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Responses of ionospheric foF2 to geomagnetic activities in Hainan

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Abstract

Responses of low-latitude ionospheric critical frequency of F2 layer to geomagnetic activities in different seasons and under different levels of solar activity are investigated by analyzing the ionospheric foF2 data from DPS-4 Digisonde in Hainan Observatory during 2002–2005. The results are as follows: (1) the response of foF2 to geomagnetic activity in Hainan shows obvious diurnal variation except for the summer in low solar activity period. Generally, geomagnetic activity will cause foF2 to increase at daytime and decrease at nighttime. The intensity of response of foF2 is stronger at nighttime than that at daytime; (2) seasonal dependence of the response of foF2 to geomagnetic activity is very obvious. The negative ionospheric storm effect is the strongest in summer and the positive ionospheric storm effect is the strongest in winter; (3) the solar cycle has important effect on the response of foF2 to geomagnetic activity in Hainan. In high solar activity period, the diurnal variation of the response of foF2 is very pronounced in each season, and the strong ionospheric response can last several days. In low solar activity period, ionospheric response has very pronounced diurnal variation in winter only; (4) the local time of geomagnetic activities occurring also has important effect on the responses of foF2 in Hainan. Generally, geomagnetic activities occurred at nighttime can cause stronger and longer responses of foF2 in Hainan.

Keywords: Low-latitude ionosphere; foF2; Geomagnetic activity

1. Introduction

Solar wind energy, transmitted into the magnetosphere, may induce influences of different magnitude on the complex morphology of the electric fields, temperature, winds and composition and affect all ionospheric parameters. Perturbations of the ionization density at ionospheric F region heights associated with geomagnetic storms, last several days and vary with location (especially with latitude), local time, season and solar activity. The effects of geomagnetic storms on the ionosphere have been studied extensively for several decades. Recent progresses and outstanding questions about changes in ionospheric F region ionization under storm conditions have been reviewed by Prolss (1995), Buonsanto (1999), Danilov and Lastovicka (2001) and Ondoh and Marubashi (2001).

In the low-latitude and equatorial regions, ionospheric response to geomagnetic activity becomes very complicated for the existence of the Equator Ionospheric Anomaly and many other factors. There have been several experimental and model studies that have provided significant contributions to the knowledge of low-latitude ionospheric responses to geomagnetic storm-induced disturbances (Forbes et al., 1987; Roble et al., 1987; Forbes, 1989; Kikuchi, 1986; Tanaka, 1981; Abdu et al., 1990, 1995; Fejer, 1991; Kelley et al., 1979; Sobral et al., 1997; Scherliess and Fejer, 1997; Sastri et al., 1997a,b; Kumar et al., 2005; Sahai et al., 2005; Liou et al., 2005; see also the reviews by Abdu, 1997 and Buonsanto, 1999). In the east-Asian low-latitude, the ionospheric response to

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geomagnetic storm-induced disturbances has been studied much less than other regions. The purpose of this study is to provide a contribution to the understanding of such processes during the geomagnetic activity. This paper discusses F2-region response to the geomagnetic activity at the equatorial anomaly latitude of Hainan (109.1°E, 19.5°N, dip angle 22.84° at sub-ionospheric points) during the period of 2002–2005.

2. Data and method of analysis

Quarter-hourly values of foF2 obtained with the DPS-4 (Digital Portable Sounder) at Hainan (109.1°E, 19.5°N; Geomagnetic ordinates: 178.95°E, 8.1°N), China were used to study the response of ionospheric foF2 to geomagnetic activity. In order to investigate the effect of solar activity, the measurement period of 2002–2005 was divided into two parts: high solar activity period (2002–2003) and low solar activity period (2004–2005). In each period all days were further classified into three seasons, namely, equinox (March, April, September and October), summer (May, Jane, July and August) and winter (November, December, January and February). And their average values of 10.7-cm solar flux are 309 sfu (equinox), 303 sfu (summer) and 311 sfu (winter) in high solar activity period, and 191 sfu (equinox), 207 sfu (summer) and 196 sfu (winter) in low solar activity period, respectively. The Dst index were obtained from World Data Center, Kyoto University, Kyoto, Japan (online at http://swdcwww.kugi.kyoto-u.ac.jp).

