



**Validation of NeQuick-2 Model for foE prediction at Ouagadougou
Under Geomagnetically Quiet Conditions.**

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Abstract

This study evaluates the performance of the NeQuick-2 model in simulating foE and capturing its variability under geomagnetically quiet conditions at Ouagadougou (latitude 12.4°N; longitude 358.5°E; magnetic dip 1.45°N), considering diurnal, seasonal, and solar-activity effects. The Ouagadougou station falls within the trough belt of the equatorial ionization anomaly region in West Africa. The analysis was carried out during the solar minimum and solar maximum phases of Solar Cycles 21 and 22.

Comparisons between NeQuick-2 predictions and ionosonde observations show that the model successfully reproduces the overall diurnal morphology of foE across all seasons and solar activity phases. However, systematic discrepancies are observed mainly at sunrise (transition between nighttime and daytime) and sunset (transition between daytime and nighttime) periods (06:00 LT and 18:00–19:00 LT), as well as during the equinoctial seasons, when the model frequently underestimates the observed values, particularly around the daytime maximum. These limitations are more pronounced during periods of low solar activity.

Statistical analysis based on the root mean square error (RMSE) and the coefficient of determination (R^2) reveals a significant improvement in the performance of NeQuick-2 during the solar maximum phases of both solar cycles. The best agreement between model predictions and observations is generally obtained during winter and summer, whereas the poorest performance occurs during spring and autumn. This agreement is particularly evident during Solar Cycle 22, for which the coefficients of determination exceed 0.9 for all seasons during the solar maximum phase.

These results show that NeQuick-2 performance depends strongly on both season and solar activity level. They confirm the model's robustness in representing the ionospheric E-layer under high solar activity while highlighting persistent limitations in reproducing equinoctial conditions and sunset conditions over the African equatorial region.



Keywords: NeQuick-2 model; foE; variability; geomagnetically quiet conditions; solar activity phases; solar cycle.

1. Introduction

The ionosphere is the region of the Earth's upper atmosphere where solar radiation ionizes neutral constituents, producing a plasma composed of electrons and ions. This region plays a key role in propagating high-frequency radio waves and strongly influences the performance of many communication and satellite navigation systems, particularly Global Navigation Satellite Systems (GNSS).

The equatorial and low-latitude ionosphere is of particular interest because electrodynamic processes generate phenomena such as the equatorial fountain, the equatorial electrojet, and the Equatorial Ionization Anomaly (EIA). These processes produce strong electron density variability and can significantly affect the performance of communication and satellite navigation systems.

To better understand ionospheric behavior, observational instruments such as ionosondes and Global Positioning System (GPS) receivers have been deployed in different regions of the world. However, in some regions, particularly Africa, ionospheric observations remain limited because of the scarcity of ground-based facilities needed to monitor the ionosphere and the near-Earth space environment. In this context, ionospheric models have become essential tools for investigating and predicting ionospheric behavior. Among the various approaches, empirical models are widely used because of their simplicity, computational efficiency, and suitability for near-real-time operational applications.

Among the most widely used empirical models are the International Reference Ionosphere (IRI) model (Bilitza, 2001; Bilitza & Reinisch, 2008) and the NeQuick model (Hochegger et al., 2000; Nava et al., 2008). The NeQuick model is a fast-running three-dimensional empirical ionospheric electron density model developed at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste (Italy) in collaboration with the University of Graz (Austria). It describes ionospheric electron density up to the F2-layer peak using a modified DGR profile formulation (Radicella & Zhang, 1995). The current version, NeQuick-2 (Nava et al., 2008), is widely used for transionospheric propagation applications and for modeling total electron content (TEC).

Due to its increasing use in ionospheric studies, this model has been widely evaluated and validated in different regions of the world and under various geophysical conditions. For example, Kashcheyev & Nava, (2019) showed that NeQuick-2 generally reproduces observed TEC variability but tends to underestimate TEC in the upper ionosphere and plasmasphere, particularly at low latitudes. Similarly, Osanyin et al. (2023) demonstrated that assimilating local data into NeQuick-2 significantly improves its performance in TEC modeling over the equatorial and low-latitude Brazilian region, especially during periods of high solar activity. On a global scale, Okoh et al. (2018) showed that the NeQuick model correctly reproduces observed



TEC variability and, overall, performs better than the IRI-Plas model. In the West African equatorial region, Yao et al. (2018) also showed that the NeQuick model generally reproduces GNSS-derived TEC variations. However, it underestimates TEC during certain periods of the day. These studies showed that NeQuick-2 is widely used and evaluated for TEC modeling.

In parallel, several studies have investigated the ionospheric E-layer over the African equatorial region. For example, Abe et al. (2013) showed that foE over Ouagadougou increases with solar activity, reaches its maximum around local noon and its minimum near sunrise and sunset, and exhibits pronounced seasonal variability, with maximum values during the June solstice and minimum values during the December solstice. More recently, Kazeem et al. (2026) highlighted the combined influence of solar and geomagnetic activity on the maximum electron density of the E-layer (NmE) over Ouagadougou. Likewise, Gédéon et al. (2025) evaluated the performance of the IRI-2016 model in reproducing foE over Ouagadougou and reported good agreement with observations during daytime hours (07:00–17:00 LT), while larger discrepancies were observed during sunrise and sunset.

Despite these advances, modeling of the ionospheric E-layer, particularly the foE parameter, remains relatively underexplored within the NeQuick-2 framework, especially in the low-latitude African region, where ionosonde facilities are limited or scarce. Yet, the E-layer plays an important role in high-frequency radio wave propagation. From a physical perspective, it is primarily governed by photochemical equilibrium, characterized by very short ionization and recombination time constants, making its behavior relatively stable and well represented by empirical formulations (Chapman, 1931; Titheridge, 1996). Furthermore, in the NeQuick-2 model, the E-layer representation is based on an empirical formulation derived from Titheridge, (1996), ensuring consistency between the climatological description of foE and the overall electron density profile.

In this context, assessing NeQuick-2's ability to model foE variability is of particular interest, especially in equatorial regions where ionosonde observations remain scarce. Therefore, this study evaluates the performance of the NeQuick-2 model in reproducing foE over Ouagadougou under geomagnetically quiet conditions during the solar minimum and solar maximum phases of Solar Cycles 21 and 22 using postprocessed experimental data.

2. Data and Methods

2.1. Experimental Data and Model Data

The experimental data used in this study were obtained from the archives of the Ouagadougou ionosonde station in Burkina Faso (latitude: 12.4°N; longitude: 358.5°E; magnetic dip: 1.45°N). The data were downloaded from the Geophysics Research Group Europe-Africa (GIRGEA) platform at: <https://www.girgea.org/recherches/logiciels/>.



100 The simulated foE data were obtained using the NeQuick-2 model code developed in Fortran-77. The results
 101 were organized by month and year, covering the entire period considered in the study.

102 **2.2. Methods**

103 **2.2.1. Method for Calculating foE in the NeQuick-2 Model**

104 The critical frequency of the E-layer (foE) is one of the anchor parameters of the NeQuick-2 model. Together
 105 with foF1, foF2, and M (3000)F2, it is used to construct the vertical electron density profile through a
 106 sequence of semi-Epstein layers (Leitinger et al., 2005; Nava et al., 2008). In NeQuick-2, the calculation of
 107 foE is based on the semi-empirical formulation proposed by Titheridge (1996), which was incorporated into
 108 the model's E-layer formulation (Nava et al., 2008). In its operational version, the expression used by
 109 NeQuick-2 is:

$$110 \quad (foE)^2 = (a_e \sqrt{F10.7}) (\cos \chi_{eff})^{0.6} + 0.49 \quad (1)$$

111 where:

- 112 (i) F10.7 is the 10.7 cm solar radio flux;
- 113 (ii) a_e is an empirical coefficient mainly dependent on geographic latitude, season, and solar
 114 activity level;
- 115 (iii) χ_{eff} is the effective solar zenith angle used by the model to more accurately represent the
 116 illumination conditions of the E-layer.

117 In the NeQuick-2 implementation, the calculation of foE relies on several input parameters, including date,
 118 universal time, geographic latitude, longitude, and solar flux F10.7. Based on these parameters, the model
 119 determines the Sun–Earth geometry to calculate the solar zenith angle, which is then converted into an
 120 effective solar zenith angle to better represent the illumination conditions of the E layer, particularly during
 121 day–night transition periods. The empirical coefficient, which depends on latitude, season, and solar activity
 122 level, is subsequently determined before applying the (Titheridge, 1996) formulation to obtain the final foE
 123 value (Leitinger et al., 2005; Nava et al., 2008; Titheridge, 1996).

124 This formulation indicates that the variability of foE simulated by NeQuick-2 is mainly controlled by the
 125 intensity of incoming solar radiation, represented by the daily F10.7 solar flux, as well as by the solar
 126 illumination geometry.

127 **2.2.2. Selection of Geomagnetically Quiet Days**

128 We selected geomagnetically quiet conditions based on the aa geomagnetic index (Mayaud, 1972). The aa
 129 index data were obtained from the International Service of Geomagnetic Indices (ISGI). For each month,
 130 the five days with the lowest aa index values ($aa \leq 20$ nT) were selected as quiet days. This approach,
 131 inspired by the work of Nanema et al. (2018), best represents the typical geomagnetically quiet conditions



of the month. The identified quiet days were then used to extract the corresponding hourly foE data (NeQuick and experimental).

2.2.3. Seasonal Characterization and Definition of Solar Cycle Phases

Seasonal variations are studied using representative months, assuming that spring, summer, autumn, and winter correspond to March, June, September, and December, respectively.

