Annual Variations of the Critical Frequency foF2 at the Equatorial Ionization Anomaly Station during the Two Last Solar Minima

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Abstract

What was unusual in the solar wind-magnetosphere-ionosphere system during the last solar minimum? Behavior of the equatorial ionosphere during this prolonged solar cycle 23-24 minimum is one of the most interesting aspects of this period. The aim of our paper is to analyze the factors which can change ionosphere parameters during the solar minima. We calculated annual variations of foF2 at station Vanimo and compared these data with annual variations of Dst-index and the solar wind parameters. From this it follows that in addition to low level of the EUV during the solar minima, the geomagnetic variations effect has to be included as the influencing factor on equatorial ionosphere.

Introduction

Behavior of the equatorial ionosphere during this prolonged solar cycle 23-24 minimum was one of the most interesting aspects of this period. There are significant disagreements between the global TEC (total electron content) and foF2 annual variations during the last two solar minima. Many authors concluded that the annual means of foF2 and the global TEC were reduced, while others investigations no found essential variations as compared with the previous solar minimum. Araujo-Pradere et al. (2011) found that vertical TEC of ionosphere showed a consistent modest decrease of the mean value during the solar cycle 23–24 minimum, while NmF2 behavior was less clear, with instances where the mean value for the minimum 23–24 was even higher than for the minimum 22–23. Model calculations of Araujo-Pradere et al. (2013) support the general assertion that thermospheric temperatures were cooler during the last solar minimum as a consequence of an unusually low and extended minimum of the solar extreme-ultraviolet flux, and in response to continually increasing long-term trend in anthropogenic carbon dioxide. The cooler temperatures not only decrease density at a fixed height, but also make the corresponding contraction of the atmosphere lowering the height of the F-region peak. Araujo-Pradere et al. (2013) suggest that the relative balance between low latitude heating from EUV flux and high latitude heating from magnetospheric sources may have changed slightly in the recent unusual minimum. Any changes in this heating balance, would affect the strength of the meridional winds, and may have modulated the impact of the general background cooling and decrease in hmF2. TEC variations overview and ionospheric climatology study from Global Positioning System (GPS) observations have been investigated extensively by Liu et al (2009). They found that the mean TEC averaged globally and at three latitude bands (low, middle, and high latitudes) in one (southern or northern) hemisphere and both hemispheres show strong solar cycle (F10.7 and extreme ultraviolet - EUV) and solar rotation modulations as well as annual/semiannual variations. It was also shown that the mean TEC has higher solar activity sensitivity at lower latitudes and with increasing (decreasing) solar activity, these mean TEC tend to increase (decrease). The saturation effects at high F10.7 have already been reported in NmF2 and TEC (e.g., Balan et al., 1994; Chen et al., 2008). Ouattara et al. (2012) have analyzed the variability of foF2 at two West Africa equatorial ionization anomaly stations (Ouagadougou and Dakar) during three solar cycles (from cycle 20 to cycle 22). Their analyze show a good correlation between foF2 and sunspot number for Ouagadougou and Dakar data. The correlation coefficient varied from one solar-cycle to another. The above mentioned authors assigned phase-to-phase variability of foF2 to solar ultraviolet radiation variability and they concluded that it is necessary to treat separately the variability of the ionosphere according to each type of solar-cycle phase. Yang et.al (2012), called their attention to the different results of the papers relating to foF2 variations obtained from the ionosonde station Jicamarca during the solar cycle 23–24 minimum comparing to the prior solar minimum. They concluded that the behavior of the ionosphere parameter could be due to the different analyzing methods and the time length chosen. They also show that the solar control on the ionospheric behavior is not linear at Jicamarca station. The yearly values of foF2 were smaller in 2008–2009 than in 1996–1997. Most if not all of authors suppose that the possible source of this phenomenon is the low level of the EUV during the solar minima.

The aim of our paper is to validate conclusions about low level of the EUV effect on the ionosphere or to propose new factor which can change ionosphere parameters during the solar minima. To do this we will analyze possible effects of the solar wind and geomagnetic variations in term of the Dst index and on the foF2 variations at the equatorial ionization anomaly station during the last two solar minima.

