International Journal of Theoretical & Applied Sciences, **17**(2): 22-30(2025)

ISSN No. (Print): 0975-1718
ISSN No. (Online): 2249-3247

Spectra Model of foF2 for Low Latitude Station during the 24th Solar Cycle

Bhanupriya[1], Madhuri Singh[2], Kalpana Maski[3*] and S.K. Vijay[4]
[1]*Research Scholar, Govt. MLB Girls PG College, Bhopal (Madhya Pradesh), India.*
[2]*SIRT, Bhopal (Madhya Pradesh), India.*
[3]*Regional Institute of Education, NCERT Bhopal (Madhya Pradesh), India.*
[4]*Govt. Maharani Laxmi Bai Girls P.G. College, Bhopal (Madhya Pradesh), India.*

(Corresponding author: Kalpana Maski)*
(Received 05 April 2025, Revised 20 May 2025, Accepted 10 June 2025)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: In the present study, a single station spectra model of the F-region foF2 for the low latitude station Brisbane (27.47S,153.02E) is developed for the years 2008-2017 of the 24th solar cycle. In this work, regression analysis is performed to explore the solar and geomagnetic correlation of foF2, and Fourier analysis method is employed to illustrate the diurnal fluctuation. A polynomial formula is utilized to include the sunspot number (R.no) into both models to represent the dependency of foF2 on solar activity. The results shows that linear and quadratic regression models have a high correlation with the observed valued, but the multiple regression model has to be modified. Modifications are also required for the Fourier expansion model to minimize the percentage error in order to move towards perfection.

Keywords: Spectra model, regression analysis, fourier expansion model, sunspot number, foF2, low latitude.

INTRODUCTION

Several regional and single-station foF2 models have been developed for various locations across the world to understand ionospheric behavior and improve forecasting accuracy. Many academician, however, have developed the single-station model (SSM) for a specific station (Moraitis *et al*., 1991; Sizun, 1991; Dick and Bradley 1992; Pancheva and Mukhtarov 1998; Liu *et al.*, 2004; Xu, 2008). The key advantages of the SSM are as follows: (1) more accurate findings for a given ionosonde station than the global one, and (2) updating an SSM is often a simple task (Pancheva and Mukhtarov 1996). Furthermore, it is well understood; foF2 is strongly dependent on solar activity.

Foundational models, including those by Bradley and Dudeney (1999); Hanbaba (1999), applied techniques such as modified spherical harmonic analysis, empirical orthogonal functions, and multi-quadric interpolation to improve ionospheric representation. In the earlier phases, Bent *et al.* (1972) created models addressing ionospheric refraction for satellite communications, utilizing extensive datasets including Alouette 1 topside soundings and bottomside ionograms. These efforts provided a robust empirical basis for modeling the F-region up to 1000 km altitude.

The strong dependence of foF_2 on solar activity is well established. Sunspot number (R) has been the traditional index for quantifying solar activity, given its long historical record and predictive utility (Caruana, 1990; Mikhailov & Mikhailov 1995). Other works have modeled ionospheric properties based on single-site measurements (Stanilawaska *et al.*, 1991; Apostolov *et al.*, 1994), often employing Fourier expansions and empirical methods (Zolesi *et al.*, 1993; De Franceschi & Desantis 1994).

In recent years, technological advancements have led to the integration of machine learning techniques in ionospheric modeling. Poole & McKinnell (2000) introduced neural network-based predictions, and newer models using Long Short-Term Memory (LSTM) networks and Informer architectures have demonstrated superior capabilities in modeling both quiet and disturbed ionospheric conditions (Zhang *et al*., 2024; Qiao *et al.*, 2022). These models utilize deep learning to capture complex temporal dependencies in foF_2 variations at stations like Brisbane, Canberra, and Hobart.

Recent studies have also questioned the adequacy of traditional solar activity proxies. Lastovicka (2024) suggested that the F30 index is a more suitable solar proxy than sunspot numbers or F10.7 for capturing long-term trends in foF_2, especially at mid-latitudes. Meanwhile, Cao *et al*. (2022) demonstrated that higher-order polynomial models offer improved correlation with solar indices during the 24th solar cycle, particularly in low-latitude regions. Additionally, localized studies confirm that geomagnetic activity significantly modulates foF_2, especially during geomagnetic storms (Perrone *et al.*, 2022; Ippolito *et al.*, 2020).

However, despite these advancements, several important research gaps persist. First, **low-latitude stations such as Brisbane remain underrepresented** in the literature, even though they are uniquely influenced by equatorial ionization anomalies and related electrodynamic processes. Second, the **24th solar cycle—**characterized by unusually weak and irregular solar activity—has not been sufficiently analyzed in terms of its impact on monthly median foF_2 at low-latitude stations. Third, while various **solar and geomagnetic indices (R, F10.7, F30, Ap, Kp)** are used, there is **limited integration of these proxies** in predictive models, particularly for monthly median foF_2 values. Lastly, many **machine learning-based models prioritize forecasting performance** but lack interpretability, reducing their utility in advancing scientific understanding of ionospheric dynamics.

