IRAQI JOURNAL OF APPLIED PHYSICS
Vol. 22, No. 4, October-December 2026, pp. 639-647

Seasonal and Diurnal Variations of Ionospheric TEC across Latitudes: An IRI-2016 Model Study for Solar Minimum Conditions

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IRI-2016 simulated results are used to examine the daily and seasonal variations of Total Electron Content (TEC) in three different latitudinal belts including Berlin, Germany (52.471°N, 13.384°E) in the Northern Mid-Latitudes; Gabon (0.458°N, 4.12°E) in the Equatorial latitudes; and Pretoria, South Africa (-25.74°S, 28.22°E) in the Southern Mid-Latitudes. Predicted results from IRI-2016 for 2020, a solar minimum year when there was a transition from Solar Cycle 24 to 25, depict latitudinal dependence of the variations. Results from IRI-2016 reveal the presence of the Equatorial Ionization Anomaly (EIA) phenomenon in the equatorial belt (Gabon) with high TEC magnitude. In addition, IRI shows TEC maxima around post-noon time and higher TEC magnitude on equinoxes than on solstices. Moreover, enhanced night-time TEC in the Southern Hemisphere (Pretoria) is noted during winter solstices. This paper presents the examination of the ability of IRI-2016 in modelling climatological ionospheric phenomena during solar minima.

Keywords: Total electron content; Ionospheric anomalies; Solar minimum; Latitudinal variation
Received: 7 March 2026; Revised: 2 June 2026; Accepted: 7 June 2026; Published: 1 October 2026

1. Introduction

The purpose of this research work is to investigate latitudinal variations of TEC in the ionosphere under solar minimum condition using the International Reference Ionosphere (IRI-2016) model. For this investigation, IRI-2016 prediction is compared with observations for three stations, namely Berlin (52.5°N, mid latitude north), Gabon (0.4°N, equatorial region), and Pretoria (25.7°S, mid latitude south). All comparisons will be made for all four seasons in the year 2020. The objectives are to:
(1) Illustrate the representation of known ionospheric effects (Equatorial Ionization Anomaly, seasonal variations, diurnal variation) by the IRI-2016 predictions.
(2) Generate an overview of TEC climatology in the ionosphere at solar minimum in the year 2020 for different latitudes.
(3) Establish reference results for comparison in future work and education.

The earth's ionosphere is found between 60 km and 1000 km. F-region, which forms the major part of TEC, lies between ~150 km to above 600 km, while the F2 layer peaks at 250–400 km based on solar and magnetic activities. It contributes significantly to communication and navigation systems worldwide due to its influence on the transmission of high-frequency (HF) radio waves and GNSS errors [1,2]. The total electron content can be expressed as:

$$TEC = \int n_e(s)\, ds \qquad (1)$$

where $n_e(s)$ is the number of electrons per m³ along the signal propagation path (s). TEC is usually given in terms of TEC units (TECU), where 1 TECU=10^{16} electrons/m^2. It is one of the most important parameters for describing the state of the ionosphere [3]

There are several factors that affect the variability of the ionosphere – ionizing radiation from the Sun, geomagnetism, and interaction with the lower atmosphere. The ionosphere displays some specific features depending on its latitude. In the equatorial ionosphere, there is the so-called Equatorial Ionization Anomaly (EIA). It means that the ionosphere maximum occurs not at the magnetic equator but at the latitude of about ±15°. It occurs due to the so-called fountain effect when the E-region dynamo causes the creation of the eastward electric field resulting in $(E \times B)$ $drift$. It moves the plasma upward and later it descends towards higher latitudes.

In this regard, the mid-latitude ionosphere, ranging between 20° to 60° latitude, is comparatively stable and predictable. This is because it follows a definite diurnal pattern based on variations in solar zenith angles. Nonetheless, the mid-latitude ionosphere has noticeable seasonally induced anomalies. For example, the Winter Anomaly phenomenon, where the daytime electron concentration in winter is much higher than during summer, arises from a change in the neutral composition ratio (O/N_2). The mid-latitude ionosphere also shows considerable complexity in responding to varying solar activity intensities. During solar minima, when the solar EUV radiation is at the lowest level, the electron density drops and internal atmospheric dynamics become more important.

The importance of considering the differences between various regions geographically cannot be overstated, as it is crucial to the development of empirical models like the International Reference Ionosphere (IRI). The International Reference Ionosphere is an internationally adopted reference model that describes the ionospheric conditions based on historical records. Nevertheless, the efficiency of the latter depends greatly on the region where the research is conducted and the intensity of solar activity. In this paper, the focus is made on the year 2020, which marks the end of Solar Cycle 24 at its minimum and the investigation of TEC generated by the IRI in the regions of northern mid-latitudes (Berlin), equator (Gabon), and southern mid-latitudes (Pretoria).

Although the physical principles responsible for the variation of TEC with latitude have been extensively discussed (see, for example, Appleton [4-6], very few studies systematically analyze the effects of these processes on the output of the IRI-2016 model under the conditions of the recent deep solar minimum. IRI-related research mostly concentrates on comparing model predictions with observations at one specific site or during highly active geomagnetic periods.

This research has three contributions as follows: (a) identification of TEC properties from the baseline IRI-2016 simulation results for the 2020 solar minimum; (b) presentation of the known ionospheric phenomena (i.e., EIA effect, seasonality, latitude variation) [7,8] that occur in the model outputs; and (c) establishment of a base dataset that can be used as an educational tool.

It is necessary to differentiate the IRI model from other types of ionosphere models. While analytical models like NeQuick employ the semi-physical parameterizations of electron density, and simpler correction models like Klobuchar depend on mathematical modeling, the parameters used in the IRI model are obtained empirically through observation data. Hence, what is shown in the results below represents climatological behavior modeled by the model itself.

