Indian Journal of Radio & Space Physics
Vol 46, December 2017, pp 103-109

Studies on F_2 layer critical frequency in the southern hemisphere during solar cycle-23

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Received 27 June 2016; accepted 20 January 2017

Annual and seasonal variability and anomalies of F_2 layer critical frequency for 3 stations in southern hemisphere over solar cycle-23 (1996-2008) have been analyzed in this paper. Annual and seasonal variability have been studied by computing the yearly and seasonal coefficient of variability of F_2 layer critical frequency. The annual analysis reveals that the variability of the equatorial station is comparatively lower at the solar active years of the selected solar cycle. For all stations, the variability is lesser at day time and peaks after midnight. During post sunrise hours the variability remains more or less same throughout the cycle in all stations. Variability is found to be higher mostly during equinoxes and the mean F_2 layer critical frequency has been observed to peak around 1400LT, in all stations. Equatorial and mid-high latitude stations show semiannual anomaly throughout the cycle, while the mid latitude station exhibits no signatures of winter anomaly during the cycle.

Keywords: Ionosphere, F_2 layer critical frequency (foF_2), Ionospheric variability, Coefficient of variability

1 Introduction

Studies related to ionospheric variability and anomalies are important due to the fact that the properties of ionosphere are direct consequences of the incoming solar radiation and the electrodynamical coupling of magnetosphere with solar events. The molecules and atoms in the F_2 region of the ionosphere are energized and ionized by solar extreme ultraviolet radiation and by energetic electrons of solar and magnetospheric origin. The ions produced then undergo chemical reaction with neutrals, recombine with electrons, diffuse to higher or lower latitudes according to their weight or are transported by neutral wind effects. The coupling between ions and neutral winds depend on latitude, longitude and local time of a station under consideration.

Ionospheric parameters such as total electron content (TEC), peak electron density of F_2 layer plasma (NmF_2), critical frequency of F_2 layer (foF_2) are usually useful for a lucid understanding of ionospheric variations. High correlation between TEC and NmF_2 values is detected during periods of low and medium solar activity[1]. F_2 layer critical frequency is an important parameter for understanding the dynamics of the F_2 region since it is directly related to the NmF_2 by the well-known relation[2] $foF_2 = \sqrt{80.6\, NmF_2}$. Ionospheric foF_2 variation study is essential as it plays a crucial role in radio wave propagation, satellite tracking, navigation, etc.

Chapman's ionization theory explains the ionospheric electron density as a function of solar zenith angle. The behavior of F_2 layer occasionally deviates from that of Chapman's theory leading to anomalies such as annual anomaly, in which NmF_2 is greater in December than in June in both hemispheres, semiannual anomaly, where NmF_2 is larger in equinoxes than in solstices, winter anomaly, in which noon-time NmF_2 is larger in winter than in summer. Annual anomaly is primarily caused by the increase in the Sun-Earth distance in December. The displacement of geomagnetic poles from the geographic poles also drives annual anomaly[3]. The global thermospheric circulation-thermospheric spoon, induced by the asymmetric hemispheric heating of the atmosphere during solstices causes the semiannual anomaly[4]. The causes of semiannual anomaly and annual anomaly are also described by Rishbeth *et al.*[5] Liying Qian *et al.*[6] studied the systematic annual and semiannual variations in the ionosphere and thermosphere and suggested that variable eddy diffusion plays an important role in the observed variation of NmF_2 at low latitudes. Zou *et al.*[7] have also studied the semiannual variations in low latitudes and southern mid latitudes for solar cycle 20 and 21. Rishbeth *et al.*[8] suggests that

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the seasonal change in [O]/[N2] ratio in the neutral layer in the F_2-layer is a main cause of winter anomaly. Rao *et al*. have established the presence of winter anomaly in the day time foF_2 in a northern mid latitude station throughout solar cycle-23 which was prominent during high solar active years. They also identified a consistent semiannual anomaly throughout the cycle[9]. Winter anomaly is more significant in the near-pole regions than in far-pole regions. But semiannual anomaly is more important in far pole regions than in near pole regions[10]. The contribution of annual anomaly makes winter anomaly stronger in northern hemisphere and weaker in southern hemisphere since winter anomaly and annual anomaly are out of phase in southern hemisphere. Burns *et al.*[11] addressed this problem by defining winter anomaly as the surplus foF_2 of particular latitude in the winter hemisphere and that of conjugate latitude in the summer hemisphere at same longitude on the same day of a year. Rishbeth *et al.*[12] have also emphasized the importance of comparing foF_2 data of conjugate stations of both hemispheres to evaluate winter anomaly.