This study aims to address these gaps by investigating the relationship between solar activity, geomagnetic activity, and monthly median foF_2 at the Brisbane ionosonde station during Solar Cycle 24. This study seeks to improve not only prediction accuracy but also the physical interpretation of ionospheric behavior in low-latitude regions.

Data and Method of Analysis. The foF2 data were taken from the Brisbane station (geographic 27.47S,153.02E) in Australia for 2008-2017 during 24^{th} Solar cycle in model to develop a single station spectra model of the F-region. In this study, hourly estimates of the monthly median of foF2 for Brisbane (2008- 2017). The regression analysis is used to investigate the solar activity and geomagnetic activity relationship of foF2.

The first regression model is a linear approximation of the association between foF2 and sunspot Number R.

$$foF2(h, m)=A_0(h, m)+ A_1(h,m).R$$

Where h and m are the hour and month of interest, respectively, whereas A_0 and A_1 are two matrices of 24x12=288 coefficients for each hour of the day and month of the year, respectively, and R is the twelve-month running mean value of the sunspot number.

The second-degree regression is predicted to improve, and the quadratic connection between the number of sunspots R and foF2 is stated as

$$foF2(h,m)= B_0(h,m)+ B_1(h,m).R+ B_2(h,m)R^2$$

Where Bo, B1 and B2 also are the coefficients at specified time, h and month m. Further significant improvement is expected from a multiple regression model taking geomagnetic activity into account. Therefore the third regression model can be expressed as

$$foF2(h, m)=C_0(h,m) +C_{1h,m}\ R+C_{2h,m}\ R^2+C_{3h,m}\ Ap\ R+C_{4h,m}\ Ap+C_{5h,\ m}\ A^2$$

Where Ap is twelve-month running mean values. C_o to C_5 are coefficients at given local time h for different month m, in which C_3 represents of coactions of solar and geomagnetic activity amplitude, while C_4 and C_5 are the geomagnetic activity amplitudes (Dominici and Zolesi 1987). The diurnal variations can be expressed by a Fourier expansion of cosine and sine functions with period of 24 hours and higher harmonics. In this way, the diurnal variation of foF2 can be expressed as

$$foF2_{(h,.m)} = C_{o,m} +(A_{i,m} \cos 2\pi ih /T +B_{i,m} \sin 2\pi ih/ T)$$

Where h is local time, i = 1to N and N=6 is the harmonic number. $C_{o,m}$, $A_{i,m}$, $B_{i,m}$ are the Fourier coefficient. Harmonic Analysis method is used to determine the values of coefficients $C_{o,m}$, $A_{i,m}$ and $B_{i,m}$. (Liu *et al.*, 2004).

RESULTS

Fig. 1 and 2 shows the sample fit results from 2008 to 2017 for 0 LT and 12 LT, Fig. 1 displays the monthly median foF2's responses to solar activity as measured by the monthly mean sunspot number R at local time 0 LT in Brisbane. It has been observed that the foF2 is linearly dependent on solar activity throughout in the months of March and April of Equinox, in the month of May, July, and August of Summer, and in the month of November for winter. The remaining months exhibit a non-linear relationship with solar activity during the period 2008-2017 for 24^{th} solar cycle.

Fig. 2 displays the monthly median foF2's responses to solar activity as reflected by the monthly mean sunspot number R at local time 12 hours in Brisbane from 2008-2017 during 24^{th} solar cycle. It is clear from the figure that in the winter months (January and November), the equinoctial months (March, April, and September), and the summer months (March, April, and September), there is a strong linear relation between foF2 and solar activity. The rest of the months are non-linearly dependent on solar activity.

The diurnal fluctuations in standard deviations of foF2 for the three regression fitted models with observed values are shown in Fig. 3; this shows that the first and second-degree regressions of foF2 shows the same variation in observed foF2, but the multiple regression model exhibits different variation as compared to observed foF2.

Fig. 4 shows a comparison of model based on fourier analysis and observed diurnal fluctuation of foF2 in Brisbane, Australia, during the 24th solar cycle, for ten years (2008-2017). This is observed from the figure that the percentage error($\leq$20%) is higher than the standard percentage error($\geq$20%) from 4LT to 8LT, 11LT to 12LT, and 20LT to 22LT at low latitude station Brisbane during 24^{th} solar cycle.