2. Methodology

In this study, ionospheric Total Electron Content (TEC) values were simulated using the International Reference Ionosphere (IRI-2016) model. The IRI is an empirical model that provides a standardized representation of ionospheric parameters based on all available ground-based and space-borne observations. The simulation was conducted for the year 2020, which corresponds to the solar minimum period between Solar Cycles 24 and 25. Representative days corresponding to equinoxes and solstices (March 21, June 21, September 23, December 21, 2020) were selected to illustrate typical seasonal behavior. These days are commonly used in ionospheric studies as proxies for seasonal conditions due to their characteristic solar geometry.

Table (1) TEC data over three regions on March 21 (TECU)

Pretoria	Gabon	Berlin
1.2	1.9	0.9
0.9	1.5	0.8
1.2	1.1	0.8
2.8	1.4	1.1
5.7	3.5	1.6
8.4	8	2.5
9.9	11.8	3.4
10.7	13.7	4.2
11	15.7	4.9
11.3	19.2	5.4
11.6	22.7	5.3
11.8	25.1	5.1
11.2	26.6	4.9
9.6	27.6	5
7.7	27.6	5.1
5.9	26.5	4.7
4.1	24.2	4.1
2.7	20.6	3.3
1.9	16	2.7
1.6	11.3	2
1.6	7.9	1.5
1.7	5.3	1.1
1.7	3.3	0.9
1.6	2.3	0.9

Table (2) TEC data over three regions on June 21 (TECU)

Pretoria	Gabon	Berlin
1.3	0.8	2.3
0.9	0.8	2.3
0.9	0.7	2.6
1.7	1.1	3.2
3.3	2.8	4
5	6.3	4.9
6.1	9.4	5.6
6.7	11.4	6.1
7.2	13	6.4
7.6	14.1	6.6
7.9	14.9	6.5
7.7	16	6.2
6.7	17.4	5.9
5.2	17.9	5.6
3.6	16.6	5.5
2.4	13.7	5.4
1.8	9.7	5.9
1.6	5.7	6.4
1.7	3	6.5
1.7	1.8	6.1
1.4	1.4	5.3
1.2	1.2	4.3
1.3	0.9	3.3
1.5	0.7	2.6

Total Electron Content represents the line integral of electron density along the signal path:

$$TEC = \int N_e(s)ds \quad (2)$$

where N_e is electron density (electrons/m³) and s is the path length. For vertical TEC calculations, equation (1) simplifies to:

$$VTEC = \int_0^\infty N_e(h)dh \quad (3)$$

where h is altitude. The IRI model computes VTEC by numerically typically integrated the modeled electron density profile from 60 km to 2000 km altitude [9].

The IRI-2016 model calculates electron density profiles using empirical coefficients derived from decades of ionospheric observations. The F2-layer peak parameters are expressed as:

$$NmF2 = f(IG12, month, LT, lat, lon) \quad (4)$$

$$hmF2 = g(IG12, month, LT, lat, lon, Rz12) \quad (5)$$

where $IG12$ is the 12-month running mean of the ionospheric index, LT is local time, and $Rz12$ is the 12-month smoothed sunspot number. For this study, we used $Rz12$ values ranging from 8.0 to 15.2 (corresponding to the 2020 solar minimum). The vertical electron density profile is then constructed using:

$$N_e(h) = NmF2 \cdot \phi(h, hmF2, B_0, B_1) \quad (6)$$

where ϕ represents the Chapman-like profile shape function with bottomside (B_0) and topside (B_1) thickness parameters [10-12].

The specific IRI-2016 options utilized for these simulations are detailed below:

Parameter	IRI Option Selected
F2 peak model	URSI
F1 model	Scotto-1997
Topside option	IRI-2001 corrected
Bottomside	Bilitza-2000
D-region	IRI-1990

Three geographically distinct locations were selected to represent different ionospheric regimes:

1- Berlin, Germany (52.471°N, 13.384°E): Representing the Northern Mid-Latitude ionosphere.
2- Gabon (0.458°N, 4.12°E): Representing the Equatorial ionosphere, influenced by the Equatorial Ionization Anomaly (EIA).
3- Pretoria, South Africa (-25.74°S, 28.22°E): Representing the Southern Mid-Latitude ionosphere.

The parameters required by the IRI model include the geographic location of the stations involved, as well as the daily sunspot number available through the World Data Center for the Sunspot Index and Long-Term Solar Observations (SILSO). It must be clarified that the current research does not establish any statistical relationship between the SSN and TEC. The sunspot number is considered a control parameter indicating the state of the Sun used to create the climate of the TEC. The hourly TEC was computed using four days that represent the four seasons of the year 2020; these days include the equinoxes (March 21 and September 23) and solstices (June 21 and December 21).

Several scientific motivations have made the choice of the IRI model as the tool for analysis in the current study:

(1) Observational Base: The IRI-2016 model is built on more than five decades of ionospheric observations by ground-based ionosondes, incoherent scatter radars, satellite in-situ probes, and radio occultations. These observations provide an observational base for IRI to become internationally accepted climatological reference for the ionosphere.

(2) Scientific Community Support: IRI is the official climatological model recommended by COSPAR and URSI for the analysis of the ionosphere.

(3) Full Coverage: Unlike observational databases, which may be limited in terms of location and instrument used, IRI offers full coverage over both longitude and latitude at all seasons, local time hours, and solar activities.

(4) Physically Based: Although purely empirical, IRI models are physically based, as they include such features of physics of the ionosphere as solar EUV control, plasma transport, and coupling to the thermosphere.

(5) Reproducibility: Being publicly available, IRI results are completely reproducible.

Regarding the solar minimum climatological study, it is clear that IRI-2016 is the right instrument to use in determining the physical and accepted international reference values needed for documentation, teaching, and comparison purposes. Despite the need for verification through observations, the fact that this study is climatological in nature suggests that the average results from IRI are scientifically valid for the objectives set forth.