In order to investigate how ionospheric foF2 varies (increases or decreases) and the extent of variation (strong or weak), linear regression analysis was used at different local time. And time-lagged regression analysis was used to investigate the lagged effect of geomagnetic activity. Lag times were from 0 to 96 hours (i.e. 0–4 days). The analyses are performed in each season and different local times. For the fixed local time and lagged time, we can get a linear regression formula as

$$\mathrm{foF2} = a\ \mathrm{Dst} + b \tag{1}$$

where, the coefficient a represents the slope of foF2 with Dst, which shows the trend of foF2 variation with Dst, i.e. how ionospheric foF2 responses to geomagnetic activity, and b is a constant. When a geomagnetic activity occurs, Dst index will decrease and become negative. The stronger the geomagnetic activity, the smaller the Dst value is. For negative value of a, it represents that foF2 will increase during the geomagnetic activity (i.e. positive ionospheric storm effect). And foF2 will decrease during the geomagnetic activity (i.e. negative ionospheric storm effect) for positive value of a. Moreover variation of foF2 is more significant for the larger absolute value of a. The local time and lagged time variations of the coefficient a are shown in Figs. 1–3 for different solar activity levels and different seasons, respectively. In this paper, we try to use Eq. (1) to study the relationship between the foF2 and Dst.

3. Results

3.1. Equinox

Fig. 1 shows the response of ionospheric foF2 to geomagnetic activity in equinox. From the left panel of the Fig. 1, it can be seen that the response of foF2 to geomagnetic activity has obvious diurnal variation in high solar activity period. Generally, negative coefficient a appears in the daytime and positive one in the nighttime, i.e. positive ionospheric storm effect at daytime and negative ionospheric storm effect at nighttime. Geomagnetic activities occurring in the period from noon to midnight have strong effect on the foF2, and can cause foF2 to decrease at post-midnight (especially at 0200–0300 LT) and increase at daytime (especially in the morning) and in the evening. It can also be found that there are bigger absolute values of a at nighttime than that at daytime, i.e. the response of foF2 to geomagnetic activity is more significant at nighttime than that at daytime, but the post-midnight negative ionospheric response is very strong only in the first day and the strong positive one can last several days.

In low solar activity period, shown in the right panel of Fig. 1, the result is similar to that in high solar activity period. Although the response of foF2 to geomagnetic activity has obvious diurnal variation, but there are obvious differences for the lasting time and occurrence time of strong response of foF2 to geomagnetic activity between high and low solar activity periods. For the daytime positive ionospheric storm effect, the strong response occurs in the afternoon, and it is notable that the geomagnetic activity which occurs before ~1400 LT (i.e. the time that the peak electron density reaches maximum in one day) has strong effect on foF2 after ~1400 LT, especially the geomagnetic activity occurring in the morning. There is also another strong response period at 0900–1000 LT, but it lasts only about one day. The daytime positive ionospheric storm effect is very significant in the first day only. For the nighttime negative ionospheric storm effect, it can last several days (at least 4 days in the current study) with strong intensity, and which has two periods of strong response. One is at pre-midnight, and foF2 has significant response to the geomagnetic activities occurring from noon to midnight in the same day or more than two days before, and it is notable that it seems that the intensity of response is stronger with lag time. The other is at 0100–0600 LT for the geomagnetic activity of the preceding 12 hours, and which switches to 0400–0600 LT for that of one or two days before.

3.2. Summer

Fig. 2 shows the response of ionospheric foF2 to geomagnetic storm in summer. From the left panel of Fig. 2,

