Nigerian Journal of Physics (NJP)
ISSN online: 3027-0936
ISSN print: 1595-0611
DOI: https://doi.org/10.62292/njp.v35(s).2026.700
Volume 35(S), 2026

The Signature of the Deep Solar Cycle 25 on the Equatorial Ionospheric F2 Layer Parameters

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Keywords:
Equatorial Ionosphere,
F2-Layer,
Deep Solar Minimum,
Equatorial Ionisation Anomaly (EIA)

Submitted: 13 Aug. 2026

Accepted: 07 Sept. 2026

Published: 16 Sept. 2026

ABSTRACT

This study examines the morphology and variability of the ionospheric F2-layer over two equatorial stations: Ilorin, Nigeria (8.50°N, 4.67°E, -2.96 dip) in the African sector, and Jicamarca, Peru (11.95°S, 76.87°W, 0.74 dip) in the Southern American sector, during the deep solar minimum of 2020 during the unset of the Solar Cycle 25. Hourly measurements of the critical frequency (foF2), peak height of ionisation (hmF2), and parameters B0 and B1 were extracted from ground-based Digisonde ionosondes and processed to generate diurnal and seasonal averages. Seasonal groupings included the March and September Equinox, June and December Solstice. Variability was quantified using the standard deviation and coefficient of variation, while Pearson correlation analysis assessed internal (foF2-hmF2) and longitudinal (Ilorin-Jicamarca) coupling, with significance tested at 95% confidence. Results indicate that foF2 exhibits pronounced daytime peaks, with maxima of 7.94 MHz at Ilorin and 9.49 MHz at Jicamarca, while hmF2 rises more sharply at Ilorin (399 km) than Jicamarca (324 km), reflecting stronger vertical plasma drifts in the African sector. Seasonal modulation is greater in foF2 (CV 19.97-31.38%) and B0 (up to 61.84%) than in hmF2 (CV < 14%). Longitudinal coupling is stronger during the March Equinox (r > 0.73), whereas solstices exhibit inverse correlations in hmF2, highlighting hemispheric phase reversals driven by thermospheric winds. Overall, Ilorin consistently shows higher in the observed value of the heights and thicker B0 and B1 parameters than Jicamarca. These findings provide a comprehensive characterisation of equatorial F2-layer dynamics under minimal solar epoch and offer critical observational constraints for refining empirical ionospheric models.

INTRODUCTION

The Sun as the primary source of energy for Earth significantly influences both the thermodynamic environment and space weather conditions (Kren et al., 2017). The ionosphere, particularly the F2 layer, plays a critical role in space weather science due to its high sensitivity to solar radiation (Daniel et al., 2016). Located at altitudes ranging from approximately 200 km to 600 km, the F2 layer contains the highest electron density in the ionosphere and persists through both day and night, supporting high-frequency (HF) radio transmissions and satellite navigation systems (Ayokunnu et al., 2023). The morphology of the ionosphere is usually described using parameters such as the critical frequency (foF2), representing the peak electron density; the peak height of ionisation (hmF2); and B0 and B1 parameters, which characterise the electron density gradient and layer thickness (Bilitza and Reinisch, 2013; Rishbeth and Mendillo, 2001).

Solar activity follows an approximately 11-year cycle, with variations in sunspot numbers and solar emissions. Solar Cycle 25 began in December 2019, and 2020 marked a deep solar minimum characterised by minimal sunspot activity and reduced solar flux. During such periods, changes in foF2, hmF2, B0, and B1 provide essential insights into ionospheric processes under weak solar epoch (Heelis et al., 2009). While extensive studies exist for periods of moderate to high solar activity, research on ionospheric responses under deep solar minimum conditions, especially within the low-latitude equatorial region remains limited.

Electrodynamic processes such as the vertical E×B plasma drifts and the development of the Equatorial Ionisation Anomaly (EIA), produce distinct diurnal structures such as pre-noon and post-noon foF2 enhancements and significant hmF2 uplift (Bilitza et al., 2023; Adewale et al., 2010). Observations during periods of low solar activity have shown that the equatorial foF2 and F2-layer height exhibit pronounced diurnal and seasonal variability (Ayokunnu et al., 2020), with empirical models such as the International Reference Ionosphere (IRI) sometimes deviating from actual observations, particularly over equatorial and low-latitude regions (Oyekola, 2011; Bilitza et al., 2014). Regional studies in the African equatorial sector highlight strong foF2 variability and seasonal shifts in virtual height, reflecting electrodynamics and thermospheric influences (Ehinlafa et al., 2024).

