Annual Variations of the Critical Frequency foF2 at Vanimo Station during the Two Last Solar Minima

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Abstract Behavior of the equatorial ionosphere during the prolonged solar cycle 23-24 minimum is one of the interesting phenomena. Many authors concluded that the annual means of the critical ionospheric frequency foF2 and the global TEC (total electron content) were reduced due to EUV variations (extreme ultraviolet), while other investigations found no essential variations compared to the previous solar minimum. To resolve these doubts we have examined the factors which can change the annual ionospheric variations of the critical frequency foF2 at the equatorial ionization anomaly stations Vanimo during the two last solar minima. With that end in view the annual variations of foF2 at Vanimo station have been calculated and compared with variations of Dst-index and of the solar wind parameters. We show that in addition to low level of the EUV during the last solar minima, the geomagnetic variations effect, associated with solar coronal holes, has to be included as the influencing factor on the equatorial ionosphere.

Keywords: Equatorial ionosphere; Dst-index; Solar minimum; Annual variation.

Introduction

What was unusual during too long solar cycle 23-24 minimum in the system of solar wind-magnetosphere-ionosphere? Behavior of the equatorial ionosphere during this prolonged solar cycle 23-24 minimum was one of interesting aspects of the period. Scientists were equipped with a thorough knowledge: a lot of space missions and ground-based observatories were operated and a lot of papers about this period have been published. The significant disagreements between global TEC and foF2 annual variations during the last two solar minima have been pointed out by Balan et al.,, (1994), Chen et al.,, (2008), Araujo-Pradere et al.,, (2011) and others. 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. Their model calculations supported 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. 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. The yearly values of foF2 were smaller at Jicamarka in 2008–2009 than in 1996–1997. They assumed that the behavior of the ionosphere parameter could be due to the different analyzing methods and the time length chosen. They also noted that the solar control on the ionospheric behavior is not linear at Jicamarca station. The variability of foF2 at two West Africa equatorial ionization anomaly stations during the solar cycles 20, 21 and 22 presented by Ouattara et al.,, (2012) showed that it is necessary to treat separately the variability of the ionosphere according to each type of solar-cycle phase.

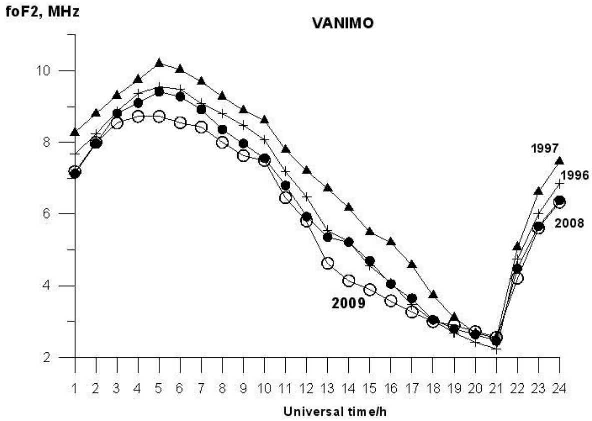
By this means, there are several reasons to expect that the possible source of TEC and foF2 differences during the two last solar minima is the low level of the EUV in 2008–2009. Taking into account the above mentioned implications we treat the two solar minima separately not only EUV which is very different, but also the ionospheric and geomagnetic activity between solar maxima as well. This is defined mainly by coronal mass ejections and coronal holes effects on magnetosphere-ionospheric system by the solar wind significantly. So, the aims of our paper is to validate conclusions about low level of the EUV effect on the ionosphere and to propose other factors 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 on the foF2 variations at the equatorial ionization anomaly station Vanimo during the last two solar minima.

Materials and methods

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 and sunspot numbers (SSN) **http://omniweb.gsfc.nasa.gov/ow.html**. We calculated annual averages of foF2, Dst index, solar wind and B of IMF data using their hourly values during the solar cycle minima 22-23 (1996-1997) and 23-24 (2008-2009). All data were lead to universal time (LT = UT + 9h at Vanimo station) to simplify the comparison of geomagnetic, interplanetary and other papers data.