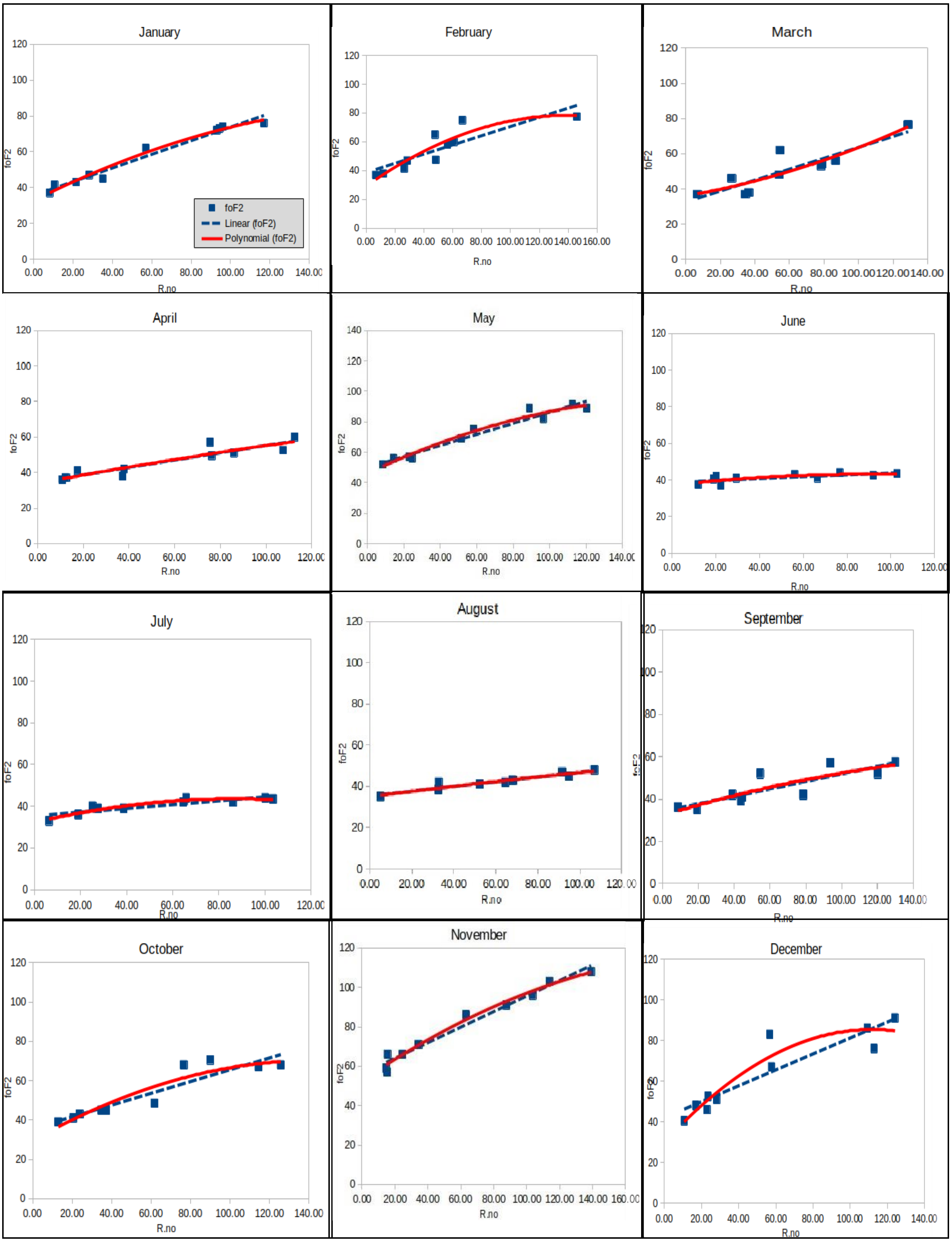

Fig. 1. The responses of the monthly median foF2 to solar activity represented by the monthly mean sunspot number R at local time 0 hours at Brisbane from 2008 to 2017. The linear and quadratic fits are represented by dashed lines, and solid lines and observed data displayed with dots.