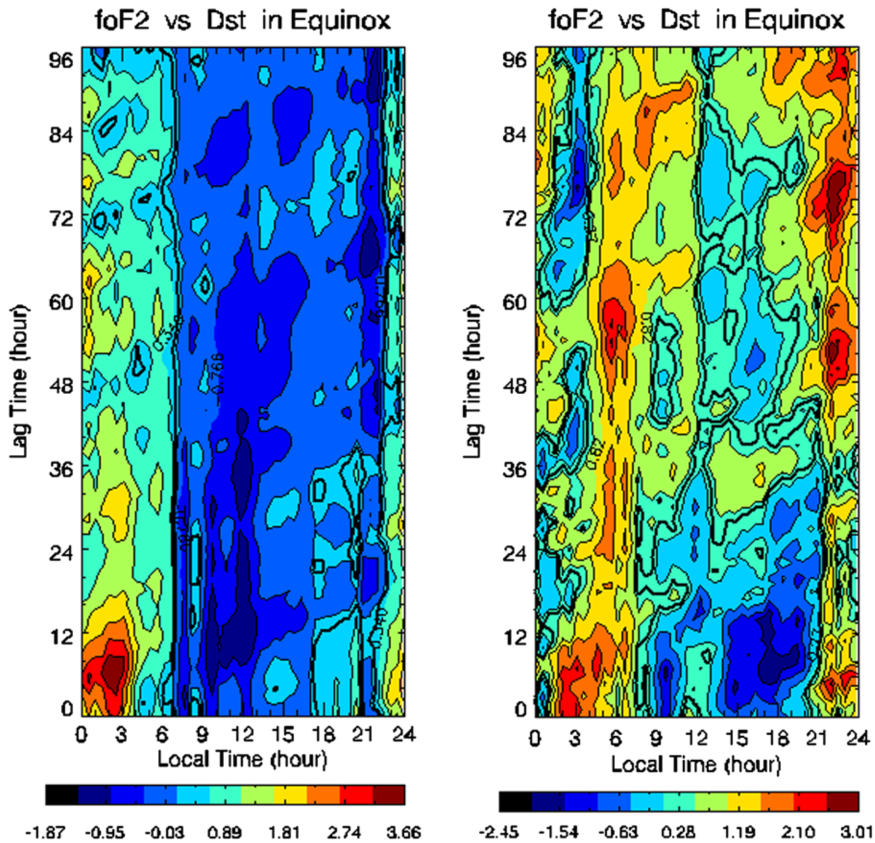

Fig. 1. Local time and lagged time variation of the slope of foF2 with Dst, *a*, in Hainan in equinox in high solar activity period (2002–2003, left) and low solar activity period (2004–2005, right). The coefficient *a* in units of 1 MHz per 100 nT. The value of thick black line is zero.

it can be seen that the diurnal variation in summer is similar to that in equinox for high solar activity period, but the nighttime negative ionospheric storm effect can last at least 4 days with very strong intensity. The strong nighttime negative ionospheric storm effect is at around midnight (2200–0200 LT) and the foF2 has very significant response to all the previous geomagnetic activities except for that in the morning. For the daytime positive ionospheric storm effect, there are two periods of strong response. One is in the morning and the geomagnetic activities occurring at midnight or noon can cause foF2 to increase obviously. The other is around sunset.

In summer for the low solar activity period, shown in the right panel of Fig. 2, the response of foF2 to geomagnetic activities has no diurnal variation as seen in the other seasons, but has close relationship to the local time in Hainan that geomagnetic activities occurred. Generally, geomagnetic activities which occurred at nighttime could cause strong ionospheric response and make foF2 decrease, this effect is stronger at 1600–2100 LT in the same day and can last several days. For the geomagnetic activities occurring in the daytime, especially around noon, the response of foF2 is very weak. It is notable that geomagnetic activities occurring from midnight to 0800 LT have intense negative ionospheric storm effects around midnight with more than 84 hours lag.

3.3. Winter

Fig. 3 shows the response of ionospheric foF2 in winter. From the left panel of Fig. 3, it can be seen that in winter for high solar activity period the diurnal variation of the response of foF2 to geomagnetic activity is very pronounced, similar to the other seasons in high solar activity period. There are three periods of the strong daytime positive ionospheric storm effect, which are 0700–0900 LT, 1300–1600 LT and 1800–2000 LT, respectively. It is notable that only geomagnetic activities occurring from 0800 LT to midnight can make foF2 increase significantly at these three periods and the response of foF2 can last several days. The response of foF2 is very weak during the other periods at daytime. For the nighttime response of foF2, there are two periods of strong negative ionospheric storm effect, which are around midnight and at 0300–0500 LT, but the ionospheric response of the latter one is more obvious and could last longer time. They all have strong response to geomagnetic activities which occurring in the evening and pre-midnight. It can be found that ionospheric foF2 has no obvious response to geomagnetic activities which occurred from midnight to ~0800 LT.