For each representative month, the diurnal variation of foE is obtained by computing the hourly mean of values from the five quietest days, according to the relation:

$$foE_h = \frac{\sum_{j=1}^5 foE_{h,j}}{5} \quad (2)$$

where foE_h denotes the hourly critical frequency of the E-layer for the selected representative month, and $foE_{(h,j)}$ is the critical frequency value at hour h for day j , with $h \in [0, 24]$ and $j \in [1, 5]$.

Furthermore, the phases of the solar cycle are defined based on the sunspot number R_z : solar minimum and solar maximum conditions correspond to $R_z \leq 20$ and $R_z \geq 100$, respectively (Ouattara & Amory-Mazaudier, 2012; Zerbo et al., 2011).

In this study, the year 1976 is considered representative of the minimum phase of solar cycle 21 (SC21), whereas 1979 represents its solar maximum phase. Similarly, for solar cycle 22 (SC22), the years 1985 and 1990 are considered representative of the solar minimum and solar maximum phases, respectively.

2.2.4. Statistical Criteria for Evaluating Model Performance

The following relationship defines the relative error:

$$\sigma foE = \frac{foE_{NeQuick} - foE_{Exp}}{foE_{Exp}} \times 100 \quad (3)$$

where and represent the values simulated by the NeQuick-2 model and the experimental data, respectively, and σfoE denotes the relative error expressed as a percentage.

To define an error tolerance specific to this study, we analyzed the distribution of $|\sigma foE|$ over the 523 observations selected from solar cycles 21 and 22. The Shapiro–Wilk test indicated a non-normal distribution ($p < 0.001$), with positive skewness (skewness = 1.89); therefore, percentiles were preferred to characterize the error distribution. The third quartile ($P_{75} = Q_3$) of $|\sigma foE|$ was equal to 10.0%, meaning that 75.33% of the observations exhibited an absolute error less than or equal to this value. An empirical tolerance of $\pm 10\%$ was therefore defined for the present study, without being considered a universal performance criterion for NeQuick-2. Values of $\sigma foE > +10\%$ were classified as overestimations beyond the tolerance, whereas values of $\sigma foE < -10\%$ were classified as underestimations beyond the tolerance; values between -10% and $+10\%$ were considered to fall within the empirical tolerance range. Figure 1 presents the distribution of $|\sigma foE|$ and its cumulative distribution function, illustrating the position of the $\pm 10\%$ threshold.



164 The statistical analysis is based on two complementary metrics: the root mean square error (RMSE) and the
165 coefficient of determination (R^2).

166 The root mean square error (RMSE) is defined as:

$$167 \quad RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (foE_{NeQuick,i} - foE_{Exp,i})^2} \quad (4)$$

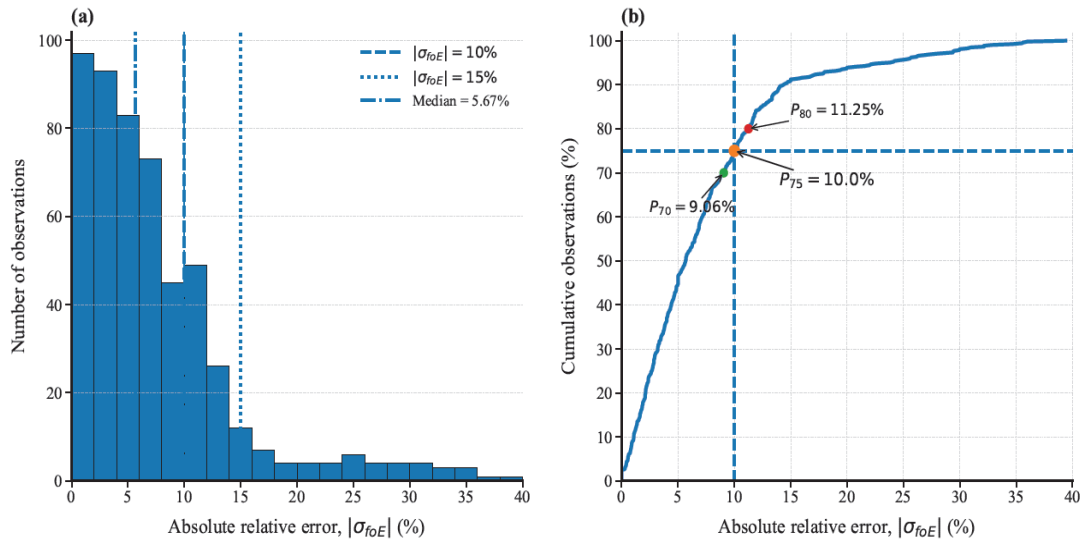
168 where $foE_{NeQuick}$ and foE_{Exp} denote the model-simulated and experimentally observed values,
169 respectively, and N is the total number of samples considered. In ionospheric modeling, a lower RMSE
170 generally indicates better agreement between simulated and observed values. In other words, the lower the
171 RMSE, the better the model performance (Kayode et al., 2026 ; Obafaye et al., 2020).

172 The coefficient of determination (R^2) is computed as:

$$173 \quad R^2 = 1 - \frac{\sum_i^n (y_i - \hat{y}_i)^2}{\sum_i^n (y_i - \bar{y})^2} \quad (5)$$

174 where y_i and $\hat{y}_i$ represent the observed and model-simulated values, respectively, and $\bar{y}$ is the mean of the
175 observations.

176 The coefficient of determination (R^2) quantifies the proportion of the observed variability explained by the
177 model. R^2 values close to unity indicate that the model accurately reproduces the variability of the
178 observations, whereas lower values reflect a more limited ability to capture their variability.



179
180 **Figure 1: Statistical justification of the $\pm 10\%$ tolerance threshold. (a) Distribution of the absolute**
181 **relative error, $|\sigma_{foE}|$. (b) Cumulative distribution function showing that 10% corresponds to the third**
182 **quartile (P_{75}) of the distribution**



3. Results

3.1. Seasonal Diurnal Variations of NeQuick-2-Simulated and Experimental foE During Solar Cycle 21

Figures 2, 4, 6, and 8 present the seasonal NeQuick-2 simulations compared with the observations, whereas Figures 3, 5, 7, and 9 show the corresponding variations in the relative error percentage (σ_{foE}). Figures 2 and 3 correspond to the minimum phase of solar cycle 21, whereas Figures 4 and 5 illustrate the variations during the maximum phase of the same solar cycle. Similarly, Figures 6 and 7 correspond to the minimum phase of solar cycle 22, while Figures 8 and 9 present the variations during the maximum phase of this cycle.

These figures illustrate the temporal variation of foE together with the relative error during winter (panels a), summer (panels b), spring (panels c), and autumn (panels d). The orange curves represent the diurnal variation of foE derived from experimental observations, whereas the green dashed curves correspond to the diurnal variation of foE simulated by the NeQuick-2 model. The purple curves represent the relative differences, expressed as percentages, between the two datasets.

3.1.1. Seasonal Comparison of NeQuick-2-Simulated and Experimental foE During the Solar Minimum Phase (1976)

During the minimum phase of solar cycle 21, the foE values simulated by the NeQuick-2 model and the experimental observations (foE/NeQuick and foE/Exp) generally exhibit similar diurnal variations, characterized by the typical parabolic pattern observed in all seasons. However, significant differences between the model-derived foE values and the experimental measurements occur during the day–night transition periods in all seasons except summer (Figure 2).

In winter, the NeQuick-2 model agrees well with the experimental values throughout the day, except at sunset (18:00 LT), when it underestimates the observations. The relative error reaches approximately -27% at 18:00 LT (Figure 3).

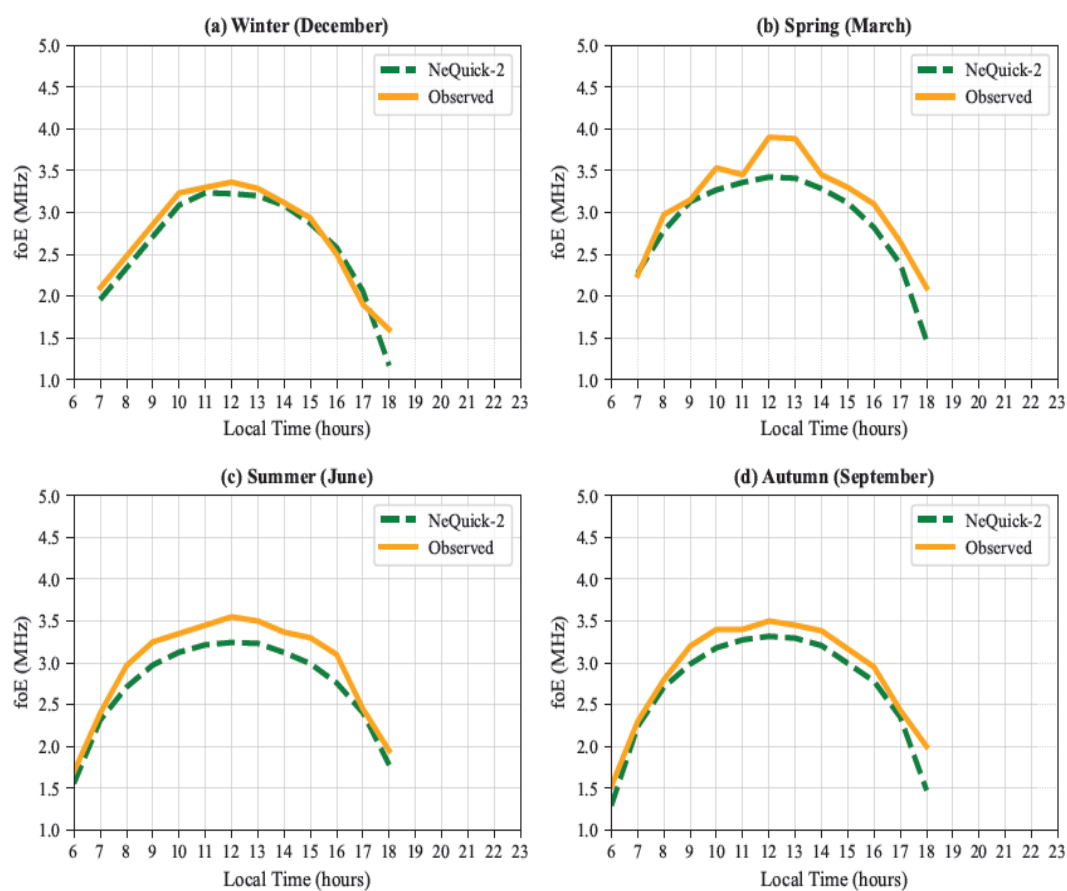
In spring, NeQuick-2 also agrees well with the experimental values throughout most of the day, except between 12:00 and 13:00 LT and at 18:00 LT. During these periods, the model underestimates the observations, with the relative error reaching approximately -11% between 12:00 and 13:00 LT and -26% at 18:00 LT (Figure 3).