Previous research emphasises the influence of latitudinal and geomagnetic positioning on F2-layer dynamics. In scholarly article, it has been reported that Ilorin and Fortaleza exhibited comparable diurnal profiles, whereas Jicamarca displayed distinct behaviour due to its proximity to the geomagnetic equator (Ayokunnu et al. 2023). In another study, it was reported that foF2 variability at Jicamarca, with heightened fluctuations around sunrise during low solar activity, is shaped by vertical plasma drifts and ionospheric chemistry (Adebesin et al. 2014). Similarly, comparative studies have shown that stations located near the Equatorial Ionization Anomaly (EIA) crest generally record higher daytime foF2 values than those situated close to the magnetic equator due to enhanced plasma accumulation associated with the equatorial fountain effect (Balan & Bailey, 1995; Adebesin et al., 2014). Scintillation studies at equatorial latitudes further support these findings, with disturbances most pronounced at night under high solar activity (Kintner et al., 2007; Basu et al., 2010; Oladipo et al., 2018).

The present study addresses the scarcity of cross-hemispheric analyses during deep solar minima by examining seasonal and diurnal variations in foF2, hmF2, B0, and B1 using Digisonde observations from Ilorin, Nigeria (Northern equatorial sector) and Jicamarca, Peru (Southern equatorial sector) for January to December of the year 2020. By quantifying hemispheric asymmetry and assessing electrodynamics modulation of the F2 layer, this research provides observational constraints for empirical ionospheric models and improves our understanding of equatorial ionospheric morphology under minimal solar epoch.

MATERIALS AND METHODS

Study Area and Data Source

We investigated the morphology of the ionospheric F2-layer over two equatorial stations: Ilorin, Nigeria (8.50°N, 4.67°E, -2.96° dip), located in the northern equatorial sector, and Jicamarca, Peru (11.95°S, 76.87°W, 0.74° dip), situated in the southern equatorial sector. Both stations are located within the equatorial ionisation anomaly (EIA) region and are strongly influenced by vertical E × B plasma drifts and meridional thermospheric winds (Rishbeth and Mendillo, 2001). The data used span from January to December 2020, a period corresponding to the deep solar minimum preceding the ascending phase of Solar Cycle 25. This interval is characterised by persistently low solar flux, allowing for the comprehensive investigation of quiet-time ionospheric behaviour under a weak solar epoch (Heelis et al., 2009; Liu et al., 2011). Hourly data were obtained from the University of Massachusetts Lowell's Center for research (UMLCAR) database (Reinisch et al., 2009).

Ionospheric Parameters

The analysis focused on several key parameters of the F2-layer. The critical frequency, foF2 (MHz), which is related to the peak electron density, NmF2, was calculated using the relation

$$N_mF2 = 1.24\times10^{10}\,(f_oF2)^2 \qquad (1)$$

where foF2 is in MHz and NmF2 in m^{-3} (Davies, 1990). The peak height of ionisation, hmF2 (km), was derived from true height ionogram inversion as described by Huang and Reinisch (1996). The thickness parameter B0 (km) and the shape parameter B1 which defines the curvature of the bottomside electron density profile were included in the study following the standard International Reference Ionosphere formulation established by Bilitza (2001).

Data Processing

Hourly values of the critical frequency foF2, peak height of ionisation hmF2, profile thickness B0, and shape parameter B1 were extracted from the digital ionosonde records of Ilorin (Africa) and Jicamarca (South America) for the 2020 deep solar minimum. From this validated dataset, hourly averages were computed to characterise diurnal variations across a 24-hour cycle. Seasonal classifications were established by grouping months into the 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). This grouping facilitates the identification of seasonal modulations in both the parameters and the ionospheric structure, as influenced by solar zenith angle and thermospheric composition alterations in accordance with conventional ionospheric climatology (Rishbeth and Mendillo, 2001).

Statistical Analysis

To quantify variability and the degree of coupling between the two sectors, several statistical metrics were employed. The Standard Deviation (SD) was used to measure the absolute dispersion of each parameter around the mean. Given the different units and magnitudes of the parameters (e.g., MHz for foF2 vs. km for B0), the Coefficient of Variation (CV) was calculated as:

$$CV = \frac{\sigma}{\mu} \times 100\% \qquad (2)$$

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \qquad (3)$$

where X and Y represent hourly parameter values at the respective stations. Statistical significance was set at $p < 0.05$.