In winter for the low solar activity period, as shown in the right panel of Fig. 3, the diurnal variation of the response of foF2 to geomagnetic activities is also very pro-

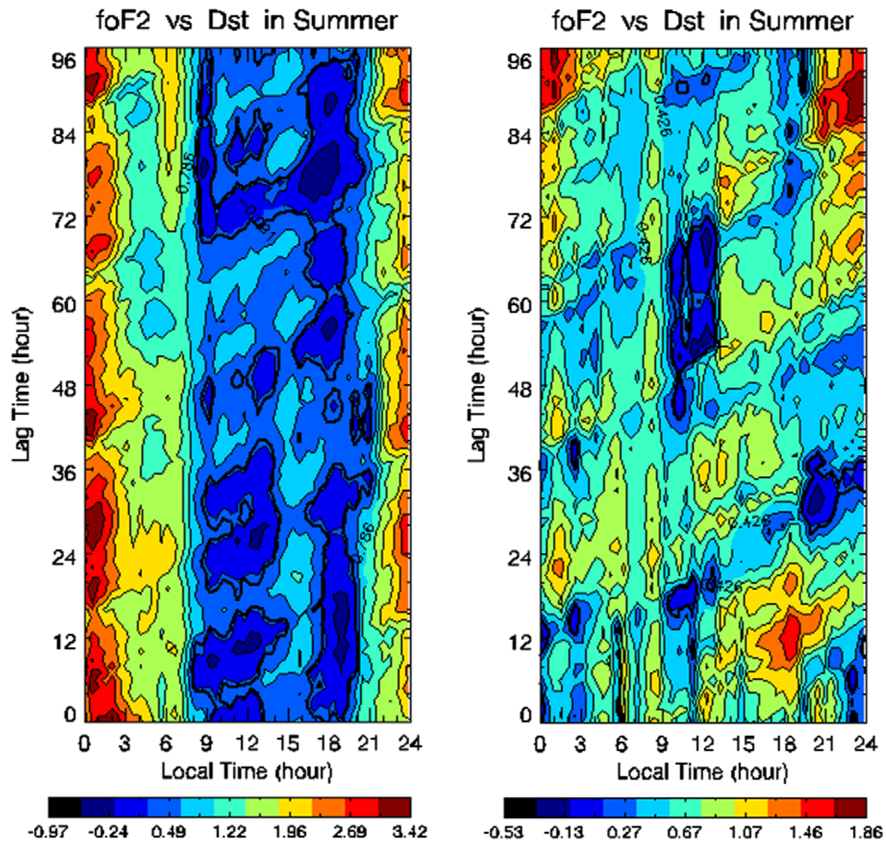

Fig. 2. Same as Fig. 1 except in summer.

nounced, not similar with the other seasons for the low solar activity period. Moreover compared with that of high solar activity period, the lasting time of daytime positive ionospheric storm effect is reduced to the interval of 0700–1400 LT only. And the daytime foF2 has strong response to the nighttime geomagnetic activities. The negative ionospheric storm effect covers not only the nighttime but also the afternoon. The pre-midnight foF2 has significant negative response to geomagnetic activities occurring from post-midnight through noon. It is notable that the response of foF2 has special time-lag effect at pre-midnight, i.e. the negative ionospheric response becomes very intense with about more than 60 hours lag.

Response of the foF2 to the Dst index is very complicated, especially in the low-latitude. In this paper, as a first approach, we use linear regression to study it and try to get an insight into it. In order to consider the reliability of the results, we also calculated the correlation coefficients of the linear regression line and its experiment data in this research. It shows that the correlation coefficients have similar layout with the coefficient a for the local time and lag time in each season for the high and low solar activity periods with positive values. Moreover there are big correlation coefficients (more than 0.40, even 0.51) corresponding to the strong ionospheric response (i.e. peak values of a). So we think the method in this study has some validity and it provides a primary way for the further research on the complicated ionospheric response.

4. Conclusions

In this paper we have investigated the responses of low-latitude ionospheric foF2 to geomagnetic activities based on the foF2 data from a low-latitude ionosonde station, Hainan, China. The conclusions can be drawn as follows:

(1) Responses of foF2 to geomagnetic activities in Hainan show obvious diurnal variation especially in the high solar activity period, except for the summer in the low solar activity period. Generally, geomagnetic activities will cause foF2 to increase at daytime and decrease at nighttime. The intensity of response of foF2 is stronger at nighttime than that at daytime.
(2) Seasonal dependence of the response of foF2 to geomagnetic activity is very obvious. The negative ionospheric storm effect is the strongest and can last longer time in summer. Moreover it can extend to the whole day for the low solar activity period. The daytime positive ionospheric storm effect is the strongest in winter. Geomagnetic activities which occur at pre-midnight could cause intense ionospheric response and it last several days in equinox for the high solar activity period.
(3) The solar cycle has important effect on the response of foF2 to geomagnetic activities in Hainan. In high solar activity period, the diurnal variation of response of foF2 is very pronounced, daytime positive iono-

