Study of the influence of atmospheric processes on ionization of the *F*2-layer of the ionosphere

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Data obtained on slant sensing paths Magadan–Irkutsk and Norilsk–Irkutsk indicate rapid increase of maximum applicable frequencies at morning and daylight hours in the period from September 24 to 26, 2005. At the same time, we observed increase of ionization according to the data of vertical sensing at the stations analyzed. The period considered is characterized by quiet geomagnetic conditions. We discuss possible mechanisms of observed variations of ionospheric parameters. Analysis included consideration of satellite data on vertical distribution of temperature in the stratosphere–mesosphere obtained by Microwave Limb Sounder (MLS) installed on the Earth Observing System (EOS) Aura satellite. Also we used data on the atomic oxygen to molecular nitrogen concentration ratios $[O]/[N_2]$ at altitudes of the lower thermosphere, collected by Global Ultraviolet Imager (GUVI), installed on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite. Since the electron concentration at altitudes of the maximum of *F*2-layer of the ionosphere is proportional to the $[O]/[N_2]$ ratio, it is hypothesized that the observed effect in ionospheric parameters may be associated with the variations of temperature and composition of the neutral atmosphere (possibly, in the course of seasonal change of the atmosphere).

Introduction

The thermosphere and ionosphere are most variable parts of the Earth's atmosphere. On one hand, they experience active impact of heliophysical factors (electromagnetic radiation of the Sun, corpuscular particle fluxes, and magnetic fields), especially during magnetic perturbations; and on the other hand, the parameters of the thermosphere are strongly affected by different geophysical factors (meteorological and seismic events, among others).

Variations of the atmospheric characteristics in the lower and middle atmosphere may lead to variations of the atmospheric parameters at ionospheric altitudes. For instance, during geomagnetic perturbations, precipitation of particles significantly alters the gaseous and ion composition of the atmosphere and ionosphere, increasing its molecular component. These perturbations at auroral latitudes intensify the neutral equatorwards wind, thereby changing the content of ions and neutral particles at midlatitudes.

The overviews in Refs. 1–3 show the importance of the study of influence of different wave motions arising in the stratosphere and troposphere on the distribution of ionospheric parameters at altitudes from 200 to 400 km. They present correlation characteristics of the effect of planetary and gravity waves on changes of critical frequencies in the *F*-region. At midlatitudes under quiet geomagnetic conditions when the geomagnetic effects on the ionospheric characteristics are minimum, the background parameters of the neutral atmosphere and ionosphere may vary from day to day in a wide range (by up to 15–20% and larger), causing variations of the characteristics of ionospheric radio channel. Therefore, the construction of atmospheric and ionospheric models faces the problems of different uncertainties: what are the processes which can be responsible for these variations, and what are their quantitative characteristics which could be taken into consideration in model development. Addressing these questions is a very important geophysical task.

This paper discusses the variations of characteristics of slant sensing, caused by changes in the ionosphere along the propagation path, and critical frequencies of the *F*2-layer at ends of the paths, from the viewpoint of variations of the parameters of the neutral atmosphere in equinox period under quiet geomagnetic conditions and minimum solar activity.

Analysis of the observation data

In September 2005, radio wave propagation along the paths of slant sensing of the ionosphere was studied in the regions of Eastern Siberia and Far East. These studies were motivated by the fact that long-term continuous observations ensure recording of characteristics under different helio-geophysical conditions and make it possible to estimate the variations of the parameters studied as functions of changes of the parameters of the medium of propagation. The Magadan–Irkutsk and Norilsk–Irkutsk paths were used in this study. The length of midlatitude path Magadan–Irkutsk is 3000 km, and the length of the path Norilsk–Irkutsk is 2100 km. Geometry of these paths is such that the point of

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emission in Magadan and mid-points of both paths (regions of Podkamennaya Tunguska and Yakutsk) have approximately the same geomagnetic latitude ~ 51°N; therefore, the conditions of passage of decameter radio waves along these paths are determined to a considerable degree by the state of the sub-auroral ionosphere and dynamics of its boundaries during variations of the level of magnetic perturbation.