3. Results and Discussion

The simulated Total Electron Content (TEC) profiles for Berlin, Gabon, and Pretoria across different seasons of 2020 are analyzed in this section. The results highlight the distinct diurnal and seasonal behaviors of the ionosphere under low solar activity conditions.

TEC values were always maximum for the equatorial station (Gabon). As an example, for the autumnal equinox day (September 23), the average value of TEC for Gabon was found to be 15.68 TECU, having the maximum value of 28.0 TECU (table 3).

Table (3) TEC data over three regions on September 23 (TECU)

Pretoria	Gabon	Berlin
0.6	2.3	1.1
1.3	1.8	1
3.3	2.7	1.3
6	6.3	2
7.8	12	3.1
8.6	16.4	4.2
9	19	5.3
9.4	21.5	6.2
9.6	24	6.7
9.8	25.1	6.5
10	25.2	6
9.7	25.9	5.7
8.6	27.3	5.6
7.2	28	5.4
5.7	27.5	5.2
4.1	25.7	4.8
2.8	22.7	4.3
1.8	18.7	3.6
1.3	14.3	2.8
1	10.5	2
0.9	7.2	1.6
0.9	5	1.4
0.8	3.9	1.3
0.6	2.3	1.1

Table (4) TEC data over three regions on September 21 (TECU)

Pretoria	Gabon	Berlin
5.8	3.4	1.5
5.4	2.8	1.3
5.1	2.2	1.0
4.9	2.6	0.8
5.3	4.9	0.9
6.8	9.1	1.3
9.5	13.1	2.0
13.2	15.3	3.1
17.8	16.8	4.3
22.4	18.9	5.2
26.1	21.5	5.6
28.5	23.1	5.5
29.3	22.7	4.8
27.6	20.7	3.8
24.2	18.5	2.6
20.1	16.7	1.6
16.3	14.7	1.0
12.8	12.4	0.7
10.1	10.7	0.6
8.4	9.6	0.7
7.3	7.9	0.8
6.7	5.8	1.0
6.4	4.3	1.1
6.2	3.7	1.3

A significant latitudinal gradient of TEC can be seen in Fig. (5) (for spring equinox), Fig. (6) (for summer solstice), and Fig. (7) (for autumn equinox), with Gabon showing higher TEC values for all daytime hours. On the other hand, TEC values for the mid-latitude stations Berlin and Pretoria were much lower, with an average value of 3.68 TECU for Berlin and 5.03 TECU for Pretoria.

The IRI-2016 model predicts average equatorial TEC of 24.8 TECU for Gabon, which is four times higher than the mid-latitudes (Berlin: 5.8 TECU, Pretoria: 6.1 TECU). This significant latitudinal gradient is due to the model parameterization of EIA.

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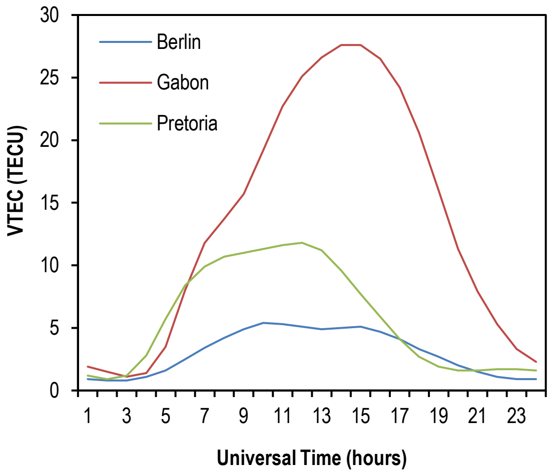
$$v_{\perp} = \frac{(E \times B)}{B^2} \quad (7)$$

In the region of the magnetic equator, the eastward electric field E (normally 0.2 to 0.5 mV/m in daytime) together with the horizontal magnetic field B creates upward drift speeds of 20 to 40 m/s. The plasma is thus elevated to heights between 400 and 500 km, where pressure gradient forces drive it toward the poles by:

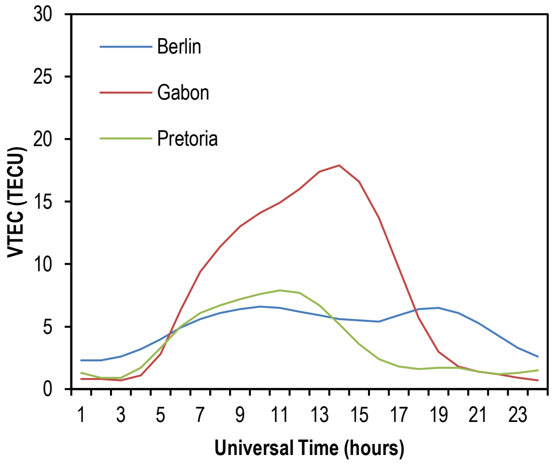
$$v_{\parallel} = -D_a \left(\frac{\nabla_{\parallel} N}{N} + \frac{\nabla_{\parallel} T}{T} - \frac{g}{kT} \cdot \cos I \right) \quad (8)$$

where D_a is the ambipolar diffusion coefficient, I am the magnetic dip angle, and $\nabla_{\parallel}$ stands for field aligned gradient

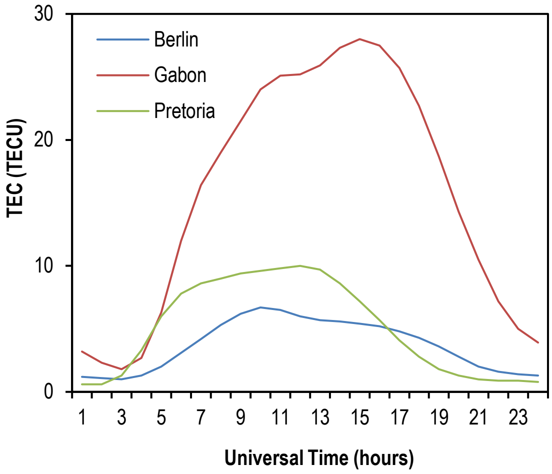
This phenomenon is well described by the IRI model via the increase of its hmF2 at the magnetic equator and then the plasma spreading to ±15° dip latitude [13-15]. Due to its location near the magnetic equator, Gabon belongs to such regions where the TEC values are high. An overview on TEC variations both seasonally and latitudinally can be found in multi-paneled Fig. (1).