Data Sets

Data used in this study are obtained from: Dst –index http://wdc.kugi.kyoto-u.ac.jp, ionospheric data of the foF2 (F2 layer critical frequency in MHz) at station Vanimo (-2.7S, 141.30E, dip.-21.6) in
http://www.ips.gov.au/WDC, solar wind data http://omniweb.gsfc.nasa.gov/ow.html

Analysis of the experimental data

Let us examine Figure 1 where diurnal variations of yearly average foF2 (MHz) at Vanimo equatorial ionization anomaly station (Papua New Guinea) during the solar cycle 22-23 (1996-1997) and 23-24 (2008-2009) minima are presented. These data were calculated in terms of the universal time (LT = UT + 14h) for simplify comparison of geomagnetic, interplanetary and other papers data. Figure1 plots annual variations of the critical frequency of foF2: for 1996 by solid line with crosses, for 1997 by solid line with triangles, for 2008 – by solid line with dark circles, for 2009 – by solid line with light circles. We can see that annual variations of foF2 have been reduced from day-time maximum at LT 14 h to night-time minimum at LT 5-7 h (19-21 UT). We do not see day-time ionization bite-outs in annual variations at Vanimo station as seen very well at equatorial and equatorial ionization anomaly regions at Jicamarca, Ouagadougou and Dakar stations at the pictures as shown in Yang et.al (2012) and Ouattara et al. (2012) papers. This appears is that Vanimo is situated at the border of equatorial ionization anomaly region. One can further see that there is a difference about ~ 1 MHz between the two solar minima in 1996 and 2008. The less difference is about 0.5 MHz between 1997 and 2008 and night-time levels of foF2. The bigger differences in foF2 for the same years were observed at Jicamarca by Yang et al. (2012). The annual variations of foF2 and or electron density at Vanimo during 23-24 solar minimum like at Jicamarca station indeed are lowest with relation to previous one but not so unusual.

These results could be interpreted by higher EUV values in 1996-1997 compared to 2008-2009 according to Solomon et al. (2010). In 1996-1997 the solar EUV 26-34 nm irradiance was about 0.7 mW/m^2 whereas in 2008-2009 it was about 0.6 mW/m^2. Richardson et al. (2012)

study shows us the same results: the solar 26 to 34 nm EUV irradiance from SOHO SEM appears 15% lower in 2008 than in 1996. One of the options that might explain this is a quantity of coronal holes (areas of open magnetic field). As concluded Richardson et al. (2012), more image analysis and irradiance modeling are required to prove this option.

The possible reasons for foF2 differences during the solar minima might be variations of the solar wind, geomagnetic variations and some others. We calculated UT variations of Dst-index during the same solar minima years as foF2 variations shown in Figure 1. Figure 2 plots the annual Dst variations in the same symbols as for the critical frequency of foF2 at Vanimo station: for 1996 by solid line with crosses, for 1997 by solid line with triangles, for 2008 – by solid line with dark circles, for 2009 – by solid line with light circles. Figure 2 shows essential distinctions between annual Dst –index variations during the two solar minima during 1996-1997 (Dst varied between -10 and -15 nT) and 2008-2009 (Dst varied between -8 and -2 nT). They are retraced in tandem with the foF2 variations at Vanimo: the less are Dst- index values during the solar minima, the greater foF2 values during this years and vice versa. The same order of events in foF2 annual values at Jicamarca can be found in the paper of Yang et al (2012).

