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Russian Studies of the Middle Atmosphere in 2003–2006

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Abstract—This review of the results of the 2003–2006 Russian studies of the middle atmosphere, which was prepared by the Middle Atmosphere Commission of the Section of Meteorology and Atmospheric Sciences of the National Geophysical Committee, Russian Academy of Sciences, is presented as a national report on meteorology and atmospheric sciences for the XXIV General Assembly of the International Union of Geodesy and Geophysics (Perugia, July 2–13, 2007).[1]

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1. INTRODUCTION

The middle atmosphere is the portion of the Earth's atmosphere that extends between the tropopause and the turbopause (roughly at heights of 10 to 100 km). As is well known, the photochemical processes, which produce most of the trace gases affecting the content of ozone, are of great importance within this height range. Ozone, in turn, absorbing solar ultraviolet radiation determines the thermal structure to a great extent and, thus, the circulation of the middle atmosphere. The lower ionosphere (the D-region) that extends at heights of 50 to 100 m also belongs to the same height range. The ion-generation processes that occur in the lower ionosphere are closely related to the chemistry of neutral components and to meteorological processes. It should be noted that a regular regime, which is determined by the absorption of solar radiation (both daily and annual cycles), is sometimes disturbed by the influence of large-scale waves arriving from the troposphere and by the processes associated with solar activity (variations in solar electromagnetic and corpuscular radiation).

This paper is based on a review of the results of Russian studies of the middle atmosphere done in 2003–2006, which was prepared by the Middle Atmosphere Commission of the National Geophysical Committee, Russian Academy of Sciences, as a national report on meteorology and atmospheric sciences for the XXIV General Assembly of the International Union of Geodesy and Geophysics (Perugia, July 2–13, 2007).

2. CIRCULATION IN THE MIDDLE ATMOSPHERE AND ITS VARIABILITY

2.1. An Empirical Global Climate Model of Prevailing Wind and Migratory Tides on the Basis of Radar and Satellite Measurements of Wind at Heights of the Mesosphere–Lower Thermosphere (MLTh, 80–100 km)

At the Institute of Experimental meteorology (IEM), the empirical climate models of prevailing wind and migratory tides have been constructed for each month of the year and for heights of 80 to 100 km (the GEWM model) on the basis of multiyear measurement data on wind speed and direction obtained with radars operating at the network of 46 stations and satellite wind data (UARS satellite, HRDI and WINDII instruments). These data cover mainly 1990–2001. Figures 1 and 2 give the height–latitude distributions of the speeds of prevailing zonal and meridional winds for January, April, July, and September [1–4].

A comparison between the GEWM model and the Hedin (HWM-93) and Fleming (1990) models has revealed a significant difference in the seasonal cycle and latitudinal structure of meridional wind. Figure 3 shows the seasonal cycle of the speeds of zonal and meridional winds according to data obtained with different models. It can seen that the HWM-93 model does not reproduce the zonal-wind variations observed at a height of 90 km. The Fleming model differs significantly from the HWM-93 and GEWM models during such variation periods.

The climatic latitudinal distributions of zonal-wind speed are shown in Fig. 4 for four months. The HWM-93 model yields the strongly smoothed latitudinal distributions of wind, and the Fleming model incorrectly reproduces the latitudinal variations in zonal-wind speed in the vicinity of the equator for January and March. A detailed analysis of interhemispheric differ-

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[1] Russian National Report on Meteorology and Atmospheric Sciences for 2003–2006, edited by I.I. Mokhov and A.A. Krivolutskii, MAKS Press, National Geophysical Committee, Russian Academy of Sciences, Moscow, 2007. See also I.I. Mokhov, Russian Studies in Meteorology and Atmospheric Sciences from 2003 to 2006, *Izvestiya Rossiiskoi Akademii Nauk, Fizika Atmosfery i Okeana* (*Izvestiya, Atmospheric and Oceanic Physics*), **49**, 163 (2009).