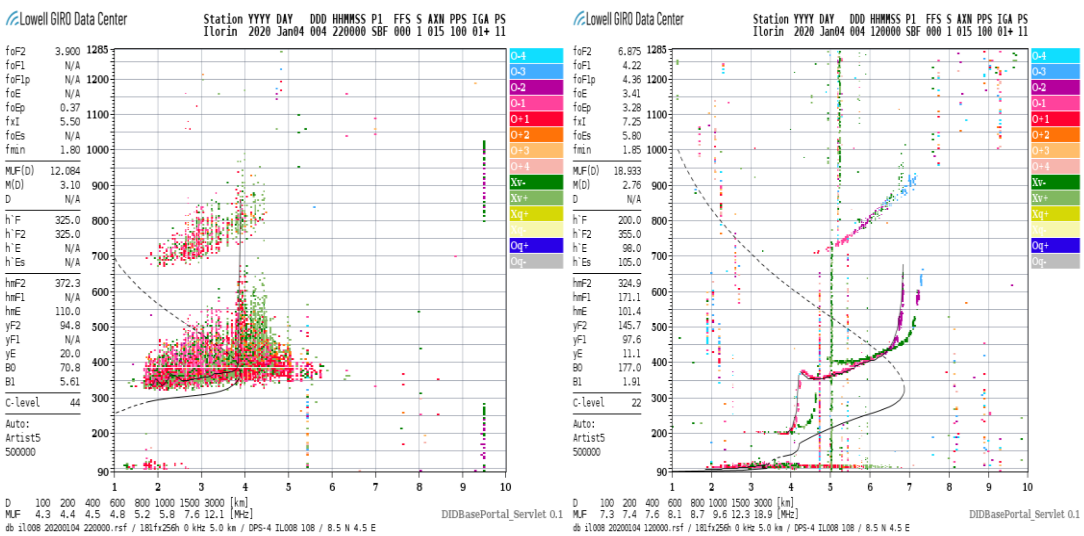
This allowed for a normalised comparison of relative variability across seasons and stations. The degree of longitudinal synchronisation and inter-parameter relationship was evaluated using Pearson Correlation Analysis (r). Specifically, this analysis was applied to investigate the relationship between foF2 and hmF2 at each station and assess the interplay between plasma density and electrodynamics uplift (Lin et al., 2007), also to show the correlation between Ilorin and Jicamarca for all four parameters (foF2, hmF2, B0, B1 by identifying periods of hemispheric symmetry or phase reversal. Statistical significance for these correlations was tested at a 95% confidence level ($p < 0.05$), ensuring that the observed coupling between the African and American sectors was not due to statistical fluctuations.

Inter-Station Comparison

Hemispheric asymmetry was assessed by directly comparing seasonal means and variability metrics between Ilorin and Jicamarca. Observed differences in magnitude and variability were interpreted in terms of geomagnetic configuration, thermospheric winds, and electrodynamics force during the deep solar minimum (Rishbeth and Mendillo, 2001). Table 1 shows the geographic and geomagnetic coordinate of the stations used.

Table 1: Geographic and Geomagnetic Coordinates of the Stations Used

Geographic Coordinate	Geomagnetic Coordinate
Ilorin Nigeria (8.5 °N, 4.5 °E)	(-1.82, 76.80, -2.96 dip)
Jicamarca, Peru (12 °S, 76.8 °W)	(0.77, 354.33, 0.74dip)



(a) (b)

Figures 1: (1a and b) Below Represent a Typical Daytime and Night Time Ionogram as Seen from the Ilorin Station

RESULTS AND DISCUSSION

The result of our observation is presented in this section.

Diurnal Variation of F2-Layer

The diurnal variation of foF2 and hmF2 captures the characteristics of equatorial ionospheric F2 layer. foF2 exhibits a pre-noon increase followed by a stronger post-noon peak at both stations. At Ilorin, maximum values reach 7.94 MHz, while Jicamarca peaks at 9.49 MHz during the December Solstice. This "midday bite-out" and peak structure are consistent with the electrodynamic drift dynamics documented by Ayokunnu et al. (2021), who noted that during low solar activity, the departure from Chapman layer theory is most pronounced during daytime hours due to plasma transport. The hmF2 profiles demonstrate a rapid post-sunrise uplift. Ilorin hmF2 peaks at 399.12 km, while Jicamarca midday values are relatively suppressed at 324 km. As highlighted by Ayokunnu et al. (2023), the steeper rise at Ilorin suggests stronger vertical plasma drifts in the African sector. Furthermore, Lee and Reinisch (2006) and Bilitza et al. (2014) noted that at the magnetic equator, hmF2 typically rises to over 400 km at dusk due to PRE, which validates the high altitude peaks observed in the data.