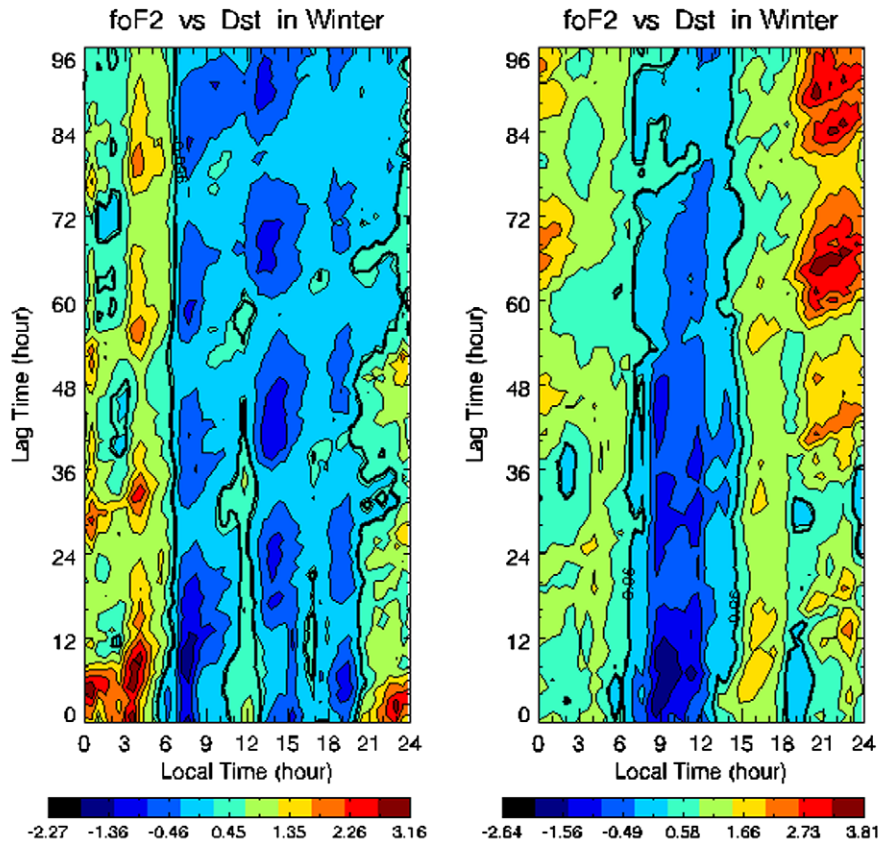

Fig. 3. Same as Fig. 1 except in winter.

spheric storm effect is very strong in each season and the strong ionospheric response can last several days in summer. In low solar activity period, negative ionospheric storm effect is more pronounced, especially in summer. Moreover the diurnal variation of ionospheric response is obvious in winter only.

(4) The local time of geomagnetic activities occurring also has important effect on the responses of foF2. Generally, geomagnetic activities occurring at nighttime can cause stronger response of foF2 in Hainan and last longer time.

Furthermore, we can find that the Equatorial Ionization Anomaly (EIA) plays an important role in the ionospheric storms in the low-latitude, especially in high solar activity period. And most results of this study can be reasonably explained using the effects of the disturbance dynamo (Fejer and Scherliess, 1995). According to the results of Fejer and Scherliess (1995), the delayed response due to the disturbance dynamo is upward $\mathbf{E} \times \mathbf{B}$ drifts (eastward electric field) from near midnight to dawn, and basically downward drifts (westward electric field) for the rest of the day in the equator region. And for Hainan, which lies in the south of the north ridge of the EIA, the disturbance dynamo will cause upward and northward (poleward) $\mathbf{E} \times \mathbf{B}$ drifts from near midnight to dawn, which cause a loss of plasma in Hainan and the decrease of foF2; and downward and southward (equatorward) drifts for the rest of the day, which will cause the north ridge of EIA move southward (equatorward) and electron density increase in Hainan. In the high solar activity period, the EIA is very strong and can continue to midnight, and we can observe its prominent effect in ionospheric storms in the results above. In the low solar activity period, the EIA is weak and its effect in ionospheric storms is also very weak except in winter.

Besides the Dst index, works for another geomagnetic activity index K_p are also done. Results show that for the two geomagnetic active indices: K_p and Dst, the ionospheric storm effect is very similar.

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