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Studying the G condition occurrence in different latitudes under solar minimum: Observation and modeling

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ABSTRACT

We analyzed the G condition occurrence, using data of ionospheric vertical sounding from stations Norilsk (69.4°N, 88.1°E), Irkutsk (52.5°N, 104°E) and Hainan (18.3°N, 109.3°E) during the last extreme low solar activity period (2006–2009). In most cases, the three stations registered the G condition in May–August; in Norilsk, however, it was registered in March–April 2008. Under quiet geomagnetic conditions, the longest intervals (up to several hours) during which the G condition was continuously registered were observed in Irkutsk and Norilsk in June–July 2008. In Norilsk, it was registered almost every day in the morning and in the daytime (LT) during these months. We performed theoretical modeling of electron density distribution for the cases when the G condition was registered, taking into account the correction of the neutral atmosphere model. The obtained calculations are in good agreement with observed data. Besides, we showed that variations in thermospheric parameters (density, composition, temperature, and wind velocity) can promote formation of the G condition under quiet geomagnetic conditions during the last extreme low solar activity.

1. Introduction

According to the rules of the URSI standard (URSI Handbook of Ionogram Interpretation and Reduction et al., 1972), the descriptive letter G is used if the F_2 layer critical frequency (f_oF_2) is indeterminable because its value becomes less or equal to the F_1 layer critical frequency ($f_oF_2 \leq f_oF_1$). The statistical analysis of critical frequencies from the global network of ionospheric stations and the model results showed that the occurrence probability of the G condition: (a) increases with decreasing solar zenith angle and is maximum during daylight hours in summer, (all other conditions being equal); (b) increases as latitude increases; (c) increases with increasing geomagnetic activity; (d) decreases when the low solar activity becomes moderate (Lobzin and Pavlov, 2002a, 2002b).

The mean (over the entire data array of 1957–1990) occurrence probability of the G condition is about 0.3% (Lobzin and Pavlov, 2002a); i.e., the G condition occurs seldom. Nevertheless, mechanisms of occurrence of the G condition have been analyzed for each case, using data from incoherent scatter stations, for quiet conditions (Pavlov and Buonsanto, 1998) and for geomagnetic storms (Oliver, 1990; Pavlov et al., 1999; Schlesier and Buonsanto, 1999; Pavlov and Foster, 2001; Mikhailov and Schlegel, 2003). Occurrence of the G condition is often due to variations in thermospheric parameters (temperature, composition, thermospheric wind speed) that lead to the additional decrease in f_oF_2, whereas f_oF_1 varies very slightly. During geomagnetic disturbances, this additional decrease in f_oF_2 is due to the negative phase of the ionospheric storm (Pavlov and Foster, 2001; Mikhailov and Schlegel, 2003; Deminov et al., 2011a, 2011b; Buresova and Laštovička, 2001; Buresova et al., 2002). With increasing solar activity, values of f_oF_2 increase more than those of f_oF_1, and, consequently, the periods of low solar activity are the most favorable for occurrence of the G condition. According to data from Irkutsk digisonde DPS-4, many cases of registration of the G condition under quiet geomagnetic conditions are associated with the period of extremely low solar activity (2007–2009) (Polekh et al., 2013). As deduced from experimental data, this period was characterized by low values of EUV radiation relative to the previous solar minimum (Solomon et al., 2010). In 2008 (i.e., in the middle of this minimum), exospheric temperature and the density of oxygen decreased by ~14 °K and 12%, respectively, relative to the predicted values; besides, abnormally low values of the density of the thermosphere (Emmert et al., 2010; Solomon et al., 2010) and of the geomagnetic activity were observed (Deng et al., 2012). Notice that the past minimum of solar cycle 23/24 was characterized by the decrease in f_oF_2 values by 0.5 MHz; at certain stations, this decrease was 1.2 MHz (Liu et al., 2011).

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The G condition indicates the occurrence of significant horizontal gradients of electron density in the ionosphere, which results in the change of ionospheric radio channel's properties. Analysis of such events during the last prolonged solar minimum is not only of scientific interest, but also of considerable practical importance. To solve this problem, we conducted morphological analysis of registration of the G condition for the stations in different latitudes and performed modeling of electron density distribution, taking into account the correction of the neutral atmosphere model.

2. Analysis of experimental data

To perform analysis, we used vertical sounding data obtained using DPS-4 Digisonde (Reinisch et al., 1997) with time resolution of 5 and 15 min from 3 stations-Norilsk (69.4°N, 88.1°E), Irkutsk (52.5°N, 104°E), and Hainan (18.3°N, 109.3°E) – in 2006–2009. The average indices of solar activity $F_{10.7}$ (solar radio flux at 10.7-cm wavelength in units of 10^{-22} W/(Hz m^2)) were 80, 73.1, 68.6, and 70.5. All ionograms were scaled manually, using the interactive ionogram scaling software SAO Explorer (Reinisch et al., 2004; Khmyrov et al., 2008). Reflection traces of digital ionogram were inversed into electron density profiles (Reinisch and Huang, 1983, Huang and Reinisch, 2001). As a result, information about the critical frequencies and peak heights of F_1 and F_2 layers (h_mF_2, h_mF_1) was obtained. We selected the intervals during which the G condition occurred from the total amount of data; then, we determined the duration of these intervals and estimated the relative frequency of the G condition occurrence during each month of the years under consideration. Mean averaged values of the A_p index (Wrenn, 1987) were used to assess and then take into account the level of magnetic disturbances during the preceding 12 h. The calculated mean average values of the A_p index allowed us to determine the intervals corresponding to different levels of magnetic disturbances: 0–4 nT are very quiet geomagnetic conditions; 4–6 nT are quiet geomagnetic conditions; 6–18 nT are moderately disturbed conditions; 18–30 nT are disturbed conditions; more than 30 nT are very disturbed conditions.

