earth and planets and the development of the theory of climate and its changes” and to foreign member of the Russian Academy of Sciences Professor Paul Joseph Crutzen “for making an outstanding contribution to the chemistry of the atmosphere and assessing the role and biogeochemical cycles in climate formation.” This issue includes an article highlighting the contributions Golitsyn and Crutzen made to the study of physics and chemistry of the atmosphere, climate, and biogeochemical cycles, as well as articles written for this special issue with the participation or recommendation of the laureates.

Keywords: atmospheric physics and chemistry, biogeochemical cycles, climate and its changes

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INTRODUCTION

Portrait of the Laureates



These photos of Golitsyn and Crutzen were taken about ten years ago and clearly demonstrate the wise and inquisitive look of real scientists. The photo of

Golitsyn was taken by his daughter Anna in the Golitsyn house near Moscow (from the article “Golitsyn, Georgy Sergeevich” on the website

<https://ru.wikipedia.org/wiki/>) and the photo of Crutzen was taken at the University of Helsinki (https://en.wikipedia.org/wiki/Paul_J._Crutzen).

Academician Golitsyn and Professor Crutzen are practically the same age and both have achieved a worldwide recognition as outstanding scientists and important organizers of science over many decades of their successful work. The scientific community may be interested in comparing the life paths of the two laureates of the highest scientific award of the Russian Academy of Sciences.

Paul Josef Crutzen was born on December 3, 1933, in Amsterdam (the Netherlands). He graduated from St. Ignatius's College in 1951, and in 1954 he completed his Civil Engineering course.

In his younger years, Crutzen served his compulsory military service and worked in design bureaus (Bridge Construction Bureau of the City of Amsterdam, the Netherlands, and House Construction Bureau, Gävle, Sweden).

He has linked his life with atmospheric sciences since 1959, working first at the Faculty of Meteorology at the University of Stockholm, then at the National Center for Atmospheric Research in Boulder and at the Faculty of Atmospheric Sciences at the University of Colorado (United States).

In 1968, Crutzen defended his Ph.D. on "Determination of parameters appearing in the 'dry' and the 'wet' photochemical theories for ozone in the stratosphere." The outstanding Swedish scientist Bert Bolin took part in the defense. In 1973 Crutzen defended his dissertation "On the photochemistry of ozone in the stratosphere and troposphere and pollution of the stratosphere by high-flying aircraft" for a Doctor of Science degree. This work was consulted by famous British scientists John Houghton and Richard P. Wayne. Both dissertations were noted as the highest achievements in the field of science.

Crutzen directed the Department of Atmospheric Chemistry at the Max Planck Institute for Chemistry in Mainz (Germany) for two decades (1980–2000), and from 1992 to 2008 he was a distinguished professor (part-time) at the Scripps Institution of Oceanography, University of California, San Diego, La Jolla, United States.

At present, Crutzen is an honorary member of the Max Planck Society (Germany); honorary director of the Department of Atmospheric Chemistry, Max Planck Institute for Chemistry in Mainz (Germany); honorary researcher at the International Institute for Applied Systems Analysis (IIASA); and honorary professor of the Scripps Institution of Oceanography, University of California (United States).

Professor Crutzen has been elected a member of more than ten national and international Academies of Sciences, including a foreign member of the Russian Academy of Sciences. A list of his posts, scientific awards, membership in academies, councils, commit-

tees and editorial boards alone occupies 16 pages on the website of the Max Planck Institute for Chemistry (<https://www.mpic.de/3864937/curriculum-vitae>).

In 2016, the Springer publishing house, in its series Briefs on Pioneers in Science and Practice. Nobel Laureates, published the monograph "Paul J. Crutzen: A Pioneer on Atmospheric Chemistry and Climate Change in the Anthropocene," which describes in detail the life and scientific path of Nobel Prize laureate Professor Crutzen.

Georgy Sergeevich Golitsyn was born in Moscow on January 23, 1935. In 1952, he graduated with a gold medal from Moscow secondary school No. 126 and, in 1958, with honors from the Faculty of Physics at Moscow State University. In the same year he became an employee at the Institute of Atmospheric Physics, which had been created by A.M. Obukhov two years earlier, and he works at this Institute to this day.

In 1961, Golitsyn defended his Candidate of Sciences dissertation "On the theory of shock waves and fluctuation phenomena in magnetohydrodynamics" at the Academic Council of the Physics Department of Moscow State University. In 1971, at the Academic Council of the Sternberg Astronomical Institute, he defended his doctoral dissertation "Dynamics of planetary atmospheres." His doctoral dissertation began with the phrase: "Winds blow in the atmospheres of the planets."

Golitsyn was elected a corresponding member of the Academy of Sciences of the Soviet Union in 1979 and became a full member in 1987. From 1988 to 2001, he was a member of the Presidium of the Academy of Sciences of the Soviet Union, and then of the Russian Academy of Sciences. For many years he was the chairman of the Scientific Council of the Academy of Sciences of the Soviet Union/Russian Academy of Sciences "Research on the theory of the Earth's climate."

At the Obukhov Institute of Atmospheric Physics, Academy of Sciences of the Soviet Union (now Russian Academy of Sciences), Golitsyn headed the Laboratory of Energy of Planetary Atmospheres, the Laboratory of Climate Theory, the Department of Climate Processes Research, and the Laboratory of Atmosphere and Ocean Interaction. Since 1990, for two decades, he was the Director of the Institute. He is currently the head of the Department of Atmospheric Dynamics at the Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences.

Golitsyn's research results in various fields of physics, hydrodynamics, and sciences about the environment are presented in 400 articles published in Russian and foreign scientific journals. He is the author of six monographs, three of which have been translated into foreign languages. He taught for three decades at Moscow State University and is an honored professor of Moscow University (since 1999). Golitsyn has been

teaching at the Moscow Institute of Physics and Technology since 1976.

Golitsyn's active life position was clearly manifested in the period of 1990–2008, when he was the Director of the Institute of Atmospheric Physics. Under his leadership, the Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, managed not only to survive the “turbulent 1990s,” but also increase the scientific potential of the institute and its prestige in Russian and world science. Under the ideological and practical guidance of Golitsyn, large-scale experiments were carried out to study the interaction of the atmosphere, ocean, and land and solar and thermal radiation and clouds, as well as carry out complex studies of smoke aerosols and the climatic effects of intense dust storms.