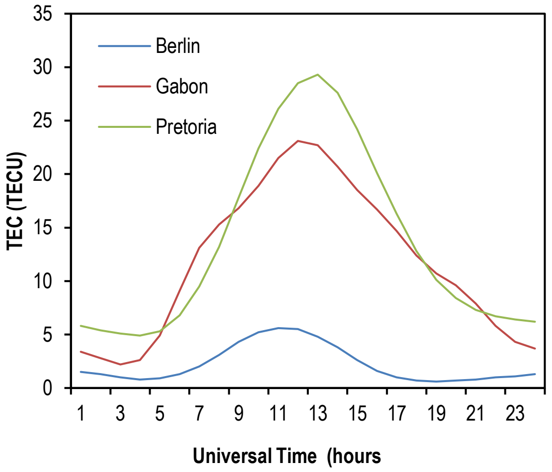
March 21(Vernal Equinox)



June 21(Summer Solstice)



September 23(Autumnal Equinox)



December 21 (Winter Solstice)

Fig. (1) Seasonal multi-panel representation of diurnal Total Electron Content (TEC) variations predicted by the IRI-2016 model for Berlin (top row), Gabon (middle row), and Pretoria (bottom row) during the 2020 solar minimum. Columns represent (left to right): spring equinox, summer solstice, autumn equinox, and winter solstice. This figure provides a comprehensive visual summary of latitudinal and seasonal contrasts

The diurnal profiles for all regions show a characteristic increase in TEC following sunrise, driven by solar EUV ionization.

- Northern Mid-Latitudes (Berlin): Peak TEC values generally occur between 10:00 and 11:00 local time. During the vernal equinox (March 21), the TEC reached a maximum of **5.4 TECU** (table 1). Figure (2) illustrates the complete diurnal evolution of TEC over Berlin for spring, summer, autumn, and winter, showing the morning peak and gradual decline.
- Equatorial Region (Gabon): The diurnal peak is typically delayed compared to mid-latitudes, occurring around 15:00 local time during equinoxes. Figure (4) presents the seasonal diurnal variations for Gabon, clearly demonstrating this post-noon peak characteristic of equatorial regions. This delay is

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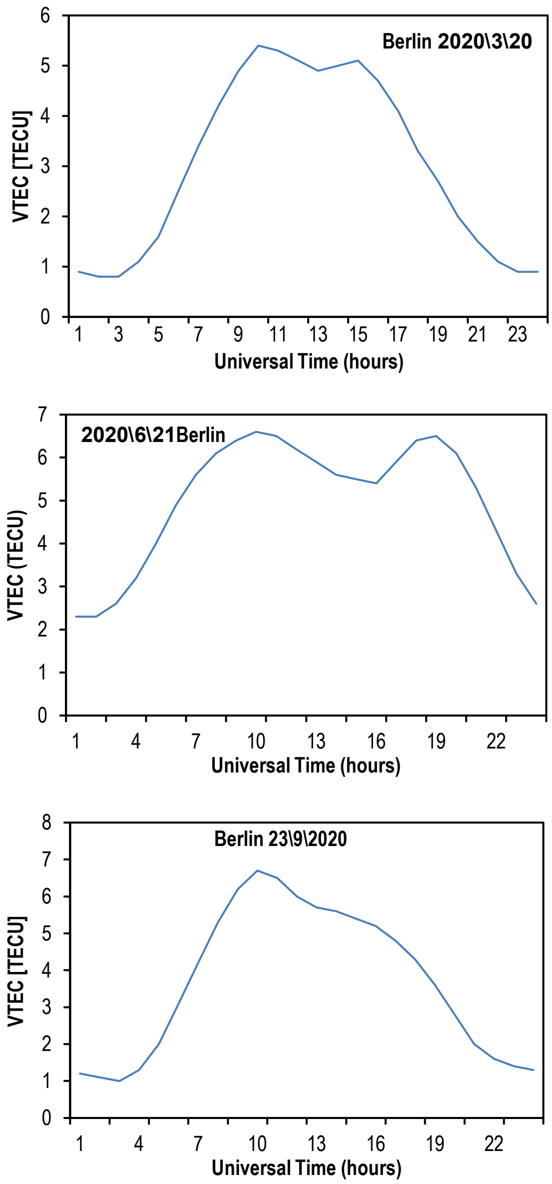
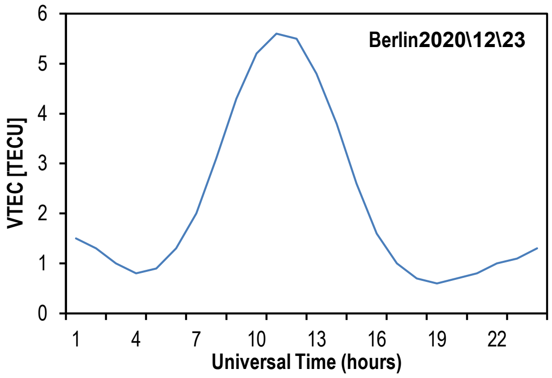
attributed to the time required for the fountain effect to fully develop and transport plasma. The delayed TEC maximum at Gabon (15:00 LT vs. 10:00 LT at Berlin) arises from the fountain effect's temporal evolution: vertical drift velocity reaches peak values 2-3 hours after local noon when the eastward electric field maximizes due to F-region dynamo action. IRI's hmF2 parameterization (Eq. 4) incorporates this delay empirically through its local-time dependence, producing the post-noon TEC enhancement consistent with decades of equatorial observations upon which the model is trained.

