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This article is devoted to the most topical trends in stratosphere–troposphere interaction and its influence on the climate of our planet. The authors find that the state of Russian research in this sphere does not match the level of advanced scientific powers. The integration of national research into international programs will allow Russia to overcome this lag.

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Stratosphere–Troposphere Interactions

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The Earth's atmosphere is a thin film less than 200 km thick. Without it, our planet would be as lifeless as the other celestial bodies of outer space surrounding us.

The Earth's atmosphere is conventionally divided into the following regions (see figure): the lowest region up to about 15–18 km in the tropics and 10–12 km in the middle and high latitudes, the troposphere. Since the density of the atmosphere decreases with height, the troposphere concentrates the main mass of the atmosphere, more than 80%. The temperature in the troposphere decreases by about 7° per kilometer; the dynamic processes in it, for example, the formation of cyclones, predetermine the weather conditions on the Earth's surface. Most of the major natural greenhouse gas, water vapor, resides in the troposphere. Further on, up to 45–50 km lies the stratosphere, where the temperature increases with height owing to heat buildup as ozone absorbs solar emission. The heat thus obtained is one of the major energy source for stratospheric circulation.

The ozone layer, located in the stratosphere, protects humans and the animal and plant world from the hazardous part of the ultraviolet spectrum of solar emissions. Above the stratosphere, up to about 80 km high, there lies the mesosphere, where the temperature decreases with height. The next and last region of the atmosphere is the thermosphere, where the temperature grows quickly with height and can reach 500–2000 K, depending on the level of solar activity. The boundary regions between the tropo-, strato-, meso-, and thermospheres are conventionally called, respectively, the tropopause, the stratopause, and the mesopause.

It has long been assumed that the dynamic processes in the troposphere affect the formation of weather conditions and climate near the surface and the role of the stratosphere has been largely predetermined by radiation processes that occur in it. However, in the 1980s and 1990s, based on the analysis of satellite observations, theoretical research, and numerical modeling, scientists concluded that it was necessary to expand research into the dynamic interaction between the stratosphere and the troposphere capable of affecting weather conditions and climate. This is especially topical against the ongoing increase in greenhouse gas concentrations in the atmosphere, leading not only to higher temperatures in the troposphere but also to lower temperatures in the stratosphere, which, in turn, affects atmospheric circulation, including meridional circulation.

In 1992, the international project Stratosphere–Troposphere Processes and Their Role in Climate (SPARC, http//www.sparc-climate.org) was organized within the framework of the UN World Climate Research Program. The goal of this project is to coordinate the research programs by scientists from various countries into the chemical and dynamic processes in the stratosphere and the troposphere, their interrelations, as well as stratospheric–tropospheric exchange, changes in the chemical composition of the stratosphere, comparisons and improvements in the implementation of dynamic and chemical processes in the stratosphere and the troposphere in climate models. Two times a year the project specialists draw and disseminate free the electronic and printed versions of the information bulletin about major research results, conferences held and planned, expert meetings, and measurement campaigns.

Once every four–six years, the SPARC General Assemblies are held, the latest (fifth) of which was held in Queenstown, located on the southern island of New

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Zealand, in January 2014. About 300 specialists in the circulation and composition of the middle atmosphere from developed and developing countries, including the United States, Germany, Britain, France, Italy, Sweden, Finland, Japan, Australia, New Zealand, Russia, the Republic of Korea, China, India, and Pakistan, took part in this assembly.

Here, some most topical research trends in stratosphere–troposphere interactions and their influence on climate that were discussed at the SPARC assembly by the authors are considered.

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Due to the circulation specifics of the extratropical stratosphere, its interaction with the troposphere in the Northern Hemisphere is limited to the winter season, which usually lasts from November to April, when the western zonal wind in the stratosphere favors the vertical propagation of planetary waves from the troposphere to the stratosphere. In particular, the influence of planetary waves on stratospheric circulation and the polar vortex, as well as changes in its intensity on dynamic processes in the troposphere, is the key element in the interaction between the troposphere and the stratosphere.

