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On the Dependence of F2 Layer Critical Frequency on F10.7 Solar Flux at an Equatorial Station

Stephen O IKUBANNI [1]*, Jacob O ADENIYI [2]

ABSTRACT [ENGLISH/ANGLAIS]

The dependence of the critical frequency of the F2 layer on solar radio flux of 10.7 cm wavelength (F10.7) was studied using data from a low latitude station of Ouagadougou, Burkina Faso (Lat. 12.4º N, Long. 1.5ºW, dip. 5.7). These span a period of 11 years i.e. 1985 - 1995 (solar cycle 22). Hourly coefficient of correlation between the hourly-monthly averaged values of foF2 and monthly averaged values of F10.7 index was obtained using the Pearson's correlation formula. These correlations was found to be dependent on time and season (or month) of the year. Good correlation (r > 0.5) was observed for larger part of the day and poor correlation (r < 0.5) was observed for few hours of the nighttime except during December solstice (December and January). Generally, daytime correlation is high (r > 0.7) for all seasons. High correlation (r > 0.7) is observed during December solstice for both daytime and nighttime hours. The possible reason for December solstice observation was discussed.

Keywords: Low latitude, critical frequency, F10.7 index, solstice, solar cycle

RÉSUMÉ [FRANÇAIS/FRENCH]

La dépendance de la fréquence critique de la couche F2 sur le flux radio solaire de 10,7cm de longueur d'onde (F10.7) a été étudiée en utilisant des données d'une station debasse latitude de Ouagadougou, au Burkina Faso (Lat. 12.4o N, Long. 1.5oW, trempette. 5.7). Ceux-ci couvrent une période de 11 ans soit de 1985 à 1995 (cycle solaire 22).Coefficient horaire de corrélation entre les valeurs moyennes mensuelles à taux horairede foF2 et mensuels valeurs moyennes de F10.7 indice a été obtenu en utilisant la formule de corrélation de Pearson. Ces corrélations ont été trouvés à dépendre du temps et de saison (ou mois) de l'année. Une bonne corrélation (r> 0,5) a été observéepour une plus grande partie de la journée et une faible corrélation (r <0,5) a été observéepour quelques heures de la nuit, sauf au cours de Décembre solstice d'(Décembre et Janvier). En règle générale, la corrélation est élevée pendant la journée (r> 0,7) pour toutes les saisons. Forte corrélation (r> 0,7) est observée au cours de Décembresolstice d'pendant des heures à la fois diurnes et nocturnes. La raison possible pourDécembre solstice d'observation a été discuté.

Mots-clés: Basse latitude, la fréquence critique, F10.7 index, solstice, le cycle solaire

Affiliations:
[1] Department of Industrial Physics, Landmark University, Omu-Aran, Kwara State, NIGERIA

[2] Department of Physics, University of Ilorin, Ilorin, Kwara State, NIGERIA

Address for Correspondence/ Adresse pour la Correspondance:
stevewolex1@yahoo.com

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INTRODUCTION

It is well known that the Sun is the source of radiation that permeates space and reaches the Earth's atmosphere. However, much importance is placed on the effect of this radiation on the upper part of the atmosphere, the thermosphere. Some neutral atoms and molecules in this region become excited as they are stripped off of their electron, thus becoming ions. The excitement is due to the solar radiations reaching them. The region where these ions exit is called the ionosphere. It is the electron density present in the ionosphere that makes radio communication possible. The ionospheric electron density is produced mainly by solar radiations such as EUV, X-rays, etc., which are generated by solar activity events. The varying absorption of these radiations across different height of the ionosphere results into its subdivision into several layers. Of these, the F2 layer with the highest electron densities is of great interest to researchers due to its importance to HF radio propagation. Hence the need to study this layer and improve on its predictability. The smoothed monthly mean sunspot number (R12) was considered a primary index of solar activity for prediction of ionospheric parameters due to the unavailability of solar ultraviolet radiation measurements in the early years of ionospheric research ([18] and the references therein,). The dependence of foF2 on sunspot number, R had been studied for a long time [4,8,9,10,12], Although a positive observation was recorded but it is flawed by the phenomenon of hysteresis.