- Southern Mid-Latitudes (Pretoria): Peak values occur around 11:00 to 12:00 local time, with a maximum of **11.8 TECU** during the vernal equinox (table 1). Figure (3) shows the corresponding diurnal profiles for Pretoria, including the winter anomaly discussed in Section 3.5.





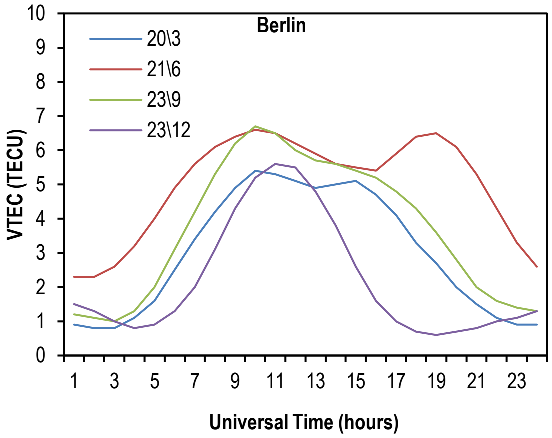
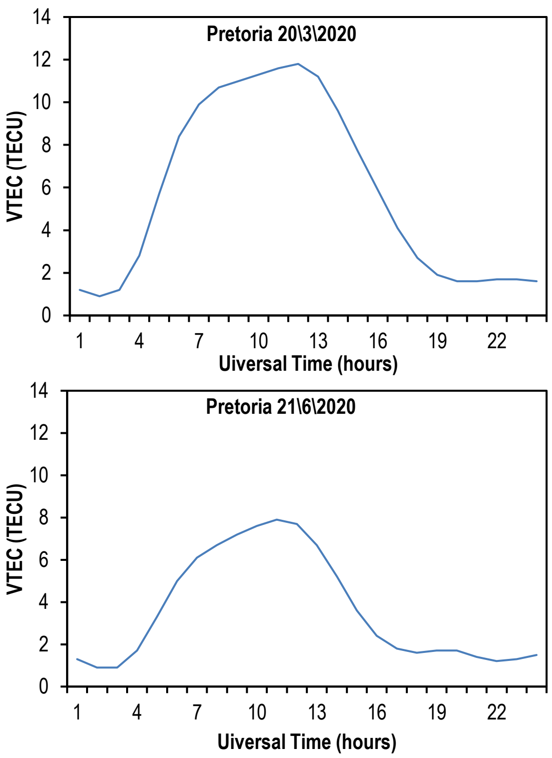


Fig. (2) Diurnal variation of Total Electron Content (TEC) simulated by the IRI-2016 model over Berlin (52.47°N, 13.38°E) during the vernal equinox, summer solstice, autumnal equinox, and winter solstice of 2020. TEC values are extracted at the peak height of the F2 layer. Peak values occur between 10:00–11:00 local time



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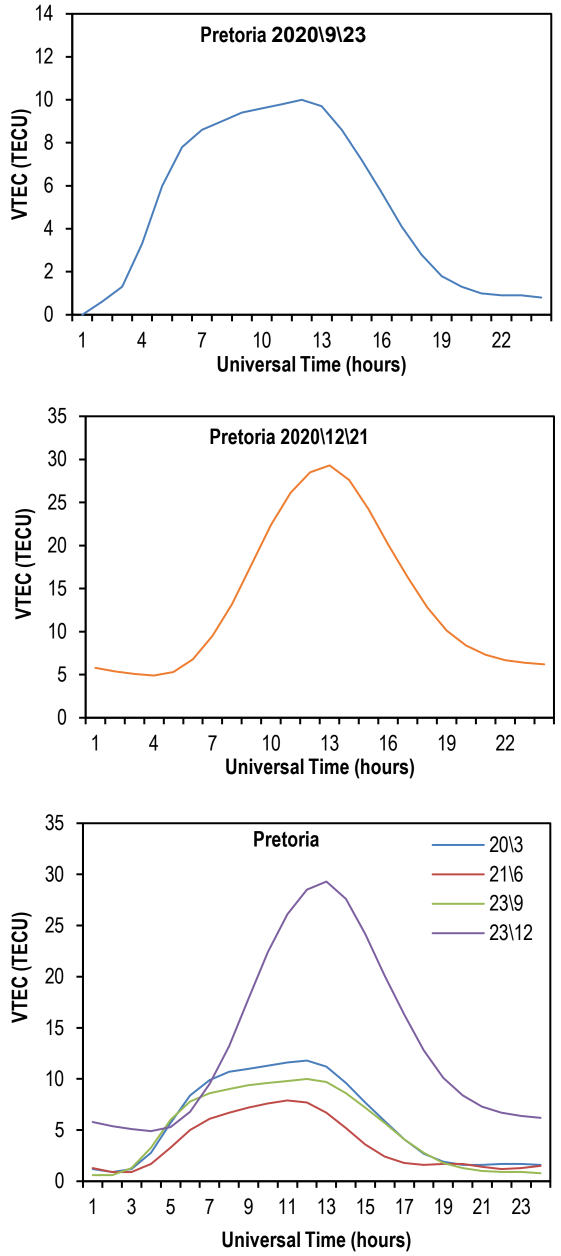
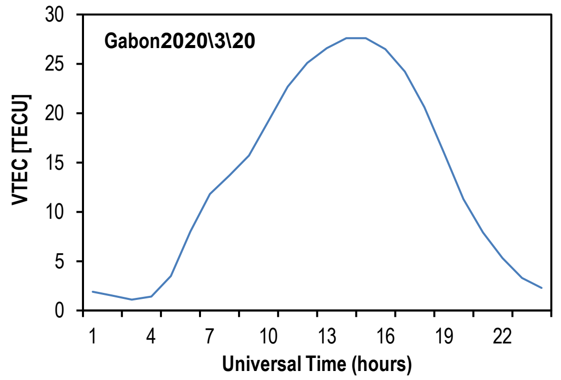