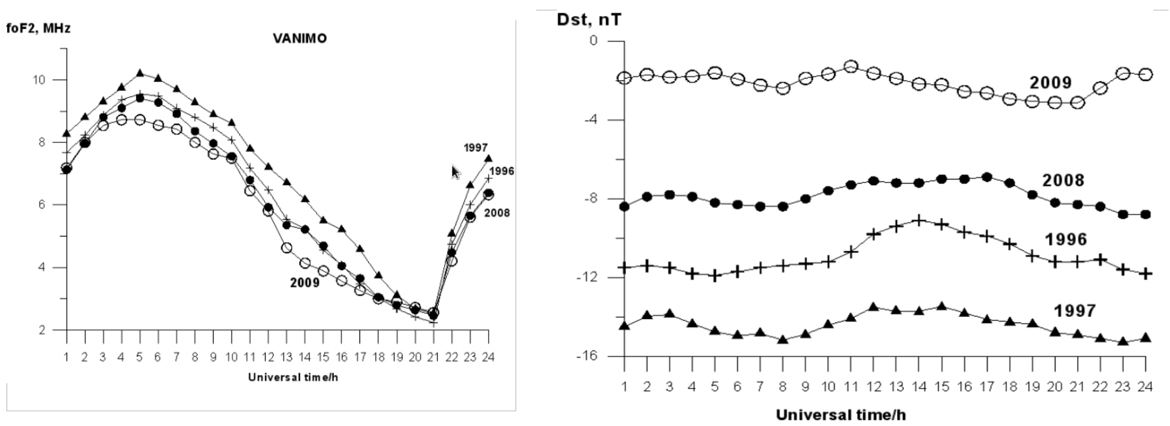

Fig. 1. (Left) Annual variations of foF2 (MHz) at Vanimo station during the solar cycle 22-23 and 23-24 minima. UT annual averages are shown: 1996 by solid line with crosses, for 1997 by solid line with triangles, for 2008 – by solid line with dark circles, for 2009 – by solid line with light circles. (Right) Annual variations of Dst-index during the solar cycle 22-23 and 23-24 minima. UT annual averages of Dst index are shown: 1996 by solid line with crosses, for 1997 by solid line with triangles, for 2008 – by solid line with dark circles, for 2009 – by solid line with light circles.

Does the solar wind variations were effected on the level of Dst variations during these solar minima? For this purpose let us analyze the solar wind data. Figure 3 presents the solar wind 27-day averaged data of the solar wind velocity (the bottom panel) and Dst variations (the top panel) obtained from OMNI data. The same symbols in plots as in Figure 1 and 2 are used for data: 1996 by solid line with crosses, 1997 by solid line with triangles, 2008 – by solid line with dark circles, 2009 – by solid line with light circles. Seasonal effects in Dst variations are seen at the top panel. Dst variations have been more quiet in 2009 when the solar wind velocity had minimum about 320 km/s. Seasonal effect is missed in Dst-index during this year since geomagnetic storms were absent. A reduction of Dst variations due to the solar wind velocity can be found in 1996-1997 in the at the ends of these years and in the beginning in 2008 when the high speed solar wind reached 520 km/s. According Richardson et al. (2012) these solar wind velocity variations were associated with solar coronal holes during the solar minima. At solar minimum, high speed streams are responsible for around three-quarters of small (∼77%)

or medium (∼70%) storms, around a half (48%) of large storms, and ∼13% of major storms, the remainder being predominantly associated with CME flows. The solar wind dynamic pressure and interplanetary magnetic field B show quiet conditions in 2008 and 2009. Figure 4 plots the solar wind dynamic pressure Pd in nPa (the top panel) and the solar wind IMF B in nT 27 day variations for the period being discussed. The same symbols as on Figure 1 and 2 for the corresponding years are used here. The graphs in Figure 1-4 clear show that the last solar minimum was the quietest as in interplanetary medium as in magnetosphere-ionosphere system.

Let us return to the Figure 1. We can clear see difference between yearly averaged foF2 critical frequencies variations at Vanimo in local evening and night when EUV is absent. Difference of diurnal variations of 12-monthly average at Jicamarca in these solar minima in evening and night-time hours also can be found in Yang's et al. (2012) graph. This effect can not be explained by EUV variations but have to be attributed partly for example to geomagnetic variations which clear seen in Figure 2. We have to take into account also that the ionosphere is produced by X-ray wavelengths. Minor contributions are coming from ionization by cosmic rays (maximum effect fall on solar minimum) and other effects on the ionosphere.