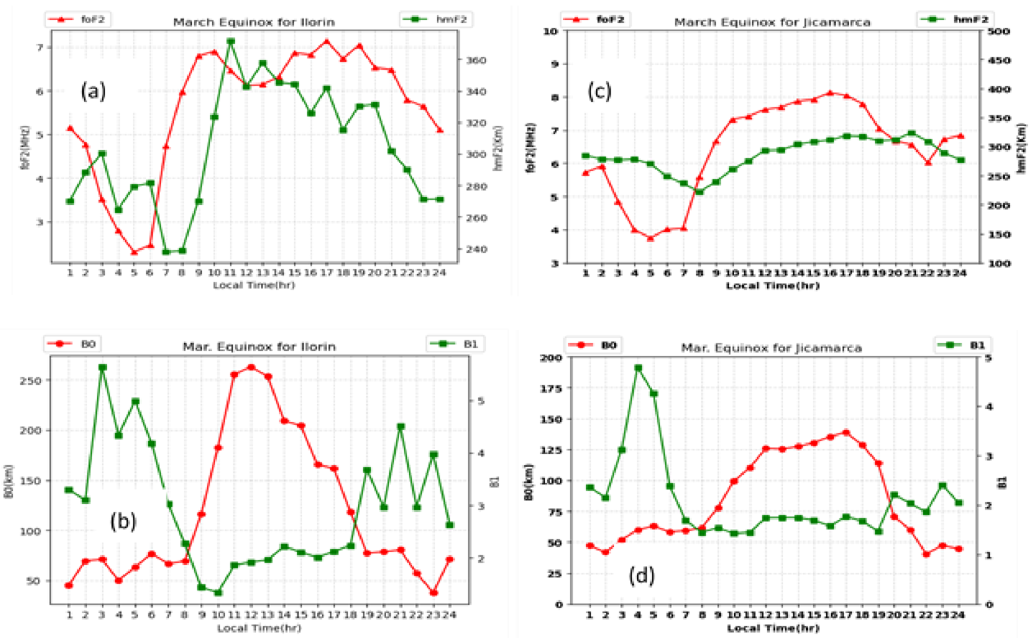


Figure 2: Diurnal Variation of foF2, hmF2, B0 and B1 at Ilorin (a–b) and Jicamarca (c–d) During the March Equinox. (c-d) Diurnal Variation of foF2, hmF2, B0 and B1 at Jicamarca During the March Equinox