Along with the anomalies, the ionospheric foF_2 variability studies are also important in improving ionospheric models such as the International Reference Ionosphere. Akala *et al.*[13] studied the impact of diurnal, seasonal and solar activity effects on the variability of ionospheric foF_2 in the African equatorial latitudes and concluded that equatorial foF_2 variability increases with decreasing solar activity during night time[14]. According to Kuznetsov *et al.*[15], the universal variability of foF_2 is different for solar minima and maxima years.

In this paper, the annual, seasonal and monthly variability and anomalies of ionospheric F_2 layer critical frequency of three stations in the southern hemisphere over 23rd solar cycle have been studied. The stations selected in the study include an equatorial station Vanimo (2.70°S, 141.30°E, magnetic latitude 11.19°S), a low latitude station Townsville (19.63°S, 146.85°E magnetic latitude 28.95°S) and a mid-high station Hobart (42.92°S, 147.32°E, magnetic latitude 54.17°S). The stations fall in different latitudes and in more or less same longitudes so that the local time for the three stations falls within a difference of one hour.

2 Data and Analysis

The study is based on ionospheric foF_2 hourly data of the three stations collected from http://www.sws.bom.gov.au/World_Data_Centre/1/3. The data sets cover the whole 23rd solar cycle (1996-2008). A 10.7 cm solar radio flux F10.7 is often used as a standard proxy for solar activity. For studying solar cycle pattern, the 10.7 cm solar flux data F10.7 (sfu) collected from http://omniweb.gsfc.nasa.gov is used.

From the definition of near pole and far pole regions[7], the Australian sector of Southern hemisphere falls in the longitudes of near pole region. Thus Hobart is a near pole station since the location of south pole during the period under consideration was around 138°E, 64°S. (http://www.ngdc.noaa.gov/geomag/data/poles/SP.xy) The statistical tool used to evaluate the variability of foF_2 is the coefficient of variability (CV).

2.1 Coefficient of variability

The coefficient of variability (CV) of a variable is statistically defined as:

$$CV= (\sigma/\mu) \qquad \dots (1)$$

Where σ is the standard deviation and μ, the arithmetic mean of the variable. It expresses the standard deviation as a proportion of the arithmetic mean. The variable with the largest value for the coefficient of variability is the one with the highest relative dispersion around the mean. The popularity of CV in many scientific areas stems from the fact that it is unit-less and can be interpreted easily compared to standard deviation[16]. The method of studying variability of ionospheric parameters by computing its CV is adopted earlier by Akala *et al*[13,14] and Bilitza *et al.*[17] In our study, the annual arithmetic mean and corresponding standard deviation of foF_2 was calculated for every hour of a year to compute the annual CV. Diurnal variation of annual CV over the whole solar cycle-23 is thus obtained. The data of each year was arranged into four groups of Equinoxes (March and September) and Solstices (June and December). The mean and its standard deviation for each quarter were computed to evaluate the seasonal CV for each hour.

The study thus addresses foF_2 variations of the three stations over solar cycle-23.

3 Results and Discussion

3.1 Diurnal variation of yearly mean of foF_2

The computed yearly means of foF_2 for each hour of day are plotted over the solar cycle-23 in order to study the diurnal and solar cycle variations of foF_2 in Fig. 1.

It is observed from Fig. 1 that the yearly mean foF_2 peaks around 1400LT throughout the cycle and falls during morning and evening hours for Townsville and