Golitsyn played a very important role in the development of international cooperation. Here we note the joint laboratory for atmospheric and climate research organized in 2007 by the institutes of atmospheric physics at the Russian and Chinese academies of sciences. He was twice (in 1982–1987 and 1992–1997) elected as a member of the Joint Scientific Committee which manages the World Climate Research Program and was the chairman of the scientific council of the International Institute for Applied Systems Analysis (IIASA) (Vienna, Austria) for five years (1992–1997).

Academician Golitsyn is an honorary scholar of the International Institute for Applied Systems Analysis (Honorary Scholar of IIASA), an honorary fellow of the Royal Meteorological Society of Great Britain, and a member of the European Academy and the European Union of Earth Sciences. He has been honored with the highest award of the European Geosciences Union—the Alfred Wegener Medal for outstanding services in the field of atmospheric, oceanic, and climate sciences.

Golitsyn has been awarded many awards by the government of Russia and the Academy, including the

Order of Honor and the Order of Merit for the Fatherland, IV degree. Of all his awards from the Academy, of special importance is the A.M. Obukhov Gold medal of the Russian Academy of Sciences for his works “making an outstanding contribution to the research of magnetohydrodynamics and the development of a number of theories in the field of planetology, climate theory, atmospheric physics, and geophysics: general circulation of planetary atmospheres, the occurrence of hurricanes and other intense atmospheric vortices, radiation effects and heat and mass transfer between the ocean and the atmosphere, and a number of other natural processes and phenomena.” He won the A.A. Friedmann Prize for a series of works on studies of the general circulation of the atmosphere and convection, the B.B. Golitsyn Prize for the monograph “Statistics and dynamics of natural processes and phenomena: methods, tools, and results,” and the Demidov Prize for Outstanding Achievement in Earth Sciences.

For clarity, the table below shows the main stages of the lives and scientific careers of Golitsyn and Crutzen.

As has been noted, the lists of scientific, popular-science, and biographical publications of each of the laureates awarded the 2019 Lomonosov Gold Medal of the Russian Academy of Sciences contains hundreds of titles. In addition, there are many articles that develop ideas and highlight the life and work of the laureates. Many of these publications are given in the previous personalia of Golitsyn and Crutzen.

The Lomonosov Prize winners themselves note that their scientific path is most fully reflected in the monographs they published over the last decade [1, 2], the covers of which are shown in Fig. 1. At the beginning of the list of references there are links to the main monographs of Academician Golitsyn [3–8]; Professor Crutzen [9–15]; and their joint fundamental publication devoted to the problem of the relationship between global warming, ozone layer depletion, and other aspects of global environmental changes [16].

Table 1. Comparative biography of Golitsyn and Crutzen

Golitsyn	Years	Paul Crutzen
Born January 23, 1935	1930	Born December 3, 1933
School	1940s	School (college)
Graduated from secondary school with a gold medal (1952) First scientific article in <i>JETP</i> (1957) Graduation with honors from the Faculty of Physics, Moscow State University and the beginning of work at the Institute of Atmospheric Physics (1958)	1950s	Graduation from St. Ignatius's College (1951) Completed training as a civil engineer (1954) Military service. Started work at the University of Stockholm (1959)
Defended Candidate of Sciences dissertation (1961) Became executive secretary of the editorial board of the journal <i>Izvestiya, Atmospheric and Oceanic Physics</i> (since 1964)	1960s	Obtained Ph.D. (1968)

Table 1. (Contd.)

Golitsyn	Years	Paul Crutzen
<p>Defended doctoral dissertation (1971)</p> <p>Participated in the voyage of the <i>Dmitry Mendeleev</i> research vessel (1974)</p> <p>Created a similarity theory for the dynamics of planetary atmospheres</p> <p>Developed the theory of convection taking into account rotation</p> <p>Election as a Corresponding Member of the Academy of Sciences of the USSR (1979)</p>	1970s	<p>Discovered the catalytic cycle of destruction of the stratospheric ozone layer by nitrogen oxides</p> <p>Obtained doctorate degree (1973)</p> <p>Discovered the catalytic mechanism of ozone formation in the troposphere.</p> <p>Described chlorine activation processes in the Antarctic stratosphere</p> <p>Became director of the Department of Atmospheric Chemistry of the Max Planck Institute for Chemistry (since 1980)</p>
<p>Article published in <i>Tellus</i> on the physical validity of the nuclear winter hypothesis.</p> <p>Elected as a full member of the Academy of Sciences of the Soviet Union (1987)</p> <p>Became director of the Institute of Atmospheric Physics of the Academy of Sciences of the Soviet Union (since 1989)</p> <p>Became chief editor of the journal <i>Izvestia, Atmospheric and Oceanic Physics</i> (since 1989)</p> <p>Awarded the Friedmann Prize by the Academy of Sciences of the Soviet Union (1990)</p>	1980s	<p>Became director of the Atmospheric Chemistry Department of the Max Planck Institute for Chemistry. His article “The atmosphere after a nuclear war: twilight at noon” in <i>AMBIO</i> pioneered research on the hypothesis of nuclear winter.</p>
<p>Became director of the Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences</p> <p>Became chairman of the Council of the International Institute for Applied Systems Analysis (IIASA) (1992–1997)</p> <p>Awarded Demidov Prize for Outstanding Achievement in Earth Sciences (1995)</p> <p>Began the TROICA project (1995)</p> <p>Elected as a member of the European Academy of Sciences (1999)</p>	1990s	<p>Became director of the Atmospheric Chemistry Department of the Max Planck Institute for Chemistry in Mainz (until 2000)</p> <p>Became Professor Emeritus at the Scripps Institution of Oceanography (1992) Nobel Prize in Chemistry (1995)</p> <p>Began the TROICA project (1995) Became a foreign member of the Russian Academy of Sciences (1999)</p>
<p>Became director of the Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences (until 2008)</p> <p>Received Alfred Wegener Medal, the highest award of the European Geosciences Union (2004)</p> <p>Created the Russian–Chinese laboratory for atmospheric and climate research (2007)</p>	2000s	<p>Became honorary member of many universities and scientific societies. Published the article that initiated the discussion of the Anthropocene hypothesis.</p>
<p>Awarded the B.B. Golitsyn prize (2016) Awarded the A.M. Obukhov Gold Medal (2018)</p> <p>Awarded the Lomonosov Gold Medal of the Russian Academy of Sciences (2019)</p>	2010s	<p>Became honorary fellow of the Royal Society of Chemistry (the Netherlands, 2017)</p> <p>Awarded the Lomonosov Gold Medal of the Russian Academy of Sciences (2019)</p>

GOLITSYN: ATMOSPHERE AND CLIMATE, STATISTICS AND ENERGY OF NATURAL PHENOMENA

This section briefly lists the main stages of the scientific path of Academician Golitsyn. They are described in this article relatively briefly, since the readers of the journal *Izvestia, Atmospheric and Oce-*

anic Physics are very familiar with his articles and personalia published in our journal.