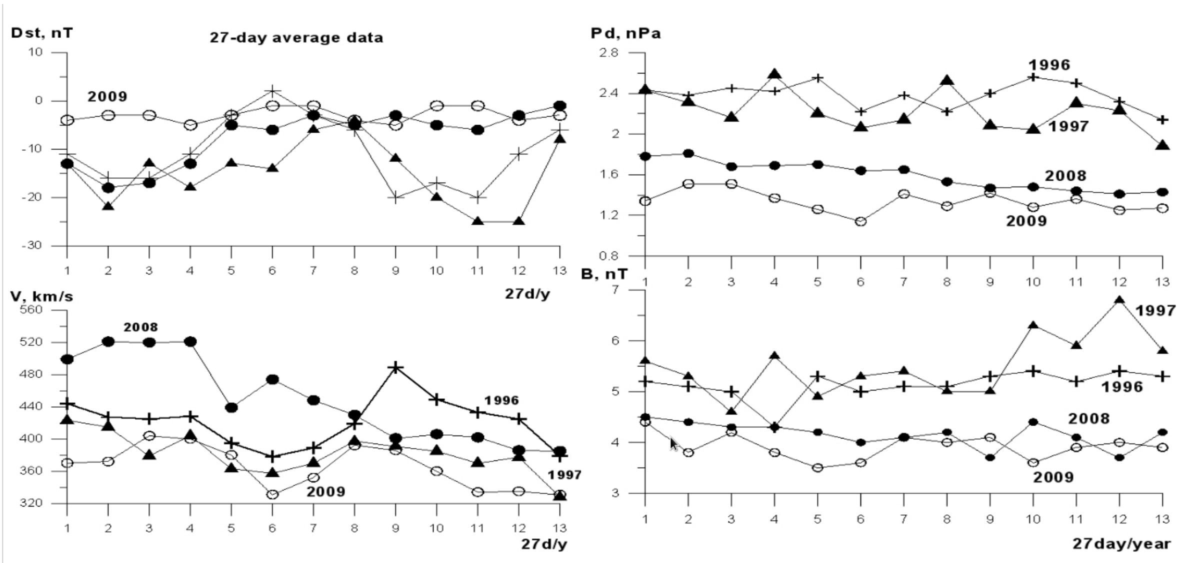

Fig. 2. (Left) The solar wind 27-day averaged data of the solar wind velocity (the bottom panel) and Dst variations (the top panel) obtained from OMNI data. The same symbols in plots as in Figure 1 and 2 are used for the solar wind data: 1996 by solid line with crosses, 1997 by solid line with triangles, 2008 – by solid line with dark circles, 2009 – by solid line with light circles. (Right) The solar wind 27 day variations of dynamic pressure Pd in nPa (the top panel) and the solar wind IMF B in nT for the period being discussed. Pd and B are shown for: 1996 by solid line with crosses, 1997 by solid line with triangles, 2008 – by solid line with dark circles, 2009 – by solid line with light circles.

Therefore, the equatorial ionospheric parameters during the solar minima are highly susceptible to EUV effect. They also can be very sensitive to geomagnetic variations caused by high latitude electric fields penetration to the equatorial ionosphere (Mazaudier (1985), Biktash et.al (2004, 2008). There are other possible reasons including meridional winds strength (as shown by Araujo-Pradere et al. (2013)) and cosmic ray effects. The questionis remains open.

Conclusion

We have calculated UT variations of annual means of the critical frequency foF2 at the equatorial ionization anomaly station Vanimo during the two last solar minima. Annual means of foF2 during 23-24 solar minimum at Vanimo station is lower compared to the previous 21-22 solar minimum, but this difference (is about $\sim$ 1 MHz) is not unusual. Comparison of these data with Dst annual variations and the solar wind parameters show us that this effect can not be only explained by EUV variations but have to be partly attributed to electric field at the equatorial ionosphere due to geomagnetic variations. It is shown that together with other solar and interplanetary parameters, the long-term variations of the Dst-index, as measure of solar-terrestrial relationships can be used for study of these kinds of ionospheric variations. It should be noted that more detail investigations of these relationships for different ionospheric regions are required.

Acnowledgements

The author would like to thank the following organizations for the data used in this study:

- World Data Center for Geomagnetism, Kyoto : Dst –index http://wdc.kugi.kyoto-u.ac.jp),
- Radio and Space Services of the Australia Bureau of Meteorology: ionospheric data of the foF2 at station Vanimo http://www.ips.gov.au/WDC,
- NASA Goddard Space Flight Center: solar wind data http://omniweb.gsfc.nasa.gov.

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Годовые вариации критической частоты foF2 на экваториальной станциии ионизационной аномалии во время двух последних солнечных минимумов

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В данной работе исследуются годовые вариации критической частоты foF2 на экваториальных станциях с целью выявления причин, которые влияют на ионосферу во время солнечных минимумов. Поведение электронной плотности в экваториальных регионах во время солнечных минимумов является предметом пристального изучения в связи с особенностями последнего глубокого солнечного минимума. Имеются существенные различия в результатах, полученных глобальных карт полного электронного содержания по измерениям на GPS во время двух последних солнечных минимумов. Эти различия, в основном, исследователи объясняют изменением ультрафиолетового излучения Солнца и особенно низким уровнем этого излучения в последнем солнечном минимуме. Мы рассмотрели годовые Dst-вариации и вариации критической частоты foF2 на станциях Хуанкайо и Ванимо. Результаты исследований показали, что одной из причин различий электронной плотности ионосферы в солнечных минимумах является геомагнитная активность, которая меняется от минимума к минимуму.