The Stratosphere Jet Stream Effects in High-latitude Ionosphere according to Vertical Radio Sounding Data

M. A. Chernigovskaya[1], **B. G. Shpynev**[1], **K. G. Ratovsky**[1], **and A. E. Stepanov**[2]

[1]Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia
[2]Institute of Cosmophysical Research and Aeronomy SB RAS, Yakutsk, Russia

Abstract— In this paper, we studied the seasonal variations of the high-frequency part of the $F2$ peak density variability caused by the traveling ionospheric disturbances associated with propagation of internal gravity waves from the lower and middle atmosphere. As a variability characteristic we used the coefficient of daytime variations in the $F2$ peak electron density. We identified periods of middle-scale wave-like motions in the stratosphere between November and February 2008–2010 based on the ECMWF ERA-Interim reanalysis data. A noticeable increase in the internal gravity wave activity was found at the heights of $F2$ layer during the periods of stratospheric wave activity over analyzed regions.

1. INTRODUCTION

The ionosphere is an ionized part of the Earth's upper atmosphere subjected to the forcing from above and from below. Helio-geomagnetic activity (solar electromagnetic and corpuscular radiation, magnetospheric effects) is the dominant factor in the thermodynamic regime of the ionosphere [1]. At the same time, numerous experimental and theoretical studies point to the fact that disturbances in the middle atmosphere can be sources of atmospheric waves (acoustic, planetary and internal gravity waves (IGW)) which penetrate into the heights of the ionosphere under certain conditions and manifest themselves as traveling ionospheric disturbances (TID) [2–4]. Some review papers [5–8] show the importance of research into the effects that different wave motions from the stratosphere and troposphere have on distribution of ionospheric parameters at heights of 200–400 km. There were many papers showing a close correlation between wave disturbances in the atmosphere and ionosphere and severe weather phenomena (thunderstorms, tornados, tropical cyclones, cold fronts, etc.). Other ionospheric effects of meteorological disturbances were also observed: infrasonic oscillations, electric fields, heating, optical emissions, scattering in the F layer (F-spread). Tropospheric and stratospheric jet streams (JS) can be sources of IGW too [9, 10]. However, until now studies dealing with analysis of meteorological effects in the ionosphere (i.e., ionospheric disturbances caused by the processes in underlying layers of the lower and middle atmosphere) are not so numerous compared to the extensive research of helio-geomagnetic effects. Thus, the study of meteorological effects in the ionosphere is still relevant in understanding the coupling of processes in the atmosphere-ionosphere system.

2. DATA AND METHOD OF ANALYSIS

The first analysis results of seasonal dependence of the high-frequency part (periods from 0.5 to 6 h) of the $F2$ peak density (N_mF2) variability from Irkutsk digisonde data were presented in [11].

In present paper, we studied the stratospheric JS effects in variations of ionospheric parameters measured in 2008–2010 with three DPS-4 digisondes: high-latitude Norilsk (69°N, 88°E; 60°N GLAT, 166°E GLON), sub-auroral Yakutsk (62°N, 130°E; 52°N GLAT, 196°E GLON) and mid-latitude Irkutsk (52°N, 104°E; 42°N GLAT, 177°E GLON). We also used the ECMWF ERA-Interim reanalysis data for a middle atmosphere dynamics analysis and Aura MLS satellite data on stratosphere and upper mesosphere temperature in years 2008–2010. This time interval featured a long solar activity minimum with low intensity of active events on the Sun and geomagnetic disturbances accompanying them. This essentially facilitated the efficiency in studying the ionospheric disturbances associated with the effect of internal atmospheric processes.

The Earth ionosphere can be divided into three latitude zones that have rather different properties according to their geomagnetic latitude (GLAT): low-latitude zone (GLAT $<$ 30°), mid-latitude zone (30° $<$ GLAT $<$ 60°) and high-latitude zone (GLAT $>$ 60°) [12]. From this classification, Irkutsk is a typical mid-latitude station, whereas Norilsk and Yakutsk being near a boundary between the mid- and high-latitude zones combine the properties of both mid- and high-latitude ionosphere.

We used the ECMWF ERA-Interim reanalysis dataset to analyze spatial and temporal variations of meteorological parameters. The spatial resolution of the dataset is approximately 80 km (0.75° in longitude/latitude) on 60 vertical levels from the surface up to 0.1 mb (http://www.ecmwf.int/en/research/climate-reanalysis/era-interim). The reanalysis data may contain some error at the higher pressure levels. Keeping this in mind, we used the ECMWF ERA-Interim reanalysis data up to 1 mb (the height is about 50 km), considering them similar to real measurement, since the quality of these data is sufficient for the purposes of our study.