Generally, under quiet conditions, single and double shock propagation of short-wave (SW) signal along this path was observed. In some experiments, higher-order modes were also observed. The maximum observed frequencies (MOFs) can be calculated with the error determined by the accuracy of description of ionospheric parameters.

During perturbations, the pattern becomes more complex: at daytime hours lower MOF values are generally observed; while at evening and nighttime hours, reflections from northward wall of main ionospheric trough (MIT) are recorded, with MOF exceeding usual median values.[4] Time of recording these signals changes as a function of boundaries of the main ionospheric trough during the perturbations.[4,5]

In the first half of September, the measurements were performed under conditions of perturbed magnetic field of the Earth, i.e., magnetic storms with long recovery phase. They caused negative perturbation in the ionosphere (i.e., decrease of the electron concentration in the *F*-region) and, as a consequence, the decrease of MOF at daytime hours and disappearance of reflections due to absorption at evening and nighttime hours were observed. After September 15, 2005, the geomagnetic situation stabilized: the magnetic field was quiet. The flux of radio-frequency radiation from the Sun, at the wavelength of 10.7 cm, $F_{10.7}$, characterizing the ionizing power of the Sun, ranged from 91 to 72 (in units of 10^{-22} W/(Hz · m^2)). Figure 1 presents variations of geomagnetic parameters and observed MOF for the studied paths in the period from September 23 to September 28.

For the Magadan–Irkutsk path, the reflections were present almost during all 24 hours. The MOF value of the single shock mode varied from 16.9 to 25.4 MHz. Also, for the Norilsk–Irkutsk path stable passage of radio signals was observed almost all day. It is worthy to note a significant influence of sporadic layers on propagation of the SW signal under quiet geomagnetic conditions, especially at nighttime and evening hours.

The specific feature of the propagation of SW radio signals during this observation period were increased daytime values of MOF recorded from September 24 to 26, and this was observed on the Magadan–Irkutsk and Norilsk–Irkutsk paths.

From Fig. 2 it is seen that negative deviations observed in the first half of September are caused by magnetic perturbations. After September 22 until September 26, the deviations are positive during a few days and, as the data of vertical sensing show, they occurred over a relatively large territory (more than 2000 km), covering the region of Eastern Siberia and Far East.

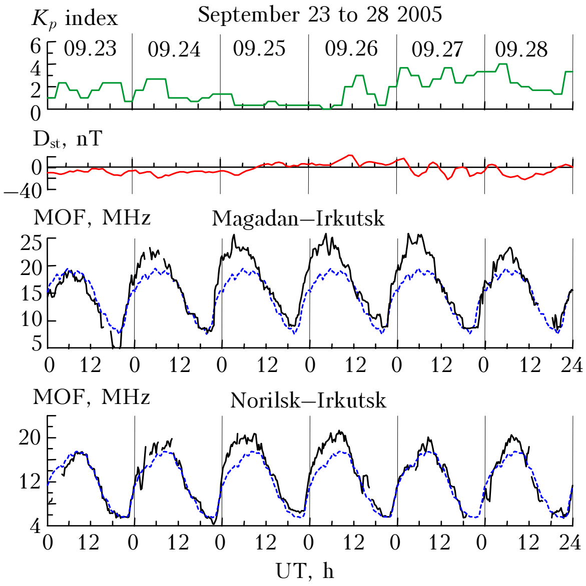

Fig. 1. Variations of the geomagnetic parameters and observed MOF for the paths studied from September 23 to 28, 2005.