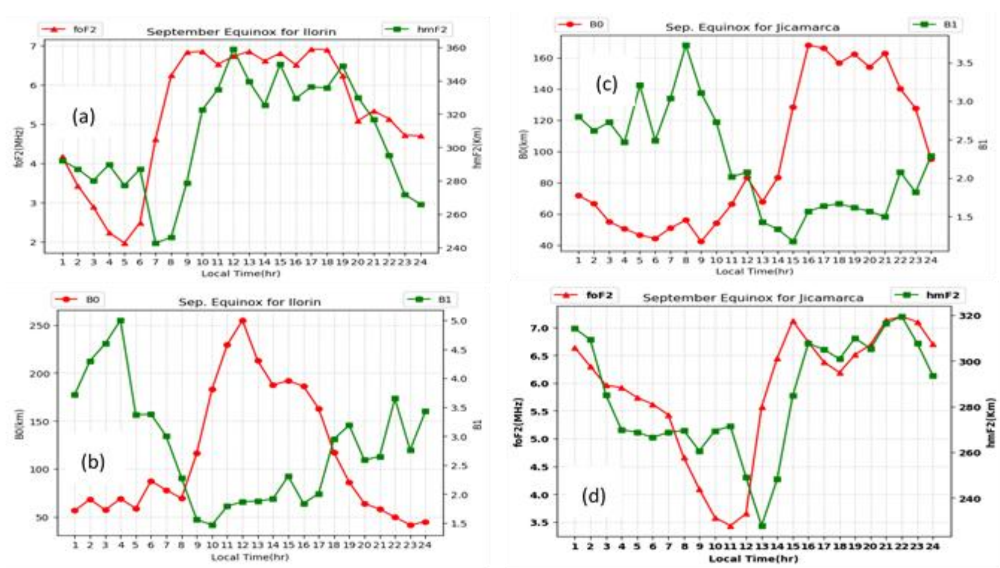


Figure 3: Diurnal Variation of foF2, hmF2, B0 and B1 at Ilorin (a–b) and Jicamarca (c–d) During the September Equinox. (c-d) Diurnal Variation of foF2, hmF2, B0 and B1 at Jicamarca During the September Equinox

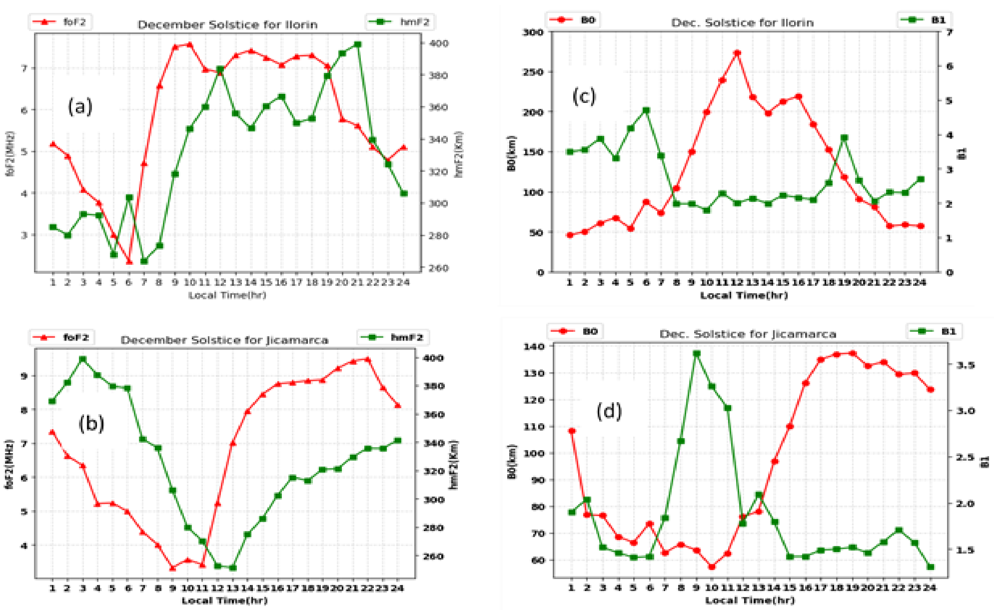


Figure 4: Diurnal Variation of foF2, hmF2, B0 and B1 at Ilorin (a–b) and Jicamarca (c–d) During the June Solstice. (c-d) Diurnal Variation of foF2, hmF2, B0 and B1 at Jicamarca During the June Solstice