However, because of this flaw, several efforts have been made to introduce a new solar activity index. These include the use of EUV data for the long-term predictions of the monthly median ionospheric parameters by [6]. According to [5] and the references therein, in the absence of solar EUV data, solar radio flux at 10.7 cm may be better than sunspot numbers when making ionospheric predictions. The use of F10.7 (solar radio flux of 10.7cm wavelength) as a widely used solar activity index is seen in the construction of some solar EUV irradiance models such as EUVAC model [13], SOLAR2000 model [14], ionospheric models such as IRI model and thermospheric model. According to [2] and the references therein, the postulation that the relationship between solar EUV and F10.7 is invariant over different solar cycle is the basis of its use. Additionally, F10.7 is usually used as the solar activity proxy to develop ionospheric and thermospheric models, such as the IRI model [16]. As a result of the above, this work is to study the hourly correlation between F10.7 and foF2 for each month and each season over a solar cycle at an equatorial station.

MATERIALS AND METHODS

The 11 year solar cycle (SC) is the most prominent variation of solar activity which has a significant effect on the equatorial ionosphere. To obtain a reliable result from the study of the dependence of the critical frequency of the F2 layer (foF2) on the F10.7 index, the parameters used span a period of 11 years (a solar cycle: 1985-1995) with the maximum activity at the middle of the cycle.

F10.7 (in solar flux units ,sfu) refers to the flux of radio emission from the Sun at a wavelength of 10.7 cm (2.8 GHz frequency). It is chosen as a proxy for solar activity because it follows the changes in the solar UV radiation over the solar cycle (1 sfu = 10^{-22} Wm^{-2} Hz^{-1}) [3].

The F2 critical frequency values are the monthly-hourly average (in MHz) They were deduced from ionograms recorded by the Ionospheric Prediction Services (IPS) 42 ionosonde located at Ouagadougou, Burkina Faso. (Lat. 12.4° N, Long. 1.5°W, dip. 5.7) while the F10.7 indices were obtained from the National Geophysical Data Centre- NOAA Satellite and Information Service (ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/INDEX/).

Using the data, the following were investigated: (i) The correlation between foF2 and F10.7 (ii) The diurnal variation of the correlation in each month. (iii) The variation in the correlation across in each season. To achieve the third objective, the twelve months were grouped into four seasons as stated: March equinox (February, March and April); June solstice (May, June and July); September equinox (August, September and October) and December solstice (November, December and January). It should be noted that individual values from these grouped months were used and not their average values.

The coefficient of correlation was obtained using the Pearson's correlation formula given by the equation:

$$r = \frac{\sum_{i=1}^{N}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\left[\left(\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^2\right)\left(\sum_{i=1}^{N}\left(Y_i - \overline{Y}\right)^2\right)\right]^{1/2}}$$

Where r is the correlation coefficient, X_i is the independent variable, Y_i is the dependent variable, $\overline{X}$ is the average value of X_i and $\overline{Y}$ is the average value of Y_i.

The independent variable is the solar F10.7 index while the dependent variable is monthly-hourly values of the F2 layer critical frequency (foF2). The correlation coefficient obtained was calculated on hourly basis for each season and each month using the 11-year data. The correlation was grouped into three: High ($r \geq 0.7$); Moderate ($0.5 \leq r < 0.7$) and Low ($r < 0.5$).

RESULTS

Tables 1 and 2 show the coefficients of correlation between the average hourly values of foF2 and the F10.7 index for different months and different seasons respectively. The values were rounded up to 2 decimal places. The values were further plotted against the local time in hour to study the diurnal variation as shown in figures 1 and 2.

As observed from figure 1, correlation is high and relatively stable during the daytime, however, the duration of the daytime correlation varies from month-to-month. The correlation is high from late evening (22 LT – 23 LT), through the midnight and then to sunrise, it remains high further until around sunset. Significant drop in the correlation was observed only around early evening.

The highest correlation (r = 0.99) was observed in October between 07 LT and 08 LT while the lowest correlation (r = 0.10) was observed in September, around early evening (19 LT). Across all months, correlation was observed to be highest between sunrise and pre-noon, while it was lowest between sunset (18 LT) and the late evening (21 LT). It is of interest to state that the correlation in December, as observed, was very high throughout (r ≥ 0.7), however the correlation during the evening period was not as high as that of the other time of the day. Similar observations were also found in months that fall originally into December solstice.