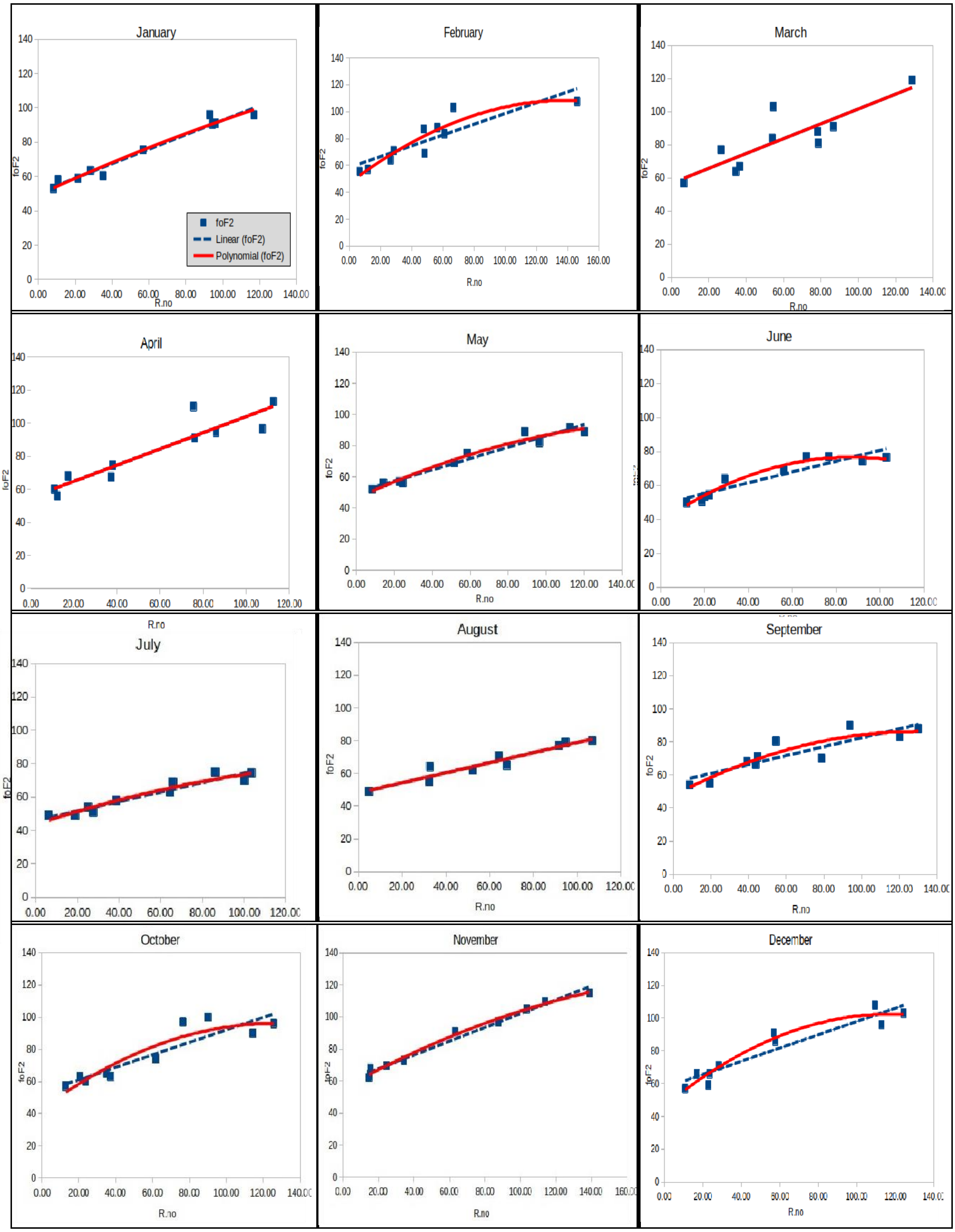

Fig. 2. The responses of the monthly median foF2 to solar activity represented by the monthly mean sunspot number R at local time 12 hours at Brisbane from 2008 to 2017. The linear and quadratic fits are represented by dashed lines, and solid lines and observed data displayed with dots.