Fig. 1 gives histograms representing distribution of the relative frequency of occurrence of the G condition (N) for each month of the years under consideration. It was defined as ratio of the numbers of cases when the G condition was registered during a month to the total number of vertical sounding sessions during this month (in percent). The numerals above the histogram bars mark the mean A_p index averaged over the intervals during which occurrence of the G condition was observed. It is seen that the G condition is observed mainly in summer, sometimes during the equinox. Occurrence of the G condition during the equinox is associated with moderate magnetic disturbances. The G condition was registered several times in Irkutsk in December 2006, during a strong magnetic storm. It follows from the figure that it was registered more often in Norilsk (high latitudes). In Hainan, the G condition was registered very seldom, no more than 10 times per year. The maximum number of cases when the G condition was registered was in 2008: it was registered almost every day from mid-April till mid-August in Norilsk. Notice that the G condition was observed at all stations, given the lowest level of geomagnetic activity (A_p=2–4 nT), in 2009. However, the occurrence frequency of such events was lower than that in 2008.

Fig. 2 shows the histogram representing occurrence of the G condition, depending on the local time, at stations Norilsk (a) and Irkutsk (b) in 2008. The total number of registrations of the G condition in this year (N_0) was sorted out local time (LT) of registration and then a relative frequency R (in percent) was defined as $R=N_{LT}/N_0 \times 100\%$, where N_{LT} is the number of registrations of the G condition for given LT. In Norilsk, the occurrence maximum of the G condition was in the forenoon; in Irkutsk, there was also the second maximum observed in the afternoon (1300–1500LT). In Hainan, the G condition occurred always in the morning.

The duration of permanent existence of the G condition varies over a wide range, from a single event of the G condition registration up to several hours. These sessions sometimes alternate with registration of the F_2 layer parameters. Fig. 3a–d presents the ionograms obtained on July 2, 2008 by Norilsk digisonde. At 0330 UT, reflections with f_oF_1 equal to 3.8 MHz were registered only from the E and F_1 layers. In the next figure (Fig. 3b), reflection traces from the F_1 layer are observed together with those from the F_2 layer, but the f_oF_2 was difficult to determine. At 0400 UT, there are reflections from the F_1 and F_2 regions, with critical frequencies of 3.8 and 4.4 MHz respectively. But at 0430 UT, there are reflection traces only from the F_1 layer, with f_oF_1 of 3.9 MHz.

The longest sessions, during which the G condition was continuously registered, were in Norilsk in 2008. From mid-April till late July, it was registered almost every day. As daylight hours extended, this interval increased up to 7–8 h (rarely up to 11–12 h). In Irkutsk, the longest intervals, during which the G condition was registered, were mainly observed during weak and moderate disturbances. Under quiet geomagnetic conditions, they were observed more seldom, and their duration was from 0.5 to 1.5 h. In Hainan, the maximum duration of continuous registration of the G condition was 1.5 h (on June 16, 2006, at 0315–0445 UT) during the recovery phase of the magnetic storm. Under quiet geomagnetic conditions, registration sessions of the G condition are not numerous, with the longest ones of no more than 45 min.

A more pictorial presentation of distribution of intervals with continuous registration of the G condition is given on the histogram (Fig. 4). The histogram was constructed using the data obtained in Norilsk (a) and Irkutsk (b) in 2008. If the G condition is registered only once over a period of time, such sessions are referred to as single (or isolated) ones. During these sessions, it is difficult to determine exactly the duration of existence of the G condition, since it is less than the sounding interval; thus, these sessions were put in a separate block. Among 2775 sounding sessions of the G condition in Norilsk, ~5.7% (158 sounding sessions) were the isolated ones. From the remaining data (2617 sessions), 227 intervals were selected with duration of 15 min and more. The total number of intervals with continuous registration of the G condition (N_d) was sorted out duration (h) and then a relative frequency K (in percent) was defined as $K=N_i/N_d \times 100\%$, where N_i is the number of intervals for given duration. It is seen that 150 intervals from 227 (66%) had the duration from 0. 25 to 2 h, 45 intervals (~20%) had a duration from 2.25 to 6 h. Distribution of longer intervals (from 6.25 to 10 and more) is relatively uniform.

Among 514 registration sessions in Irkutsk, ~14% are single cases. From the remaining data 101 intervals were selected; the most of them (95%) had duration from 0.25 to 2 h. Long intervals of the continuous registration of the G condition are relatively rare, but they were observed during the periods with very low geomagnetic activity: on July 6, 2008 (0530–0830 UT), on July 25, 2008 (0330–0730 UT), and on July 9, 2009 (0400–0845 UT).

In Hainan, the G condition was registered 3 times in 2008. Duration of the first of them was 45 min (4 sessions), while the other two were isolated. In Fig. 4, they are not presented due to the small number of data.

Consequently, the morphological analysis of registration of the G condition in different latitudes during the years under low solar activity allowed us to draw the following conclusions.

1. In the years of minimum solar activity, the G condition was registered in summer and during the equinoxes at all the