In summer, the NeQuick-2 model slightly but persistently underestimates the experimental values, reaching up to -11% at 16:00 LT (Figure 3).

During autumn, the model generally agrees well with the experimental observations throughout the day, except at sunrise (06:00 LT) and sunset (18:00 LT), where it underestimates the observed values. The corresponding relative errors are approximately -15% at 06:00 LT and -26% at 18:00 LT (Figure 3).



217



218

219 **Figure 2: Seasonal Variations of f_oE (NeQuick vs. Observations) During the Solar Cycle 21 Minimum**

220 **Phase (year 1976)**

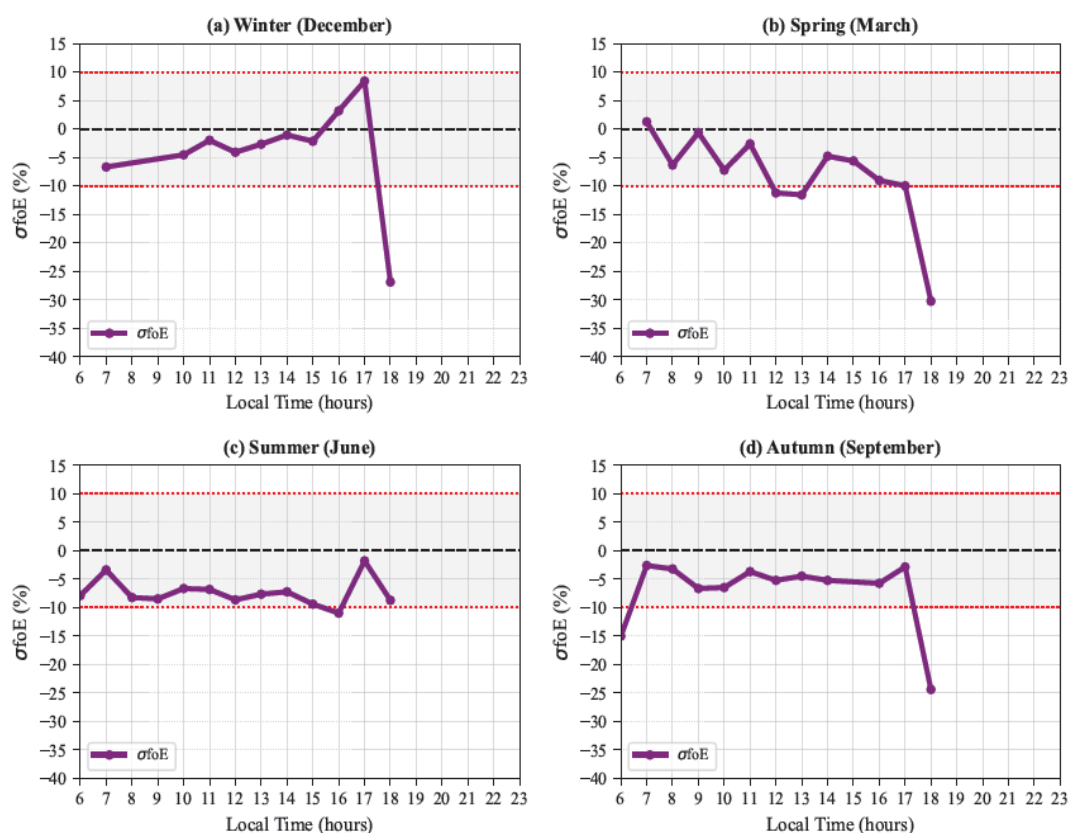


Figure 3: Mean seasonal relative errors during the solar cycle 21 minimum phase (1976)

3.1.2. Seasonal Comparative analysis of foE output by the NeQuick-2 model and Experimental data at the solar maximum phase (1979)

During the maximum phase of Solar Cycle 21, the main differences between the NeQuick-2 simulations and the observations appear in spring and autumn, when the experimental data show a pronounced peak at 13:00 LT and 14:00 LT, which is less pronounced in the simulations. For these same seasons, a significant difference between the two profiles is also observed during the dusk hours (Figure 4).

In winter, the model shows very good agreement with the observations throughout the day, except during the early morning (06:00 LT) and evening transition (18:00 LT) periods, where it underestimates the experimental values. The relative differences reach approximately -20% at 06:00 LT and -13% at 18:00 LT (Figure 5).

In spring, the model predictions are also in good agreement with the observations during most of



the day, except around midday and in the late afternoon/evening periods, particularly between 12:00 LT (−14%) and 13:00 LT (−18%), as well as at 18:00 LT (−32%). During these periods, the NeQuick-2 model underestimates the observed values (Figure 5). In summer, the model shows good agreement with observations throughout the day (Figure 5). In autumn, observations show behavior similar to spring, with model underestimation during midday and evening periods, particularly at 14:00 LT (−17%) and 19:00 LT (−35%). However, at 18:00 LT, the model overestimates, with a relative difference of approximately 15%.

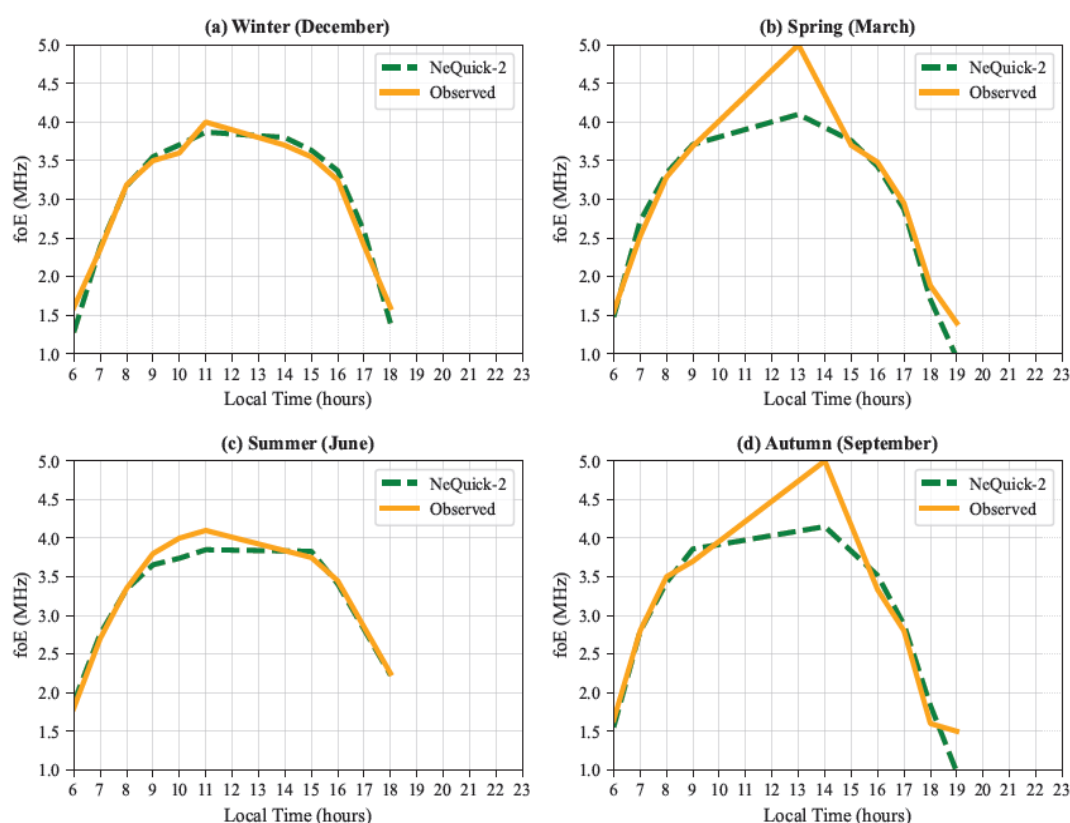


Figure 4: Seasonal variations of foE (NeQuick vs Experimental data) during the solar cycle 21 maximum phase (1979)