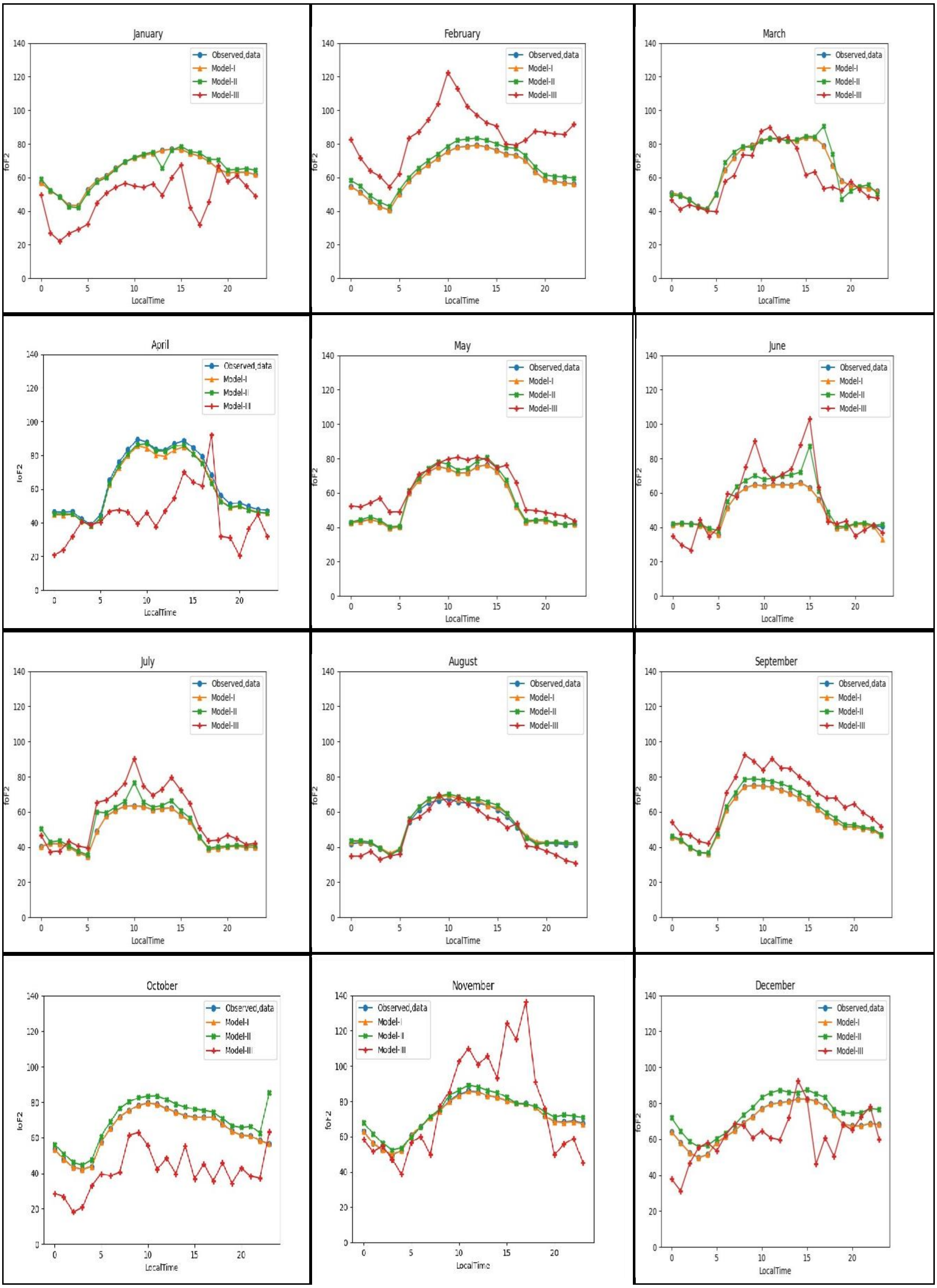

Fig. 3. The diurnal fluctuations in standard deviations for the three regression fitted models using observed values.