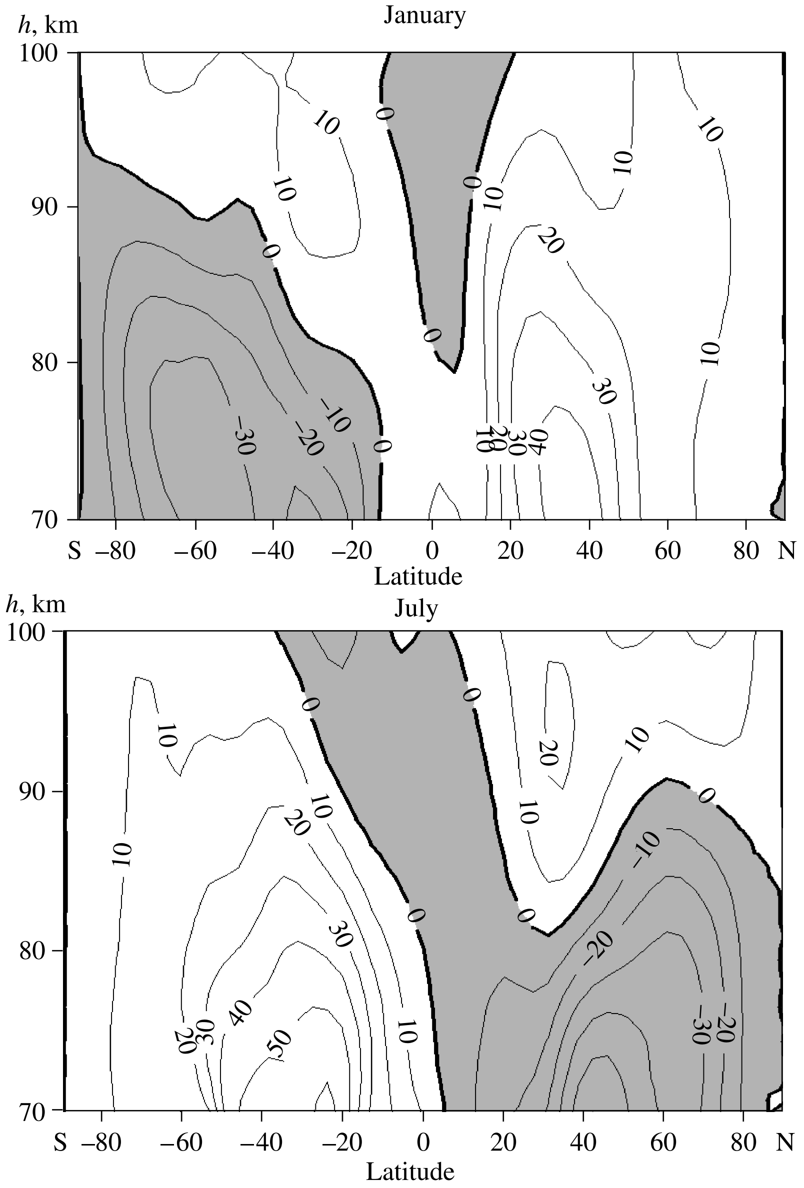

Fig. 1. Altitude–latitude sections of the monthly mean zonal wind (positive values are in the eastward direction).

ences between the parameters of wind regime in the polar mesosphere and lower thermosphere is given in [5].

2.2. *An Analysis of Long-Term Trends in the Parameters of the MLTh Wind Regime*

The varying trends in the MLTh wind regime in the middle latitudes of the Northern Hemisphere have been analyzed at the IEM on the basis of multiyear measurement data on wind parameters obtained at the Obninsk (Russia), Collm (Germany), and Saskatoon (Canada) stations. For the first time, possible structural trend variations have been taken into account to reveal and date such variations in the trends of wind-regime parameters over the course of 1964–2004. The results of the analysis suggest that, in 1964–2004, the trends of some wind-regime parameters changed their rates and directions (there were increases and decreases) [6, 7].

Figure 5 shows the variations in the annual mean speeds of the prevailing zonal and meridional winds obtained from data averaging over the three stations. The speed of the zonal wind ceases to decrease and the tendency for an increase occurs. The speed of meridional wind ceases to increase, and no significant trend has been observed since the early 1990s.

Figure 6 shows the variations in the annual mean semidiurnal-tide amplitude [8] obtained from averag-

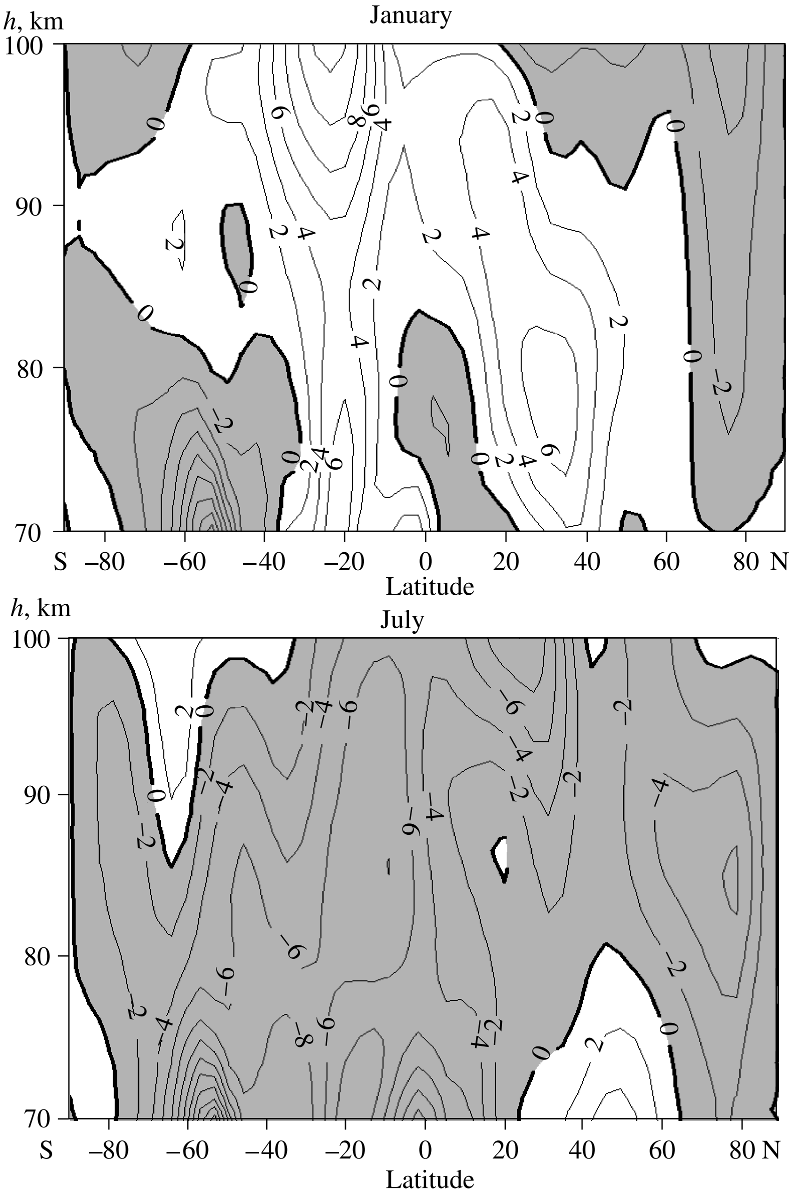

Fig. 2. Altitude–latitude sections of monthly mean meridional wind (positive values are in the northward direction).

ing over the three stations. It is seen that the rate of decrease in the amplitudes of semidiurnal tide significantly decreases (approximately by a factor of six). The rate of amplitude decreasing was 1.1–1.4 m/s/year in the 1960s and about 0.2 m/s/year after the trend change.

2.3. An Analysis of the Instability of Zonal Flow in the Middle Atmosphere and Nonlinear Planetary-Wave Interactions

It has been shown theoretically (numerical simulation) and on the basis of experimental data on the wind-regime parameters for the MLTh in the region of both middle and high latitudes that interdiurnal wind variations with periods of 2 to 5 days during solstice may occur due to zonal-flow instability [9–11]. This instability generates a few primary waves which nonlinearly interact with one another and with the inhomogeneities of the background atmosphere. These interactions generate a spectrum of secondary planetary waves, which continue to interact nonlinearly, and thus occurs a cascade of nonlinear interactions. The energy transfer in this cascade trends mainly towards large zonal and time scales.