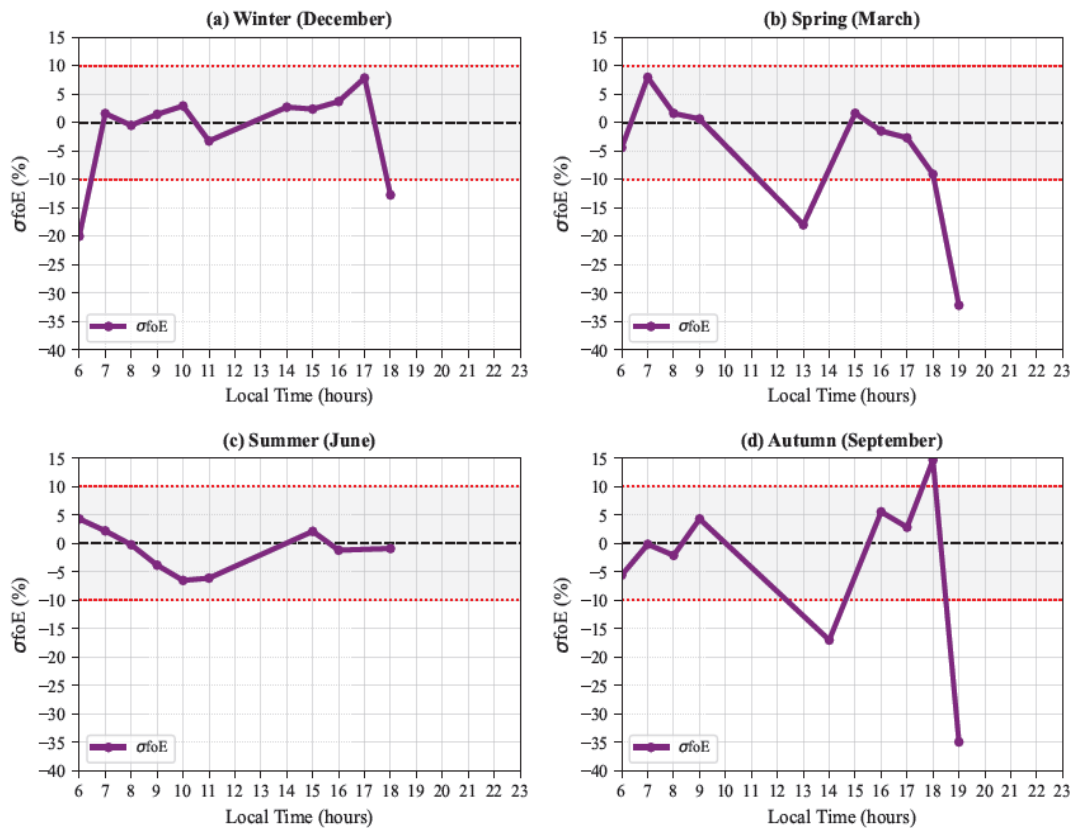


Figure 5: Mean seasonal relative errors during the solar cycle 21 maximum phase (1979)

3.2. Seasonal Diurnal Variations of NeQuick-2-Simulated and Experimental foE During Solar Cycle 22

3.2.1. Seasonal Comparison of NeQuick-2-Simulated and Experimental foE During the Solar Minimum Phase (1985)

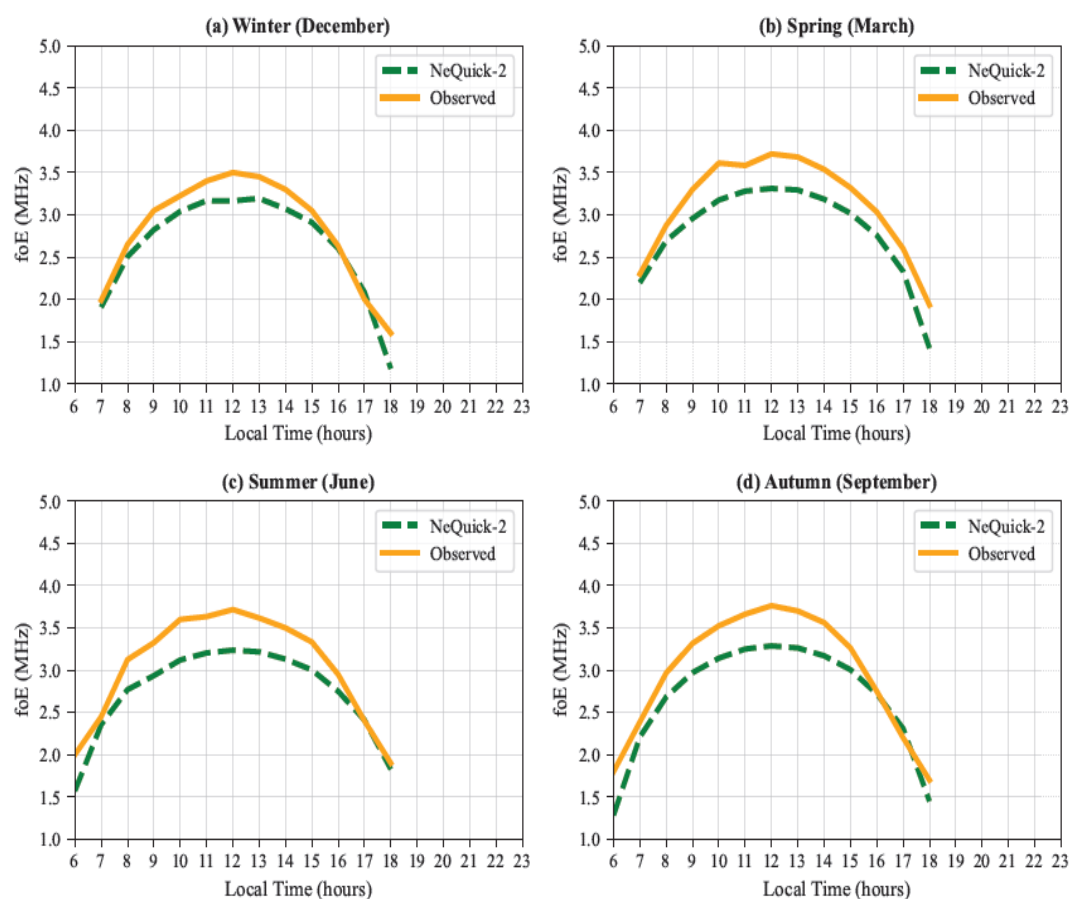
During the minimum phase of Solar Cycle 22, the differences between the NeQuick-2 simulations and the observations vary across seasons.

Winter appears to be the season during which the model predictions are closest to the observations. The σ_{foE} values remain within the range of -10% to $+10\%$ during most of the day, except at 18:00 LT, where a more pronounced underestimation is observed ($\sigma_{foE} = -26.5\%$) (Figure 7).

In spring, the model reproduces the general diurnal trend of the experimental observations but shows recurrent underestimations at several times of the day (09:00, 10:00, 12:00, 13:00, 17:00, and 18:00 LT), with relative deviations ranging from -10.22% (09:00 LT) to -26.31% (18:00 LT).



258 During summer, the model exhibits several underestimations. A significant underestimation is observed as
 259 early as 06:00 LT ($\sigma_{foE} = -21.26\%$). Subsequently, a prolonged period of underestimation occurs between
 260 08:00 and 14:00 LT, with relative deviations ranging from -10.49% to -13.33% . The best agreement
 261 between simulations and observations is observed in the early morning (07:00 LT) and in the late afternoon,
 262 between 16:00 and 18:00 LT (Figure 7).
 263 In autumn, the model behavior is generally comparable to that observed in summer. A pronounced
 264 underestimation occurs at 06:00 LT ($\sigma_{foE} = -28.31\%$). Further underestimations persist between 09:00 and
 265 14:00 LT, with σ_{foE} values ranging from -10.45% to -12.60% . Although an improvement is observed after
 266 15:00 LT, with deviations returning to the range of good agreement, a notable underestimation reappears at
 267 18:00 LT ($\sigma_{foE} = -14.71\%$) (Figure 7).



268
 269 **Figure 6: Seasonal variations of foE (NeQuick vs. Observations) during the solar cycle 22 minimum**
 270 **phase (1985)**

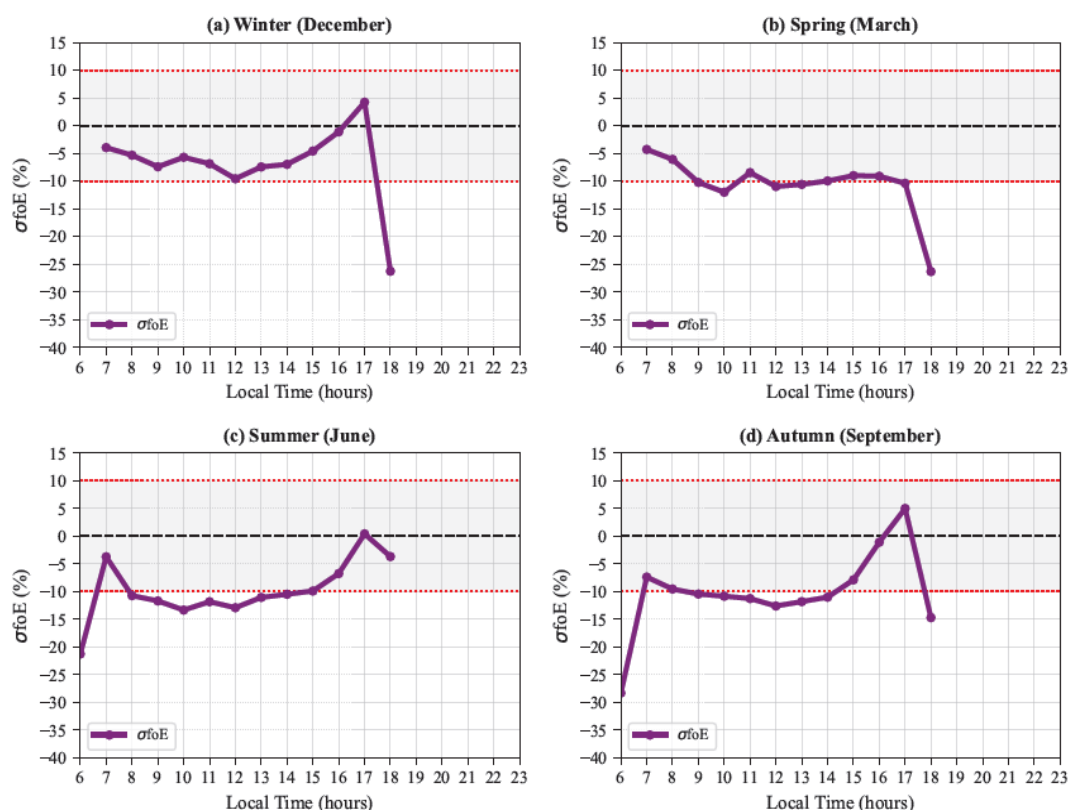


Figure 7: Mean seasonal relative errors during the solar cycle 22 minimum phase (1985)