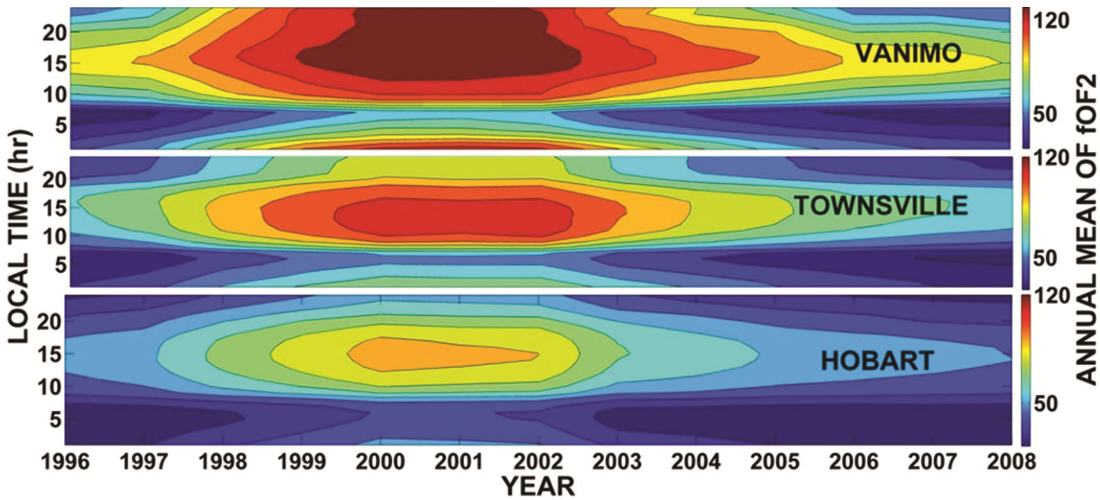

Fig. 1 — Contour plots showing the diurnal variations of yearly mean of foF_2 for the three stations over solar cycle-23.

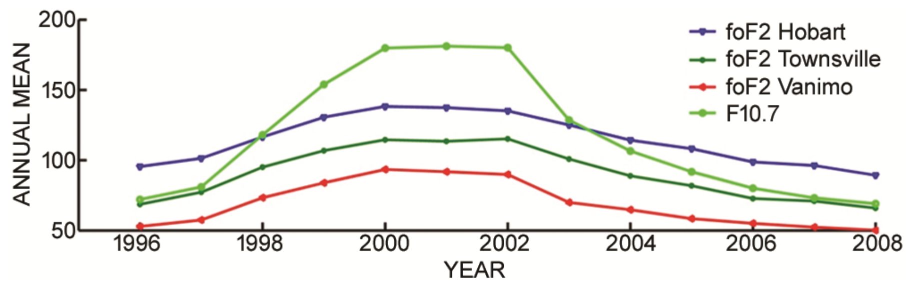

Fig. 2 — Annual mean of foF_2 at 1400LT of the three stations along with annual mean of F10.7 (sfu) for the whole 23rd solar cycle.

Hobart stations. The figure also indicates for the equatorial station Vanimo being located near the crest of Appleton anomaly, foF_2 remains high even after 1400 LT till next day mornings, especially in solar active years. In the equatorial region, the eastward daytime electric field shows a significant enhancement along with its reversal to westward direction after sunset. This pre-reversal enhancement of zonal electric field which is dependent on solar activity enhances the well-known EXB drift and causes foF_2 to be high at post-sunset hour also[18, 19].

Yearly mean foF_2 at 1400LT for three stations along with the solar activity proxy F10.7 for the whole solarcycle-23 is plotted in Fig. 2 and is clear from the figure that the foF_2 variations follow F10.7 especially at the inclining and declining phases of the cycle.

3.2 Yearly variability of F_2

The yearly CV (%) computed for each hour of each station is represented on image plots for the selected solar cycle in Fig. 3. From the figure, it is clear that the variability is high for all stations during night time and early morning hours and the variability falls rapidly around 0700-0800LT. Thereafter the variability remains more or less the same up to 1200LT showing the consistent nature of foF_2 during day time. Akala *et al.*[13] have also reported the existence of higher foF_2 variability in nighttime for African equatorial stations (Daker, Ouagadougou and Djibouti) for the years 1973 and 1978, the low and high solar active years of solar cycle 21. Variability studies of F_2 layer by Rishbeth *et al.*[20] by computing ratio of standard deviation of NmF_2 to NmF_2 also shows that the variability is greater in night than day time for years 1973 and 1979. We have also observed that variability is more during night and early morning hours compared to daytime for all stations throughout the cycle. During night, the ionospheric density is dependent only on the recombination rate of ions and hence the mean foF_2 is comparatively lesser. This makes the night time variability higher. The reason for larger night time variability over day time is addressed by others also. Akala *et al.*[13] explains the night time variability enhancement due to the magnetic meridional winds and gravity waves. According to Rishbeth *et al.*[20], the