Results and discussion

Let us examine the top panel of Figure 1 where annual averages of 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 shown. Annual variations of foF2 are represented by symbols: 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 (UT = 5 h) to night-time minimum at LT 5-7 h (19-21 UT). For comparison the foF2 annual variations at Jicamarca according Yang et al.,, (2012) are presented at the low panel of Figure 1 for the same years and in the same symbols as at Vanimo station. We can see that the foF2 variations at Jicamarca change one after another as well as at Vanimo station. We do not see day-time ionization bite-outs in the annual variations at lower latitude Vanimo whereas at Jicamarca station we see the pronounced bite-outs. Bite-outs can be found at equatorial Ouagadougou and Dakar stations in the pictures of Ouattara et al.,, (2012). The absence of bite-outs at Vanimo is that the station situates at the border of equatorial ionization anomaly region and has lower latitude than above mentioned stations. It is interesting to note that Vanimo is positioned as the equatorial station for neutral components of the atmosphere and as the low latitude station for ions. One can further see from Figure 1 that there is a difference more than 1.5 MHz between the two solar minima in 1997 and 2008 during day-time ours. The less difference is about 0.5 MHz between 1997 and 2008 and at night-time levels of foF2 variations. Day time difference in foF2 was about 1 MHz for the same years at Jicamarca according Yang et al.,, (2012). The annual variations of foF2 and electron density at Vanimo station 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/m2 whereas in 2008-2009 it was about 0.6 mW/m2. Solomon et al.,, (2010) have shown that the solar EUV images, such as from SOHO EUV Imaging Telescope (EIT), clearly indicated lower radiance from coronal holes (areas of open magnetic field). Richardson et al., (2012) showed 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 effect also is a quantity of coronal holes. Using CHIANTI spectral models of the quiet sun and coronal hole differential emission measures Landi et al., (2006), estimated that the Sun needs to have 18% more coronal holes in 2008 than in 1996 to explain a 15% reduction of the 26 to 34 nm irradiance. Thus, one option that might explain lower EUV irradiance is to have more coronal holes. We assume also after Richardson et al., (2012) that the possible reasons for foF2 differences during the solar minima might be variations of the solar wind, geomagnetic variations and some other reasons associated with coronal holes and solar magnetic field.



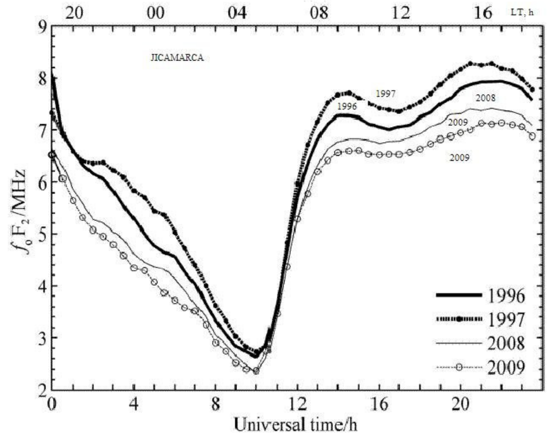


Figure 1 The top panel: annual variations of foF2 (MHz) at Vanimo station during the solar cycle 22-23 and 23-24 minima. UT annual averages are shown: 1996 by solid line with crosses, for 1997 by solid line with triangles, for 2008 – by solid line with dark circles, for 2009 – by solid line with light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

Annual average values of a reverse y-axis orientation of module IMF B (-B), Dst index, SSN and the solar wind velocity V in km/s during 20-23 cycles are presented in Figure 2. In general, we can see a quite good relationship between presented data. Correlation coefficient between Dst and B of IMF is 0.7. By this means, a long-term Dst index and module of the IMF B (-B) in 20-23 cycles demonstrate the validity of using of uninterrupted Dst index instead the IMF module. Unfortunately records of in situ space measurements of the IMF and most other indicators of solar activity cover only a few decades and have a lot of gaps for calculations of long-term variations. It is very good seen during solar cycle 20 where the annual variations of the IMF B are sensibly constant while Dst variations and SSN show annual variations. As is easy to see the solar wind velocity V has maxima during the descending phases the 20-23 solar cycles in 1974, 1985

1995 and 2004. These maxima were associated with features of corotating high velocity streams from solar coronal holes leading to geomagnetic activity. Corotating streams effects are presented in all geomagnetic indices and specifically they can be seen in Dst variations of these years.

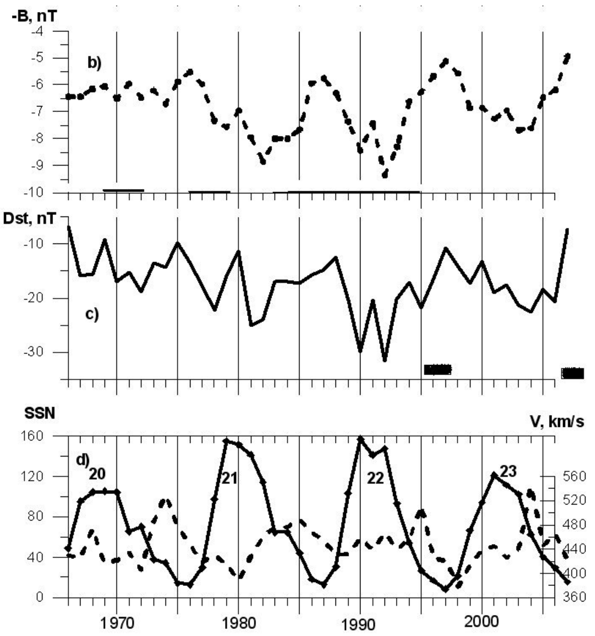


Figure 2 Annual variations of a reverse y-axis orientation of modul IMF B (-B), Dst index, SSN (sun spot numbers) and the solar wind velocity V in km/s during 20-23 SCs.