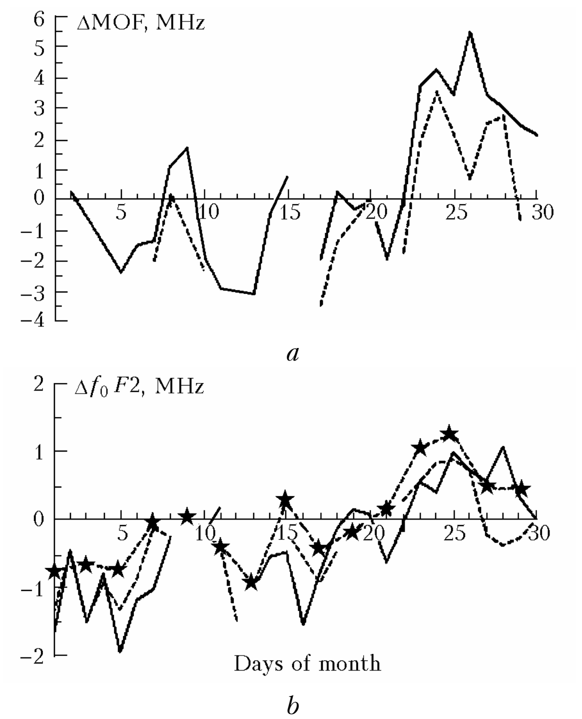

Fig. 2. Variations of deviations of the midday MOF values from their median values on the Magadan–Irkutsk (solid line) and Norilsk–Irkutsk (dashed line) paths (*a*) and variations of deviations of critical frequencies for ionospheric stations Irkutsk (solid line), Yakutsk (dashed-dotted line), Magadan (line plus symbols) (*b*) in September 2005.

Discussion and conclusions

1. It is assumed that the positive perturbations in the ionosphere (i.e., increase of electron concentration in the F-region) are caused by growth of the atomic oxygen to molecular nitrogen concentration ratio $[O]/[N_2]$. At altitudes of the maximum of the $F2$-layer, this ratio is lower in summer and increases in winter. During magnetic storms, the ratio decreases. From Fig. 3 it is seen that magnetically quiet conditions ($A_p < 10$) are typically characterized by the largest $[O]/[N_2]$ ratios.

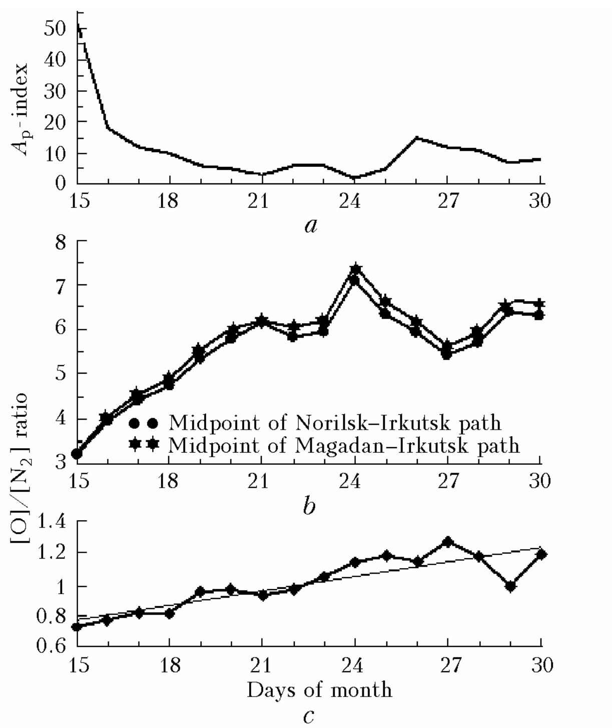

Fig. 3. Variations of the diurnally mean magnetic planetary A_p index (a); diurnally mean values of the $[O]/[N_2]$ ratio calculated from MSIS-90 model up to the height of 300 km at midpoints of the paths (regions of Podkamennaya Tunguska and Yakutsk) (b); and GUVI TIMED satellite data of $[O]/[N_2]$ ratios at altitudes of the lower thermosphere (~ 100 km) for the region of Irkutsk (c) in the second half of September 2005.