The wavelet-transformations of wind data obtained at the Esrange station in summer 2000 and numerical-simulation data have been calculated [9, 11]. The first peak of activity of quasi-two-day oscillations is asso-

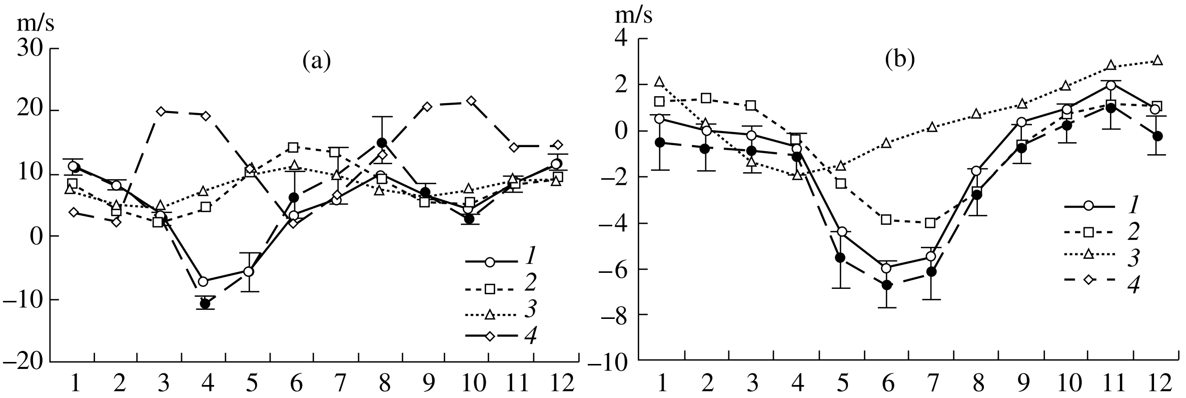

Fig. 3. Comparison of the seasonal variations in the zonally mean prevailing wind: (a) zonal and (b) meridional wind at a height of 90 km in the middle latitudes (52°–56° N) of the Northern Hemisphere according to experimental data ((*1*) corresponds to GEWM-1; (*2*) corresponds to HWM-93, (*3*) corresponds to WINDII, and (*4*) corresponds to Fleming et al. (1990)).

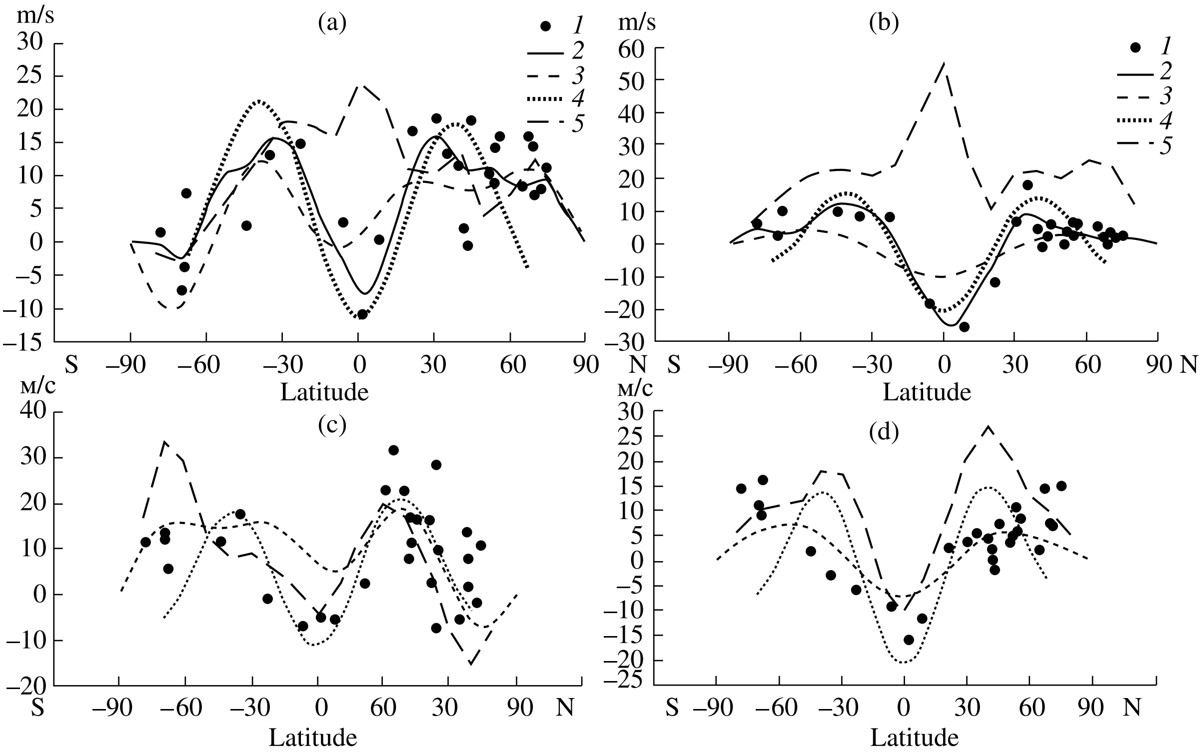

Fig. 4. Comparison of latitude variations in zonal prevailing wind at a height of 90 km on the basis of different experimental data for (a) January, (b) March, (c) July, and (d) September ((*1*) corresponds to ground-based data; (*2*) corresponds to GEWM-1 data; (*3*) corresponds to HWM-93 data, (*4*) corresponds to WINDII data; and (*5*) corresponds to Fleming et al. (1990)).

ciated with an unstable summer mean zonal flow and an excited two-day wave with the zonal wavenumber 4. Then, due to the interaction between this oscillation and the planetary wave with about a nine-day period observed in the stratosphere according to the Met Office data, secondary waves occur with the zonal wavenumbers 3 and 2. The superposition of secondary waves forms the peaks of wave activity; these peaks follow the first wave.