3.2.2. Seasonal Comparative analysis of foE output by the NeQuick-2 model and Experimental data at the solar maximum phase (1990)

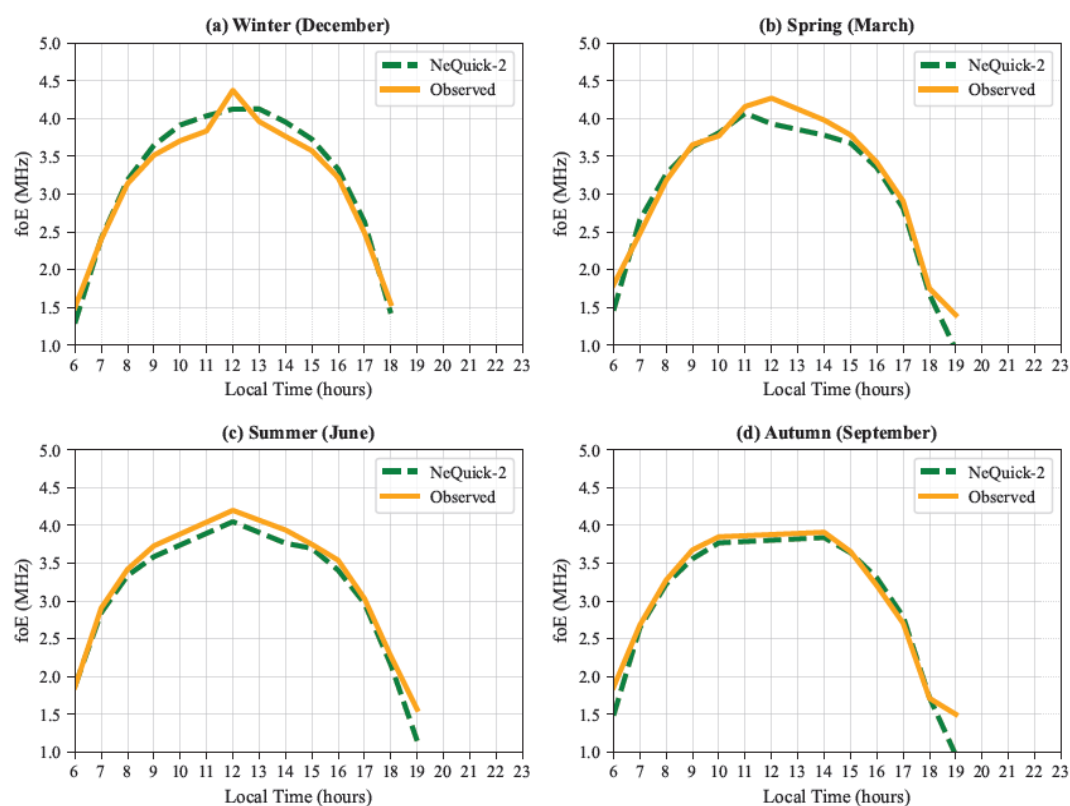
During the maximum phase of Solar Cycle 22, the NeQuick-2 model generally shows good agreement with the experimental observations, with some localized discrepancies depending on the season and time of day. In winter, the model agrees well with observations throughout the day, except at 06:00 LT, where it underestimates the experimental values by about 14% (Figure 9).

In spring, the NeQuick-2 model shows good agreement with the experimental values throughout the day, except during the early morning (06:00 LT) and twilight hours (18:00–19:00 LT), where it underestimates the observed values, with relative deviations reaching -18.88% at 06:00 LT and -32.85% at 19:00 LT (Figure 9).

The model predictions for the summer season are in excellent agreement with the observations throughout the day, except at 19:00 LT, where an underestimation is observed ($\sigma_{foE} = -26.47\%$) (Figure 9).

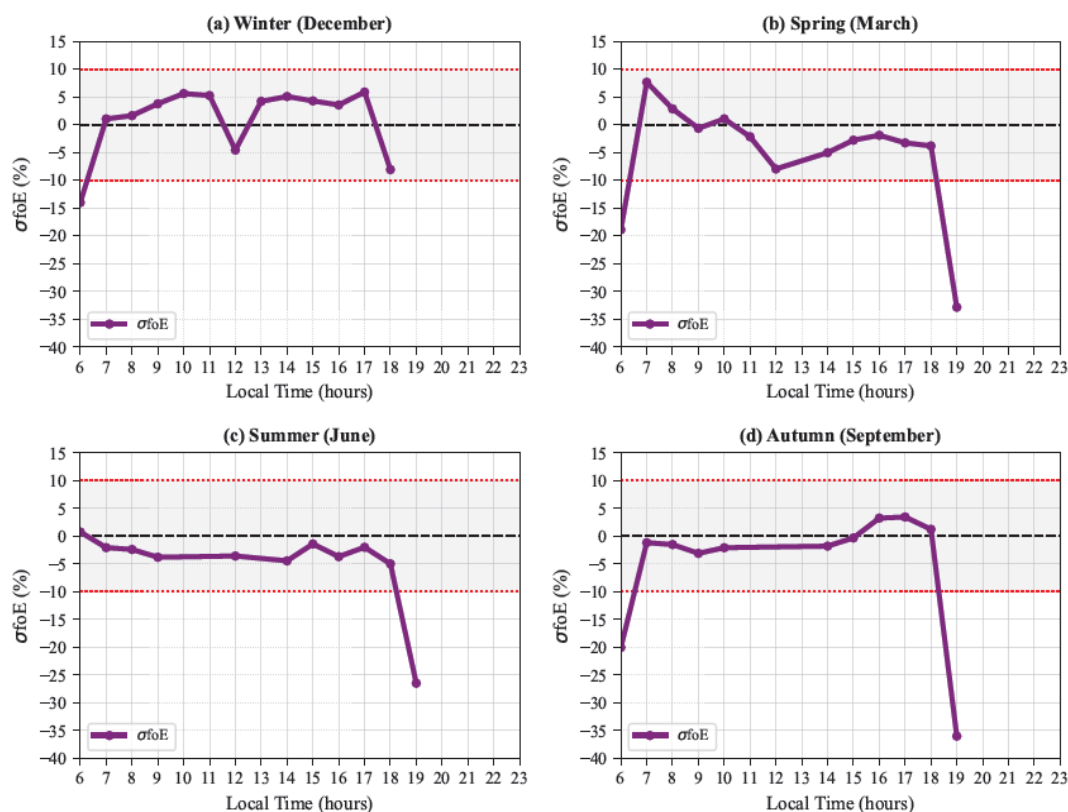


286 In autumn, the model behavior is similar to that observed in spring, with underestimations occurring in the
 287 early morning (06:00 LT) and twilight hours (19:00 LT). The relative deviations at these times are -20.04%
 288 and -36.00% , respectively (Figure 9).



289
 290 **Figure 8: Seasonal variations of foE (NeQuick vs Experimental data) during the solar cycle 22**
 291 **maximum phase (1990)**

292



293

294 **Figure 9: Mean seasonal relative errors during the solar maximum phase**

295 3.3. Seasonal and statistical evaluation of the NeQuick model for foE during the minimum and 296 maximum phases of solar activity

297 To evaluate the performance of the NeQuick-2 model in reproducing the foE parameter, a statistical analysis
 298 based on the root mean square error (RMSE) and the coefficient of determination (R^2) was performed. This
 299 analysis aims to identify the seasons in which the model best reproduces the observations, as well as those
 300 in which the discrepancies are greater. It also allows examination of the influence of solar activity on model
 301 performance by comparing the minimum and maximum phases of Solar Cycles 21 and 22.
 302 Figure 10 presents a seasonal evaluation of NeQuick-2 performance during the minimum (low solar activity)
 303 and maximum (high solar activity) phases of Solar Cycles 21 and 22. Panel (a) shows the
 304 seasonal distribution of RMSE, while panel (b) presents the variations in the coefficient of
 305 determination (R^2).



306 In winter, the model generally performs best for both solar cycles. During the minimum phase of SC21
307 (1976), the RMSE reaches its lowest value (0.14 MHz), while the coefficient of determination is high (0.91),
308 indicating both good agreement between the simulations and observations and a good reproduction of the
309 observed foE variability. At the maximum of the same cycle (1979), performance remains excellent, with
310 an RMSE of 0.15 MHz and an R^2 of 0.97. For SC22, the performance is slightly lower during the solar
311 minimum (1985), with an RMSE of 0.23 MHz and an R^2 of 0.87. Performance improves at solar maximum
312 (1990), with RMSE decreasing to 0.19 MHz and the coefficient of determination increasing to 0.94. These
313 results show that winter is a particularly favorable season for foE modeling during both low and high solar
314 activity.