To study the influence of the processes in the lower and middle atmosphere on the ionosphere, we used the coefficient of daytime variations in the $F2$ peak electron density (VrN_mF2):

$$VrN_mF2 = 100\% \cdot \sqrt{\langle (N_mF2 - \langle N_mF2 \rangle)^2 \rangle} / \langle N_mF2 \rangle \tag{1}$$

Here we used the averaging over the period T centered near the local noon. A disturbance of an ionospheric parameter is considered as deviation of the observed value from a regular behavior. The Equation (1) implies that the VrN_mF2 coefficient proportional to N_mF2 variations in the range of periods not exceeding the averaging period T. If T is of the order of several hours, the VrN_mF2 variation coefficient describes the high-frequency part of the $F2$ peak density variability. The high-frequency part of the ionosphere variability (in the range of periods from 0.5 to 6 h) is mainly caused by the TIDs associated with propagation of IGW. Consequently, the coefficient reflects the IGW activity at heights of the $F2$ layer. So, this coefficient was chosen as a parameter of the TID variability.

For the Irkutsk ionosphere data, we used the averaging over the period 09-15 LT. A 6-hour interval corresponds to the daytime duration at the $F2$ peak height over Irkutsk in winter. Compared to Irkutsk, the ionosphere above Norilsk and Yakutsk is partially lighted only for ∼4 hours during the daytime at the $F2$ peak height in winter. So the Norilsk and Yakutsk VrN_mF2 coefficient was calculated for a 4-hour interval (10–14 LT), as well as for a 6-hour interval (09–15 LT) similar to Irkutsk.

3. RESULTS OF DATA ANALYSIS AND DISCUSSION

Based on the ECMWF ERA-Interim reanalysis data, we identified periods of strong middle-scale wave-like motions in the stratosphere at the heights of 10 mb between November and February 2008–2010.

Figure 1 shows the examples of the stratosphere JS locations on the isobaric surface of 10 mb in the northern hemisphere for certain days in winter 2009. Stratospheric JSs occurred on the boundary of the polar night where the maximum temperature gradient resulted from the difference between radiative cooling inside and outside this zone in winter. The highest horizontal gradients of temperature were between 50–80°N. As a result, it occurred as stratospheric JS flowing mainly eastward and having wind velocities of more than 120 m/s at the height of 30 km. It went around the Arctic and formed the so-called circumpolar vortex (CPV). At a boundary between gas flows with different velocities and/or directions (such as, for example, a stratospheric CPV with high velocities and ambient atmosphere with relatively weak winds), instabilities are formed with atmospheric waves of various scales, including Kelvin waves and IGW at certain critical wind velocities in the JS. Figure 1 shows strong middle-scale wave-like motions in the stratosphere on the isobaric surface of 10 mb (Figure 1(b)), which is associated with the stratospheric JS (Figure 1(a)). According to the ECMWF ERA-Interim reanalysis data, we see a wave-like disturbance propagation from the stratosphere up into the lower mesosphere with the increase in the amplitude (Figure 1(c)). Traveling upward, these waves cause changes in the structure and internal dynamics of the lower thermosphere and ionosphere and manifest themselves as traveling atmospheric and ionospheric disturbances.

At first we analyzed the high frequency parts of the ionosphere variability in 2008–2010 over the high-latitude Norilsk station which was located in the region of the winter CPV formation in the Northern hemisphere. For the comparison, we conducted a similar analysis for the mid-latitude Irkutsk station which was also located near the region of the winter CPV at the certain periods during the winter.

The upper panels of Figure 2 present the time changes in VrN_mF2 coefficient over Norilsk (Figure 2(a)) and Irkutsk (Figure 2(b)) for the years under study. For both stations, there is a significant difference between ionospheric disturbances in winter and in summer. According to Figure 2 a noticeable increase in the IGW activity was observed at the heights of the $F2$ layer during