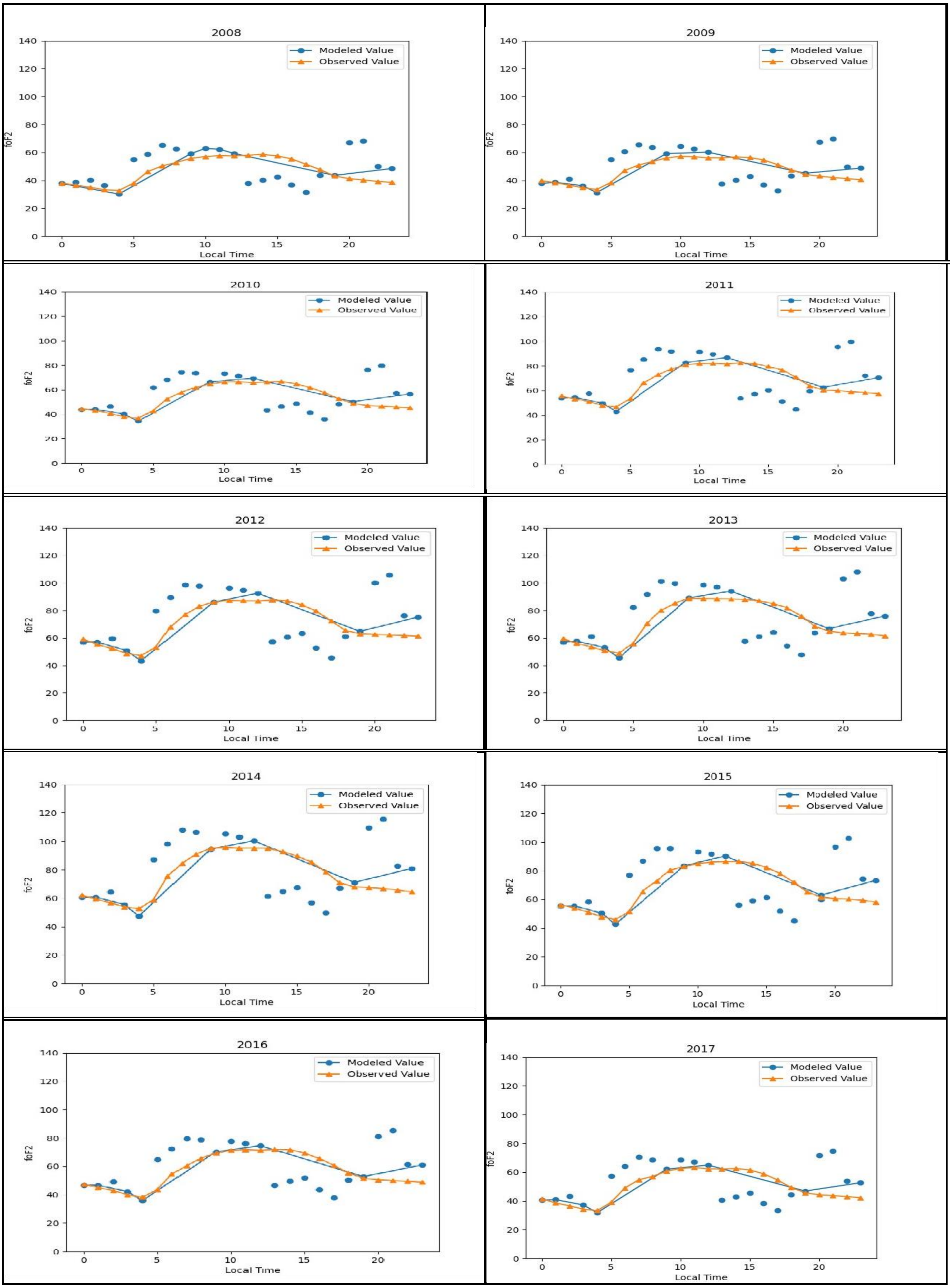

Fig. 4. Year wise variation of observed values (red line) and modeled values (blue line) for all the years from 2008 to 2017 for the Brisbane station.

DISCUSSION

Single-station models are valuable and frequently considered as the apex of any ionospheric service since global models may spread out features peculiar to a given region (Holt *et al.*, 2002; Pancheva and Mukhtarov 1998; Liu *et al.*, 2004; Xu, 2008). Solar radiation primarily causes ionospheric electron density, so electron density in the F region increases with increasing solar activity (Balan *et al.*, 1994; Kouris, 1998; Richards, 2001; Sethi *et al.*, 2002), whereas monthly median foF2 increases in a more complicated way (Kouris, 1998; Richards, 2001).

The monthly median foF2 increases in linearly with long-term solar activity; but only approaches saturation during extremely high solar epochs (Kane, 1992; Liu *et al.*, 2003). Furthermore, several investigations have revealed a non-linear relationship between foF2 and solar activity. Our findings also shows that solar activity varies linearly and non-linearly. Xu (2008); first reported this phenomenon based on data from the Chongqing station in China from 1977 to 1997, indicating that the phenomenon may exist in mid-latitude China but requiring further ionosonde observations data to validate.

Over Sofia, Pancheva and Mukhtarov (1994), developed a single-station spectral model using R and Ap. In numerous cases, they found that an increase in the monthly standard deviation corresponded to an increase in the geomagnetic activity index aa. Long-term prediction models should contain not only R as well as some solar indexes and geomagnetic indexes, two important factors that have gotten little attention to date (Kane, 1992). The climatological models explain the characteristics of foF2 and their variations across time, season, and solar cycle.

The degree of solar activity and geomagnetic disturbances has a major impact on the ionosphere. A multiple regression model that takes geomagnetic activity into account has to be improved even more. Our results show that the first and second-degree regression models indicate variations in good agreement with observed variations; however, the third-degree regression model requires modifications. For low and medium sunspot counts; the relationship is basically linear, but foF2 has a saturation effect (Huang, 1963; Kane, 1992). As a result, a second-degree relationship between foF2 and solar activity indices is commonly used (Sizun, 1992; Xenos *et al.*, 1996; Pancheva and Mukhtarov 1998).

For determining the electron concentration at places in and around the northern equatorial anomaly crest for minimum solar conditions, Bhuyan and Tyagi (1984) devised a semi-empirical model based on harmonic analysis. Harmonic coefficients are seasonal in all places, they observed. In worst-case scenarios, a set of 25 coefficients made up of the mean, first, and second harmonics are demonstrated to be sufficient for computing the electron content to within 15% of the reported values. This model does not require the integration of electron density profiles because it uses a precalculated set of coefficients as input. Our results shows percentage error more than 20% at some points henceforth need to modify to minimize the error.

CONCLUSIONS

This study explored the relationship between solar and geomagnetic activity and the monthly median foF_2 values at the low-latitude ionosonde station in Brisbane during Solar Cycle 24. Several modeling techniques were employed to evaluate how well different statistical and empirical methods represent foF_2 variability under varying solar conditions.

The findings indicate that the monthly median foF_2 response to solar activity, represented by the monthly mean sunspot number (R), exhibits both linear and nonlinear characteristics at local times 0 and 12 hours. While linear and quadratic regression models largely followed the observed trends in foF_2, the multiple regression model displayed inconsistent patterns, suggesting that refinements are needed to improve its fit and reliability.

Further, diurnal variations in foF_2 were assessed using a Fourier analysis approach over the period 2008–2017. Notably, larger percentage errors were observed during specific time intervals between 4–8 LT, 11–12 LT, and 20–22 LT indicating limitations in the model's accuracy during these periods. To enhance its precision, adjustments to the Fourier model are necessary, particularly to reduce errors during these peak fluctuation times.