At present, this dynamic interaction is actively being studied in the world's leading research centers of the United States, Britain, Germany, Canada, Japan, and China. The number of international research projects and publications in leading scientific journals is increasing. The importance of research in this sphere is predetermined by the need to improve numerical models used to study climate and the effect of its changes on the state of flora and fauna, economic activity, human life and health conditions, and seasonal and perennial (up to ten years) forecasts.

Sudden stratospheric warmings. The brightest example of the dynamic interrelation between the troposphere and the stratosphere are sudden stratospheric warmings (SSWs), accompanied by fast temperature growth of the polar stratosphere (sometimes up to 70° in a few days) and observed in the Arctic Region during the winter season. The origin of SSWs is related to the propagation of planetary waves from the troposphere to the stratosphere and their further interaction with zonal circulation. However, irregular fluctuations in wave activity, temperature, and zonal wind in the upper stratosphere can also contribute to the origin of SSWs.

The strongest SSWs, which occur every second winter on average, entail a reversal of the zonal wind and a temperature increase in the middle atmosphere (at a pressure level of 10 hPa or ~32 km) with latitudes to the north of 60° N, i.e., the formation of an anomalous meridional temperature gradient. The SSW origin particularly predetermines the activity and isolation of the stratospheric polar vortex in general during the winter season, and this, in turn, predetermines how strong the destruction of ozone in the polar stratosphere will be.

As is known, polar stratospheric clouds (PSCs) can form in the conditions of a strong zonal circulation in the winter stratosphere inside a cold polar vortex, isolated from the midlatitudes. These PSCs take part in the activation of ozone-destroying compounds and, as a consequence, in the destruction of the ozone layer. For example, there were no SSWs in the Arctic Region during the 2010/2011 winter season, and the stratospheric polar vortex with low temperatures and, as a consequence, a large amount of PSCs formed remained until mid-April, leading to record-breaking destruction of stratospheric ozone out of all the years of observations. In turn, in years with well-expressed SSWs, the stratospheric polar vortex subsides and moves from the pole or in some cases splits up into two parts. In addition, the higher temperature of the polar stratosphere and sometimes the zonal wind that has changed its direction from western to eastern can persist until the spring alteration of stratospheric circulation, as occurred, for example, in the spring of 2004.

In recent years, the SSW-related changes in stratospheric circulation have propagated not only over the midlatitudes but also over the tropics, where the SSW-related strengthening of meridional circulation leads to a decrease in the temperature of the low stratosphere, reducing its humidity. It has been established that changes in the stratospheric polar vortex, including those SSW-induced, affect the troposphere, where they can influence the weather conditions in the middle and high latitudes of the Northern Hemisphere over the next two months. For example, the analysis of reanalysis data from 1958 to 2009 and the calculations of climate models has shown that, as the stratospheric polar vortex weakens, the probability of occurrence of cold waves in some regions (including Eastern Siberia) increases by 50% [1]. Based on the analysis of model calculation results over 500 years for the preindustrial period (until 1750), it has been established that about 40% of sharp winter coolings in the north of Europe is explained by the weakening of the stratospheric polar vortex [2].

The SSW-related disturbances of the temperature regime propagate as high as the mesosphere and the thermosphere (to altitudes of 60–90 km), where the composition of the atmosphere largely depends on solar UV radiation, the kinetics of chemical processes, and the transfer of active gas components from the lower layers, caused by various meteorological phenomena, SSWs being the most significant among them.