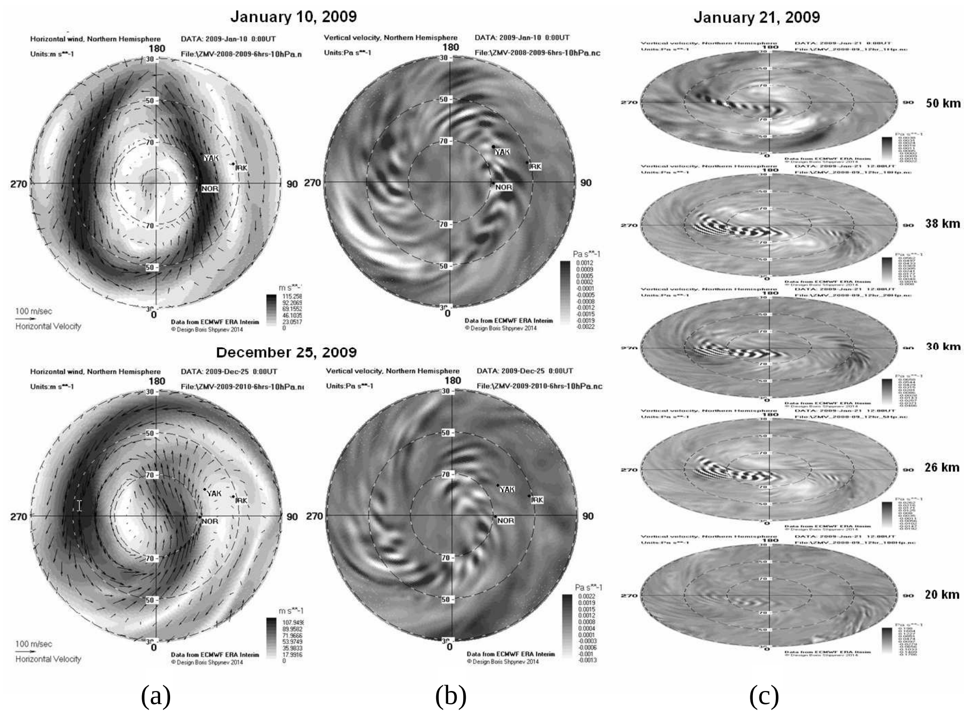

Figure 1: The examples of (a) stratospheric JS locations (fields of horizontal velocity, m/s); (b) middle-scale wave-like motions (fields of vertical velocity, Pa/s) associated with stratospheric JSs at 10 mb for certain days in winter 2009; (c) the middle-scale wave-like motions (fields of vertical velocity, Pa/s) at different heights of the stratosphere and lower mesosphere.

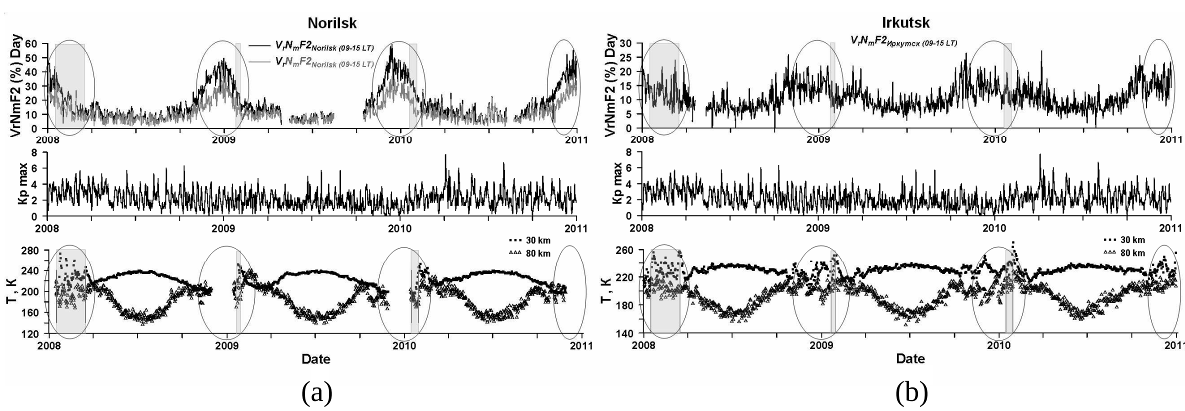

Figure 2: Time changes of VrN_mF2 variation coefficient (top panels); the daily maximum geomagnetic index K_p (middle plots) and Aura MLS temperature data in the daytime at the heights of 30 and 80 km over (a) Norilsk and (b) Irkutsk in 2008–2010.