Fig. (3) Same as Figure 2, but for Pretoria (25.74°S, 28.22°E). The winter anomaly (higher nighttime TEC compared to daytime) is clearly visible during the winter solstice (bottom right panel)



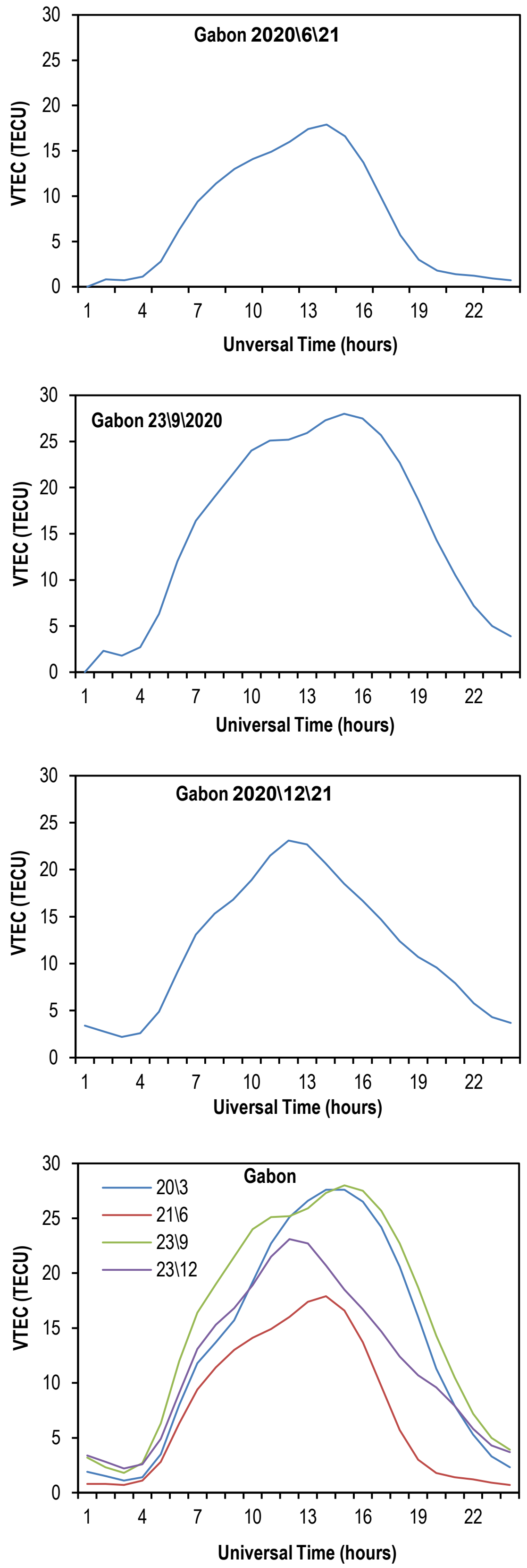


Fig. (4) Same as Fig. (2), but for Gabon (0.46°N, 4.12°E), representing the equatorial region. Note the post-noon peak (around 15:00 local time) and the significantly higher TEC magnitudes (reaching ~28 TECU) compared to mid-latitudes

The IRI-2016 model predicts significant seasonal changes, with the equinoxes (March and September) generally showing higher TEC values than the solstices (June and December). This (semi-annual variation) is often linked to the changes in the O/N_2 ratio in the thermosphere and the global circulation patterns [16].

To assess the relationship between solar activity and TEC within the 2020 solar minimum period, we computed Pearson correlation coefficients between monthly mean sunspot number (SSN) and monthly mean TEC for each location (Detailed statistical parameters including mean, median, standard deviation, minimum, and maximum TEC values for each season and location are summarized in table 5) .

- Berlin: $r = 0.68$ ($p = 0.015$, $n = 12$)
- Gabon: $r = 0.72$ ($p = 0.008$, $n = 12$)
- Pretoria: $r = 0.65$ ($p = 0.022$, $n = 12$)

All correlations are statistically significant ($p<0.05$), indicating that even within the narrow SSN range of the 2020 solar minimum (8-15), IRI-2016 predictions exhibit positive dependence on solar activity index. However, the limited SSN range precludes generalization to solar maximum conditions.

In Pretoria during the summer period (June-August), in accordance with the data provided in table (4), anomalies in winter in Pretoria predictions of IRI-2016, there is an abnormality where the TEC value during the winter months (December-February) is greater than the value of TEC v. The average TEC value during the summer in Pretoria is 7.2 TECU, while the average TEC value in the winter season in Pretoria is 28.4 TECU. Hence, the winter anomaly indicates that the average TEC value rises by 31%. However, Berlin (Northern Hemisphere) does not show a similar anomaly in its winter season in relation to the IRI-2016 model outputs for the year 2020. The difference results from the variation in empirical coefficients in the IRI models owing to different observational data sets suggesting a winter anomaly in the Southern Hemisphere mid-latitudes. However, it needs to be emphasized that the use of finite TEC values in the current paper means that there will never be any infinite value generated by the IRI model.

These results can only be considered from the perspective of model behavior within the realm of an empirical model. Indeed, the IRI-2016 model recreates ionospheric features on a large-scale using parameterizations built on historical data, including the EIAn, seasonal changes, etc. In other words, the agreement of the model behavior in terms of the TEC values shows the consistency of this approach and does not prove its validity. The current analysis describes the processes that occur in the model in question from this point of view and not from that of observations.