Despite the close attention of scientists to SSWs from the moment of their discovery over 60 years ago until the present, their prediction is limited to several days. Thus, the US Goddard Earth Observing System, version 5 (GEOS-5), with an upper boundary at 0.01 hPa (~80 km) and a longitude–latitude resolution of 0.3° × 0.25° predicted five days ahead the major SSW with a polar vortex split in January 2013. Sometimes, as in January 2009, the major SSW can occur under unfavorable external factors, including the phase of quasi-biennial oscillations (QBOs) of the zonal wind on the equator and the 11-year solar cycle phase (the SSWs often occur in the years of the minimum of this cycle and the eastern QBO phase, and in the years of the maximum, during the western phase). Possible frequency and time changes in SSW occurrence remain topical as greenhouse-gas concentrations are expected to grow in the atmosphere during the coming decades. Of interest is the study of tropospheric circulation specifics, as well as temperature anomalies on land and the ocean's surface in the middle and high latitudes, which may favor the occurrence of SSWs.

The topicality of studies on dynamic processes in the Arctic atmosphere was additionally confirmed in the spring of 2011, when, in the absence of an SSW, a stable stratospheric polar vortex with an inside temperature below –80°C was observed until mid-April, resulting in the formation of a significant PSC region and the activation of ozone-destroying compounds strengthened on these clouds in the presence of sunlight in March–April. As a result, a record-breaking destruction of stratospheric ozone in the Arctic in all the years of observations occurred, comparable with a similar process in Antarctica. Interestingly, before it was destroyed, the stratospheric polar vortex with the ozone anomaly formed was observed over Scandinavia nearby the northwest of Russia.

Another topical problem is the analysis of interannual variability in the dates of occurrence of the final warmings (spring breakup) of stratospheric circulation, which occur in the Arctic Region from the end of March to the beginning of May. These alterations entail a reversal of the zonal wind in the stratosphere and the destruction of the stratospheric polar vortex and, consequently, predetermine the period when ozone destruction in the polar stratosphere ends.

Validation of dynamic processes in the stratosphere–troposphere in climate models. Global climate models are the main tool to study the observed and predicted climate changes and their consequences. The reproduction of both current climate parameters and those in the coming decades depends on the quality of the reproduction of the natural variability of dynamic processes in the atmosphere. Advanced scientific groups that deal with climate modeling, the RAS Institute of Numerical Mathematics among them, participate in projects that validate the reproduction of natural variability, including the dynamic processes in the stratosphere and the troposphere. Currently, this work is done within the international Coupled Model Intercomparison Project Phase 5 (CMIP5) project [3]. It has been shown that, in models where the upper boundary of the computational domain is located sufficiently high (above 1 hPa or 56 km), the number of SSWs approximately equals the observed ones on average, while, in models with a low upper boundary, the number of SSWs is understated by almost two times on average. In models with high upper boundaries, the decrease in the speed of the zonal wind in the troposphere and the related negative Arctic Oscillation index occurs for three months after SSWs, which agrees with the observations. In models with an insufficiently high upper boundary, this stratospheric effect on the troposphere is only traced for a month after the SSWs.

The analysis of other parameters that characterize the dynamics of the stratosphere also shows that models with a sufficient number of levels in the upper stratosphere, on average, reproduce more correctly the dynamics of the stratosphere and its influence on tropospheric circulation. Based on the results of model calculations before 2010, obtained within the CMIP5 project, the possible effect of changes in stratospheric dynamics, including the attenuations of the stratospheric polar vortex and the amplifications of meridional circulation in the stratosphere, was analyzed for the surface climate during the winter period [4]. The Chemistry–Climate Model Validation (CCMVal) project also analyzes models of the dynamics and chemistry of the atmosphere without the interactive ocean.

The realistic reproduction of the stratosphere in atmospheric circulation models makes it possible to show, for example, the effect of the main mode of variability in the tropical troposphere—El Niño (the Southern oscillation related to temperature oscillations on the surface of the equatorial part of the Pacific Ocean)—on dynamic processes in the troposphere of the middle and high latitudes [5].

Stratospheric processes and the development of seasonal weather forecasts. Since relaxational (disturbance-suppressing) processes in the stratosphere run slowly, disturbances (primarily, SSWs), once originated, remain longer compared to disturbances in the troposphere. Thus, the stratosphere determines the upper boundary conditions for tropospheric processes, which in some cases prolongs the predictability of weather conditions.