Golitsyn coauthored the first scientific article on some issues of magnetohydrodynamics with his scientific adviser K.P. Stanyukovich in 1957 while still a student at the Faculty of Physics of Moscow State University.



As Golitsyn notes himself, during his long scientific life, he had to deal with many different subjects: “magnetohydrodynamics; the propagation of various waves in turbulent media; planetary atmospheres; convection in various media, including rotating ones; the spectrum of cosmic rays; the theory of earthquakes; the formulation and management of natural experiments, including international ones; the theory of sea wind waves and their role in the spread of pollution on the water surface; the theory of hurricanes; the explanation of experimental results on the statistical structure of the relief of planetary surfaces; and a number of other processes and phenomena.”

Golitsyn obtained important new results in the field of magnetohydrodynamics and atmospheric research, the study of wave motions of various natures in the atmosphere, the interpretation of measurement data on spacecraft, theoretical planetology and climate theory, the study of convection as a hydrodynamic phenomenon, and the study of heat and mass transfer between the ocean and atmosphere. He estimated the velocities of convective motions in the atmosphere, ocean, and mantle of the Earth.

Golitsyn is one of the authors of the concept of “nuclear winter,” changes in the thermal and dynamic regimes of a smoky atmosphere and the climatic consequences of a possible nuclear war. In the 1980s, Golitsyn was a member of the UN working group on climatic and other consequences of nuclear war. According to the report of this group, the 44th UN General Assembly in 1988 adopted a resolution on the inadmissibility of nuclear war.

Golitsyn played an important role in the discussion and adoption of the Kyoto Protocol by Russia, defending at the highest level the scientifically grounded provisions of the climate theory and the role of anthropogenic factors in the process of global warming.

Golitsyn’s main scientific results include the following:

- (i) at the end of the 1960s (when there were no numerical models of atmospheric circulation), the creation a similarity theory for planetary atmospheres which determines the key features of the dynamics of the atmospheres of the planets of the solar circulation system;
- (ii) a description of the mechanism of global dust storms on Mars in the early 1970s;
- (iii) the development of the fundamentals of climate theory, including studies of the sensitivity, stability, and extreme properties of the climate system; changes in the hydrological regime in the Caspian Sea and Lake Ladoga basins; and changes in temperature in the middle and upper atmosphere;
- (iv) experimental and theoretical research in the field of geophysical convection and turbulence;
- (v) system research of statistics and energy of natural processes and phenomena;
- (vi) a description of the processes of interaction between the atmosphere and the ocean and the development of the theory of heat and mass transfer between the atmosphere and the ocean under weak winds;

(vii) versatile research into the formation and statistics of tropical cyclones, polar mesocyclones, extratropical cyclones, and anticyclones;

(viii) a study of the phenomenon of nuclear winter—the climatic consequences of a possible nuclear war;

(ix) management of a comprehensive project to study the role of cloudiness and aerosol in the transportation of solar and thermal radiation;

(x) a theoretical explanation of the results of field experiments on the spreading of impurity spots on the ocean surface.

The theory of the dynamics of planetary atmospheres developed by Golitsyn is of exceptional importance for understanding the features of atmospheric and climatic dynamics on the Earth.

One of the largest regional climate changes on Earth in the last few decades was the dramatic change in the level of the Caspian Sea in the 20th century. As part of a Russian–German project under the leadership of Golitsyn, the mechanisms of changes in the hydrological regime, including precipitation, evaporation, and river runoff, in the Caspian Sea basin under changes in the global climate have been studied. In particular, a significant connection was revealed between changes in the level of the Caspian Sea, the Volga runoff, and precipitation in the basin with temperature anomalies in the tropical part of the Pacific Ocean—in the area of the formation of El Niño phenomena. This connection has been confirmed in numerical experiments with a general circulation climate model. Predictive model estimates were obtained with a significant increase in the Volga runoff in the 21st century with a significant drop in runoff in the first third of the century.

Golitsyn made a significant contribution to the study of atmospheric vortex regimes—tropical cyclones, polar mesocyclones, extratropical cyclones, and anticyclones. Estimates are made based on the theory of dimension and similarity, and a physical interpretation is given to the features of distribution functions obtained from observations, reanalysis, and model calculations. A significant part of atmospheric vortices is characterized by exponential distributions in accordance with Boltzmann–Gibbs distributions. In this case, the ocean plays the role of a giant thermostat, and for the atmosphere associated with the ocean, the fluctuations are distributed exponentially. The exception is the “tails” of distributions, which are characterized by significant deviations from the general exponential distribution.

Golitsyn’s use of a general methodological approach to the study of a wide variety of processes—from atmospheric microscales to processes in the universe—is of particular importance. His interests include both cosmic rays and planetary quakes—not only earthquakes, volcanic activity, dynamics of lithospheric plates, and planetary surface topography. An important place in the research of Golitsyn is occu-

ried with the study of sea waves and the interaction of the atmosphere and the ocean.

Within the framework of the Soviet program of climatology of cloudiness and radiation, which was directed by Golitsyn, a number of unique studies have been carried out, including as part of the Zvenigorod experiments. These studies were continued as part of the international ARM program.

Particularly noteworthy is Golitsyn’s role in the organization and management (together with Crutzen) of the TROICA project (Trans-Continental Observations Into the Chemistry of the Atmosphere), which included 12 trips along the Trans-Siberian railway from Moscow to the Far East and 3 trips north to south from Murmansk to Kislovodsk and Sochi, as well as along the large ring road around Moscow.

A complete list of Golitsyn’s works up to 2010 can be found in the publication *Georgy Sergeevich Golitsyn, M.: Nauka, 2010 (Materials for the Biobibliography of Scientists: Physical Sciences, issue 49)*. An editorial in *Izvestia, Atmospheric and Oceanic Physics* was dedicated to Golitsyn’s 80th birthday in 2015, and his publications for 2010–2014 were presented.