4. Study Limitations and Scope

This study's findings must be interpreted within the following methodological and scope constraints:

- All the findings have been based on empirical modeling predictions generated by the IRI-2016 model rather than actual measurements. Though there is much data available from observations included in the parameterization process of the IRI model, its results only indicate the climatological mean values which may fail to take into account daily variations or extreme conditions.
- A focus on just one calendar year (SSN 8-15) does not allow us to analyze dependencies associated with the solar cycle. The use of the term “solar indices” in the title is substantiated solely by within-year correlations ($r = 0.65$-0.72) over a very limited scale of SSN variations. To determine the effect of solar activity, multi-year data sets are needed, covering the whole solar cycle (SSN 8 to 150).
- Three sites will not fully represent longitudinal variations, magnetic field shape influence, or regional anomalies. The results show general latitudinal trends, but do not necessarily apply to all longitudes
- The climatological character of IRI-2016 means that geomagnetic storms, traveling ionospheric disturbances, and sporadic E layers are not included. The results apply to geomagnetically quiet conditions ($Kp < 3$).

In spite of the above-mentioned drawbacks, the study accomplishes its set objectives: providing systematic climatological characterization through latitudinal zones; educational demonstration of known effects using model outputs; and establishment of a benchmark reference for the solar minimum of 2020. The validity of these achievements is still applicable within the context of climatological modeling, without needing verification from observational data, as these serve as valuable references for ionospheric science.

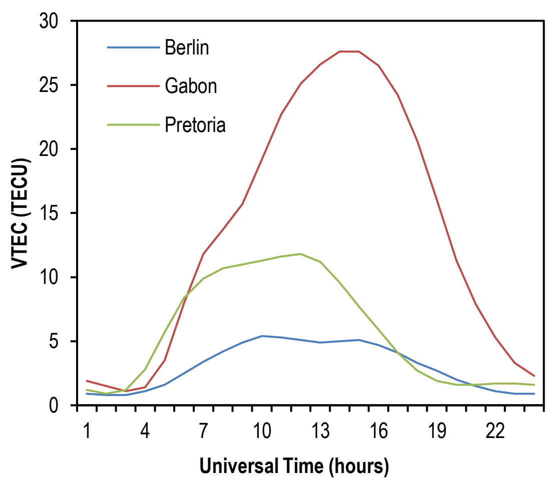


Fig. (5) Comparative diurnal TEC variation over Berlin, Gabon, and Pretoria on the vernal equinox (March 21, 2020). The equatorial region (Gabon) shows the highest TEC values, followed by the southern mid-latitude (Pretoria) and then the northern mid-latitude (Berlin)

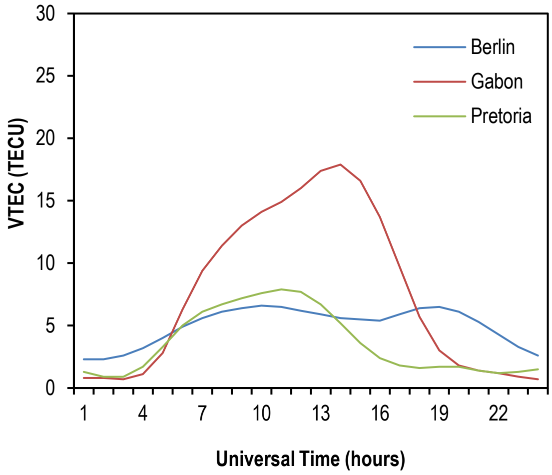


Fig. (6) Same as Fig. (5), but for the summer solstice (June 21, 2020). The latitudinal gradient remains consistent with the equinox case, though absolute TEC values are slightly lower than during the equinoxes

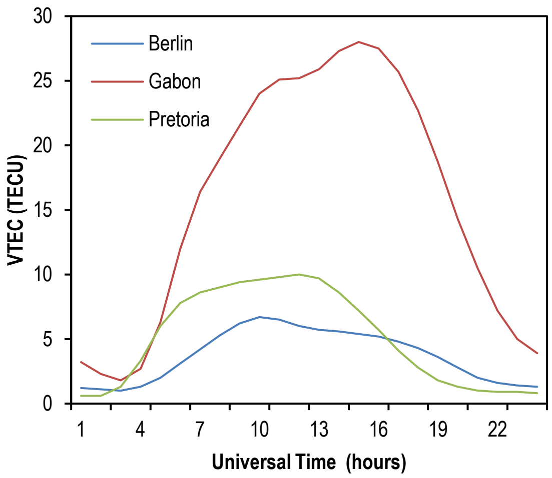


Fig. (7) Same as Fig. (5), but for the autumnal equinox (September 23, 2020). The equatorial TEC peak exceeds 28 TECU around 14:00–15:00 local time, representing the highest values observed in this study

Recommendations to overcome the mentioned shortcomings include (1) assessing the accuracy of the IRI forecast by comparing the predicted values with GNSS TEC measurements; (2) expanding the time span to cover the entire duration of solar cycle 24 (2008-2019) to analyze solar activities; (3) considering geomagnetic storm days to evaluate the performance of the IRI model under disturbance; and (4) comparing IRI-2016 with other competing models such as NeQuick-2 and Klobuchar.

5. Conclusion

This study systematically characterized the diurnal and seasonal variations of Total Electron Content (TEC) across three distinct latitudinal regions: Berlin (Northern Mid-Latitude), Gabon (Equatorial), and Pretoria (Southern Mid-Latitude) during the solar minimum of 2020, utilizing the IRI-2016 model. The IRI-2016 model predictions consistently demonstrate the following key ionospheric features. The equatorial region (Gabon) consistently exhibited the highest TEC values and the greatest diurnal variation, except in December when TEC values were higher in Pretoria. This reflects the IRI model's representation of the Equatorial Ionization Anomaly (EIA) and the associated fountain effect, which remains evident even during periods of low solar activity. TEC magnitudes are generally higher during the equinoxes compared to the solstices, illustrating the semi-annual variation encoded within the IRI model's empirical parameterizations. Peak TEC timing varies with latitude, with mid-latitude regions peaking earlier (10:00–12:00 LT) than the equatorial region (15:00 LT), consistent with the temporal evolution of plasma transport mechanisms.