Beyond these model-specific insights, the study addresses several critical issues in ionospheric modeling. Most notably, low-latitude regions like Brisbane remain significantly underrepresented in the global modeling landscape, despite their distinctive electrodynamic behaviors influenced by the equatorial ionization anomaly. Moreover, Solar Cycle 24's relatively weak and irregular nature adds complexity to foF_2 modeling, underscoring the need for cycle-specific analyses.

A further limitation identified is the insufficient integration of multiple geophysical indices such as F10.7, F30, Ap, and Kp into current predictive frameworks. Existing models often rely on single-proxy inputs, which may not adequately capture the multifactorial influences on ionospheric conditions. While machine learning approaches such as LSTM and Informer models offer high predictive accuracy, their lack of interpretability presents challenges for scientific understanding and validation.

In conclusion, the study highlights the need for more refined, interpretable, and region-specific foF_2 models. Improving model accuracy during critical local time intervals, integrating multiple geophysical indices, and addressing the modeling gaps specific to low-latitude regions like Brisbane are essential steps toward advancing ionospheric science and operational forecasting.

FUTURE SCOPE

Future research may benefit from the following directions:

1. Development of Multi-Proxy Models: Integrating multiple solar and geomagnetic indices) can provide a more comprehensive picture of foF_2 variability, especially for monthly and seasonal timescales.

2. Comparative Regional Studies: Expanding the analysis to include other low-latitude and equatorial stations will help determine the spatial consistency of foF_2 responses under similar solar conditions.

3. Real-Time Forecasting Systems: Building interpretable, real-time forecasting models that can operate effectively during geomagnetic disturbances.

4. Cycle 25 Analysis: As Solar Cycle 25 unfolds, comparing it with Cycle 24 could reveal how foF_2 patterns evolve with solar cycle strength and variability.

5. Data Assimilation Techniques: Future work can incorporate satellite-based and GNSS-derived ionospheric data for real-time assimilation to enhance model accuracy and coverage.

Acknowledgement. The authors gratefully acknowledge the data support provided by the Australian Bureau of Meteorology for ionosonde observations at Brisbane. The study also benefited from the open-access resources made available by NASA's OMNIWeb and NOAA for solar and geomagnetic indices. Special thanks to the academic contributions from earlier researchers whose models and datasets provided the foundational context for this analysis.

Conflict of Interest. None.

REFERENCES

Apostolov, Alberca, E. L. & Pancheva, D. (1994). Longterm prediction of the foF2 on the rising and falling parts of the solar cycle. *Adv. Space. Res.*, *14*, 47-50.

Balan, N., Bailey, G. J., Nair R. B. & Titheridge J. E. (1994). Nighttime enhancements in ionospheric electron content in the northern and southern hemisphere. *Journal of Atmospheric and Terrestrial Physics, 56*, 67-79.

Bent, R. B., Llewelen, S. K. & Walloh, M. K. (1972). Description and Evaluation of the Bent ionospherie model" Space and Missile system organization report SAMSO TR-72-239 Loys Angles, California.

Bhuyan, P. K. & Tyagi, T. R. (1984). A Semi Empirical Model of Ionospheric Electron Content at Low Latitude for Solar Minimum. *Indian Journal of Space Physics 13*, pp 63-68.

Bradley, P. A. & Dudeney, J. R. (1999). A simple model of the vertical distribution of electron concentration in the ionosphere. *J. Atmos. Terr Phys.*, *35*, 2131-2146.

Cao, J., Zhang, Y., Li, H. & Chen, J. (2022). The impact of space weather on communication systems: A comprehensive study. *Radio Science*, *57*(1), e2022RS007539.

Caruana, J. (1990). The IPS monthly T-index, Proc. of the solar-Terrestrial prediction Workshop, Leura, Australia, *2*, 257-263.

De Franceschi, G. & Desantis, A. (1994). PASHA: regional long term predictins inospheric parameters by ACHA, *Ann. Geophysics*, *37*, 209-220.

Dick, M. & Bradley, P. (1992). The RAL multi-quasiparabolic model ionosphere, Porc. Of PRIME Workshop, *Roquetes, Memoria, 16*, 67-83.

Dominici, P. & Zolesi, B. (1987). A model for the normal ionosphere over Rome. *Nuovo Cim, C*, *10*(2), 191-208.

Hanbaba, R. (1999). Improved Quality of Services in lonospheric Telecommunication System Planning and Operation, Action 251, Final Report, Warsaw, Poland, Space Research Center,. European Cooperation in the field of Scientific and Technical Research (COST).

Holt, J. M., S. R. Zhang, S. R. & Buonsanto, M. J. (2002). Regional and local based on Millstone Hill inco-herent scatter radar data, ionospheric models. *Geophys. Res. Lett.*, *29*(8), 1207.