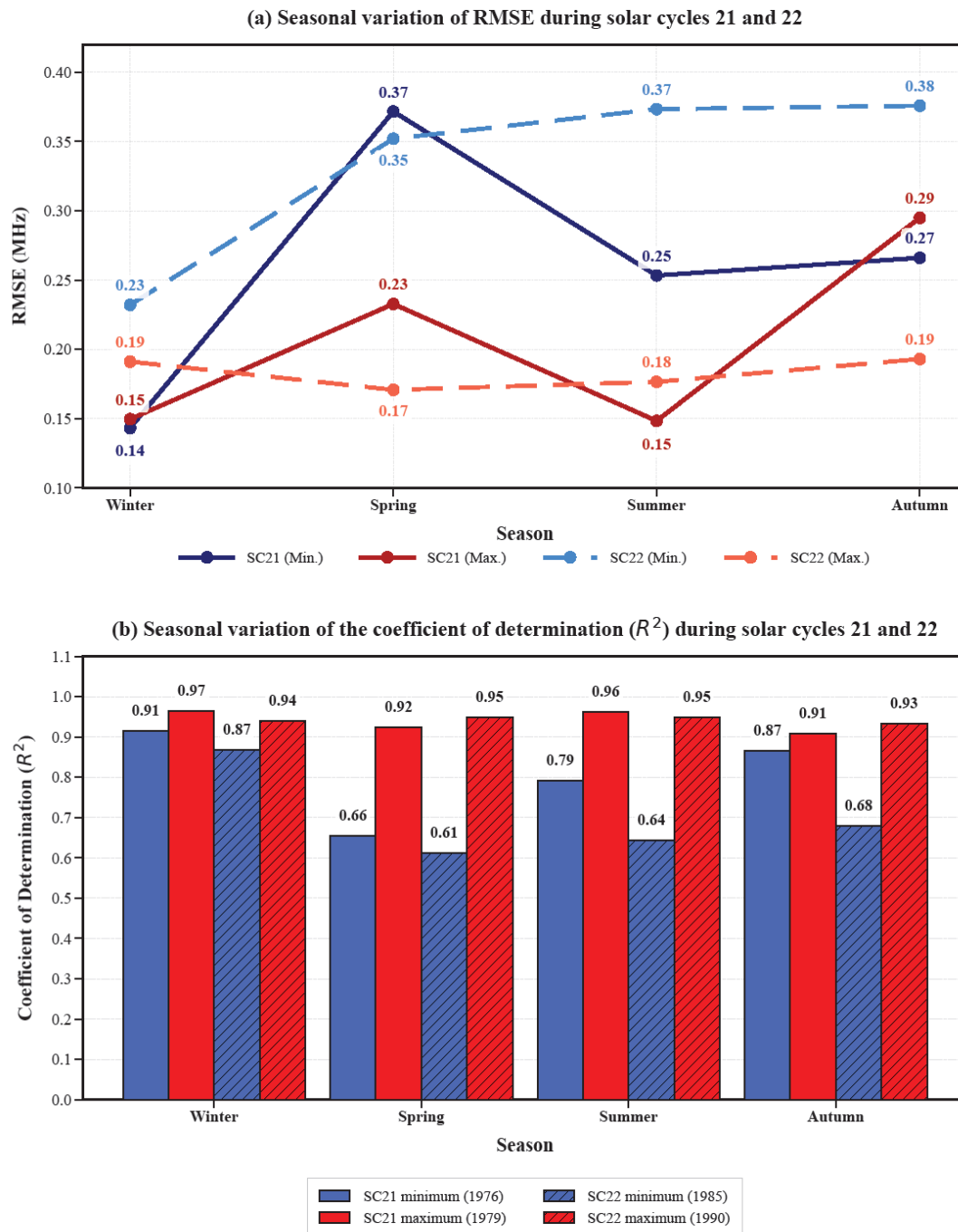
315 In spring, the model performs poorly, particularly during solar minimum phases. The RMSE values reach
316 0.37 MHz and 0.35 MHz for Solar Cycles 21 and 22, respectively, while the coefficients of determination
317 remain relatively low ($R^2 = 0.66$ and 0.61 , respectively). These results indicate substantial discrepancies
318 between the simulations and observations, as well as a limited ability of the model to reproduce the observed
319 foE variability. In contrast, a clear improvement is observed during the solar maximum phases. The RMSE
320 decreases to 0.23 MHz for SC21 and 0.17 MHz for SC22, while the coefficients of determination reach 0.92
321 and 0.95, respectively. The simultaneous decrease in RMSE and increase in R^2 indicate better agreement
322 between the simulations and observations, as well as a better reproduction of foE variability during periods
323 of high solar activity.

324 In summer, model performance also varies according to the solar phase and the cycle considered. During
325 the solar minima, the RMSE values reach 0.25 MHz for SC21 and 0.37 MHz for SC22, while the coefficients
326 of determination remain moderate ($R^2 = 0.79$ and $R^2 = 0.64$, respectively). These results indicate that the
327 model has difficulty reproducing both the observed values and their temporal evolution during these periods.
328 Performance improves markedly during the solar maxima. For SC21, the solar maximum shows one of the
329 best agreements among all the results, with an RMSE of 0.15 MHz and an R^2 of 0.96. Similarly, the SC22
330 maximum shows very good performance, with an RMSE of 0.18 MHz and an R^2 of 0.95. The decrease in
331 RMSE and increase in R^2 between the minimum and maximum phases indicate that the model better
332 reproduces both the foE values and their variability under high solar activity.

333 In autumn, model performance is more variable. During the solar minima, the RMSE values reach
334 0.27 MHz for SC21 and 0.38 MHz for SC22, while the coefficients of determination are 0.87 and
335 0.68, respectively. These values indicate that, despite a relatively good ability to reproduce foE variability
336 during the SC21 minimum, substantial discrepancies remain between the simulations and observations,
337 particularly during SC22. During the solar maxima, performance generally improves, particularly for SC22,
338 for which the RMSE decreases to 0.19 MHz and the R^2 reaches 0.93. For SC21, the coefficient of
339 determination also increases from 0.87 to 0.91, but the RMSE increases slightly, from 0.27 to 0.29 MHz.



340 This behavior indicates that the model better reproduces the temporal variability of foE at solar maximum
341 while retaining slightly larger amplitude differences between the simulations and observations.
342 Overall, the results show that the NeQuick-2 model performs better during periods of high solar activity
343 than during periods of low solar activity. This trend is particularly pronounced for SC22, especially in
344 spring, summer, and autumn, when model performance deteriorates substantially during periods of low solar
345 activity. Best performance is mainly observed in winter and summer during solar maxima, with RMSE
346 values ranging from 0.15 to 0.19 MHz and high coefficients of determination ranging from 0.94 to 0.97. In
347 contrast, the equinoctial seasons represent the periods when model performance is most limited, particularly
348 during solar minimum phases. In spring, the RMSE values reach 0.37 MHz and 0.35 MHz for SC21 and
349 SC22, respectively, with coefficients of determination of 0.66 and 0.61. In autumn, the RMSE values reach
350 0.27 MHz and 0.38 MHz for SC21 and SC22, respectively, with coefficients of determination of 0.87 and
351 0.68.
352 These results therefore show that the model generally reproduces both the foE values and their variability
353 more accurately during periods of high solar activity, with a particularly marked improvement during SC22.
354 Winter appears to be the most favorable season for foE modeling, with good performance during both the
355 solar minimum and maximum phases.
356 The RMSE and coefficient of determination (R^2) values obtained for the different seasons and phases of
357 SC21 and SC22 are presented in Table 1.



358

359 **Figure 10: Seasonal performance of the NeQuick-2 model for foE during Solar Cycles 21 and 22**



Table 1: Seasonal RMSE and coefficient of determination (R^2) values during the minimum and maximum phases of Solar Cycles 21 and 22.

Solar Cycles	Solar Phases	Winter		Spring		Summer		Autumn	
		RMSE (MHz)	R^2	RMSE (MHz)	R^2	RMSE (MHz)	R^2	RMSE (MHz)	R^2
SC21	Min (1976)	0.14	0.91	0.37	0.66	0.25	0.79	0.27	0.87
	Max (1979)	0.15	0.97	0.23	0.92	0.15	0.96	0.29	0.91
SC22	Min (1985)	0.23	0.87	0.35	0.61	0.37	0.64	0.38	0.64
	Max (1990)	0.19	0.94	0.17	0.95	0.18	0.95	0.19	0.93

4. Discussion

4.1. Analysis of the Seasonal Diurnal Variations of foE Simulated by the NeQuick-2 Model During Solar Cycles 21 and 22.

The analysis of diurnal variations in foE shows that NeQuick-2 generally reproduces the observed daily morphology across different phases of Solar Cycles 21 and 22. The simulated values generally follow the increase in foE after sunrise, reach a maximum around local noon, and then gradually decrease during the afternoon and toward the end of the day. This good reproduction of the diurnal trend is also reported by Mostafa et al. (2018), who found similar variations in observed and simulated foE, with a daytime maximum occurring near local noon. However, the differences between the simulations and observations vary with season, local time, and solar activity level.

During the solar minimum phases of both cycles, underestimations are observed mainly during daytime hours, particularly in spring, summer, and autumn, with more frequent and widespread discrepancies during SC22. A substantial proportion of these underestimations occurs around the daytime foE maximum, particularly between 08:00 and 16:00 LT. This behavior may be related to the predominantly photochemical nature of the E layer, whose electron density strongly depends on incoming solar radiation and solar zenith angle (Chapman, 1931; Titheridge, 1996). This interpretation is consistent with the results of Kazeem et al. (2026) at Ouagadougou, which show that the diurnal variation of NmE is primarily controlled by solar radiation and reaches a maximum around local noon. Under these conditions, rapid changes in ionization throughout the day may be difficult to represent using a climatological approach such as NeQuick-2, which could contribute to the underestimations observed around the daytime maximum. These results also indicate that periods of low solar activity may be more challenging for reproducing diurnal variations in foE, particularly during certain seasons.