Table 1: This table shows the hourly correlation coefficient for the twelve months. (LT is the Local Time in hours)

LT(Hr)	January	February	March	April	May	June	July	August	September	October	November	December
0	0.91	0.87	0.64	0.70	0.89	0.88	0.84	0.95	0.80	0.87	0.85	0.93
1	0.89	0.88	0.66	0.81	0.84	0.90	0.81	0.95	0.84	0.91	0.74	0.92
2	0.94	0.92	0.63	0.88	0.88	0.93	0.92	0.94	0.85	0.98	0.92	0.91
3	0.95	0.91	0.84	0.92	0.74	0.91	0.84	0.94	0.96	0.96	0.87	0.94
4	0.97	0.92	0.92	0.97	0.94	0.88	0.75	0.96	0.93	0.96	0.90	0.92
5	0.96	0.94	0.94	0.98	0.96	0.91	0.54	0.96	0.97	0.96	0.91	0.91
6	0.96	0.89	0.94	0.99	0.98	0.94	0.65	0.98	0.95	0.96	0.94	0.94
7	0.96	0.93	0.96	0.99	0.99	0.98	0.89	0.98	0.96	0.99	0.98	0.98
8	0.98	0.97	0.95	0.98	0.99	0.97	0.96	0.96	0.93	0.99	0.96	0.98
9	0.93	0.94	0.94	0.98	0.95	0.95	0.92	0.93	0.91	0.98	0.92	0.96
10	0.92	0.89	0.92	0.95	0.93	0.86	0.92	0.90	0.87	0.97	0.95	0.95
11	0.92	0.92	0.92	0.96	0.92	0.87	0.95	0.83	0.88	0.96	0.94	0.96
12	0.92	0.97	0.91	0.97	0.91	0.91	0.97	0.92	0.88	0.99	0.93	0.97
13	0.91	0.95	0.91	0.97	0.92	0.89	0.98	0.95	0.83	0.99	0.94	0.97
14	0.90	0.94	0.89	0.94	0.91	0.93	0.95	0.87	0.79	0.98	0.94	0.95
15	0.88	0.85	0.87	0.89	0.90	0.89	0.95	0.82	0.82	0.96	0.94	0.96
16	0.87	0.75	0.85	0.89	0.83	0.85	0.92	0.90	0.72	0.97	0.92	0.89
17	0.89	0.62	0.84	0.87	0.35	0.75	0.82	0.81	0.73	0.94	0.51	0.74
18	0.87	0.39	0.76	0.73	0.32	0.53	0.35	0.53	0.32	0.42	0.44	0.71
19	0.84	0.48	0.44	0.24	0.38	0.21	0.52	0.48	0.10	0.29	0.35	0.87
20	0.87	0.52	0.44	0.49	0.36	0.29	0.41	0.77	0.54	0.72	0.41	0.77
21	0.82	0.76	0.58	0.59	0.79	0.35	0.34	0.85	0.15	0.75	0.57	0.88
22	0.85	0.75	0.51	0.78	0.89	0.85	0.49	0.85	0.54	0.52	0.64	0.89
23	0.91	0.77	0.54	0.70	0.86	0.94	0.73	0.93	0.79	0.90	0.67	0.91

Likewise, from the plots in figure 2, correlation is relatively high and uniform during the daytime for all seasons; this is similar to observations from figure 1. A 24-hour strong correlation was seen from the plot of the diurnal variation for December solstice. Considering the seasons, the correlation was highest (r = 0.95) around 08 LT during the March equinox and lowest (r = 0.07) around 19 LT during the June solstice. Highest correlation was obtained between sunrise and pre-noon for all seasons except in December solstice where it was highest at noon, while the lowest correlation was obtained from sunset (18 LT) till around late evening (21 LT).