3. THEEFFECTS OF EXTRA-ATMOSPHERIC FACTORS

The effects of extra-atmospheric factors which result in the observed variability of ozone are reduced, first, to the direct influence of solar UV-radiation variations on ozone and, second, to their influence on the chemical components affecting the photochemical balance of ozone (such as atomic oxygen formed under O_2 dissociation by UV radiation, as well as and

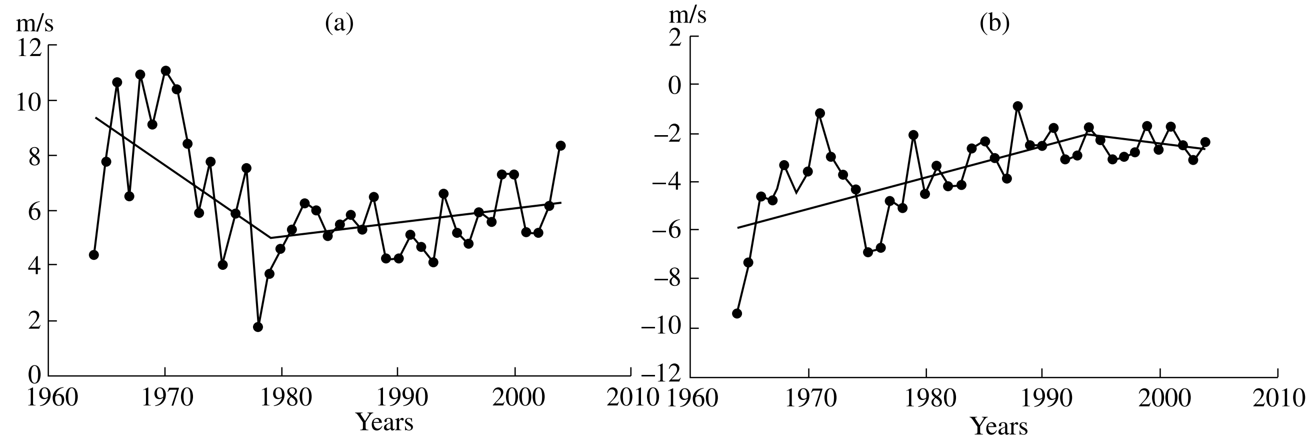

Fig. 5. Time variations in annual mean (a) zonal and (b) meridional winds (the solid curves show trends).

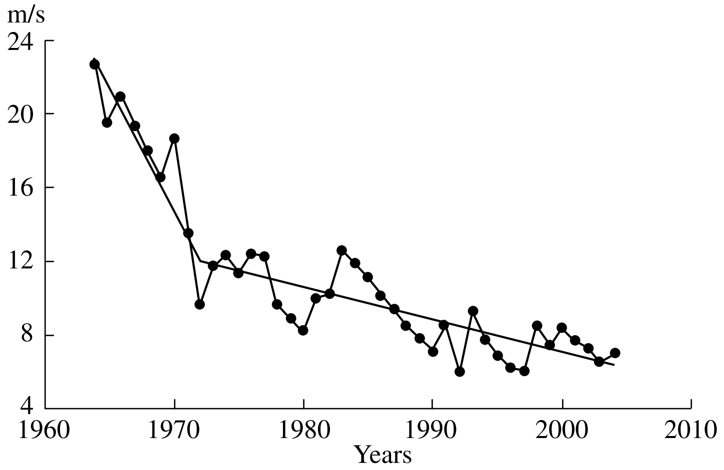

Fig. 6. Time variations in the amplitudes of annual mean semidiurnal tide at a height of 90 km (zonal component) (the solid curve shows trend).

nitric oxides and water-containing radicals) which are formed after atmospheric ionization by high-energy particles arriving in the polar atmosphere after proton storms on the Sun. The obtained theoretical estimates of the efficiency of generating both NO and OH molecules under a solar-proton ionization of the atmosphere have shown that, in this case, for every pair of ions formed under a retardation of active protons, there are 1.27 molecules of odd nitrogen and approximately two OH radicals formed in the atmosphere due to a chain of ion-molecular reactions. After that, chemical catalytic cycles intensify and result in ozone destruction within storm periods:

$$NO + O_3 \longrightarrow NO_2 + O_2$$

$$\underline{NO_2 + O \longrightarrow NO + O_2}$$

$$\text{Net: } O_3 + O \longrightarrow O_2 + O_2$$

$$OH + O \longrightarrow H + O_2$$

$$\underline{H + O_3 \longrightarrow OH + O_2}$$

$$\text{Net: } O_3 + O \longrightarrow O_2 + O_2.$$

The chemical lifetime of the “family” of odd nitrogen in the Earth’s atmosphere over the polar region is long; therefore, the corresponding effects on ozone may have long-term consequences. The lifetime of the corresponding family of odd hydrogen is much shorter, but its role in the mesosphere is significant. The results of a three-dimensional simulation of the consequences of one of the most powerful proton events of the 23rd cycle of solar activity (July 14, 2000) [12, 13] are given below.

Time variations in ionization within a period of the solar proton storm of July 2000 have been calculated from the satellite (GOES) measurements of the fluxes of active particles in different energy channels. The calculations have shown that the maximum ionization during the given proton event occurs on July 15, 2000, and the total duration of the period of increased ionization is no more than 2–3 days. The calculated values of the rates of ionization have been used in a chemical block of a three-dimensional model, which resulted in an increase in the rate of formation of both hydrogen and nitric oxides. In the three-dimensional calculations, the given profile of the rate of ionization is assumed to be unchanged in the polar latitudes (above 60°) at both of the Earth's hemispheres. This model was developed at the Laboratory of Chemistry and Atmospheric Dynamics of the Central Aerological Observatory.