At midlatitudes, after the fall equinox day, active seasonal change (in composition and thermobaric and dynamic fields) of the atmosphere, from summer to winter conditions, takes place. This is clearly seen from model results (according to International reference model MSIS-90) for early and late September. At a fixed A_p value, the atomic oxygen to molecular nitrogen concentration ratio $[O]/[N_2]$ is lower at the beginning than at the end of this month, i.e., there is a distinct tendency toward increase of this ratio by the end of this month. The calculated model data are supported by the data of satellite measurements of the ratio $[O]/[N_2]$ ratio using Global Ultraviolet Imager (GUVI)[6] installed on Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite. The TIMED satellite was launched by NASA in 2001 with focus on the study of energetics, dynamics, as well as of interactions of the ionosphere with lower thermosphere and mesosphere and the underlying atmospheric layers. The TIMED data bear information on the least studied boundary region between the Earth's atmosphere and near outer space (known as mesosphere, lower thermosphere, and ionosphere (MLTI) region) at altitudes from 60 to 180 km. The satellite orbit has the altitude of 625 km and inclination of 74.1°.

From Fig. 3c it is seen that, in addition to the general tendency toward small increase from September 24 to 28, there is observed a growth of the ratio $[O]/[N_2]$ with an abrupt drop by September 29. Very similar pattern was observed near Magadan and around midpoints of the studied paths.

2. To better understand the causes of such considerable variations of ionospheric and atmospheric parameters on September 24–26, 2005, we have analyzed the data on vertical profiles of atmospheric temperature, inferred from measurements of scanning ultra-high frequency microwave limb sounder (MLS), installed onboard an Aura satellite.[7] The Aura satellite was launched by NASA in July 2004 as part of the International Program on Earth Observing System (EOS) aimed at studying global climate change. The MLS Aura measurement data are used for reconstruction of the profiles of chemical composition, relative humidity, and temperature in the regions of the atmosphere including the troposphere, stratosphere, mesosphere and up to the upper thermosphere. The satellite has polar orbit with the altitude of 705 km and near-global spatial coverage (from −82° to +82° latitude). The vertical resolution of measurements is approximately 3 km. One vertical profile is measured over 1.5° (~165 km) along the track. The satellite makes about 15 revolutions about the globe per day.

Figure 4a presents for Irkutsk and Magadan, as an example, the height profiles of deviations of daytime atmospheric temperatures on days when in Irkutsk, Magadan, and at midpoints of these paths the midday MOF simultaneously increased during several days (for September 24–26, 2005) relative to the temperatures on preceding quiet days (September 20–22, 2005). We can note strong temperature variations both with altitude (Fig. 4), and from day to day (Fig. 5).

Considerable temperature variations were observed at heights of mesopause (~80–90 km) (see Figs. 4 and 5a). Near Irkutsk on September 25, the temperature at heights of mesopause decreased by approximately 30° (from 199 to 170 K) (see Fig. 4a) as compared with temperature on September 21; for Magadan (Fig. 4b) and Yakutsk, the temperature decrease was approximately 15°. On next days, by the end of September, the temperature increased back, e.g., up to 212 K for Irkutsk (Fig. 5*a*). At altitudes of stratopause (~50 km) there was increase of temperature by 5–10° (Figs. 4 and 5*b*).

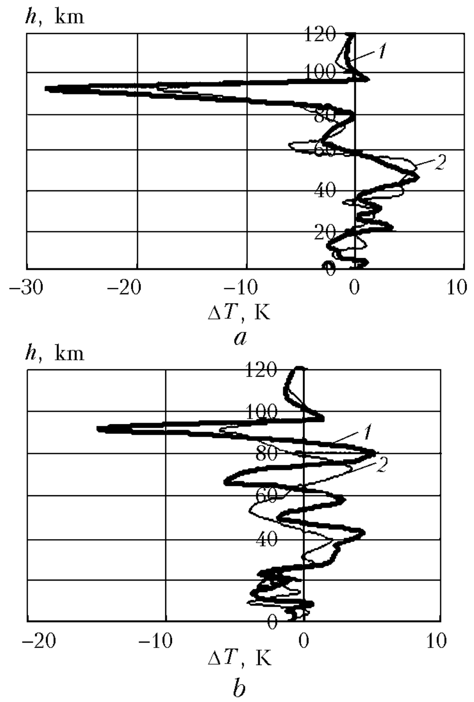

Fig. 4. Height profiles of deviations of daytime temperatures for the region of Irkutsk on September 25, 2006 relative to September 21, 2006 (curve *1*), and on September 26, 2006 relative to September 21, 2006 (curve *2*) (*a*); and for the region of Magadan on September 25, 2006 relative to September 20, 2006 (curve *1*) and on September 24, 2006 relative to September 20, 2006 (curve *2*) (*b*).