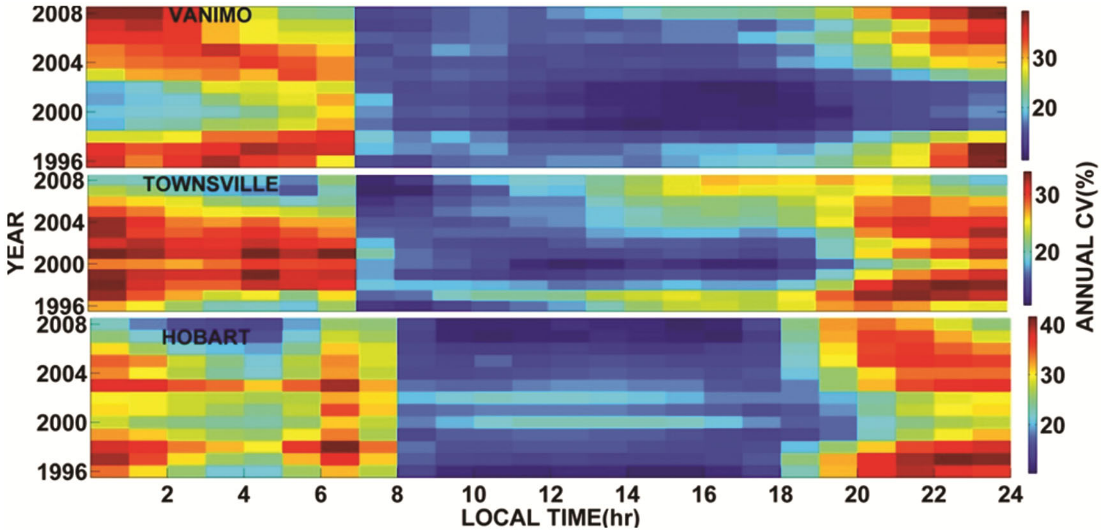

Fig. 3 — Annual variation of foF_2 of the three stations over solar cycle-23.

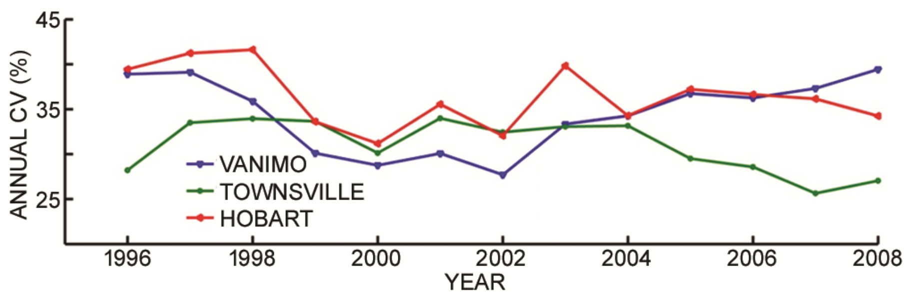

Fig. 4 — Diurnal maximum of yearly CV (%) for the three stations over solar cycle-23.

night time higher variability is a consequence of lower electron density and lack of strong photochemical control during night compared to day time.

Variability is also observed to be comparatively low during solar active years especially for Vanimo and Hobart, whereas no such effect is observed in Townsville. The low variability during solar active years is pronounced in Vanimo, the equatorial station. The higher variability of foF_2 during low solar active years for equatorial stations was pointed out by Akala *et al.*[14] and Bilitza *et al.*[17] for each year of low and high solar active years of solar cycle-22.

The diurnal maximum of yearly CV (%) is plotted against each year of 23[rd] solar cycle in Fig. 4. It is clear from the figure that Hobart station shows the maximum variability among all stations. Vanimo and Hobart exhibit peak variability in the inclining phase of the solar cycle. Except for Vanimo, the equatorial station, the variability falls during the declining phase of the cycle. Yearly variability shows a double peak at 2001 and 2004 for all stations.

3.3 Seasonal variability

The foF_2 data for the whole cycle is grouped into March equinox (March, April, May), June Solstice (June, July, August), September Equinox (September, October, November) and December Solstice (December, January, February) for each year. The seasonal CV (%) of foF_2 for each hour is computed to study the seasonal variability. The diurnal maximum value of the seasonal variability is used to study the seasonal variability pattern and is plotted in Fig. 5. The detailed discussion on the variability in reference to Fig. 5 is given below.

The seasonal variability of Vanimo peaks mainly in June solstice over the cycle except in the years 1996, 2007 and 2008. In these years the variability peaks during March and September Equinoxes. Variability is also observed to be low during December throughout the whole cycle.