Figure 7 gives the calculated variations in the content of ozone (for 65° N and 65° S) obtained from a comparison of two scenarios: with and without considering the storm effect (model climatological ozone distribution). It can be seen that ozone in the mesosphere over the northern polar region is almost completely destroyed due to the emission of additional hydrogen and nitric oxides. In this case the influence of protons on the ozone (in relative units) decreases with a decrease in height. It can also be seen that the proton-storm effect in the southern polar region is much weaker than in the northern polar region; this can be explained by the photochemical factor: the catalytic cycles destroying ozone are much less intensive in the absence of solar radiation.

The calculated spatiotemporal distribution of ozone caused by its destruction during the proton storm must change the thermal regime and circulation of the atmosphere over the northern (sunny) polar region, because ozone is a radioactive gas. Ozone variations have been taken into account in a radiation module of the model of general circulation, and this has made it possible, for the first time, to calculate the three-dimensional dynamic response of the middle atmosphere [13].

Figure 8 shows the latitudinal and temporal variations in air temperature for July 18 after the storm. It follows from Fig. 8 that, in spite of the fact that the destruction of ozone occurred in the high latitudes of the Northern Hemisphere, the temperature variations reach much lower latitudes. These variations are negative and account for several degrees in the region of ozone destruction, which is in agreement with what we expect, because, in the sunny region, a decrease in the content of ozone results in a corresponding decrease in warming. The surprising thing is that a sufficiently strong positive temperature variation is observed above the level of ozone destruction; this is evidently not associated with the reasons for the radiation's character. A more detailed analysis has shown that this effect is caused by variations in the forcing of gravity waves propagating from the troposphere.

Figure 9 shows the latitudinal and temporal structures of the variations in the field of zonal wind caused by variations in warming due to the proton storm. These variations (in the absolute value of zonal wind) are negative everywhere, which is in accordance with the trend of variations in thermal wind in the atmosphere. It can be seen that strong variations in zonal wind also occur above the level of ozone destruction and reach the lower thermosphere. It should be noted that no reactions are observed in air temperature or wind speed over the southern polar region (polar night); this is natural, because ozone variations (slight) in the absence of solar radiation do not result in an energy imbalance of the atmosphere.

In a series of studies [12–17], the response of the polar ozonosphere to the solar proton events of the 23rd cycle of solar activity has been studied with the aid of a photochemical simulation. A review of the results obtained in this area is given in [18].

At the Arctic and Antarctic Research Institute (AARI) of the Federal Service for Hydrometeorology and Environmental Monitoring of the Russian Federation, a significant relationship has been revealed—using the method of superposition of epochs [19–21]—between variations in solar-wind intensity and meteorological parameters (air temperature, wind, and cloudiness) for the Antarctic region. It is also shown that the morphology of the reaction of these meteorological parameters and a possible mechanism of such an effect are caused, to a great extent, by the specific (unique) conditions of this continent.

On the basis of published data on variations in solar activity (the number of spots and the flux F 10.7) and air temperature, a spectral structure of cyclic aperiodic (quasi-biennial) variations in these parameters has been studied in [23]. It was shown that the quasi-biennial temperature variations in the mesopause layer correlate well with the analogous variations in the indices of solar activity and the distribution of amplitudes in the vicinity of the mean value (27 months) is normal. On the basis of these data, it was concluded that the period values obtained using spectral analysis are probably of a random character.

4. QUSI-BIENNIAL OSCILLATIONS IN THE ATMOSPHERE

A series of statistical studies (on the basis of measurement data obtained in the middle latitudes of North America and western Europe) have been conducted at the Institute of Atmospheric Physics, Russian Academy of Sciences. These studies have made it possible to reveal two periods of quasi-biennial variations (QBVs) in air temperature, wind velocity and direction, and ozone concentration in the stratosphere and troposphere, which group in the vicinity of 2 and 2.5 years [23, 24]. The studies conducted allow one to conclude that the QBVs in these parameters reflect a combined effect of El Niño–Southern Oscillation,