Table 3 presents the average correlation coefficient for daytime and nighttime hours for each season. Hours between 06 LT and 17 LT, through the midday were grouped as daytime hours while hours between 18LT and 05LT through the midnight were grouped as nighttime hours. For nighttime hours, correlation is lowest during the March equinox while it is highest during the December solstice. For daytime hours correlation is lowest during the June solstice while it is highest during December solstice and March equinox. Generally, the daytime and nighttime averaged coefficient of correlation is good for all seasons. It is high (r ≥ 0.7) for all seasons during daytime but generally moderate (0.5≤ r < 0.7) during the nighttime except for December solstice (r= 0.80).

Table 2: This table shows the hourly correlation coefficient for the four seasons. (LT is the Local Time in hour)

LT(Hr)	Mar. Equinox	June Solstice	Sept. Equinox	Dec. Solstice
0	0.69	0.80	0.70	0.83
1	0.73	0.81	0.72	0.80
2	0.77	0.85	0.74	0.84
3	0.88	0.80	0.86	0.85
4	0.93	0.78	0.89	0.90
5	0.94	0.73	0.89	0.89
6	0.87	0.80	0.93	0.83
7	0.92	0.89	0.92	0.79
8	0.95	0.89	0.85	0.89
9	0.93	0.85	0.83	0.89
10	0.90	0.80	0.86	0.91
11	0.91	0.82	0.85	0.91
12	0.92	0.83	0.87	0.92
13	0.91	0.83	0.84	0.91
14	0.89	0.80	0.75	0.90
15	0.83	0.77	0.72	0.89
16	0.77	0.71	0.75	0.87
17	0.67	0.53	0.73	0.76
18	0.46	0.16	0.40	0.74
19	0.38	0.07	0.29	0.74
20	0.46	0.29	0.57	0.73
21	0.58	0.44	0.43	0.74
22	0.64	0.73	0.52	0.76
23	0.61	0.77	0.68	0.79

Table 3: This table shows the average correlation coefficient for daytime and nighttime hours for each season.

Seasons	Daytime hours	Nighttime hours
March Equinox	0.87	0.52
June Solstice	0.79	0.60
September Equinox	0.83	0.64
December Solstice	0.87	0.80

The daytime hours were from 0600LT, through the midday, to 1700LT, while the nighttime hours were from 1800LT, through the midnight, to 0500LT

DISCUSSION

We have investigated the solar activity dependence of foF2 on a very important solar activity proxy, the solar radiation flux (F10.7) at an African low latitude station. The ionospheric data used for this study spans solar cycle 22 (1985-1995). Significant variation in the linear dependence with local time and season has been identified. First, the solar activity dependence varies with local time. It is stronger during the daytime than at nighttime. This can be explained by the fact that the region's upper atmosphere is heated by solar EUV radiation during the day. The gradual heating from sunrise results into increasing number of electrons. The production of electrons reaches a peak when recombination process begins. The high electron rate in the F2 layer ionosphere thus results into a higher critical frequency (foF2). However, the solar EUV radiations which are generated by solar activity events increase with increasing solar activity, hence increasing electron production rate.

According to [11] and the references therein, solar ionizing flux, meterological influences, and solar wind conditions are the origins of changes in the state of the ionosphere. All these effects are dependent on local time, season etc. There is virtually little or no solar radiations at night, nonetheless, foF2 was observed to correlate with the F10.7 index for larger part of the nighttime hours. This could be explained by the action of the equatorial vertical **E** x **B** drift, thermospheric composition, and neutral winds etc. that possibly enhance or counteract the direct effect of the EUV radiation [2]. The sharp drop in the correlation from around 16 LT is as a result of the sudden faster depletion of electrons from the equatorial ionosphere by the equatorial vertical **E** x **B** drift. The drifting causes a trough in the region, so a sharp drop in foF2 value while the F10.7 index remains unaffected causes a sharp drop in the correlation. Later an equatorial-ward drifting of the electrons increases the density, thus foF2 increases again. This response of the equatorial ionosphere to the dynamics of the Lorentz force is observed in the rise in the coefficient of correlation. The dynamics of the equatorial vertical **E** x **B** drift accounts for the maintenance of the F2 layer at night and also explains why the correlation drops, then rise, drop again before rising till daytime. As stated in the result, correlation during the December solstice was observed to be strong (r $\geq$ 0.70) throughout the day. A possible explanation for this is low drift velocity of the E x B drift. This is in line with [1] and the references therein, who observed a very low drift velocity during the December solstice.