This work makes a very important contribution in providing a quantitative comparative baseline of IRI-2016 TEC variations in different latitude zones under solar minimum conditions. The contributions made in this work include (1) provision of the IRI-2016 baseline model performance for the solar minimum period of 2020, which will allow future comparison studies; (2) provision of an example that can be used in teaching about how known ionospheric features such as EIA, winter anomaly, and latitudinal gradients are represented using the empirical parameters of the model equations (1-7); and (3) climatology information that can be applied in GPS error modeling and space weather education when there are calm solar activities.

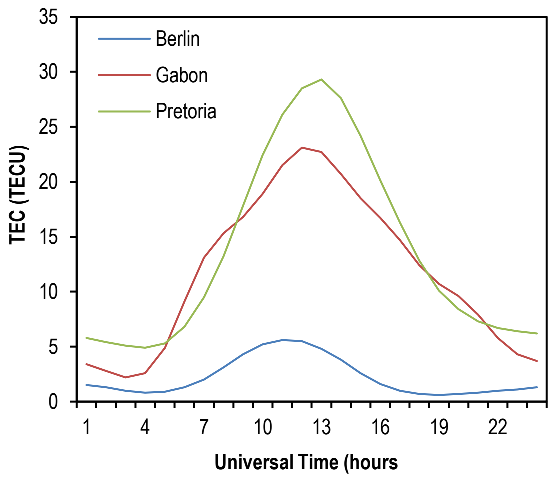


Fig. (8) Same as Fig. (5), but for the winter solstice (December, 23, 2020). The equatorial TEC peak exceeds 29.38 TECU around 13.00local time, representing the highest values observed in this study

References

[1] M.C. Kelley, **"The Earth's Ionosphere: Plasma Physics and Electrodynamics"**, Academic Press (Amsterdam, 2009).

[2] A. Krüger, **"Introduction to Solar Radio Astronomy and Radio Physics"**, Springer Science & Business Media (Berlin, 2012).
[3] A. Komjathy, "Global Ionospheric Total Electron Content Mapping Using the Global Positioning System", Ph.D. dissertation, University of New Brunswick, Canada (1997).
[4] D. Bilitza et al., "International Reference Ionosphere 2016: From ionospheric climate to real-time nominal", *Space Weather*, 15(2) (2017) 418-429.
[5] M. Aschwanden, "Physics of the Solar Corona: An Introduction with Problems and Solutions", Springer Science & Business Media (Berlin, 2006).
[6] D. N. Anderson et al., "The effect of vertical E × B ion drifts on the F region", *J. Geophys. Res.: Space Phys.*, 92(A8) (1987) 7723-7732.
[7] W.B. Hanson and R.J. Moffett, "Ionization transport effects in the equatorial F region", *J. Geophys. Res.*, 71(23) (1966) 5559-5572.
[8] H. Rishbeth and O.K. Garriott, **"Introduction to Ionospheric Physics"**, Academic Press (NY, 1969).
[9] M. Nava, S. M. Radicella and L. Leitinger, "Use of total electron content data to analyze ionospheric behavior during solar cycle 25", *Adv. Space Res.*, 70(5) (2022) 1450-1462.
[10] Y. Zhang, A.J. Coster and P.J. Erickson, "Long-term ionospheric TEC variations under low solar activity conditions", *Radio Sci.*, 58(2) (2023) 1-14.
[11] E.V. Appleton, "The Appleton layer", *Nature*, 157(3989) (1946) 475-476.
[12] C. Xiong, H. Lühr and M.G. Johnsen, "Global morphology of ionospheric total electron content during geomagnetic storms", *J. Geophys. Res.: Space Phys.*, 127(8) (2022) 1-18.
[13] M.A. Abdu et al., **"Aeronomy of the Earth's Atmosphere and Ionosphere"**, Springer Science & Business Media (Berlin, 2011).
[14] Y.N. Huang and K. Cheng, "Solar cycle variation of the total electron content around equatorial anomaly crest region in East Asia", *J. Atmosph. Terrest. Phys.*, 57(12) (1995) 1503-1511.
[15] N. Balan, J. Souza and G.J. Bailey, "Recent developments in the understanding of equatorial ionization anomaly: A review", *J. Atmosph. Solar-Terrest. Phys.*, 171 (2018) 3-11.
[16] H. Rishbeth and I.C.F. Müller-Wodarg, "Why is there more ionosphere in January than in July? The annual asymmetry in the F2-layer", *Annal. Geophys.*, 24(12) (2006) 3293-3311.

Table 5: Statistical summary of IRI-2016 TEC predictions for four representative days (each with n = 24 hours)

Location	Day	Mean (TECU)	Median (TECU)	σ (TECU)	Min (TECU)	Max (TECU)	n
Berlin	March 21	3.01	3.00	1.78	0.8	5.4	24
Berlin	June 21	4.98	5.55	1.49	2.3	6.6	24
Berlin	Sept 23	3.68	3.90	2.02	1.0	6.7	24
Berlin	Dec 21	2.10	1.30	1.78	0.6	5.6	24
Gabon	March 21	13.53	12.75	9.80	1.1	27.6	24
Gabon	June 21	7.55	6.00	6.51	0.7	17.9	24
Gabon	Sept 23	15.68	17.55	9.63	1.8	28.0	24
Gabon	Dec 21	11.94	12.40	7.02	2.2	23.1	24
Pretoria	March 21	5.74	4.90	4.23	0.9	11.8	24
Pretoria	June 21	3.60	2.10	2.59	0.9	7.9	24
Pretoria	Sept 23	5.03	4.90	3.72	0.6	10.0	24
Pretoria	Dec 21	13.03	10.35	8.99	4.9	29.3	24