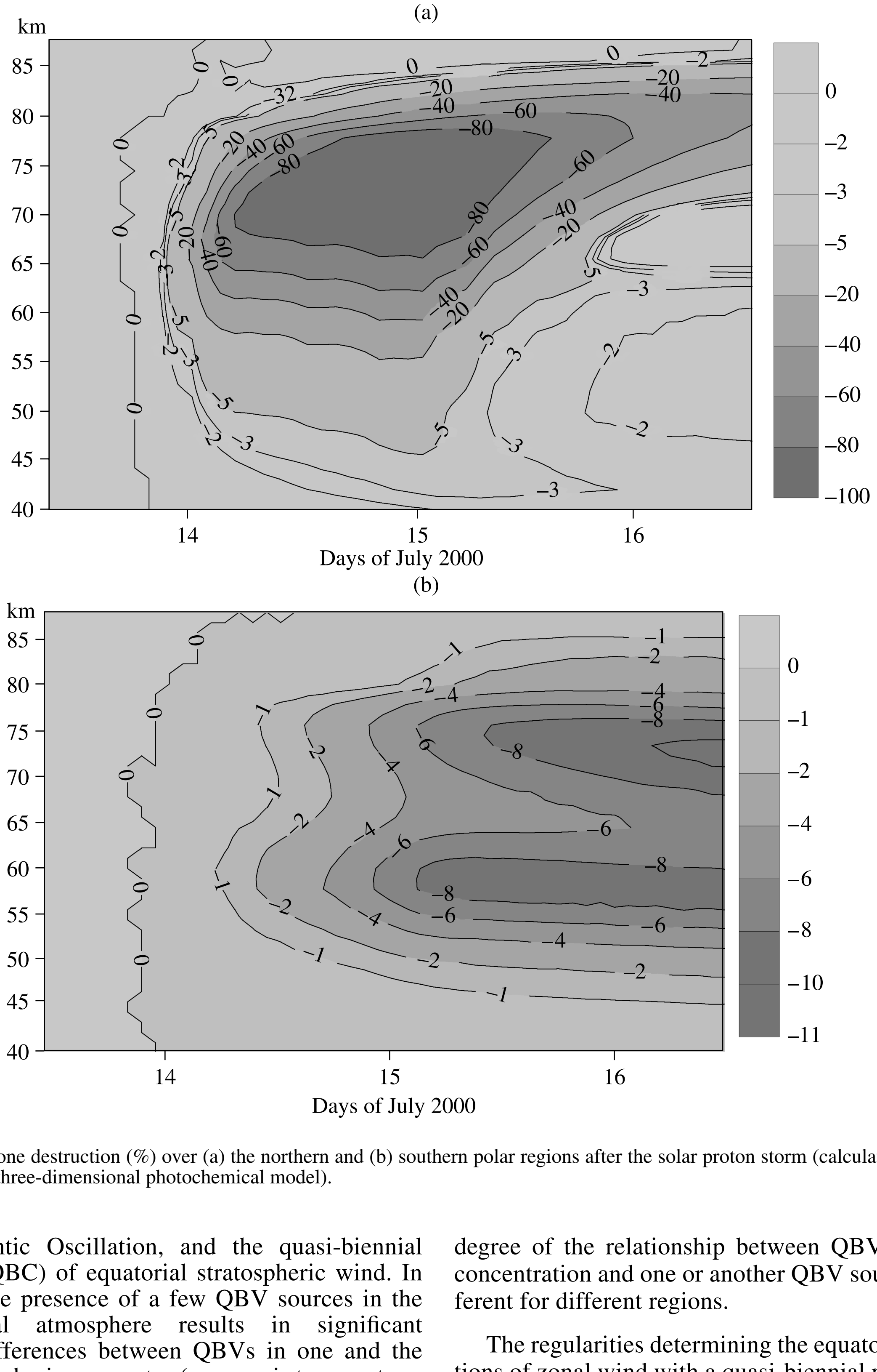

Fig. 7. Ozone destruction (%) over (a) the northern and (b) southern polar regions after the solar proton storm (calculation on the basis of a three-dimensional photochemical model).

North-Atlantic Oscillation, and the quasi-biennial cyclicity (QBC) of equatorial stratospheric wind. In this case the presence of a few QBV sources in the extratropical atmosphere results in significant regional differences between QBVs in one and the same atmospheric parameter (ozone, air temperature, etc.), as well as in important differences between QBVs in different parameters within the same region. In particular, the period and phase of the ozone QBVs strongly vary in height, and this dependence and the degree of the relationship between QBVs in ozone concentration and one or another QBV source are different for different regions.

The regularities determining the equatorial oscillations of zonal wind with a quasi-biennial period, their relation to seasonal variations, and their dependence on the level of solar activity have been studied statistically at the Arctic and Antarctic Research Institute (AARI) [28–30]. A relationship has been revealed

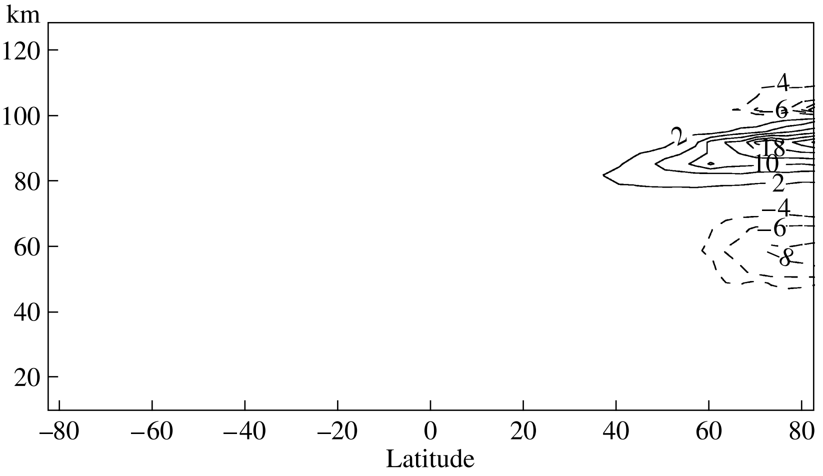

Fig. 8. Latitudinal structure of variations in the atmospheric temperature (K) for July 18 due to the solar flare of July 14, 2000 (calculations on the basis of a general circulation model).

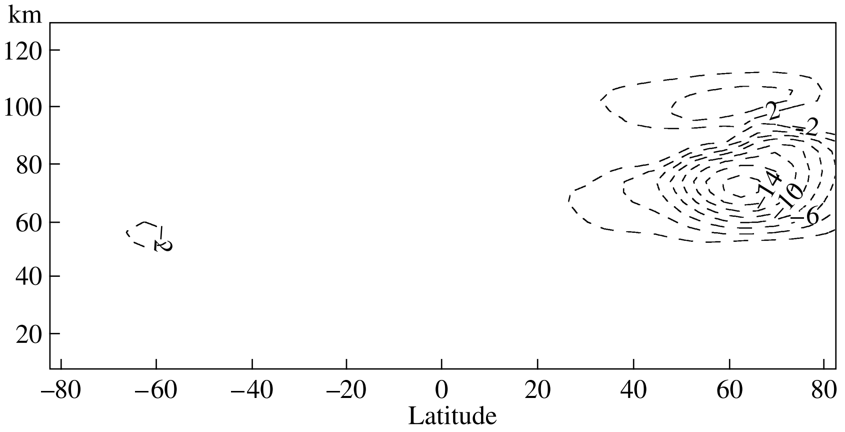

Fig. 9. Latitudinal structure of variations in zonal wind (m/s) for July 18 due to the solar flare of July 14, 2000 (calculations on the basis of a general circulation model).

between equatorial oscillations and the phenomenon of "ozone anomaly" in the Antarctic region.