the periods of the increased stratospheric wave activity associated with stratospheric JSs (marked by ovals). Average values of VrN_mF2 are more than doubled in winter compared to the undisturbed summer period. There were very intense, long-time, major sudden stratospheric warmings (SSW) covering large part of the Northern hemisphere in January–February 2008, January 2009 and January 2010 (shown as grey rectangles on Figure 2). Occurrence of the major SSWs had not led to any significant increases of VrN_mF2 variability. The VrN_mF2 coefficient is more for a 6-hour averaging period than for a 4-hour period in case of Norilsk (Figure 2(a)). This difference is maximum in winter ($\sim$12%), being insignificant in summer. Separate peaks in the variation coefficient in the $F2$-layer maximum electron density were associated with the increase in geomagnetic activity (the second diagram on top) that could lead to the increase in wave activity at the heights of the ionosphere. Correlation between the indices VrN_mF2 and K_p was observed only in some cases.

Ionospheric disturbances can be also due to temperature variations in the stratosphere and mesosphere. We analyzed time variations of temperature in the stratosphere (∼30 km) and mesosphere (∼80 km), using Aura MLS satellite measurement data which provide daytime and nighttime vertical profiles of temperature in the stratosphere and upper mesosphere (http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/MLS). During the periods of increased stratospheric wave activity accompanied by a noticeable increase in the IGW activity at the heights of the $F2$ layer, significant variations in satellite temperature were observed at heights of the stratosphere and mesosphere (marked by ovals in lower panels of Figure 2).

After we compared the high frequency parts of the ionosphere variability over the high-latitude Norilsk and mid-latitude Irkutsk stations for 2008. When comparing the data, we used additionally the sub-auroral Yakutsk station, which occupies an intermediate geographical position. Yakutsk was also located in the region of the winter CPV in 2008. For the comparison of the ionosphere variability over Irkutsk, Yakutsk and Norilsk we used the averaging over the 4-hour period (10–14 LT). For all the analyzed stations, the largest variability in the ionosphere $F2$-layer was observed in winter and the smallest one in summer (Figure 3). The summer-winter difference is more pronounced for Norilsk than for Yakutsk and Irkutsk.

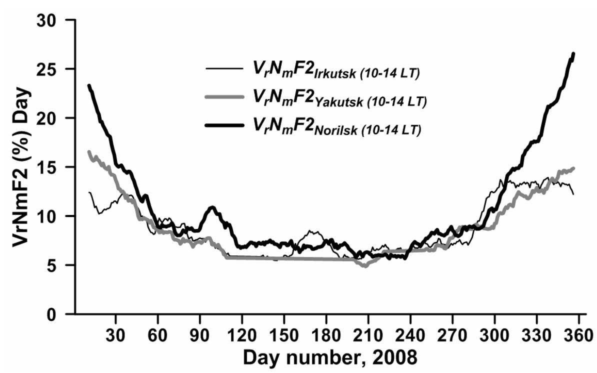

Figure 3: Time changes of the VrN_mF2 variation coefficient smoothed by a running mean for 21-days interval over Norilsk, Yakutsk and Irkutsk in 2008.

The reasons why the IGW activity at the heights of the $F2$ layer above Norilsk, Yakutsk and Irkutsk were different in winter could be associated with the fact that those regions are affected by different parts of CPV which had different structure every winter. Middle-scale wave motions whose characteristics were determined by a stratospheric jet were generated above a CPV. Under certain conditions, these waves propagate upward to the thermosphere and ionosphere modifying the $[O+]/[N2]$ balance and causing, consequently, variations of ionospheric parameters. In addition, it should be noted when discussing the ionosphere reaction particularities on traveling from below atmospheric disturbances of the meteorological origin it is necessary to take into account regular regional features of the ionospheric characteristics from digisonde measurements over the analyzed stations [13–15].

4. CONCLUSIONS

As a result of the analysis aimed at determining JS effects in variations of ionospheric parameters from vertical sounding at Norilsk, Yakutsk and Irkutsk in years 2008–2010, we made the following conclusions.

(1) Based on ECMWF ERA-Interim, we identified periods of intensification of strong middle-scale wave-like motions in the stratosphere at the heights of 10 mb between November and February for all the 2008–2010 period. These waves are associated with stratospheric jet streams mostly localized at 50–80°N.

(2) Reanalysis also showed a wave-like disturbance propagation from the stratosphere up into the lower mesosphere with the increase in the amplitude.

(3) Aura MLS temperature measurements confirmed the existence of variations in parameters of the stratosphere and upper mesosphere, which were accompanied by increases in the $F2$ layer wave disturbance activity.