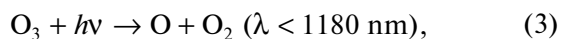
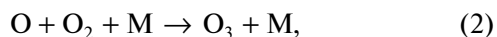
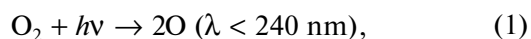
Academician Golitsyn continues his scientific activities to this day. The breadth and variety of his scientific interests are well illustrated by a list of his publications over the past five years [16–41]. In addition to publishing original scientific articles, Golitsyn participates in various Russian and international scientific conferences, and of special importance is the conference dedicated to the 100th birthday of Academician Obukhov, who founded of the Institute of Atmospheric Physics and whose works were published in the book *Turbulence, Atmosphere and Climate Dynamics*, published by the Fizmatkniga publishing house in 2018 [43].

CRUTZEN: ATMOSPHERIC CHEMISTRY

Crutzen’s main fields of research are chemistry of the troposphere and stratosphere and the role of biochemical cycles in the formation and changes of climate. He received the Nobel Prize in Chemistry for his achievements in these fields in 1995, along with Mario J. Molina (Mexico) and F. Sherwood Rowland (United States). The key result of his research, which showed the possibility of a catastrophic impact of human activity on the environment, was the proof that nitrogen compounds of anthropogenic origin determine the destruction of stratospheric ozone and the formation of high concentrations of ozone in the troposphere. Crutzen’s scientific achievements are described in detail in many publications, in particular, in [2].

For several decades, in accordance with the theory of S. Chapman [44], published in 1930, it was believed that the ozone layer is in a state of stable photochemical equilibrium. The formation of “odd

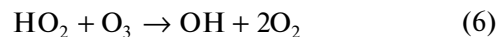
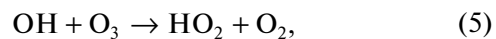
oxygen” ($O_x = O + O_3$) occurs as a result of the photolysis of molecular oxygen O_2 by solar radiation, and the destruction of ozone O_3 occurs during the recombination of O and O_3 :



Since the ozone layer forms a biosphere-friendly radiation balance on the Earth’s surface and makes a significant contribution to the Earth’s heat balance, much attention has been paid to ozone observations. In preparation for and during the International Geophysical Year (1957), a global network of ozonometric stations was created. Regular observations of about 30 stations began only in Russia at this time [45]. Based on observations of the UV spectral composition of solar radiation reflected from the Earth on the Russian Kosmos-121 satellite in June 1966, the first maps of the global ozone distribution were constructed [46]. An analysis of the data of numerous observations has shown a large influence of dynamic processes of various scales on the spacetime variability of ozone [47]. Modeling the state of the ozone layer by solving the transport equations with the Chapman photochemical cycle included in them has become an effective tool for studying the impact of atmospheric circulation, solar activity, wave processes, and other factors on the ozone content. Several such analytical and numerical models were developed in the 1960s–1970s at the Faculty of Physics at Moscow State University under the guidance of Prof. A.Kh. Khrgian. In particular, one of the authors of this article has constructed an analytical three-dimensional model of the impact of a jet stream in the upper troposphere on the ozone distribution, taking into account the helicity of the air flow, Chapman’s photochemistry in the stratosphere, and dry deposition of ozone on the Earth’s surface [48]. The calculations that were performed demonstrated the characteristic features of the ozone distribution in the region of polar and subtropical jet streams and confirmed the results of observations of such structures from the Kosmos-121 satellite [46].

At the same time, the model constructions of the vertical ozone distribution, as a rule, noticeably differed from the results of measurements carried out using the ozone probes. D. Bates and M. Nicolet [49] suggested that the rapid formation of odd oxygen in the mesosphere can compensate for the catalytic reactions of ozone destruction with the participation of OH and HO_2 radicals. Taking into account this assumption and the results of laboratory experiments on the assessment of reaction rates carried out by a

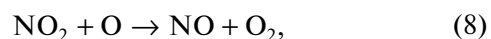
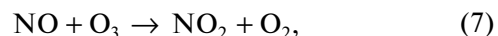
group of Cambridge University researchers [50, 51], J. Hampson [52] postulated the reactions



as a catalytic cycle of ozone destruction in the stratosphere. This cycle, introduced by B. Hunt [10] into the photochemical stratospheric model, led to results that are in much better agreement with observational data.

Having joined the work on atmospheric chemistry, Crutzen [54] drew attention to the fact that the hydrogen cycle does not explain the vertical distribution of ozone in the lower stratosphere and, moreover, at the reaction constants (5) and (6) chosen in [52, 53], it leads to an unrealistically rapid destruction of ozone in the troposphere. Crutzen pointed out an additional runoff of OH in the troposphere—its reaction with methane (CH_4), and subsequently showed that the CH_4 oxidation chain plays an important role in tropospheric chemistry.

The inclusion of CH_4 in the system of photochemical interactions led to the conclusion that the constants of reactions (5) and (6) are highly overestimated, so the hydrogen cycle cannot provide the necessary ozone sink in the stratosphere. Crutzen found a solution to the problem by including interactions of nitrogen oxides NO_x ($NO_x = NO + NO_2$) and the corresponding catalytic cycle of ozone destruction in the system [55]:



The end result of this cycle (7) + (8) is equivalent to the direct reaction (4). At the same time, the efficiency of the nitrogen cycle is much higher, since the cycle is active even at very low NO_x concentrations. A small amount of NO that is constantly formed in the atmosphere during the oxidation of nitrous oxide N_2O with atomic oxygen (1D)



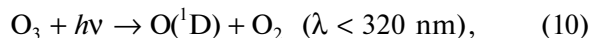
enough for the nitrogen cycle, played a decisive role in ozone destruction in the stratosphere at altitudes of 25 to 45 km.

In the fall of 1970, Crutzen got acquainted with the materials of studies of critical environmental problems [56], which, in particular, provided estimates of possible emissions of nitrogen oxides into the stratosphere by supersonic aircraft (Concorde, TU-144, and Boeing) during their operation. Comparing the intensity of natural sources of NO_x in the stratosphere with the emissions of the emerging fleet of supersonic aircraft, Crutzen immediately realized that humanity is facing a global environmental threat. Soon after the feverish work, Crutzen published an article with cal-

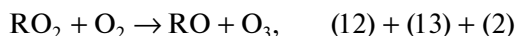
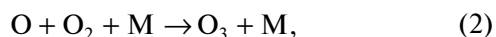
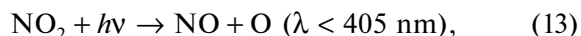
culations of the possible impact of supersonic aviation on the ozone layer [57]. It clearly demonstrates the seriousness of the problem: a global change in the ozone layer will be noticeable even after the flights of 500 supersonic aircraft, and serious ozone anomalies can form over regions with high flight intensity. The article had a huge scientific and social resonance and contributed to the rapid development of atmospheric physics and chemistry.