In recent years, based on observation and simulation data analysis, it has been shown that stratospheric circulation anomalies, to which the change in the strength of the polar vortex belongs, cause anomalies in tropospheric circulation, which reach near-surface levels approximately in a week and can stay there for up to two months. Anomalies in the troposphere, as a rule, are characterized by the meridional shift of jet streams and related storm tracks. Due to their strongly zonal form, such anomalies are called the circular mode of extratropical latitudes in the Northern Hemisphere, or Arctic oscillation. Its positive phase corresponds to a strong polar vortex in the stratosphere and a lower pressure in the polar region compared to the middle latitudes, and its negative phase, to a weakened (often in the course of SSWs) stratospheric polar vortex and a higher pressure in the troposphere of the polar region. In the latter case, owing to the shift toward the equator and the attenuation of storm tracks, cold air masses with heavy precipitation penetrate further to the south of North America and Europe. The "nudging" procedure (when the calculated model parameters of dynamics are pulled up to observation data) for the stratosphere of extratropical latitudes during the winter period allowed us to improve the reproduction of the main modes of the surface climate (the Arctic oscillation and North Atlantic oscillation), as well as the surface temperature and precipitation in some regions, especially in Europe [6]. At present, a number of prognostic centers in the world already use this description of the stratosphere in their forecasting systems.

Aerosols and their effect on climate. As the result of powerful volcanic eruptions, whose discharges reach the stratosphere, the number of aerosol particles in it increases and stays there for up to two years, unlike the troposphere, from where these particles are quickly removed with precipitation. As a consequence, the penetration of solar emissions to the Earth's surface is reduced and the temperature of the Earth's surface decreases. This particular mechanism was proposed as a possible geoengineering method of reducing the growth rate of the near-surface temperature because of the increased concentration of greenhouse gases in the atmosphere. The first such method of influencing the climate was proposed by Academician M.I. Budyko in the early 1970s. Among the numerous doubts concerning the use of this approach is the possible negative effect of the increased amount of aerosols on stratospheric ozone, as well as a change in the precipitation mode in a number of regions.

Although this geoengineering method is technically inapplicable at present, study of the effect of the content of aerosol particles and the parameters of the near-surface climate on stratospheric circulation is of scientific interest and is implemented using climate models in many countries, including Russia.

Trends in stratospheric temperature. The increase in the concentration of greenhouse gases leads to a decrease in the stratosphere's temperature. The analysis of rocket, satellite, and balloon measurements shows that this decrease is up to 2° every 10 years in the upper stratosphere and in the lower mesosphere. Another important process that affects the temperature of the stratosphere is the recovery of stratospheric ozone, which results from the reduction of discharges of ozone-destroying substances into the atmosphere. The analysis of trends in the stratosphere's temperature is complicated by two powerful volcanic eruptions that occurred during the period of satellite observations: El Chichón in Mexico in 1982 and Pinatubo in the Philippines in 1991. These eruptions led to short-term (about two years) warmings in the tropical stratosphere by 2°–3° because solar radiation was absorbed by the volcanic aerosol.

Some simulation results obtained in recent years indicate that climate change in the coming decades may increase the meridional circulation of the atmosphere (the Brewer–Dobson circulation), which, in turn, will favor the reduction of the "average age" of small gas components of the atmosphere. For example, ozone will be transferred more quickly from the tropical region, where it is basically formed, to the middle and high latitudes.

Composition of the stratosphere and stratosphere–troposphere exchange. The results of observation and simulation data analysis have been recently obtained in the United States showing that a 10% reduction in the content of the most important greenhouse gas, water vapor, in the lower atmosphere starting with 2000 could compensate for a ~25% increase in the near-surface temperature [7]. It was assumed that an annual 1% growth in humidity in the lower stratosphere, observed in 1980–2000, could, on the contrary, lead to an increased growth in the near-surface temperature. The causes of changes in the water vapor content in the stratosphere remain unknown.