Thus, as indicator of long-term geomagnetic activity, we calculated annual variations of Dst-index during the same solar minima years as foF2 variations at Vanimo station. The plots of the annual Dst variations in the same symbols as for the critical frequency of foF2 at Vanimo and Jicamarca stations are presented in Figure 3: 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. There are the essential distinctions between annual Dst variations during the two solar minima 1996-1997 (Dst varied between -10 and -15 nT) and 2008-2009 (Dst varied between -8 nT and -2 nT). Comparison of Figure 1 and of the top panel of Figure 3 shows that annual Dst variations retraced the foF2 in reverse order the critical frequency variations at Vanimo station: than the geomagnetic field is quieter (the weak power Dst- index), and the greater foF2 values during this years is observed 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) as seen at the low panel of Figure 1.

In addition, 27-day mean values of the IMF B and the solar wind velocity variations are shown at the middle and low panels of Figure 3. Quietest Dst variations were observed in 2009. It was associated with lowest IMF B conjointly with the solar wind velocity minimum about 320 km/s. A reduction of Dst variations due to the solar wind velocity can be found in 1996-1997 in the ends of these years and in the beginning of 2008 when speed of the 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. They showed that at solar minima, 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. So, the graphs in Figure 1-3 clearly show that the last solar

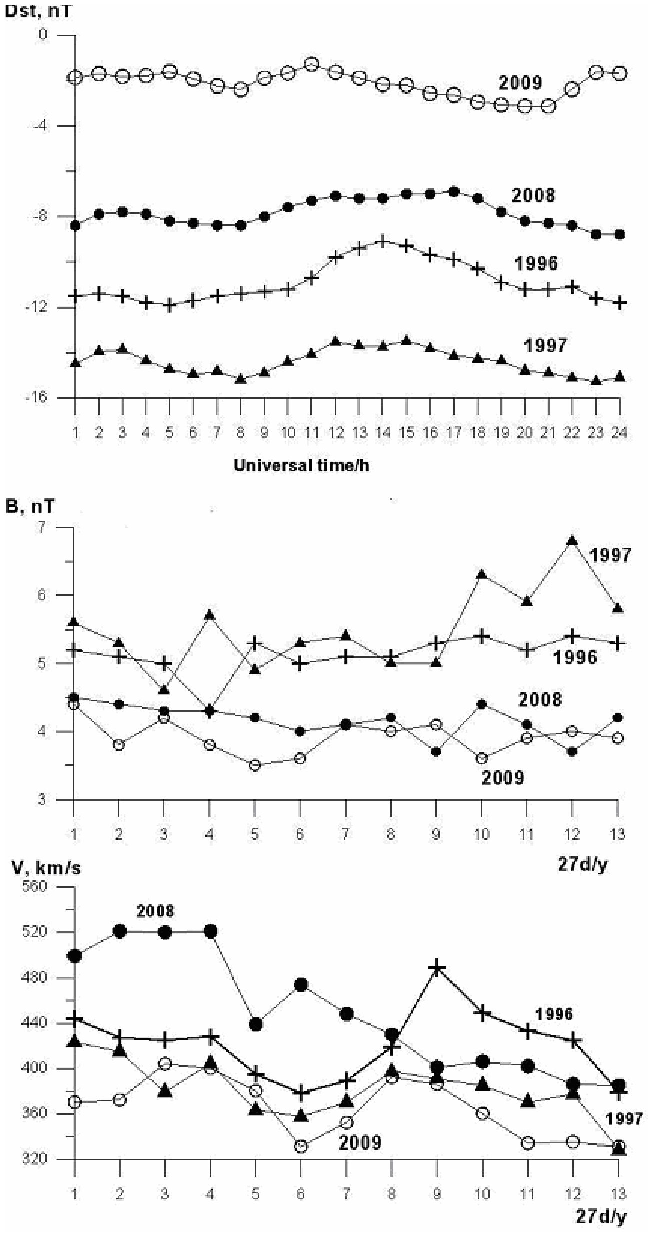


Figure 3 The top panel: annual variations of Dst-index during the solar cycle 22-23 and 23-24 minima. Dst variations in: 1996 - solid line with crosses, 1997 - solid line with triangles, 2008 - solid line with dark circles, 2009 - solid line with light circles. The middle panel: 27-day averaged data of the IMF B in nT for: 1996 - solid line with crosses, 1997 - solid line with triangles, 2008 - solid line with dark circles, 2009 - solid line with light circles. The low panel: solar wind velocity in km/s in the same symbols as the IMF B.

minimum was the quietest as in interplanetary medium and in magnetosphere-ionosphere system.