One consequence of the controversy that arose in society was the formation of a laboratory whose main task was to study atmospheric ozone and its precursor gases in 1976 at the Institute of Atmospheric Physics, Academy of Sciences of the Soviet Union. This laboratory was one of the first in the world to begin regular measurements of nitrogen dioxide (NO_2) at a high-altitude station created in the North Caucasus, as well as observations of the spacetime variability of NO_2 over northern Eurasia from an aircraft [58–60]. The data and their subsequent use in stratospheric models fully corresponded to the conclusions of Crutzen on the predominant role of the nitrogen cycle in ozone chemistry in the middle stratosphere.

Another, similar in importance, achievement of Crutzen in the field of atmospheric chemistry was the discovery and justification of the chemical mechanism of the formation of high concentrations of ozone in the troposphere. It was believed that the source of ozone in the troposphere is transport from the stratosphere. However, episodes of high concentrations of ozone under smog conditions that were hazardous to human health, which were especially often recorded in California [61], could not be explained by atmospheric air intrusions. Crutzen stated an assumption about the possible existence of chemical sources of ozone in the troposphere back in 1969 [54]. However, only after the publication of the work of H. Levy III [62] did he receive the basis for further research in this area. Levy presented the formation of hydroxyl OH in the form of ozone photolysis by shortwave solar radiation ($\lambda < 320 \text{ nm}$), followed by the combination of $\text{O}(^1\text{D})$ and H_2O ,



and showed that OH initiates the oxidation of CO and CH_4 in the atmosphere. Based on Levy's results, Crutzen found that the formation of ozone occurs in a catalytic cycle with the participation of NO and peroxyradicals—the oxidation products of CO, CH_4 and volatile organic compounds (VOCs) in the reactions:



where $\text{R} = \text{H}$, CH_3 , or other organic peroxyradicals. Ozone destruction occurs during reactions (5), (6) and (10), (11). Thus, the catalytic role of NO is twofold. In the stratosphere at altitudes greater than 25 km, the nitrogen cycle leads to the predominance of ozone destruction over its formation, and, in the troposphere, to the predominance of ozone formation over its destruction. In clean background conditions, when the concentration of NO, which is mainly of anthropogenic origin, can be very low (less than 10 ppt), the oxidation of CO, CH_4 , and VOCs leads to a decrease in the ozone content in the air, since most of the RO_2 peroxyradicals react with O_3 (see (6)).

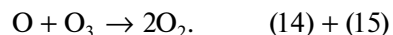
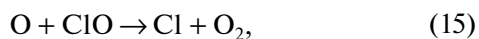
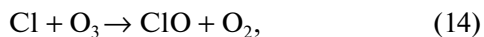
The inclusion of NO in oxidative processes promoting the formation of O_3 and OH was of great importance for further studies in the field of atmospheric chemistry and the numerical modeling of possible changes in the composition of the atmosphere. In particular, including reaction (12) in modeling the consequences of supersonic aircraft flights sharply reduced the initially significant value of destruction of the ozone layer and removed the severity of this problem.

Numerical simulations of the atmosphere taking into account the nitrogen cycle performed by Crutzen and P. Zimmermann [63] showed the inevitability of an increase in the concentration of O_3 and OH in the troposphere in the industrial era when compared with the preindustrial era. This result caused reasonable concern not only because of the increase in toxic ozone in the air, but also because of the possible adverse and poorly predictable consequences associated with an increase in OH content. First, the atmospheric runoff of CH_4 , the most active greenhouse gas, depends on OH and, secondly, the photochemical system of the tropical and subtropical atmosphere is extremely sensitive to OH. Regular natural fires in this area of the globe during dry seasons are an active source of aerosols and greenhouse gases and are an important element of the Earth's climate system.

The discovery of the photochemical mechanism of ozone formation in the troposphere has provided a theoretical basis for the efforts being made by many countries to create systems for monitoring the state of surface air in cities and to develop measures to improve its quality. Much attention has begun to be paid to reducing CO and NO_x emissions. Power plants in industrialized countries have begun to more actively use natural gas as fuel instead of coal. The development of new car models with reduced emission of reactive compounds has begun. These actions have led to positive results, especially in countries located at low latitudes (Mexico, Japan, etc.), where, at a high level of UV illumination, photochemical processes with the formation of toxic substances are most active [64]. Similar actions were taken in Russia [65], most actively in the last two decades. In Moscow, Europe's largest metropolis, the optimization of urban infrastructure in these years contributed to a decrease in

the surface concentration of CO, NO, and SO₂ at a rate of 3.6, 5.0, and 3.7% per year, respectively [66].

The high sensitivity of the ozone layer to anthropogenic impact and the threat of its possible destruction have mobilized the scientific community to conduct large-scale research in the field of atmospheric chemistry. In 1974, four articles were published simultaneously [67–70], which presented the chlorine catalytic cycle of ozone destruction in the stratosphere:



The main difference between the articles is the assumed sources of chlorine in the stratosphere. If R.S. Stolarski and R.J. Cicerone [67] considered volcanic eruptions a source (later this source turned out to be insignificant), then M. Molina and F. Rowland [68] and Crutzen [69] associated the appearance of chlorine in the stratosphere with the photolysis of freons 11 and 12, which are produced in large quantities by industry in different countries. According to Crutzen, a decrease in ozone concentration at an altitude of 40 km could reach 40% in the future if the level of freon production in the world remains at the level of 1970. A similar estimate of ozone destruction by 1980–1985 was cited by Cicerone et al. [70], provided that the emissions of chlorofluorocarbons will continue at the level of 1970.