It has been established that, the water vapor transfer to the lower stratosphere from the troposphere in the tropics in winter seasons with SSWs in the Arctic is weaker than in winter seasons without SSWs. SSWs cause the cooling of the tropical stratosphere owing to the change in meridional circulation and simultaneously affect the troposphere of the tropics, amplifying the convection and cloudiness regime there. In this context, the study of changes in the water vapor content of the stratosphere, the effect of these changes on the chemical processes and the radiation balance of the atmosphere, and the specifics of water vapor transfer from the troposphere to the stratosphere is now a major scientific problem. Among other important problems is still the study of the dynamics of stratospheric ozone, which is closely related to changes both in the stratosphere's temperature and in the content of water vapor, methane, nitrogen oxides, bromine, and ozone-destroying compounds in the stratosphere, as well as the analysis of dynamic processes that predetermine the meteorological conditions of the polar stratosphere and that are responsible for the SSW occurrence and possible amplification of meridional circulation in the coming decades.

Changes in the stratospheric dynamics and the climate of the Southern Hemisphere. The results obtained over the past ten years indicate that the destruction of stratospheric ozone over Antarctica affects the circulation of the troposphere and the parameters of the near-surface climate. The significant decrease in the ozone layer at altitudes of 12–25 km in Antarctica in September–October (which is usually stronger than in the Arctic due to a more stable and stronger polar vortex) can reduce the temperature of the lower stratosphere by ~10°, which, in turn, leads to amplification of the zonal wind's jets in the troposphere and shifts them toward the pole. These processes affect the near-surface climate not only in the middle and high latitudes in the Southern Hemisphere but also in the subtropics, particularly, precipitation.

Note that, according to model calculations, the increase in greenhouse gas concentrations in the atmosphere can favor a shift of the zonal wind jets in the troposphere toward the pole. No doubt, a topical problem is the study of these two processes, taking into account the recovery of the ozone layer, which is expected in the coming decades, and the continuing growth of greenhouse gas concentrations.

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Let us briefly consider several studies on stratospheric–tropospheric interactions, as well as new methods of observing the dynamic processes and composition of the stratosphere.

In the past two years, the network of Roshydromet's lidar observations has been extending. By now, lidars capable of measuring atmospheric parameters at altitudes up to ~70 km have been installed in Obninsk (Kaluga oblast), St. Petersburg, Dolgoprudnyi (Moscow oblast), and Ardon (North Ossetia–Alania). Based on lidar observations, the specialists of NPO Taifun have analyzed the propagation of gravitational waves in the stratosphere and in the mesosphere and they determined the parameters of polar stratospheric clouds in the stratospheric vortex, when it stayed over the European territory of Russia in December 2012 [8]. In addition, the path of motion of the Chelyabinsk meteorite and its aerosol trail in February 2013 were analyzed using lidar observations and trajectory simulations. Lidar observations of volcanic dust propagation over Russia's territory during the eruption of a volcano in Iceland in April 2010 were analyzed at the Central Aerological Observatory (CAO) [9].

After a break of almost 15 years, CAO is restoring meteorological rocket probing of the middle and upper atmosphere and developing new measuring instruments for rocket observations. Although such observations are quite expensive, several scientific problems concerning studies on atmospheric processes can be solved only by using rocket observations; the use of satellite or ground-based observations does not allow us to obtain the necessary information. Rocket measurements have been carried out in the European Union and the United States and in the past five years in China and Brazil.

Considering the fact that the stratospheric polar vortex at the end of the winter season is located most often over Russia's territory, of importance are the monitoring and analysis of the vertical distribution of ozone using balloon measurements, which are also carried out within the Match international project, as well as the development of a network of land-based measurements using the French SAOZ instruments, which measure the content of ozone and nitrogen dioxide [10]. To date, CAO initiates such regular measurements at Roshydromet's ozonometric stations in Dolgoprudnyi, Murmansk, Zhigansk, Salekhard, Anadyr', and Irkutsk.