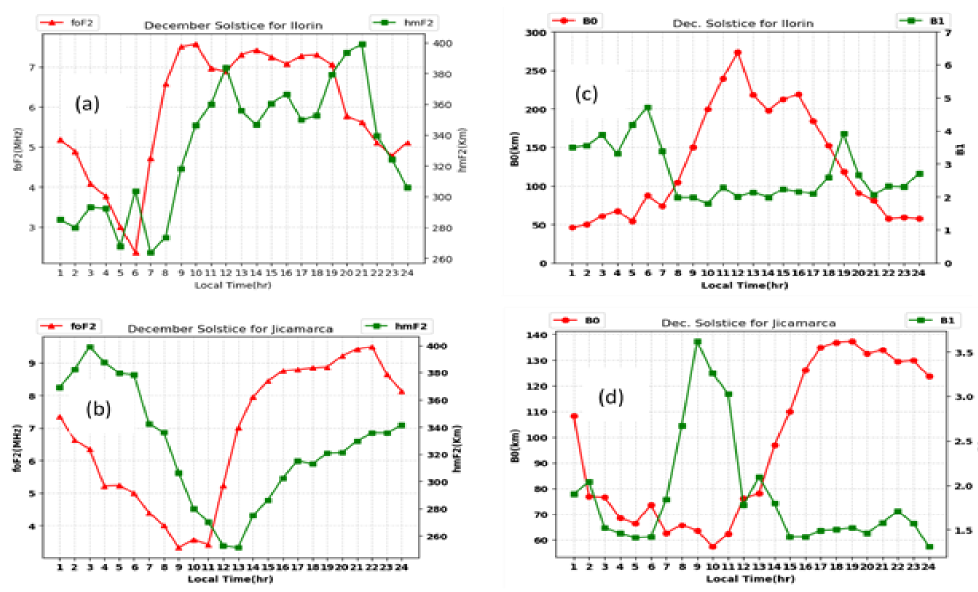


Figure 5: Diurnal Variation of foF2, hmF2, B0 and B1 at Ilorin (a–b) and Jicamarca (c–d) During the December Solstice. (c-d) Diurnal Variation of foF2, hmF2, B0 and B1 at Jicamarca During the December Solstice

Seasonal Mean and Variability

The seasonal analysis reveals distinct modulations across all four parameters: foF2 and hmF2: Seasonal mean foF2 varies between 4.86 MHz and 6.80 MHz. With CV values spanning 19.97% to 31.38%, peak electron density shows significantly higher sensitivity to seasonal modulation than hmF2, which maintains a CV below 14%. This supports the findings of Ayokunnu et al. (2023) that peak electron density responds more dynamically to seasonal solar forcing than layer height during solar minimum.

B0 and B1: Seasonal means for B0 are consistently higher at Ilorin (99-127 km) than at Jicamarca (84-97 km). The observed peak B0 at Ilorin correlates with the observed values of the past work (Ayokunnu et al. 2023) regarding the latitudinal effect on true height profiles. B_1 values range from 1.87 to 2.95, tending to exhibit lower daytime values during the deep solar minimum in agreement with the observations of Ameen et al. (2021). The high CV for B0 at Ilorin (up to 61.84%) compared to its relative stability in other seasons confirms that bottomside thickness is the most seasonally variable parameter in the African sector, also in agreement with (Ayokunnu et al. (2021).

Longitudinal Coupling and Sectorial Asymmetry

Pearson correlation analysis confirms high longitudinal synchronisation during the March Equinox, particularly for foF2 ($r = 0.89$, $p < 0.001$), B0 ($r = 0.81$, $p < 0.001$), and B1 ($r = 0.73$, $p < 0.001$). However, the significant inverse correlation in hmF2 during solstices (r approx -0.65 to -0.69, $p < 0.001$) highlights a phase reversal. This hemispheric contrast is likely driven by meridional thermospheric winds, as discussed by Adewale et al. (2012) and Derghazarian et al. (2021), who noted that during the 2019 - 2020 deep solar minimum, the equatorial ionosphere's properties were strongly influenced by summer-to-winter hemispheric winds, causing opposite vertical motions in the northern and southern sectors.

CONCLUSION

The characterisation of foF2, hmF2, B0, and B1 during the 2020 solar minimum concludes that, while hmF2 maintains structural stability (CV < 14%), foF2 and B0 are highly sensitive to seasonal modulation. This supports the findings of Ayokunnu et al. (2022) that peak electron density responds more dynamically to solar forcing than layer height during solar minimum. Ilorin (Africa) consistently demonstrates higher hmF2 and a thicker (B0) than Jicamarca (America). This validates the sectorial asymmetry reported by Ayokunnu et al. (2023) and Adewale et al. (2012) regarding the longitudinal variability of the equatorial ionosphere. The March Equinox is the period of maximum global synchronisation for all four parameters ($r > 0.73$), while solstice periods are characterised by decoupled or inverse behavior in layer height. The diurnal variations captured in B0 and B1 demonstrate that the thickness and profile shape are largely governed by electrodynamic transport processes, such as E x B vertical drifts and diffusion. The fact that these variations persist even under minimised solar epoch aligns with the equatorial transport-driven thresholds modeled by Ayokunnu (2021), as well as the quiet-time profile behaviors observed by Ameen et al. (2021) during a deep solar minimum. These findings underscore that the African equatorial ionosphere is more dynamic than the American sector during deep solar minimum. These results provide critical observational validation for improving empirical models like the IRI, which, as noted by Ayokunnu et al. (2021) and Bilitza et al. (2022), often require regional adjustments to accurately represent the African sector.

ACKNOWLEDGEMENTS

The authors acknowledge the Center for Atmospheric Research, University of Massachusetts Lowell (UMLCAR), for providing access to the Global Ionospheric Radio Observatory (GIRO) database.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit organisations.

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