385 In contrast to the solar minimum phases, during which daytime underestimations were relatively recurrent
386 in both cycles, the solar maximum phases show a more contrasting behavior between Solar Cycles 21 and
387 22. During the maximum of SC21, NeQuick-2 adequately reproduces the diurnal variations in foE in winter
388 and summer, but larger discrepancies appear in spring and autumn. These discrepancies occur mainly around
389 12:00–14:00 LT, when the observations show a pronounced foE peak that the model does not reproduce
390 accurately. Thus, during SC21, the quality of the NeQuick-2 reproduction of foE is more strongly dependent
391 on season, with a particularly noticeable degradation in performance during the equinoctial seasons.
392 This seasonal dependence observed during the maximum of SC21 is not found during the maximum of
393 SC22. During the latter phase, NeQuick-2 satisfactorily reproduces the diurnal variation of foE across all
394 seasons considered. The simulated values generally remain close to the experimental observations
395 throughout most of the day, with the most noticeable discrepancies mainly limited to the morning and dusk
396 hours. Thus, unlike the maximum of SC21, which is characterized by larger biases during the equinoctial
397 seasons, the maximum of SC22 is characterized by a more consistent reproduction of foE across seasons.
398 This difference between the two cycles suggests that an increase in solar activity does not necessarily lead
399 to a uniform improvement in NeQuick-2 performance from one solar cycle to another. The good agreement
400 obtained during the maximum of SC22 is nevertheless consistent with observations by Abe et al. (2013) at
401 Ouagadougou, which show that foE variability may exhibit more regular behavior during periods of high
402 solar activity. This regularity may better represent foE variations in empirical models. However, the
403 behavior observed during the maximum of SC21 shows that this relationship is not systematic, as significant
404 biases persist during the equinoctial seasons despite the high level of solar activity.
405 The differences observed between the two solar maxima may therefore reflect the E-layer response's
406 sensitivity to ionospheric conditions specific to each solar cycle and season. These results thus highlight
407 inter-cycle variability in NeQuick-2 performance that cannot be attributed solely to the level of solar activity
408 and underscore the importance of considering both solar cycle and season when evaluating the NeQuick-2
409 model for foE at Ouagadougou.

410 **4.2. General Discussion of the Discrepancies Observed During Morning and Dusk Transition** 411 **Periods**

412 A recurring finding of this study is the discrepancy between the foE values simulated by NeQuick-2 and the
413 experimental observations during the day-to-night transition periods, particularly around 06:00 LT and
414 18:00–19:00 LT. These discrepancies were observed in most seasons during both the minimum and
415 maximum phases of SC21 and SC22. This behavior is consistent with results reported by Gédéon et al.
416 (2025) in their evaluation of the IRI-2016 model over Ouagadougou. They showed that the largest
417 discrepancies between observations and model predictions occur at sunrise and sunset, whereas good



418 agreement is generally achieved between 07:00 and 17:00 LT. The consistency of these findings across two
419 different empirical models suggests that these discrepancies are not specific to NeQuick-2 but rather reflect
420 a more general limitation in representing the physical processes governing the ionospheric E layer during
421 diurnal transition periods. Indeed, at sunrise and sunset, the E-layer undergoes rapid changes in ion
422 production due to abrupt variations in the incoming solar radiation. Under these conditions, photochemical
423 production becomes highly dependent on the solar zenith angle and on the balance between ionization and
424 recombination processes, resulting in pronounced temporal gradients in electron density. Such rapid
425 transitions are inherently difficult to reproduce using climatological models such as NeQuick-2, which are
426 based on averaged representations of ionospheric conditions.

427 The summer season of SC21 also showed virtually no significant discrepancies during the morning and dusk
428 transition periods, unlike Solar SC22, where discrepancies were observed at 06:00 LT during the solar
429 minimum phase and at 19:00 LT during the solar maximum phase. This difference may reflect inter-cycle
430 variability in local ionization conditions or characteristics specific to the periods investigated, although
431 further analysis is required to clarify its underlying causes.

432 These results highlight persistent time-dependent biases in the NeQuick-2 model, whose magnitude varies
433 with season and solar cycle phase. The following section discusses the model's overall performance based
434 on the statistical indicators presented in the Results section.

435

436

437 **4.3. Statistical Evaluation of the Seasonal Performance of the NeQuick-2 Model During Solar** 438 **Cycles 21 and 22**

439 The statistical analysis shows that NeQuick-2 performance depends on both season and solar activity level.
440 However, a comparison of Solar Cycles 21 and 22 shows that the influence of these two factors is not
441 uniform and that their relative importance varies by season.

442 From a seasonal perspective, winter appears to be the most favorable period for the reproduction of foE by
443 NeQuick-2. This season exhibits relatively low errors and high coefficients of determination during both
444 the solar minimum and maximum phases of the two cycles. In summer, the best performance is mainly
445 observed during the solar maximum phases. In contrast, performance is generally more limited during the
446 equinoctial seasons, particularly during the solar minimum phases. This limitation is also observed during
447 the SC21 maximum, especially in autumn, when the RMSE remains relatively high. This pattern, observed
448 during both solar cycles, suggests it is not specific to a particular cycle but may instead relate to the increased
449 complexity of equatorial ionospheric conditions during the equinoxes. Okoh et al. (2018) reported similar
450 results, showing that, at low latitudes, discrepancies between ionospheric models (NeQuick and IRI-PLAS



2017) and observations are generally larger during the equinoxes than during the solstices. Although their study focused on VTEC, it indicates that empirical models generally struggle to reproduce equinoctial ionospheric conditions at low latitudes. Okoh et al. (2018) attributed this degradation to enhanced ionization during the equinoxes, particularly due to a decrease in the solar zenith angle. In the case of foE, this configuration may also increase variability in the E layer and consequently reduce model performance. These poorer performances during the equinoxes may also be associated with the particularly complex dynamics of the equatorial ionosphere during these periods. Indeed, the equinoctial seasons are characterized by enhanced equatorial electric fields, increased $E \times B$ vertical drifts, and stronger thermospheric wind effects, leading to greater ionospheric variability (Heelis & Maute, 2020; Kayode et al., 2026). Although these mechanisms are generally discussed in the context of TEC and the F region, they more broadly reflect stronger ionosphere–thermosphere coupling during the equinoxes, which may also affect the variability of the equatorial E layer. Under these conditions, an empirical climatological model such as NeQuick-2 may have difficulty reproducing all of the observed variations, which likely contributes to its reduced performance during the equinoxes.

The influence of solar activity is also clearly reflected in the results for both cycles. NeQuick-2 generally performs better during periods of high solar activity than during periods of low solar activity. This improvement is particularly pronounced during SC22, especially in spring, summer, and autumn. This trend is consistent with the results reported by Abe et al. (2013), who showed that the annual variation of foE in the equatorial ionosphere over Ouagadougou is more regular and stable during years of high solar activity than during years of low solar activity. A more stable ionosphere may better reproduce foE variations in empirical models such as NeQuick-2. This improvement may also be related to the fact that photochemical processes primarily govern the E layer. According to Chu et al. (2009), the electron density in this region is well described by Chapman theory Chapman, (1931) in which the peak electron density depends directly on the ionization production rate induced by solar radiation. During periods of high solar activity, increased EUV flux enhances ionization production, which may lead to a more regular mean structure of the E layer and, consequently, make it easier to represent using a climatological model. Recent work by Kazeem et al. (2026), conducted at Ouagadougou, also shows a strong dependence of NmE on the level of solar activity. Their results emphasize the dominant role of solar radiation in controlling E-layer ionization. Under these conditions, the mean characteristics of the E layer become more regular, which may favor better representation by a climatological model such as NeQuick-2.

However, the differences observed between the two cycles show that solar activity alone is not sufficient to explain model performance. During the solar minimum phases, NeQuick-2 generally performs worse during SC22 than during SC21, as indicated by systematically lower coefficients of determination and generally higher RMSE values during SC22. In contrast, during the solar maximum phases, the differences between



the two cycles are less systematic, with particularly marked improvement during SC22 in spring and autumn. This comparison suggests that variations in solar activity alone cannot fully explain the differences observed between the two cycles and that other geophysical or ionospheric conditions may also play a role.

5. Conclusion

This study evaluated the performance of the NeQuick-2 model in reproducing the diurnal and seasonal variability of foE under geomagnetically quiet conditions over the equatorial station of Ouagadougou during the solar minimum and solar maximum phases of Solar Cycles 21 and 22. The results show that NeQuick-2 successfully captures the general parabolic diurnal morphology of foE, characterized by a steady morning rise, a midday maximum near local noon, and a smooth afternoon decay. However, persistent discrepancies were observed at sunrise (transition between nighttime and daytime) and sunset (transition between daytime and nighttime) periods (around 06:00 LT and 18:00–19:00 LT) as well as during the equinoctial seasons. The similarity of these discrepancies to those reported for other empirical models, particularly IRI-2016, suggests that they are not peculiar to NeQuick-2 but rather reflect a broader limitation of climatological models in representing the rapid physical and photochemical processes governing the E-layer during sunrise and sunset transitions. The statistical analysis further shows that model performance depends strongly on both season and solar activity. The best performance was achieved during the winter and summer seasons, whereas the equinoctial seasons consistently represented the most challenging periods throughout Solar Cycles 21 and 22. The recurrence of these limitations indicates that the reduced performance observed during the equinoxes reflects a persistent difficulty for NeQuick-2 in representing ionospheric conditions in the African equatorial region due to strong equatorial electrodynamics, rather than behavior specific to a particular solar cycle.

The study also shows that model performance improves significantly during periods of high solar activity, with this effect being particularly pronounced during Solar Cycle 22, where the coefficients of determination (R^2) increased substantially from the solar minimum to the solar maximum phase ($R^2 > 0.93$), especially during spring, summer, and autumn. This finding confirms that NeQuick-2's ability to reproduce foE is closely linked to the level of solar activity and that inter-cycle variability in background ionospheric conditions plays a critical role.