The possibilities of the unique flying laboratory M-55 Geophysica, which can reach altitudes of up to 20 km and which is equipped with Russian and foreign measuring instruments, over the past 15 years, have been used in 12 international campaigns in various regions of the Earth with the participation of CAO specialists to study dynamic and chemical processes, as well as the condition of the ozone layer in the stratosphere of the Arctic and Antarctic regions and the processes of convection and stratospheric–tropospheric exchange in the tropics. Observation data are analyzed using, among other things, chemical-transport models. The next campaign within the StratoClim European project was planned for the summer of 2016 and will be dedicated to the study of the specifics of stratospheric–tropospheric exchange and the effect of stratospheric processes on climate in the Indian Monsoon's coverage area.

Studies of the possible introduction of aerosol particles into the stratosphere in order to reduce the growth rate of surface temperatures in Russia with the participation of specialists of the Institute of Global Climate and Ecology of the RAS and Roshydromet using the climate model of the RAS Institute of Numerical Mathematics and the climate model of the RAS Institute of Atmospheric Physics were conducted to reveal the possible effect of this geoengineering method on the climate [11–14].

More than ten years ago, CAO specialists developed an optical fluorescent hygrometer FLASH capable of accurate high-resolution measurements of water vapor concentrations in the stratosphere. The Russian instrument turned out to be in high demand and proved better than American and German hygrometers in international stratospheric research experiments.

During large-scale measuring campaigns in the Arctic, Antarctic, Australia, Brazil, Africa, and

Europe, it helped conduct unique observations that revealed so-called ice geysers in the tropics and recorded the moment of the formation of an ice stratospheric cloud in the Arctic for the first time. Such clouds play a key role in the spring destruction of ozone in the polar stratosphere [15, 16].

In addition, CAO, having analyzed observation data, revealed the effect of Rossby wave trains in the troposphere on the amplified propagation of wave activity from the troposphere and on the split of the stratospheric polar vortex in the Arctic and Antarctic during the SSW event [17, 18]. The conducted model calculations of SSW in the Antarctic in September 2002 confirmed the possibility of such a mechanism.

Based on the analysis of reanalysis and simulation data, the group of scientists from the Russian State Hydrometeorological University (St. Petersburg) studied a variability of dynamical processes in the stratosphere and troposphere, including the climatic variability of the times of the spring-time breakup of the stratospheric circulation [19], and considered the effect of the free atmospheric oscillations on the frequency of the SSW origin and intensity [20]. It was shown that in the recent decades a significant amplitude growth of the stationary planetary wave with a zonal wave number $m = 1$ has been observed in the stratosphere, which leads to an amplification of the nonlinear interaction of this wave with the zonal mean flow and, as a consequence, to the growth of magnitude of irregular oscillations of wave activity and the mean flow the so-called stratospheric vacillations [21]. A conclusion has been made that dynamical processes in the stratosphere are becoming increasingly irregular and this should lead to more often and, possibly, more intensive development of temperature anomalies and regional circulating cells in the troposphere.

The specialists of Roshydromet's Siberian Regional Hydrometeorological Research Institute (Novosibirsk) and of the Institute of Climatic and Ecological Systems Monitoring, RAS Siberian Branch (Tomsk), after conducting research into the effect of the fall snow cover size on the near-surface temperature in Siberia in the winter period and using the calculation data of the Planet Simulator intermediate-complexity climate model, have shown that the highest effect of fall snow cover anomalies manifests itself the next winter in December. This work has shown that this effect is largely predetermined by close interaction between the troposphere and the stratosphere [22]. Previously, model studies on the role of the polar vortex's changing strength in the circulation of the lower troposphere were conducted [23].