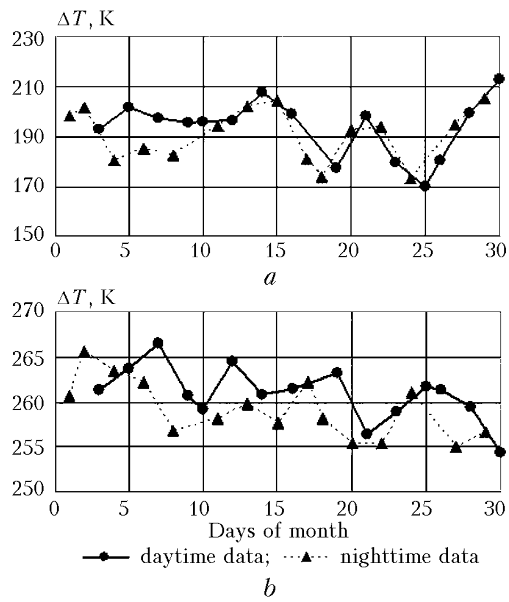

Fig. 5. Diurnal temperature variations at altitudes on the order of 90 (*a*) and 50 km (*b*) for the region of Irkutsk in September 2005.

The possibility of operatively determining the field of vertical profiles of the Earth's atmospheric parameters is among most important achievements of the spaceborne remote sensing because it makes it possible to consider the atmosphere as an integral system.[8] Analysis of measurement data acquired from MLS Aura on altitude distribution of atmospheric temperature, enabled us to reveal that during 4–5 days, there simultaneous change occurred, over a vast area of ~2000 km extension, of a set of parameters of the atmosphere and ionosphere, namely, temperature variations at heights of strato- and mesopause, variations of the [O]/[N_2] ratio at heights of the lower thermosphere and variations of midday MOFs, indicating an increase of the ionosphere ionization in the *F*2-region.

We have already noted above that the studied time interval is within timeframe of seasonal change of the atmosphere in equinoctial period, involving all atmospheric layers including the troposphere and stratosphere and overlying layers. Primarily, this concerns the dynamic regime, which, in turn, determines largely the properties and parameters of the atmosphere (temperature, density, pressure, chemical composition, etc.).

The Earth's atmosphere is a complex dynamical system with wide range of spatiotemporal variations of parameters of motion. An efficient mechanism of interlayer interaction is transfer of substance and energy by means of upward propagating internal waves of different scales. The perturbations of atmospheric properties of a global horizontal scale with time scale larger than one day constitute planetary waves (Rossby waves).[9] These waves may propagate upward up to heights of the thermosphere and ionosphere with the growth of amplitude. However, the transfer processes can be hindered by the system of horizontal winds dominating at altitudes of strato-/mesosphere.

Easterly (summertime circulation) and strong westerly winds are most effective filters for large-scale atmospheric waves and serve as their reflecting barriers. Throughout most of the winter, when westerly winds dominate at these altitudes, as well as in periods of seasonal changes, when there occurs the change from summertime easterly to the wintertime westerly circulation, most favorable conditions for upward propagation of planetary waves are created. Possibly, the global variations of atmospheric and ionospheric parameters, considered in the paper, are associated with propagating planetary wave with the period on the order of 4 or 5 days.

Thus, analysis of data of slant and vertical sensing, obtained under quiet geomagnetic conditions for low solar activity, revealed positive perturbations over vast area with the duration of 3–4 days. The use of satellite observations of composition and temperature of the neutral atmosphere confirmed the existence of considerable spatial variations of parameters of the neutral atmosphere in these days. This allows us to assume that these variations of electron concentration at the altitudes of the maximum of F-layer of the ionosphere are associated with generation of planetary waves in the middle atmosphere and their propagation to higher altitudes.

Acknowledgments

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