Soon, other halogen-containing compounds that are stable in the lower atmosphere were identified, which, entering the stratosphere, undergo photolysis, releasing active chlorine, bromine, or iodine. The possibility that human activities could, even unintentionally, cause catastrophic environmental changes stirred up society, and a campaign began to ban the production and release of ozone-depleting substances into the atmosphere. The results of theoretical research had to be confirmed by observations. Numerous national and international experiments were organized and conducted. Methods and instruments for measuring the content of impurities in the atmosphere and numerical modeling developed rapidly. The Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences made a significant contribution to the study of the composition of the atmosphere. Measurements of the content of ozone, nitrogen oxides, aerosols and other components in the atmosphere were carried out at the scientific stations of the institute, aboard aircraft laboratories, helicopters, and research vessels. Experiments performed on the Salyut space station revealed the presence of a characteristic layered vertical structure in the global distribution of ozone and aerosol [71–74]. Based on the results of ground-based and airborne observations, quantitative estimates of the influence of internal gravity waves, solar eclipses and atmospheric circulation, and various types of anthropogenic impact on the content of

ozone, NO₂, and other impurities in the atmosphere were obtained [75–77].

In 1985, J.C. Farman [78] reported on an ozone anomaly over Antarctica, which was called the ozone hole. The joint efforts of many scientists established how it formed. A key element in the study of this phenomenon was Crutzen's explanation of the competing role of two catalytic cycles—nitrogen and chlorine—in the destruction of ozone. Under normal conditions, the interaction between NO_x and ClO_x results in the formation of a neutral compound ClONO₂ and HCl. Chlorine is present in the atmosphere mainly in the composition of these compounds. Crutzen suggested that NO_x can escape from the gas phase. Laboratory experiments have shown that solid particles of nitric acid trihydrate can form at temperatures below 200 K [79]. In the Antarctic stratosphere in winter, the temperature drops to 190 K. NO_x radicals turn into a solid, sharply increasing the ozone-depleting effect of the chlorine catalytic cycle. Crutzen's proposed mechanism underlies the description of the processes that occur in the Antarctic, and more recently in the Arctic, stratosphere.

CRUTZEN AND GOLITSYN: EXPERIMENTS AND EXPEDITIONS

Obtaining important results in the field of theoretical chemistry and numerical modeling, Crutzen always sought to confirm them by conducting field observations. He proposed and implemented numerous field experiments to measure the composition of the atmosphere using various means, including satellites, ships, trains, and airplanes. At some point, Crutzen, who noticed that atmospheric scientists travel a lot, suggested taking special canisters with them to collect air samples while traveling, especially when traveling to conferences. Few were able to do this due to practical problems with explaining it all to customs officers at the border, but, nevertheless, important information was collected about some regional features of the composition of surface air and its greenhouse-gas content. It is interesting that young scientists of different specialties responded to such an initiative, which contributed to the formulation of new tasks and influenced the rapid development of the science of atmospheric chemistry.

The high demand for observational data of chemically active and radioactive gas impurities and aerosols in the atmosphere has contributed to the expansion of the global network of observation stations. Under the influence of the problems identified by Crutzen, background high-altitude stations were created, such as the Jungfrauoch Swiss Alpine site and Kislovodsk High Mountain Station (North Caucasus). At the same time, the territory of the World Ocean remained uncovered by network measurements. It was necessary to intensify the conduct of expeditions, mainly inter-

national, by ship, air, and satellite. However, the cost of specialized platforms for regular measurements of atmospheric composition was too high. In this regard, Crutzen guided his colleagues to the use of cargo and passenger vehicles. The INDOEX project (Indian Ocean Experiment, 1998–1999) [35] is a good example of this approach to measurements on long routes using shipping. Crutzen and his colleagues convinced the managers of Hapag Lloyd to install several gas detectors on a cargo ship that delivered cars from Hamburg to Japan and from Japan to Hamburg. There were many difficulties associated with the location of instruments, automation of measurements, and change of crews but, in the end, the system worked and continued to work for many years, collecting valuable data on ozone in the surface layer of the atmosphere [80]. As far as we know, such a long-term operation of the measuring system is very rare.

One of the most successful experiments in the field of atmospheric research was the TROICA project (Transcontinental Observations Into the Chemistry of the Atmosphere) [81–85]. The project was initiated by Crutzen and Golitsyn and consisted of observing the composition and state of the atmosphere on transcontinental rail routes from Moscow to Vladivostok and from Murmansk to Sochi and Kislovodsk. A specially created laboratory consisted of two cars and carried out automated measurements of a large number of gas impurities (40–60 compounds), aerosols, and radiation and meteorological characteristics of the atmosphere. Numerous TROICA results and scientific discoveries have been widely published and have made a significant contribution to understanding the processes occurring in the continental atmosphere. A separate article is devoted to the results of TROICA experiments in this issue of the journal.

The use of civil aircraft has always been the focus of atmospheric chemistry specialists. Fast movement in a free atmosphere over long distances makes aircrafts a convenient platform for observation. However, until the eruption of Mount Pinatubo in 1991, when airlines faced the severe effects of clouds of volcanic dust on aircraft, airlines were not natural partners of scientists. The necessity of controlling the aerosol content in the atmosphere, as well as the problem of aviation's impact on the ozone layer and the climate, has significantly fueled the interest of airlines in monitoring the composition of the atmosphere.

Indeed, several projects appeared, and some of them are still in operation. The long-term CONTRAIL project was implemented in Japan [86]. A simple concept was used—collecting air samples in flight without measurements onboard the aircraft. After landing at the airport, the flasks were analyzed in a laboratory. This measurement technique proved to be very reliable, and a lot of data were collected on the concentration of carbon dioxide at cruising altitude. Later, the number of traceable gas impurities increased. A simi-

lar project has been operating in Taiwan since 2007, providing valuable data on CO₂ emissions over the Pacific Ocean (<https://calec.china-airlines.com/csr/environment/en/charity-plan-1.html>).

In the late 1980s, Crutzen and his coworkers set out to obtain and equip an Airbus aircraft for atmospheric research, and they made considerable efforts to do so. However, faced with problems of the joint use of large investments with other European Union countries, the aircraft-laboratory was abandoned. Instead, within the framework of European Union funding, the MOZAIC (Measurement of Ozone and Water Vapor by Airbus in service Aircraft) project initiated by France was born, which provided important information about the distribution of ozone and water vapor in the upper troposphere [87]. Later, this project was transformed into its successor, IAGOS (In-Service Aircraft for a Global Observing System), focused on studies of increasing ozone concentration in the troposphere [88].

Designed and implemented by Crutzen and his coworkers, the CARIBIC (Civil Aircraft for the Regular Investigation of the atmosphere) project used a completely different concept; namely, measurements of the content of impurities in the atmosphere were carried out using instruments enclosed in a special container. The concentrations of greenhouse gases, ozone, carbon monoxide, nitrogen oxides, and some other gases were measured in real time. A container weighing 1.5 t is loaded into the cargo compartment of the aircraft and connected to a special air intake, which is part of the aircraft structure. The equipment works automatically and is removed after 2–6 consecutive flights. In the laboratory, the data is read and the samples are analyzed. Airplane flights with measurements take place about once a month for many years. They provided a huge amount of information about the global compositional features of the upper troposphere and lower stratosphere [89].