Huang, Y. N. (1963). The hysteresis variation of the semithickness of the F2-layer and its relevant phenomena at Kokubunji, Japan, *J. Atmos. Terr. Phys.*, *25*, 647-658.

Ippolito, A., Battaglia, A. & Mancuso, S. (2020). A study of solar energetic particle events and their relationship with space weather phenomena. *Journal of Space Weather and Space Climate*, *10*, 52.

Kane, R. P. (1992). Sunspots, solar radio noise, solar EUV and ionospheric foF2. *J. Atmos. Terr. Phys.*, *54*, 463–466.

Kouris, S. S. (1998). The solar cycle variation of M(3000)F2 and its correlation with that of foF2. *Ann. Geophys.*, *41*(4), 583-590.

Lastovicka, J. (2024). A study on space weather impacts on Earth's ionosphere. *Advances in Space Research*, *73*(3), 685–694.

Liu, L., Shen, X. & Yao, Z. (2004). Investigating the long-term variation of geomagnetic activity using the aa index. *Annales Geophysicae, 22*, 2973–2983.

Liu J. Y. Chen Y. I. & Lin J. S. (2003). Statistical investigation of the saturation effect in the ionospheric foF2 versus sunspot, solar radio noise and solar EUV radiation, *Journal of Geophysical Research*, *108*(A2), 1067.

Liu, L., Wan W., Ning. B. & Pirog O. M. (2004). Statistical modeling of ionospheric foF2 over Wuhan, *Radio Sci.*, *39*, 2013.

Mikhailov, A. & Mikhailov V. (1995). A new ionospheric index MF2. Adv. *Space. Res.*, *15*, 93-97.

Moraitis, G., Kecic Z. & Cander L. (1991). lonospheric modeling at single stations. Proc. of PRIME Workshop, Rome, 154-160.

Pancheva, D. & Mukhtarov, P. (1994). Monthly mean spectral model of foF2 over Sofia. Proc. of PRIME Workshop, El Arenosillo, 291-304.

Pancheva, A. & Mukhatarov, P. (1998). A single-station spectral model of the monthly median F2 and M(3000)F2. *Studia Geophysica et Geodaetica, 42*, 183–196.

Pancheva, D. & Mukhatarov P. (1996). A single-station spectral model of the monthly F-region critical frequency. *Ann. Geophysics*, *39*, 807-818.

Perrone, L., De Michelis, P. & Guglielmi, A. (2022). Investigating geomagnetic storms and their impact on satellite systems: A novel approach. *Space Weather, 20*(3), e2022SW003047.

Poole, A. W. V. & McKinnell, L. A. (2000). On the predictability of foF2 using Neural Network. *Radio Science*, *35*(1), 225-235.

Qiao, Y., Shi, Y., Liu, Y., Yang, C. & Wang, J. (2022). An explainable dynamic prediction method for ionospheric foF_2 based on machine learning. *Remote Sensing, 15*(5), 1256.

Richards, P. G. (2001). Seasonal and solar cycle variations of the ionospheic peak electron density: Comparison of measurement and model. *J. Geophys. Res.*, *160*, 12803-12819.

Sethi, N. K., Goel, M. K. and Mahajan, K. K. (2002). Solar Cycle variations of foF2 from IGY to 1990. *Ann. Geophysicae*, *20*, 1677-1990.

Sizun, H. (1992). F2 layer critical frequency modelization as function of upward and downward phase of solar activity cycle. Proceedings of the PRIME/URSI Joint Workshop, Roquetes, May 1992, Memoria, *16*, 205-217.

Sizun, H. (1991). foF2 variation with R12 solar index. Proc. of Prime Workshop Rome, 87-91.

Stanilawaska, I., Klos, Z. & Stasiewicz, K. (1991). Local Model of ionosphere based upon data Miedzeszyn station. Proc. of PRIME Workshop, Rome, 161-164.

Xenos, T. D., Kouris, S. S. & Zolesi B. (1996). Assesment of solar cycle dependence of foF2. *Annali di Geofisica, 39*(6).

Xu, T. (2008). A single-station spectral model of the monthly median foF2 over Chongqing, China. *Annales Geophysicae, 23*, 2961–2966.

Zhang, J., Li, X., Wang, Y. & Liu, Z. (2024). The impact of space weather on satellite communication systems: A comprehensive study. *Frontiers in Astronomy and Space Sciences, 11*, 1418918.

Zolesi, B. Cander, L. R. & De Franceschi R. (1993). Simplified ionospheric regional model (SIRM) for telecommunication applications. *Radio Science, 4,* 603-612.

How to cite this article: Bhanupriya, Madhuri Singh, Kalpana Maski and S.K. Vijay (2025). Spectra Model of foF2 for Low Latitude Station during the 24th Solar Cycle. *International Journal of Theoretical & Applied Sciences, 17*(2): 22–30.