Figure 1: This figure shows plots showing the diurnal variation in the correlation of the critical frequency of the F2 layer (foF2) with F10.7 index for different months

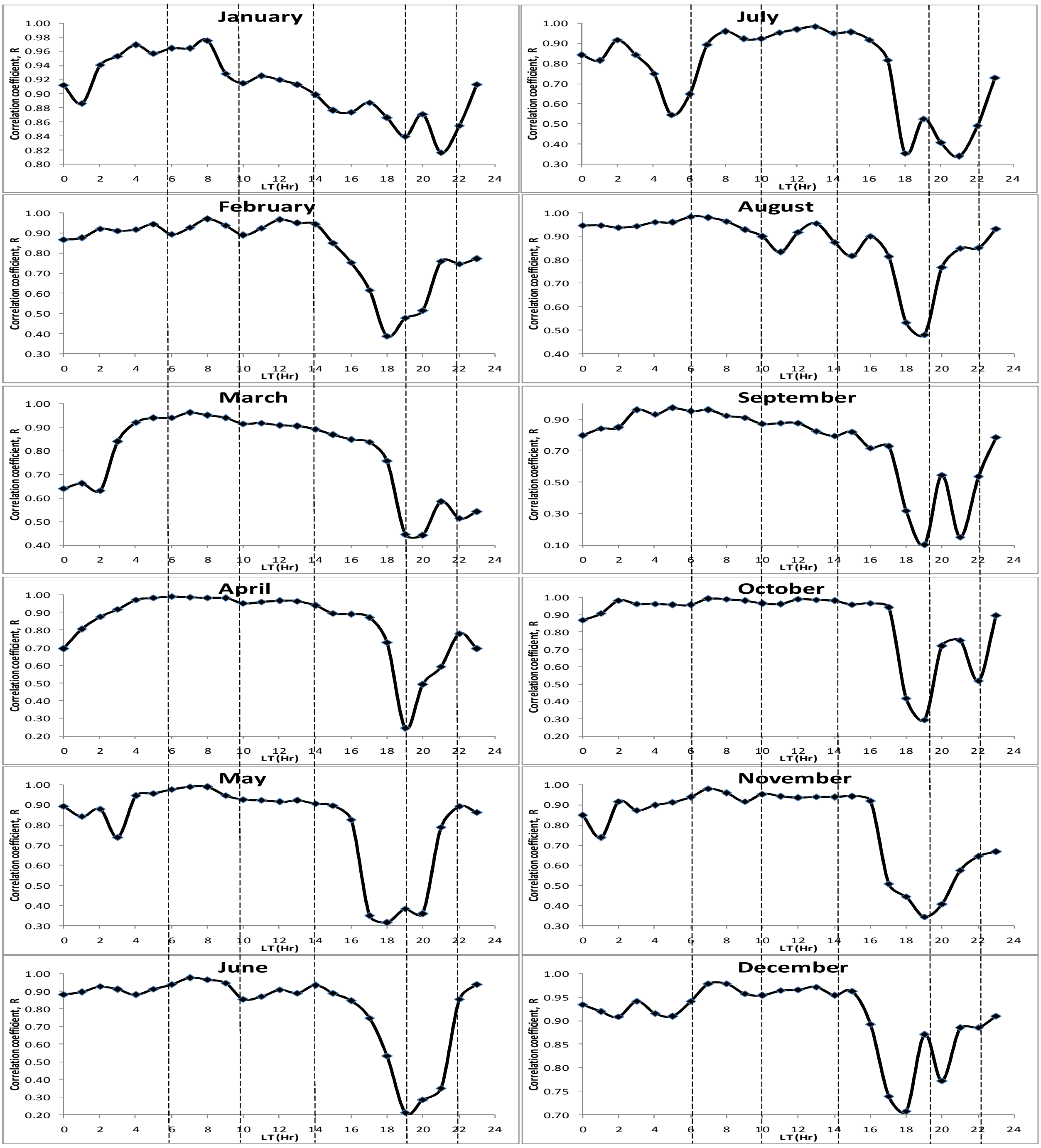
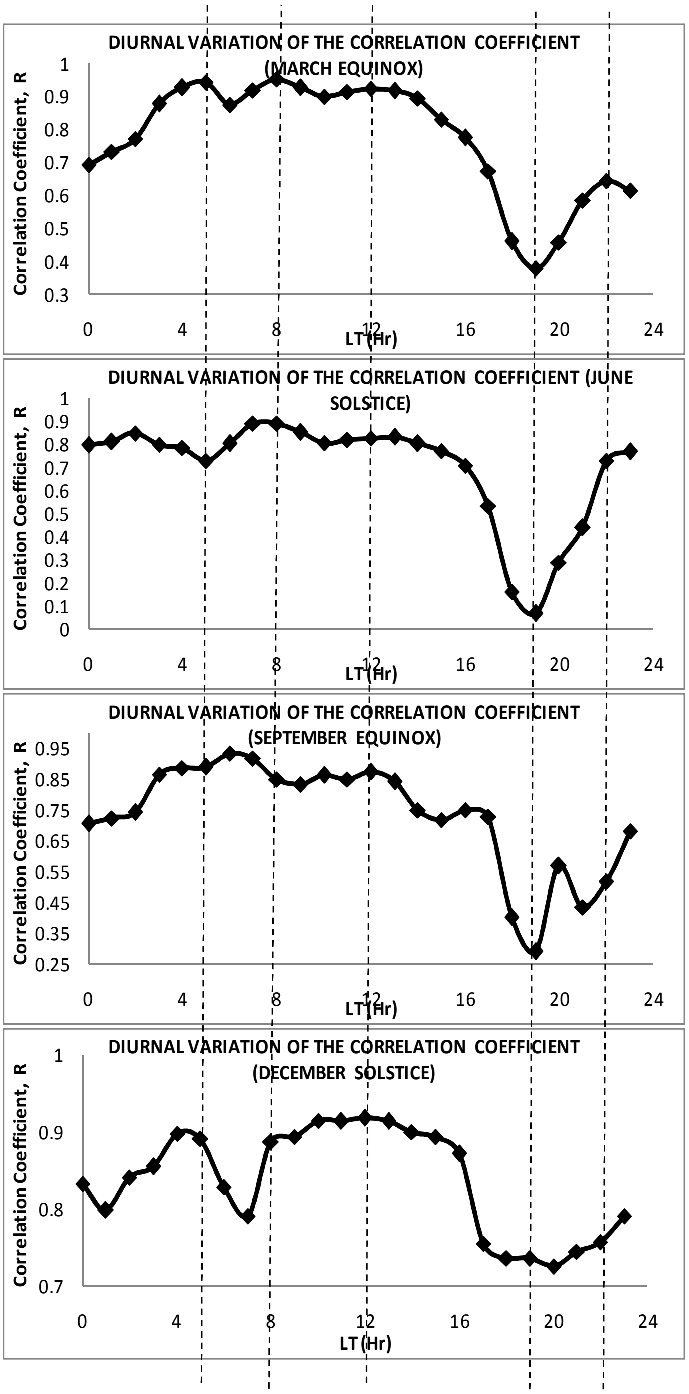


Figure 2: This figure shows plots showing the diurnal variation in the correlation of the critical frequency of the F_2 layer (foF_2) with F10.7 for different seasons (1st panel: March Equinox; 2nd panel: June Solstice; 3rd panel: September Equinox; 4th panel: December Solstice)



CONCLUSION

Conclusively, the correlation is observed to be dependent on seasonal and diurnal changes of the factors causing ionospheric variation. The dynamics of the ionospheric F2 layer can be said to play a very important role in the hourly correlation. Hence, these complex dynamics must be considered when employing F10.7 index in the prediction of the ionospheric F2 layer critical frequency. The daytime high correlation as observed implies a strong daytime dependence of the ionospheric F2 layer solar radiation while the nighttime variation in the correlation implies the stronger influence of the upper atmospheric dynamics on the ionospheric F-region.

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CONFLICT OF INTEREST

No conflicts of interests were declared by authors.