As was noted by Golitsyn in his lecture at the General Meeting of the Russian Academy of Sciences, the largest and longest project of the Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences is the TROICA project (Tropospheric Investigation of Chemistry of Atmosphere), initiated by him together with Crutzen a quarter of a century ago and operating for about two decades. In February 1995, the future Lomonosov Prize laureates agreed to start joint measurements of small impurities in the atmosphere, and by November of the same year the first specially equipped carriage went from Moscow to Khabarovsk and Vladivostok [90, 91]. It is interesting to note that Professor Crutzen suggested such a Russian sounding name, TROICA, for this project.

The project became world-famous, and scientists from Germany, Austria, the United States, and Finland took part in it. Foreign experts assumed that the increase in the methane content in the atmosphere

was associated with leaks from Russian gas pipelines, but an isotopic analysis of carbon in those places where there was an excess of methane showed that the content is normal and there was no methane in the gas. For organizing this project, N.F. Elansky received the title of Environmental Hero in the United States. This title is awarded by the NOAA (National Oceanic and Atmospheric Administration of the United States) to one person every year. A detailed description of the work, carried out within the framework of this unique project, is given in the article by N. F. Elansky, Golitsyn, Crutzen, et al. "Observations of atmospheric composition over Russia: TROICA experiments" published in this issue of the journal.

TWILIGHT AT NOON AND NUCLEAR WINTER

After World War II, in the 1960s and 1970s, the number and power of nuclear charges began growing rapidly around the world, and the question arose about assessing the impact of high-power explosions on large cities and industrial centers, as well as the possible global long-term consequences of a nuclear war, which seemed quite real at that time.

In 1975, the National Academy of Sciences of the United States issued the report "Long-Term Large-Scale Effects of Multiple Nuclear Explosions," noting the possibility of global radioactive fallout, which could cause the death of tens of millions of people from cancer and genetic changes, and ionizing radiation, which could change the ecological situation on Earth in unpredictable ways. The report also discussed a decrease in the ozone layer estimated at 30–70%, which could have a significant impact on the stratosphere and, due to the increase in solar radiation flux, cause a slight impact on the temperature at the Earth's surface. In 1980, the UN Secretary General was presented with the report "Comprehensive Study on Nuclear Weapons" prepared by a group of experts which included scientists, diplomats and military specialists from around the world.

A real breakthrough in the study of the possible consequences of a nuclear war occurred in the early 1980s. In 1982, the international scientific community was shaken by a special issue of the Swedish magazine *AMBIO* with the catchy title *Nuclear War: The Aftermath*. Scientists all over the world took note of the article published in this issue by Paul Jozef Crutzen and John W Birks "The Atmosphere after a nuclear war: twilight at noon" [92]. This outstanding article caused a boom in research on the hypothesis of nuclear winter, and the first publication on this topic was the work of American scientists [93].

By 1983–1985, American and Soviet scientists formulated the main provisions of the nuclear winter hypothesis and evaluated the climatic consequences of a possible large-scale nuclear exchange. There were

review articles on possible atmospheric and climatic consequences of nuclear war, where it was noted that, until now, when considering atmospheric consequences, most attention was paid to the ozone layer of the atmosphere. Now the study has begun of other characteristics of the atmosphere which can change after explosions and fires. However, the picture is still far from clear. Nuclear explosions and fires will also noticeably alter the albedo of the land surface and introduce huge amounts of substances into the atmosphere, thus significantly affecting its optical properties. This, in turn, will lead to changes in atmospheric circulation and then—due to the large number of direct and feedback connections in the Earth's climate system—to climatic effects on a regional and global scale.

During these years, it became clear that atmospheric processes and connections resulting from nuclear exchange "cannot be considered in isolation; they are insufficiently studied and can produce effects of different signs and intensities. To estimate the total effect, numerical models of atmospheric circulation should be used, taking into account its chemical, optical, and other measurements."

Since the main mechanism of the formation of the phenomenon of nuclear winter is massive fires, in the 1980s, the Obukhov Institute of Atmospheric Physics of the Academy of Sciences of the Soviet Union began studying the possible atmospheric and climatic consequences of a full-scale nuclear conflict and search for natural analogues of this climatic catastrophe.

On the basis of the pioneering works of Golitsyn on the dynamics of planetary atmospheres and the work of A.S. Ginzburg on the radiation regime of the dusty atmosphere of Mars during the great confrontation, it was possible to construct a simple analytical model of a catastrophic cooling on Earth in the hypothetical case of large-scale fires from the massive use of nuclear weapons [94, 95]. This model was later applied to estimate the temperature effects of large forest and oil fires.

The results of the first years of research on a nuclear winter are summed up in a number of international reports prepared with the direct participation of Golitsyn [96, 97]. It is important to note that in recent years there has been renewed interest in the phenomenon of nuclear winter in terms of describing significant changes in the Earth's climate.

In the search for natural analogues of nuclear winter, the analysis of the largest natural fires and the optical properties and temperature effects of their smoke has become especially interesting and important. The active participation of Crutzen and Golitsyn in assessing the possible atmospheric and climatic consequences of a nuclear war, in a sense, became the forerunner of their idea for TROICA.

THE ANTHROPOCENE

Prof. Crutzen entitled his lecture for the General Meeting of the Russian Academy of Sciences “We live in the Anthropocene, so will our grandchildren.” As Crutzen emphasizes, the concept of the Anthropocene is based on the concept of the Noosphere, formulated by V.I. Vernadsky. Academician Vernadsky wrote in 1938 about scientific thought as a geological force. In his works, Crutzen writes that Soviet scientists seem to have used the term Anthropocene as early as the 1960s to refer to the Quaternary period, the most recent geological period. American ecologist E.F. Stoermer began using the term *Anthropocene* in the 1980s in the modern sense.

However, this term gained wide popularity only in the 21st century after the publication of an article by Nobel laureate Prof. Crutzen and Stoermer [98] in 2000, in which the thesis was formulated that human influence on the Earth’s atmosphere in recent centuries has become so significant that it defines a new geological epoch. It is interesting to note that, although this article was published in *IGBP Newsletters* and is not included in the list of peer-reviewed publications of Crutzen, it is considered key in most subsequent publications devoted to the discussion of whether the geological epoch of the Anthropocene has already begun and, if so, when it began.