Let us return to the Figure 1. We can clearly see difference between yearly averaged foF2 critical frequency variations at Vanimo station in local evening and night hours when EUV is absent. Difference of foF2 diurnal variations at Jicamarca in these solar minima in evening and night-time hours also can be found at the low panel of Figure 1. This effect can not be explained by EUV variations but have to be attributed partly, for example, to geomagnetic variations which are clearly seen in Figure 2.

The equatorial ionospheric characteristics during the solar minima are highly susceptible to EUV effect. 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. They concluded that 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. 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). A good correlation between foF2 and SSN for Ouagadougou and Dakar data was shown in their analyze. The correlation coefficient varied from one solar cycle to another. The 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. We have to take into account that the ionosphere is produced also by X-ray wavelengths. Minor contributions are coming from ionization by cosmic rays and its maximum effect falls on solar minimum. Ionospheric characteristics can also be very sensitive to geomagnetic variations caused by high latitude electric fields penetration to the equatorial ionosphere (Mazaudier (1985), Biktash et al., (2004, 2008). Our present study of foF2 variations at Vanimo station demonstrates that geomagnetic variations has influence on the ionosphere during solar minima.

Conclusion

Many authors concluded that the annual means of foF2 and the global TEC were reduced during the last solar minimum, while other investigations found no essential variations as compared with the previous one. TEC variations and ionospheric climatology using Global Positioning System (GPS) observations investigated by Liu et al., (2009). They showed that mean TEC globally at three latitude bands (low, middle, and high latitudes) in one (southern or northern) hemisphere and both hemispheres have strong solar activity (F10.7 and extreme ultraviolet - EUV) and solar rotation modulations as well as annual/semiannual variations. The most salient feature works were shown for low latitudes. The latitudes of the crests of the equatorial ionization anomaly were displaced by a few degrees toward the equator in TEC compared to that in NmF2. The same results were well documented earlier in works of Balan et al., (1994), Chen et al., (2008) and in various works.

There were no well consensus between TEC and ionosonde stations results. Because of these features we can take better advantage of comparison either TEC or ionosonde stations measurements. 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 with respect to the previous 21-22 solar minimum, but this difference (is about ~ 1,5 MHz) is not unusual. Comparison of these data with Dst annual variations and the solar wind parameters shows us that this effect can not be explained solely 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 geomagnetic and solar wind effects on ionosphere. It should be noted that more detail investigations of these relationships for different ionospheric regions are required.

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- ✓ NASA Goddard Space Flight Center: solar wind data http://omniweb.gsfc.nasa.gov.

References

Araujo-Pradere, E., Redmon, R., Fedrizzi, M.: 2011, Solar Phys. 270, 439.

Araujo-Pradere, E., Buresova, D., Fuller-Rowell, D.J., Fuller-Rowell, T.J.: 2013, Adv. Space Res. 51, 630.

Balan, N., Otsuka, Y., Fukao, S., Abdu, M.A., Bailey G. J.: 2000, Adv. Space Res. 25, 153. Biktash, L. Z.: 2004, Annales Geophys. 22, 3195.

Biktash L.Z., Maruyama T., Nozaki N.: 2007, Adv. Space Res. 41, 562.

Chen, Y., Liu, L., Le, H.: 2008, J. Geophys. Res. 113, A11306.

Landi E., Phillips K.J.H.: 2006, The Astroph. J. Supplement Series. 166, 421

Liu, L, Wan, W., Ning, B., and Zhang M-L.: 2009, J. Geophys. Res. 114, A06308.

Ouattara, F., Gnabahou, D., Mazaudier, C.A.: 2012, Int. J. Geophys. ID 640463, doi : 10.1155/2012/640463.

Mazaudier, C.: 1985, J. Geophys. Res. 90, 1355.

Richardson, I.G., and Cane, H.V.: 2012, J. Space Weather Space Clim. 2 A01 DOI: 10.1051/swsc/2012001.

Solomon, S.C., Woods, T.N., Didkovsky, L.V., Emmert, J. T., and Liying Q.: 2010, Geophys. Res. Lett. doi: 10.1029/2010GL044468.

Yang, G.J., Liu Li-Bo., Chen, Yi-Ding., and Le H.J.: 2012, Chinese J. of Geophys. 55, 457.