5. STUDIES OF THE TEMPERATURE AND COMPOSITION OF THE MIDDLE ATMOSPHERE

5.1. Relation between the Temperature and Composition of the Middle Atmosphere

Atomic oxygen is an important component in the atmosphere at heights of 80 to 110 km; it is formed due to photodissociation under the influence of ultraviolet solar radiation. In this case the process of dissociation of molecular oxygen with the following recombination of atomic oxygen determines both the thermal and dynamic regimes of the middle atmosphere. A model of the altitude distribution of atomic oxygen (for night hours) in the mesopause region and the lower thermosphere has been developed in [31] on the basis of multiyear data on the altitude distributions of the middle-atmosphere temperature using an empirical model of variations in oxygen emission (557.7 nm) during night hours and the current photochemical processes of its occurrence. Seasonal variations in the altitude distribution of the concentration of atomic oxygen have been obtained, as have their dependence on solar activity and multiyear trend. Comparing model results with rocket data has shown a satisfactory agreement between them. This model can be used in analyzing multiyear variations in the atmospheric composition at heights of 80 to 100 km.

As is shown in Section 3 of this review, solar proton storms have a strong influence on the chemical composition, temperature, and dynamics of the middle atmosphere in the polar latitudes. The intensification of nightly nonthermal emissions of carbon dioxide in the 4.3- and 15-μm bands in the mesosphere and the lower thermosphere during proton events was estimated for the first time in [32]. It was shown that, within these periods, an increase of emission in the 4.3-μm band is probable, but its significant increase in the 15-μm band is highly improbable. Whatever the energy of the incoming protons is, an increase of emission in the 4.3-μm band is likely only above 80 km. In this case, the oscillatory excitation of theN_2molecules by the impacts of secondary electrons formed during solar proton events, which is followed by an CO_2-molecule excitation during the N_2–CO_2 collisions, is what excites the oscillating states of carbon-dioxide molecules (the transitions from which form an emission in the 4.3-μm band).

In [33], an attempt was made to analyze the response that the monthly mean temperature of the middle atmosphere has to solar activity. In addition, seasonal variations and their response to solar activity have also been revealed on the basis of rocket and spectrophotometric data on atmospheric temperature at heights of from 30 to 100 km. The maximum and minimum seasonal variations are observed at heights of 80–95 km and 55–70 km, respectively. The height of the zero response of middle-atmospheric temperature to solar activity ranges from 55 to 70 km throughout the year. An empirical model of the response of middle-atmospheric temperature with respect to height and season is also presented. In [34], the profiles of atmospheric temperature and concentration were calculated for heights of 30–110 km.

One distinctive feature of the summer polar mesosphere (cold) is the occurrence of noctilucent clouds at heights of from 80 to 85 km. In accordance with theoretical considerations, a decrease in air temperature below 150 K is favorable to their formation. In [35], the longitudinal and temporal distributions of the occurrence of noctilucent clouds in the summer months (June–July) have been analyzed using data obtained from 20-year observations; this has made it possible to reveal that the chances of their occurrence over the continents are better than over the oceans. The longitudinal inhomogeneity of the distribution, which (in the authors' opinion) is related to a spatial modulation by planetary waves, was also revealed.

5.2. Stratospheric Content of NO_2 and its Variations

Nitric oxides play a key role in the photochemical balance of atmospheric ozone. In the middle atmosphere, the portion of a nitric cycle amounts to 50% of the photochemical destruction of ozone. At the Zvenigorod Scientific Station (ZNS) of the A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, the vertical distribution and total content of nitrogen dioxide NO_2 have regularly been measured since the 1990s [36]. The ZNS is among the stations of the International Network for the Detection of Atmospheric Composition Change (NDACC), and the measuring capabilities of the instruments used at this station have been confirmed by international comparisons made under the NDACC aegis. The method of retrieving the NO_2 content that was used makes it possible to efficiently separate the stratospheric and tropospheric (affected by lower-tropospheric pollutants) portions of the total NO_2 content in a vertical atmospheric column; this is very important for identifying long-term stratospheric variations and allows one to separately study the stratospheric and tropospheric portions of NO_2 [36–38].

A significant negative trend of the NO_2 content in a stratospheric column ~ –(12 ± 4)% over ten years) was obtained from 14-year measurements at the ZNS. This trend is significantly larger (in module) than and opposite in sign to the total NO_2 trend obtained at the Lauder station in New Zealand (see Liley et al., Journal of Geophysical Research, 105 (D9), 11633–11640 (2000)). The observed trends of the stratospheric content of NO_2 still cannot be explained in the framework of photochemical models. Calculations with a SOCRATES two-dimensional model have yielded an insignificant negative trend of the NO_2 content in a stratospheric column in the middle and polar latitudes [39].

5.3. The Numerical Simulation of Long-Term Variations in the Mesosphere

The SOCRATES two-dimensional interactive model of the photochemistry, radiation, and dynamics of the atmosphere developed at the US National Center for Atmospheric Research has been used to study both mesospheric thermal and chemical responses to the variations in the concentrations of greenhouse gases observed in the second half of the 20th century (CO_2, CH_4, water vapor, N_2O, and chloro- fluorocarbons), as well as responses to possible variations in zonal-flux drag and diffusion in the middle and upper atmospheres due to internal gravity waves (IGWs) [40]. According to the results of model calculations, the increase (over 50 years) in the concentrations of greenhouse gases causes a cooling of the middle mesosphere and the mesopause layer by 4–6 K and 3–7 K, respectively. The accompanying variations in the meridional circulation of the mesosphere decrease the purely radiative effect of greenhouse gases. The effect of cooling the upper mesosphere and the mesopause vicinity reaches its maximum in winter if the simultaneous increase in the concentrations of greenhouse gases and in drag and diffusion due to IGWs is taken into consideration. According to one chosen value of increase in drag and diffusion (from 30 to 50%), the model predicts the cooling of the extratropical upper mesosphere in winter by 6–10 K to 10–20 K over 50 years of the 20th century. However, the model thermal