In Townsville (Fig. 5), seasonal variability peaks during September equinox in all years except in 2000, 2001 and 2002. In these years the variability is higher during March Equinox. It is also clear that the

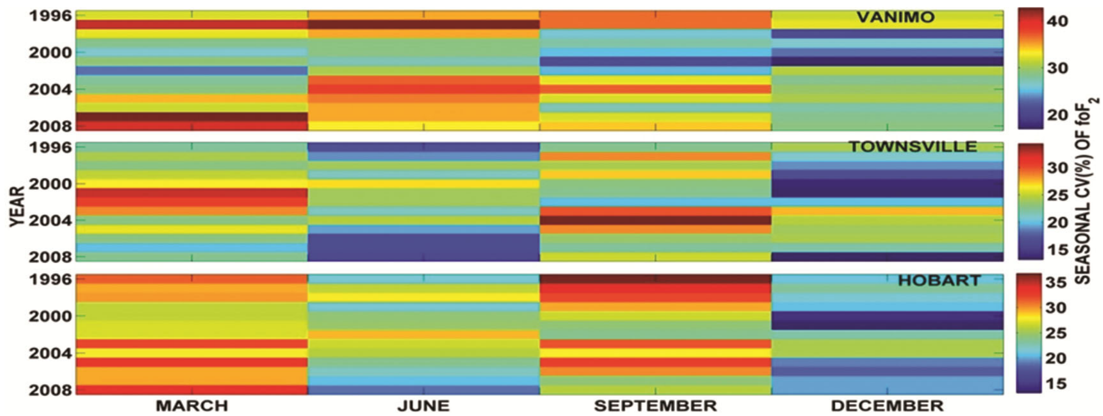

Fig. 5 — Seasonal variation of foF_2 for the three stations over solar cycle-23.

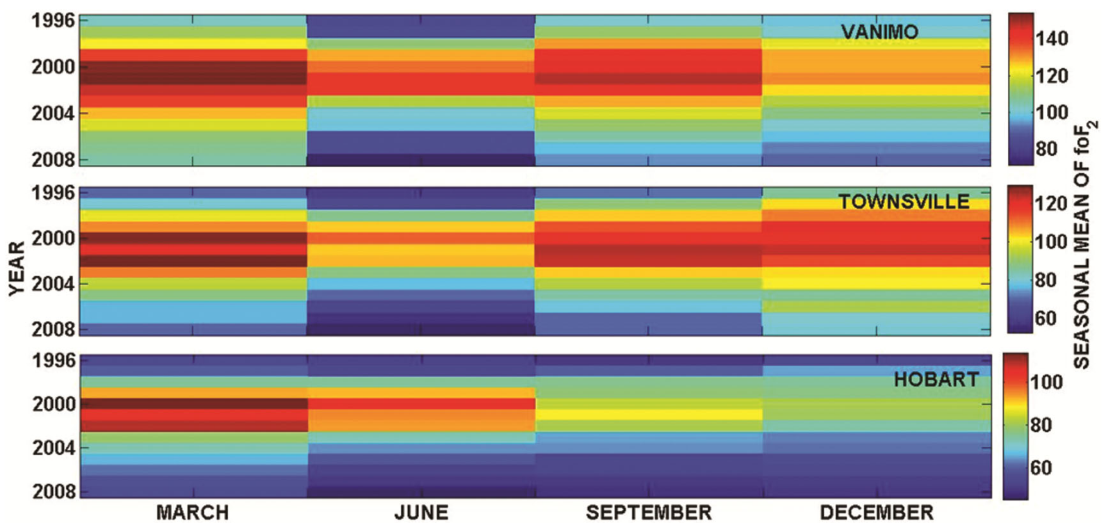

Fig. 6 — Diurnal maximum of seasonal mean of foF_2 to study the anomalies of the three stations over solarcycle-23.

difference in variability between September and December is more during the inclining phase of the cycle and is high during 2001. During the inclining and declining phases of the cycle, the variability is very much less in June Solstice.

Figure 5 also reveals that seasonal variability of Hobart is more in September during 1996-2006 except during 2001-2003. The maximum variability is seen during June Solsticein 2002 and in March Equinox during the other years. Also variability is observed to be low during December as in Vanimo.

Thus seasonal variability for the three stations in general is found to be greater in equinoxes throughout out the cycle. This result is in agreement with the findings of Rishbeth *et al.*[20] for the station Slough, though their method of finding variability and the period of study were different from the current study. But Akala *et al.*[13], found no seasonal dependence of variability of foF_2 for African equatorial stations. It shall be noted that their studies were limited to two years of solar cycle-22 representing high and low solar active years.