(4) During the periods of stratospheric wave activity, we observed a significantly increased IGW activity at the ionosphere $F2$-layer above the Asian region of Russia according to vertical sounding

at Norilsk, Yakutsk and Irkutsk for all the years analyzed.

(5) A clear seasonal dependence of the high-frequency part of the $F2$ peak density variability was observed for all the stations. The largest variability in the ionosphere $F2$-layer was observed in winter and the smallest one in summer. The summer-winter difference was more pronounced in the case of Norilsk.

ACKNOWLEDGMENT

This study was supported by the RAS Basic Research Program II.16.1.2, by RF President Grant of Public Support for RF Leading Scientific Schools (NSh-2942.2014.5) and by the RFBR project No. 15-05-05227.

REFERENCES

1. Dudok De Wit, T. and J. Watermann, "Solar forcing of the terrestrial atmosphere," *Comptes Rendus Geoscience*, Vol. 342, No. 4, 259–272, 2010.
2. Hocke, K. and K. Schlegel, "A review of atmospheric gravity waves and travelling ionospheric disturbances: 1982–1995," *Ann. Geophys.*, Vol. 14, 917–940, 1996.
3. Vadas, S. L., "Horizontal and vertical propagation of gravity waves in thermosphere from lower atmospheric and thermospheric sources," *J. Geophys. Res.*, Vol. 112, 2007, Doi: 10.1029/2006JA011845.
4. Yiğit, E. and A. S. Medvedev, "Internal wave coupling processes in Earth's atmosphere," *Adv. Space Res.*, Vol. 55, 983–1003, 2015, http://dx.doi.org/10.1016/j.asr.2014.11.020.
5. Kazimirovsky, E. S., "Coupling from below as a source of ionospheric variability: A review," *Ann. Geophys.*, Vol. 45, No. 1, 11–29, 2002.
6. Lastovicka, J., "Forcing of the ionosphere by waves from below," *J. Atmos. and Solar-Terr. Phys.*, Vol. 68, 479–497, 2006.
7. Rishbeth, H., "F-regon links with the low atmosphere?" *J. Atmos. and Solar-Terr. Phys.*, Vol. 68, 469–478, 2006.
8. Vincent, R. A., "Gravity wave coupling from below: A review," *Climate and Weather of the Sun-Earth System (CAWSES): Selected Papers from the 2007 Kyoto Symposium*, 279–293, Terrapub, Tokyo, 2009.
9. Plougonven, R., H. Teitelbaum, and V. Zeitlin, "Inertia gravity wave generation by the tropospheric midlatitude jet as given by the fronts and Atlantic storm-track experiment radio soundings," *J. Geophys. Res.*, Vol. 108, No. D21, 4686, 2003, Doi: 10.1029/2003JD003535.
10. Manney, G. L., M. I. Hegglin, W. H. Daffer, M. L. Santee, E. A. Ray, S. Pawson, M. J. Schwartz, C. D. Boone, L. Froidevaux, N. J. Livesey, W. G. Read, and K. A. Walker, "Jet characterization in the upper troposphere/lower stratosphere (UTLS): Applications to climatology and transport studies," *Atmos. Chem. Phys.*, Vol. 11, 6115–6137, 2011, Doi: 10.5194/acp-11-6115-2011.
11. Ratovsky, K. G., A. V. Medvedev, and M. V. Tolstikov, "Diurnal, seasonal and solar activity pattern of ionospheric variability from Irkutsk Digisonde data," *Adv. Space Res.*, 2014, http://dx.doi.org/10.1016/j.asr.2014.08.001.
12. Hunsucker, R. D. and J. K. Hargreaves, *The High-latitude Ionosphere and Its Effects on Radio Propagation*, Cambridge University Press, New York, 2003.
13. Ratovsky, K. G. and A. V. Oinats, "Local empirical model of ionospheric plasma density derived from Digisonde measurements at Irkutsk," *Earth, Planets and Space*, Vol. 63, No. 4, 351–357, 2011.
14. Ratovsky, K. G., A. V. Oinats, and A. V. Medvedev, "Regular features of the polar ionosphere characteristics from Digisonde measurements over Norilsk," *Adv. Space Res.*, Vol. 51, No. 4, 545–553, 2013.
15. Ratovsky, K. G., J. K. Shi, A. V. Oinats, and E. B. Romanova, "Comparative study of high-latitude, mid-latitude and low-latitude ionosphere on basis of local empirical models," *Adv. Space Res.*, Vol. 54, No. 3, 509–516, 2014.