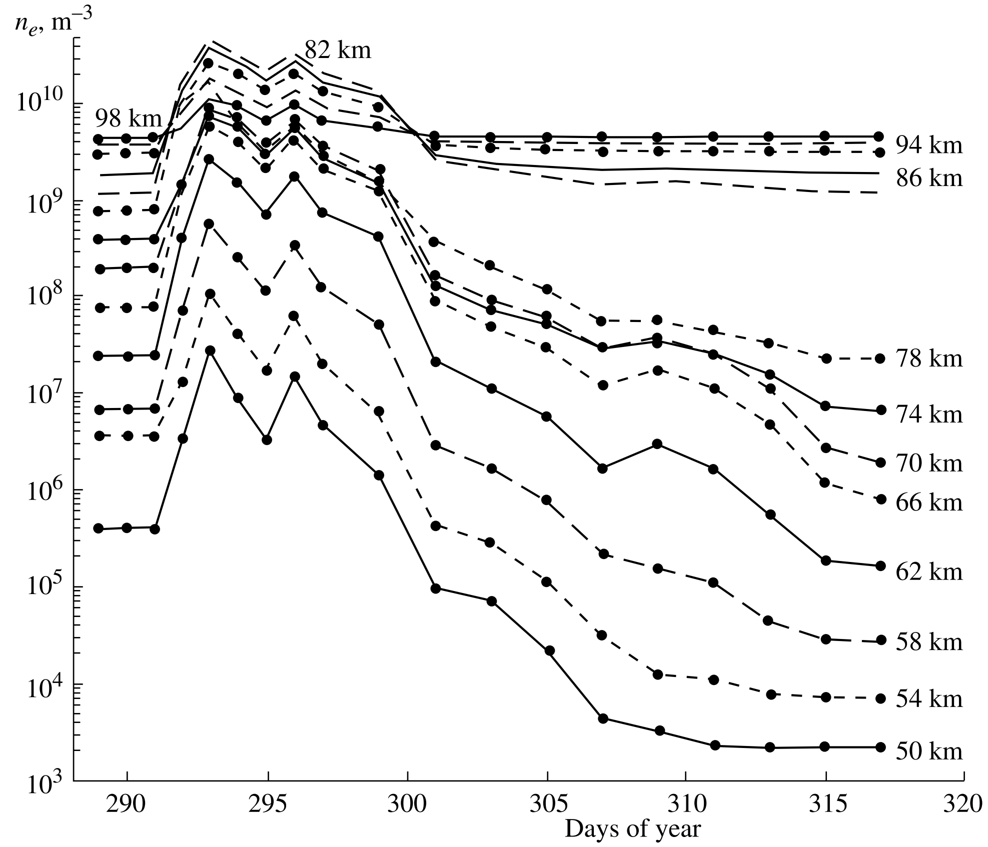

Fig. 10. Variations in electron concentration for 70°N during the solar proton storm of October 1989 (photochemical modeling).

response of the mesopause vicinity is insignificant in summer, which is in agreement with observational data. In spite of the fact that the calculated cooling of the winter mesopause is less than the long-term cooling observed at the end of the last century at some observation sites (for example, at the ZNS), these results make it possible to conclude that the temperature trends observed in the mesosphere cannot completely be explained only by increased concentrations of greenhouse gases. The long-term variations in the dynamics of the middle atmosphere (and the troposphere), including variations in the activity of IGWs, can significantly contribute to the observed long-term variations in the thermal structure and chemical composition of the mesosphere.

5.4. The Lower Ionosphere

As noted in the Introduction, the parameters of the lower ionosphere are closely related to the parameters of the neutral middle atmosphere, which, in turn, is affected by the troposphere in the form of wave disturbances propagating upward and by the disturbances arriving from above in the polar regions during solar flares (see Section 4). During proton storms (and, as a result, the rapid increase of ionization in this height range), an intensive interaction occurs between neutral and charged chemical components which results in the additional generation of nitric oxides and hydrogen radicals. In these periods, the parameters of the lower ionosphere significantly vary. For example, the electronic concentration in the periods of intense flares may be comparable to the corresponding values in the F-region of the ionosphere and may increase by a few orders of magnitude. The content of other ionic components also significantly changes (it increases).

At the Laboratory of Chemistry and Atmospheric Dynamics of the the Central Aerological Observatory, in cooperation with colleagues from the Bratislava University (Slovakia), a series of studies on the response of the ionic composition of the D-region of the ionosphere during periods of intense proton storms has been conducted. These studies are based on numerical photochemical models. In addition, the ionization of the polar atmosphere has been calculated from data on the fluxes of solar cosmic rays obtained from satellite measurements in different energy channels. Then, with the aid of a photochemical model of neutral composition, its variations (in this case, the most important are variations in the content of nitric oxide) were calculated when the efficiencies of the emissions of nitric- and hydrogen-oxide molecules are specified (see Section 4). The calculated rates of ionization and variations in the neutral composition due to the proton storm have been used in the photochemical model of the D-region of the ionosphere to calculate variations in the concentrations of electrons and other negative and positive ions. Figure 10 shows the curves of electron concentrations at different heights during the solar proton storm of October 1989 [14]. A rapid increase in electronic concentration during this solar proton event is seen in Fig. 10. In [41] it is shown that the main role in the formation of the nighttime D-region of the ionosphere over the Molodezhnaya station (Antarctic) located under the southern auroral oval is played by electrons that are pouring out. The results of processing experimental data have made it possible to determine the parameter λ for primary ions, the formation rate of electrons, and their stream. The independent measurements of electron streams with the energies $E > 40$ keV have made it possible to calculate the height distribution of electron streams. The possibility of revealing meteorological effects in the behavior of the electron concentration in the high-latitude D-region at the stations on Hase Island and Molodezhnaya has been considered. No statistically significant dependences have been revealed for Hase Island. The dependences that electron concentration has on the zonal component of wind speed in the summer and on the meridional component in winter have been found for the station Molodezhnaya. Rocket data have been used for this analysis.

CONCLUSIONS

The presented results of the studies of the processes occurring in the middle atmosphere, which were obtained by Russian scientists in 2003–2006, are new. They have been widely presented at the international level and published in journals under review. These results obtained on the basis of observational data (including domestic) and numerical simulations demonstrate the complexity of the physical processes occurring in this height range caused by the nonlinear interaction between atmospheric dynamics and chemistry. In particular, it is shown that the effect of cosmic rays contributes to the variability of the chemical components of the middle atmosphere, including ozone. One can find a more detailed discussion of the results obtained using the list of references, including the reviews [18, 42].

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SPELL: 1. Portnyagin