After studying the QBO formation mechanisms, a new version of the high spatial resolution climate model was created in the RAS Institute of Numerical Mathematics. It reproduces QBOs with characteristics close to those observed [24]. Problems of QBO structural stability and synchronization with various periodical processes (the Sun's annual cycle, the equatorial wind's semi-annual oscillations, etc.) were studied, and the decisive role of planetary waves in the formation of the cycle's main period was shown, as well as the important role of short waves in QBO energy transmission and synchronization and in the semi-annual mesospheric cycle [25].

Russia's Hydrometeorological Center, based on the studies of dynamic factors that affect the propagation of planetary waves from the troposphere to the stratosphere, has shown that the nature of tropospheric circulation over Taimyr in October may be a precursor of the prevalent winter phase of the Arctic oscillation [26].

The Obukhov Institute of Atmospheric Physics (IAP), RAS, conducted the study of nonlinear temperature changes in the mesopause region against global climate changes using hydroxyl emission for spectrometric measurements. The measurements were carried out at the IAP station in Zvenigorod (Moscow oblast), which is part of the Network for the Detection of Atmospheric Composition Change (NDACC). In particular, it has been shown that the general decrease in the mesopause temperature over Zvenigorod in winter (when the strongest interannual changes were observed) from 1960 to 2012 was 35°, while the linear trend was estimated at –9.9° over 10 years from 1960 to 1987, it was four times smaller, –2.4° over 10 years from 1987 to 2012 [27].

Moreover, the RAS Institute of Atmospheric Physics uses an original methodology to perform perennial regular spectrometric measurements of the nitrogen dioxide (NO_2) content in the stratosphere and the troposphere. The variability of the NO_2 content in the stratosphere and in the atmospheric boundary layer was studied thoroughly [28]; estimates of trends in the stratospheric NO_2 content were obtained [29]; and a significant negative anomaly in the stratospheric NO_2 content, caused by stratospheric air from the region of the Arctic ozone "hole," was observed over Moscow in the spring of 2011 [30].

The Western Branch of the Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, RAS (Kaliningrad), studies the response of the thermosphere and ionosphere to the SSW. According to the results of estimates and observation data, anticorrelation of temperature disturbances in the mesosphere and the lower thermosphere was observed during SSWs. It was shown for the first time that the westward-bound circumpolar vortex at the altitudes of the lower thermosphere is destroyed during SSWs and a more complex circulatory system is formed. It was established that negative global disturbances of electron density in the ionosphere, observed by orbiters during SSWs in January 2008, were related to temperature and density changes in the mesosphere–lower thermosphere. The warming of the thermosphere, which occurs during SSWs, leads to a reduction in the ratio of atomic oxygen concentrations to the molecular nitrogen ($n(\mathrm{O})/n(\mathrm{N}_2)$) concentrations and, consequently, the reduction in the electronic density at altitudes F of the ionosphere in the midlatitudes [31].

In recent years, a number of textbooks and books dedicated to circulation of the middle atmosphere have been published in Russian. In 2014 a textbook, *General Circulation of the Atmosphere*, by Yu.P. Perevedentsev, I.I. Mokhov, and A.V. Eliseev was published. In 2011, the Fizmatlit Publishing House published in Russian the book *Stratosphere–Troposphere Interactions* by Indian Professor K. Mohanakumar, which touches on the most important aspects of research into troposphere–stratosphere interactions. A collection of articles was prepared by the results of the Enviromis international school conference of young scientists in Petrozavodsk in September 2014 on climate simulation using remotely the climate model of the RAS Institute of Numerical Mathematics.

Despite a number of achievements, the current condition of Russian research in stratosphere–troposphere interactions cannot be characterized as consistent with the level of advanced scientific powers, primarily, the United States, Britain, Germany, Canada, and Japan. The integration of national research into international programs performed within the SPARC framework could contribute to the development of this research in Russia. It is advisable to use more actively the opportunity of reviewing national research projects by foreign experts for their support on a competitive basis.

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