The Anthropocene is a proposed geological epoch dating from the commencement of significant human impact on Earth’s geology and ecosystems, including, but not limited to, anthropogenic climate change. Various dates have been proposed for the beginning of the Anthropocene: from the beginning of the agricultural revolution 12000–15000 years ago to the 1960s [99–102].

As of February 2020, the International Commission on Stratigraphy (ICS) and the International Union of Geological Sciences (IUGS) have not yet been officially approved the term as a recognized Geological Time Division, although proposals for defining the Anthropocene epoch in geologic time scale were presented to the International Geologic Congress in 2016. The ratification process continues, although the date of the beginning of the Anthropocene has not yet been definitively determined. Today, the most preferred time for the beginning of the Anthropocene is considered the middle of the 20th century—the time of the explosion of the first atomic bomb and the conclusion of the Partial Test Ban Treaty. It is hard to overstate the role Nobel laureate Prof. Crutzen played in this process.

CONCLUSIONS

This issue of the journal contains articles devoted to the development of the ideas of Academician Golitsyn and Professor Crutzen, including publications with the participation of the laureates themselves and

authors invited by the laureates and the editorial board of the journal [103–112].

As was noted above, the article by Elansky et al. summarizes the results of unique experiments on observations of the composition and state of the atmosphere over Russia performed as part of the TROICA project, which involved scientists and technicians from different countries. The article discusses the most important results published earlier and new ones obtained recently, which makes it possible to form a complete picture of the spatial distribution and temporal variability of the atmospheric composition over the vast territory of northern Eurasia.

V.A. Semenov’s article “Modern Arctic climate research: progress, change of concepts, and urgent problems” is a review of some significant achievements in researching climate change in the Arctic. It identifies the mechanisms of positive feedbacks that enhance climate changes in the high latitudes of the Northern Hemisphere and formulates the most important current problems that need to be addressed.

In the paper “Helicity and turbulence in the atmospheric boundary layer” by N.V. Vazayeva, O.G. Chkhetiani, M.V. Kurgansky, and M.A. Kallistratova, it is noted that helicity is inherent in a variety of circulation movements and structures in the atmospheric boundary layer and, therefore, the helicity factor requires correct consideration when constructing the atmospheric models. The article provides a qualitative and quantitative comparison of the measured values and the results of numerical modeling using a quasi-two-dimensional model and a WRF-ARW mesoscale atmospheric nonhydrostatic model.

The work of A.S. Ginzburg and S.A. Dokukin, “Influence of thermal air pollution on the urban climate (estimates using the COSMO-CLM model)” develops Crutzen’s ideas [63] on the role of heat pollution in the formation and dynamics of the urban heat island.

The article by Golitsyn, Yu.I. Troitskaya and G.A. Baidakov “Frequency spectra and laws of the growth of sea waves from the viewpoint of the probabilistic laws of A.N. Kolmogorov and his school” analyzes the data of full-scale measurements of surface-wave parameters performed at various degrees of its development. The paper uses the probabilistic laws of A.N. Kolmogorov and his school and an interpretation of the features of the impurity diffusion in the field of surface waves at various accelerations is proposed.

In E.B. Gledzer’s work “On the thermodynamics of Kolmogorov scaling in turbulence,” the model energy balance equations for turbulence are written in the form of the first law of thermodynamics and it is shown that, for the energy distribution according to the Kolmogorov–Obukhov law, the entropy takes the same form as for an ideal gas in thermodynamics. The article suggests a possible formula for the turbulence temperature that takes into account the main mecha-

nism of energy transfer in turbulence—hydrodynamic instability.

The article by A.N. Gruzdev and A.S. Elokhov “Changes in the total content and vertical distribution of NO₂ based on 30-year measurements at the Zvenigorod Research Station of the Institute of Atmospheric Physics, Russian Academy of Sciences,” analyzes variations and trends in the total content and vertical distribution of NO₂ over 30 years of observations in the western Moscow region. It provides seasonally dependent estimates of NO₂ trends.

A.E. Aloyan, A.N. Ermakov, and V.O. Arutyunyan’s article “Modeling the influence of ions on the dynamics of formation of atmospheric aerosol” describes a new numerical model for the transport and transformation of gaseous and aerosol impurities in the atmosphere, taking into account the processes of photochemistry, nucleation involving neutral molecules and ions, and condensation/evaporation and coagulation. The simulation results indicate a significant role of the ion nucleation process in the formation of atmospheric aerosol. It is shown that, along with the level of air ionization, the key factors determining the dynamics of ion nucleation are also temperature and relative humidity.

I.K. Larin’s work “On the influence of global warming on the ozone layer and UVB radiation” is devoted to the influence of global warming on the ozone layer and the intensity of near-surface, near-noon UVB radiation. It presents the results of calculations of changes in the ozone layer by 2100 obtained using a one-dimensional photochemical model and an interactive two-dimensional photochemical model.

In the article by V. S. Rakitin, N. F. Elansky, A. I. Skorokhod, et al., “Long-term tendencies of carbon monoxide in the atmosphere of the Moscow megapolis,” the long-term variability of the total content (TC) of CO and meteorological parameters was investigated, the characteristics of the accumulation of carbon monoxide in calm days in the atmospheric boundary layer were obtained, and estimates of the integral emissions of Moscow were obtained which are consistent with the literature data. This paper presents the results of a comprehensive analysis of measurements of total carbon monoxide content at the IAP RAS stations in the city of Moscow and Moscow oblast, data from automated stations of the Moseco-monitoring network using satellite monitoring results, and information on the parameters of the atmospheric boundary layer in Moscow and surrounding regions.

In conclusion, we quote from a lecture by Prof. Crutzen prepared for the General Meeting of the Russian Academy of Sciences: “**Our curiosity and desire to understand everything that surrounds us, including ourselves, makes science overturn every stone.**” This remarkable description of the scientific approach to the world around us fully reflects the work of the laureates of the Lomonosov Gold Medal of the Russian

Academy of Sciences and is an inspiration for current and future researchers.

Scientific reports of the winners of the Grand gold medal named after M. V. Lomonosov of the Russian Academy of Sciences for year 2019 were presented at the general meeting of members of the Russian Academy of Sciences on December 9, 2020 and published in the Bulletin of the Russian Academy of Sciences [112, 113].

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