3.4 Anomalies seen over solar cycle-23

The seasonal mean of foF_2 for each hour is computed to study the anomalies in the stations. The diurnal maximum value of the seasonal mean (foF_2smax) is taken to study the pattern of anomalies as shown in Fig. 6 and the analysis shows the following results for the three stations.

foF_2smax of Vanimo shows a double peak at March and September equinoxes in each year showing strong semiannual anomaly throughout the cycle. Comparing the equinoxes, foF_2smax is found to be higher during March equinox than September showing equinoctial asymmetry. The result is in agreement with the studies of Zhao *et al.*[10] in which equinoctial asymmetry shown to be most prominent in

South Australian regions. The intensity of the semiannual anomaly was studied by computing the difference of foF_2smax between that of March Equinox and June Solstice. From the calculations it is clear that the intensity of semiannual anomaly is more obvious during low solar active years in Vanimo. By analyzing Fig. 6 and the corresponding data of Vanimo in detail, a weak winter anomaly is seen during 2000 and 2001 and weak annual anomaly is seen during rest of the years. Pavlov *et al*.[21] have reported that the percentage of winter anomaly increases with an increase in solar activity studying the anomalies in Argentine Island in Southern Hemisphere supporting our result. From the results of Sheffield University Plasma sphere Ionosphere Model (SUPIM) model and CF3 observations, Nanan *et al*[22]. has also reported the disappearance of the winter anomaly during the last solar minimum.

In the period 1996-1999 and 2006-2008, the seasonal mean foF_2 reaches the peak value during December showing annual anomaly in Townsville. During the solar active phase of the cycle (2000-2005), seasonal mean of foF_2 peaks in March equinox exhibiting semiannual anomaly and equinoctial asymmetry. Also from the Fig. 6 it is clear that foF_2 seasonal mean is the least during June solstice among the four seasons throughout the cycle, showing the complete absence of winter anomaly in the station. The absence of winter anomaly in southern middle latitudes is emphasized by Lee *et al*.[23], Zou *et al*.[7] have also noted the absence of winter anomaly in a southern station Port Stanley due to the effect of annual anomaly.

But in Hobart, the seasonal mean peaks mostly during March equinox showing semiannual anomaly during the cycle. The mean foF_2 remains more or less the same during the inclining and declining phases of the solar cycle throughout the seasons. A noticeable seasonal difference is seen only during solar active years (1999-2003). A strong winter anomaly is also seen during 1998-2004. Winter anomaly is seen to be absent in southern mid latitudes as in Townsville[23]. But Hobart is a mid-high latitude station nearer to magnetic south pole. The dominance of winter anomaly at high mid latitudes nearer to magnetic poles as pointed out by Zou *et al*.[7] for solar cycles 20, 21 is now found to be true for solar cycle-23 also. Rishbeth[24] has suggested that this effect as due to the dominance of neutral composition of plasma density over effects of solar zenith angle during winter in near pole regions. Liu *et al*.[25] have also noticed winter anomaly at high-mid latitudes in Australian sector at high solar activity using FORMOSAT-3/COSMIC radio occultation measurements.

4 Conclusions

The anomalies and variability of foF_2 of three stations in southern hemisphere during solar cycle-23 is presented in this study. The diurnal analysis in our work shows that the mean foF_2 peaks around 1400 LT for all stations throughout the cycle. Mean foF_2 clearly shows solar cycle dependence. Of the three stations, the equatorial station and the high-mid latitude station shows primarily semiannual anomaly during the whole cycle and weak winter anomaly during solar active years. The low latitude station shows semiannual anomaly in the active phase of the cycle and annual anomaly in the inclining and declining phases of the cycle. Also winter anomaly is completely absent throughout the cycle in the low latitude station. The analysis of annual variability shows more night time variability throughout the solar cycle for all stations. Rishbeth *et al*.[20] has proposed that the night time higher variability is due to lower electron density and lack of strong photochemical control compared to day time. Also it is observed that variability is lower at solar maximum years for Vanimo and Hobart (more evident in Vanimo, the equatorial station). These results can be compared with that of Akala *et al*. and Rishbeth *et al*. for equatorial stations for solar cycle 22. Also our studies show that the seasonal variability is more during equinoxes generally for three stations. Further studies using data from ionosondes are required to have a detailed understanding of the seasonal pattern of foF_2 variability.

Acknowledgement

Authors sincerely acknowledge the Space Weather Services, Australia for providing the ionospheric foF_2 data. One of the authors, Seema C S, acknowledges University Grants Commission (UGC), Government of India for financial assistance under the Faculty Development Programme (FDP).

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