Overall, this study confirms that NeQuick-2 is a valuable tool for foE modeling over the African equatorial region under geomagnetically quiet conditions, while also highlighting persistent limitations during the sunrise and sunset transition periods and the equinoctial seasons. These findings provide a useful benchmark for future developments of the NeQuick-2 model and emphasize the need to improve the representation of the photochemical and electrodynamic processes that govern the equatorial E-layer, thereby enhancing the



517 accuracy of simulations for space weather applications. Future developments should focus on the
 518 incorporation of geomagnetic and solar wind drivers to account for the influence of B on NmE variability.

519 **Data availability**

520 The experimental foE data used in this study were obtained from the Ouagadougou ionosonde archive
 521 available through the Groupe de recherche en Géophysique Europe-Afrique (GIRGEA) data platform
 522 (<https://www.girgea.org/recherches/logiciels/>). The geomagnetic aa index data were obtained from the
 523 International Service of Geomagnetic Indices (ISGI) data service (https://isgi.unistra.fr/data_download.php
 524). The annual Zürich sunspot number (Rz) data used to define the solar-cycle phases were taken from the
 525 historical sunspot-number series (version 1.0) maintained in the SILSO version archive
 526 (<https://sidc.be/SILSO/versionarchive>). The NeQuick-2 foE values used in this study were generated using
 527 the NeQuick-2 model and the foE extraction program described in the Methods section. The processed
 528 datasets generated and/or used in this study are available from the authors upon reasonable request.

529 **Author contribution**

530 Issiaka Kaboré : Conceptualization, Methodology, Investigation, Data curation, Formal analysis,
 531 Visualization, Writing – original draft.
 532 Doua Allain Gnabahou: Supervision, Methodology, Scientific interpretation, Writing – review and editing.
 533 Yenca Migoya-Orué: Software, Methodology, Technical support, Scientific interpretation, Statistical
 534 evaluation, Writing – review and editing.
 535 Oladipo Emmanuel Abe: Scientific interpretation, Data analysis, Discussion, Writing – review and editing.
 536 All authors discussed the results and approved the final version of the manuscript.

538 **Conflict of interest**

539 The authors declare no conflict of interest.

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546 **References**

547 Abe, O. E., Rabiou, A. B., & Adeniyi, J. O. (2013). Variability of fE in the equatorial ionosphere with solar
 548 activity. *Advances in Space Research*, 51(1), 69-75. <https://doi.org/10.1016/j.asr.2012.08.010>



- 549 Bilitza, D. (2001). International Reference Ionosphere 2000. *Radio Science*, 36(2), 261-275.
 550 <https://doi.org/10.1029/2000RS002432>
- 551 Bilitza, D., & Reinisch, B. W. (2008). International Reference Ionosphere 2007 : Improvements and new
 552 parameters. *Advances in Space Research*, 42(4), 599-609. <https://doi.org/10.1016/j.asr.2007.07.048>
- 553 Chapman, S. (1931). The absorption and dissociative or ionizing effect of monochromatic radiation in an
 554 atmosphere on a rotating earth. *Proceedings of the Physical Society*, 43(1), 26. [https://doi.org/10.1088/0959-](https://doi.org/10.1088/0959-5309/43/1/305)
 555 [5309/43/1/305](https://doi.org/10.1088/0959-5309/43/1/305)
- 556 Chu, Yen-Hsyang, Wu, Kong-Hong, Su, & Ching-Lun. (2009, décembre 22). A new aspect of ionospheric
 557 E region electron density morphology. *Journal of Geophysical Research*, 114, A12314.
 558 <https://doi.org/10.1029/2008JA014022>
- 559 Gédéon, S., Roger, N., & Yacouba, S. (2025). *Comparison of E-layer Critical Frequency over the*
 560 *Ouagadougou Station with IRI*.
- 561 Heelis, R. A., & Maute, A. (2020). Challenges to Understanding the Earth's Ionosphere and Thermosphere.
 562 *Journal of Geophysical Research: Space Physics*, 125(7), e2019JA027497.
 563 <https://doi.org/10.1029/2019JA027497>
- 564 Hochegger, G., Nava, B., Radicella, S., & Leitinger, R. (2000). A family of ionospheric models for different
 565 uses. *Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science*, 25(4), 307-310.
 566 [https://doi.org/10.1016/S1464-1917\(00\)00022-2](https://doi.org/10.1016/S1464-1917(00)00022-2)
- 567 Kashcheyev, A., & Nava, B. (2019). Validation of NeQuick 2 Model Topside Ionosphere and Plasmasphere
 568 Electron Content Using COSMIC POD TEC. *Journal of Geophysical Research: Space Physics*, 124(11),
 569 9525-9536. <https://doi.org/10.1029/2019JA026971>
- 570 Kayode, Y. O., Onori, E., Ometan, O., Okoh, D., Balogun, H. O., Alomaja, A. J., Fakunle, O. A., Hunge, P.
 571 M., Hundeyin, J. S., & Hunge, O. F. (2026). Modeling and forecasting of ionospheric total electron content
 572 using a radial basis function neural network over Lagos, Nigeria. *Geomatica*, 78(1), 100108.
 573 <https://doi.org/10.1016/j.geomat.2026.100108>
- 574 Kazeem, A. K., Rabiou, A. B., & Amory-Mazaudier, C. (2026). Solar-geomagnetic activity effect on NmE
 575 over Ouagadougou, an equatorial anomaly station in the African sector. *Journal of Atmospheric and Solar-*
 576 *Terrestrial Physics*, 280, 106756. <https://doi.org/10.1016/j.jastp.2026.106756>
- 577 Leitinger, R., Zhang, M. L., & Radicella, S. M. (2005). An improved bottomside for the ionospheric electron
 578 density model NeQuick. *Annals of Geophysics*, 48(3). <https://doi.org/10.4401/ag-3217>
- 579 Mayaud, P.-N. (1972). The aa indices: A 100-year series characterizing the magnetic activity. *Journal of*
 580 *Geophysical Research (1896-1977)*, 77(34), 6870-6874. <https://doi.org/10.1029/JA077i034p06870>



- 581 Mostafa, M. G., Haralambous, H., & Oikonomou, C. (2018). Statistical ionospheric E layer properties
582 measured with the Cyprus Digisonde and comparisons with IRI predictions. *Advances in Space Research*,
583 61(1), 337-347. <https://doi.org/10.1016/j.asr.2017.10.029>
- 584 Nanema, E., Gnabahou, D. A., Zoundi, C., & Ouattara, F. (2018). Modeling the Ionosphere during Quiet
585 Time Variation at Ouagadougou in West Africa. *International Journal of Astronomy and Astrophysics*,
586 08(02), 163-170. <https://doi.org/10.4236/ijaa.2018.82011>
- 587 Nava, B., Coisson, P., & Radicella, S. M. (2008). A new version of the NeQuick ionosphere electron density
588 model. *Journal of Atmospheric and Solar-Terrestrial Physics, Ionospheric Effects and Telecommunications*,
589 70(15), 1856-1862. <https://doi.org/10.1016/j.jastp.2008.01.015>
- 590 Obafaye, A. A., Okoh, D. I., Adewale, A. O., Udochukwu, B. C., & Rabiou, A. B. (2020). *Comparison of*
591 *IRI-01cor, IRI-Plas 2017, NeQuick-2 and NIGTEC models with GPS-TEC measurements over Nigeria.*
592 *Balkan, Black sea and Caspian sea Regional Network for Space Weather Studies.*
593 <https://doi.org/10.31401/SunGeo.2019.02.07>
- 594 Okoh, D., Onwuneme, S., Seemala, G., Jin, S., Rabiou, B., Nava, B., & Uwamahoro, J. (2018). Assessment
595 of the NeQuick-2 and IRI-Plas 2017 models using global and long-term GNSS measurements. *Journal of*
596 *Atmospheric and Solar-Terrestrial Physics*, 170, 1-10. <https://doi.org/10.1016/j.jastp.2018.02.006>
- 597 Osanyin, T. O., Candido, C. M. N., Becker-Guedes, F., Migoya-Orue, Y., Bosco Habarulema, J., Obafaye,
598 A. A., Chingarandi, F. S., & Moraes-Santos, S. P. (2023). Performance of a locally adapted NeQuick-2
599 model during high solar activity over the Brazilian equatorial and low-latitude region. *Advances in Space*
600 *Research*, 72(12), 5520-5538. <https://doi.org/10.1016/j.asr.2023.07.018>
- 601 Ouattara, F., & Amory-Mazaudier, C. (2012). Statistical study of the equatorial F2 layer critical frequency
602 at Ouagadougou during solar cycles 20, 21 and 22, using Legrand and Simon's classification of geomagnetic
603 activity. *Journal of Space Weather and Space Climate*, 2, A19. <https://doi.org/10.1051/swsc/2012019>
- 604 Radicella, S. M., & Zhang, M. L. (1995). The improved DGR analytical model of electron density height
605 profile and total electron content in the ionosphere. *Annals of Geophysics*, 38(1). [https://doi.org/10.4401/ag-](https://doi.org/10.4401/ag-4130)
606 4130
- 607 Titheridge, J. E. (1996). *Model results for the ionospheric E region : Solar and seasonal changes.*
- 608 Yao, J. N., Nava, B., Obrou, O. K., & Radicella, S. M. (2018). Validation of NeQuick 2 model over West
609 African equatorial region using GNSS-derived Total Electron Content data. *Journal of Atmospheric and*
610 *Solar-Terrestrial Physics*, 181, 1-9. <https://doi.org/10.1016/j.jastp.2018.10.001>
- 611 Zerbo, Ouattara, F., Zoundi, C., & Gyébré, A. (2011). Zerbo, J.L., Ouattara, F., Zoundi, C. and Gyébré, A.
612 (2011) Solar Cycle 21 and Geomagnetic Activity since 1868. *Revue CAMES Serie A*, 12, 255-262. -
613 *References—Scientific Research Publishing.*
614 <https://www.scirp.org/reference/referencespapers?referenceid=2600247>