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Comparative Performance Analysis of IRI-2020 and AfriTEC Ionospheric Models over Ethiopia During Geomagnetically Disturbed Periods

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Abstract: This paper evaluates the comparision of IRI-2020 and AfriTEC ionospheric models in predicting TEC variations during geomagnetically disturbed time over East Africa in case of Ethiopia. In equatorial places like Ethiopia, the geomagnetic disturbance of the ionosphere can cause significant changes during disturbed time, which could lead to inaccurate position, timing data in satellite navigation and communication systems. For Ethiopian sectoral long-distance radio transmission, it is significant that the electron density can fluctuate diurnally, monthly and seasonally because of variations in the height and peak density of the F-region. To minimize this problem, we use the IRI-2020, the AfriTEC, and GNSS data. The IRI-2020 data predicted from the instant run version, the AfriTEC data predicted using the Matlab toolbox, and GNSS data were collected from the IGS network of ground-based dual-frequency GPS receivers across five Ethiopian sectors. By using geomagnetic parameters from omniweb data explorer, particularly the Dst index ranging from -70 to 20 nT for 2016. The results show a consistent daily and monthly correlation between the estimated TEC from both models and the GNSS, with notable seasonal variations. While the models showed good agreement across all seasons, discrepancies were observed in December and June. Seasonal equinox and solstice periods were particularly analyzed, with AfriTEC showing an overestimation of TEC by 2 to 5 TECU in April, yet having a lower root-mean-square error (RMSE) of 0.36 compared to IRI-2020. Finally, the diurnal, monthly, and seasonal statistical RMSE values indicate that the IRI-2020 model has the highest error, while the AfriTEC model has the lowest error. Therefore, the evidence shows that the AfriTEC ionospheric model gives a better prediction of the TEC and shows its superior performance in capturing ionospheric behavior during disturbed periods in Ethiopia. Accurate modeling of TEC is therefore essential for reliable long-distance radio communication in this region.

Keywords: IRI-2020 Model, AfriTEC Model, Vertical Total Electron Content, GNSS, RMSE

1. Introduction

The ionosphere, a highly dynamic region of the Earth's upper atmosphere extending from approximately 60 km to 1000 km in altitude, plays a crucial role in space weather studies. This region consists of ionized particles generated by solar radiation, which significantly affect the propagation of radio signals, satellite communications, and global navigation satellite systems (GNSS) [2]. The ionosphere exhibits complex variability due to solar activity, geomagnetic storms, and diurnal and seasonal changes, making it a critical focus in space weather research [15]. In equatorial regions such as Ethiopia, ionospheric disturbances can introduce significant errors in GNSS-based positioning and communication systems, especially during periods of heightened geomagnetic activity [1]. To understand and predict ionospheric response, various models have been developed to estimate parameters such as total electron content (TEC), electron density profiles, and ionospheric irregularities. Ionospheric modeling is essential for mitigating the adverse effects of space weather on communication, navigation, and satellite operations [10]. The International Reference Ionosphere (IRI) is one of the most widely used models, which is an empirical global model providing estimates of electron density, ion composition, and temperature at different altitudes [4]. The latest version, IRI-2020, integrates updated empirical data and new assimilation techniques to improve its accuracy in predicting ionospheric response [24]. However, IRI models often struggle to capture localized ionospheric variations, particularly in equatorial and low-latitude regions where electrodynamic processes such as the equatorial ionization anomaly (EIA) and ionospheric scintillations occur [23].

To address these limitations, regional ionospheric models such as the AfriTEC model have been developed to provide more accurate TEC predictions by utilizing ground-based GNSS data from African stations [17]. AfriTEC offers improved real-time and near-real-time TEC estimations compared to global models by incorporating region-specific ionospheric dynamics. However, despite its advantages, the model's accuracy can be affected by data availability and quality issues, as well as the complex nature of ionospheric disturbances over equatorial Africa [14]. Other models, such as NeQuick, a three-dimensional ionospheric electron density model, have also been used for trans-ionospheric radio propagation applications, particularly for GNSS error corrections [12]. Accurate ionospheric modeling is critical for a variety of applications. GNSS-based positioning systems, including GPS, rely on ionospheric models to correct signal delays caused by TEC variations [11]. During geomagnetic storms, rapid changes in the ionosphere can lead to severe positioning errors, affecting aviation, geodesy, and autonomous navigation [6]. High-frequency (HF) radio communications are also influenced by ionospheric response, with fluctuations in electron density impacting signal reflection and absorption [19]. Additionally, space weather forecasting depends on ionospheric models to predict how disturbances propagate through the Earth's atmosphere and influence technological infrastructure [3].

Despite substantial progress in ionospheric modeling, accurately representing ionospheric behavior in equatorial regions such as Ethiopia remains a persistent challenge. The equatorial ionosphere is marked by steep ionization gradients and irregularities, which give rise to complex phenomena like plasma bubbles and ionospheric scintillations that are not well captured by global models [5]. Additionally, the ionosphere's response to geomagnetic storms is highly variable and event-dependent, complicating efforts to model short-term disturbances with precision [16]. The scarcity of dense, ground-based GNSS networks across Africa further limits the reliability of both global and regional models in these regions [22]. Although several studies have assessed the performance of the IRI model across various locations, comparative validations of IRI-2020 and the AfriTEC model under geomagnetically disturbed conditions in East Africa remain limited. To address this gap, the present study evaluates and contrasts the predictive performance of IRI-2020 and AfriTEC against GPS-derived TEC measurements over Ethiopia. By focusing on geomagnetically disturbed periods, the study aims to identify which model more accurately captures ionospheric variability in the equatorial region, thereby supporting enhanced space weather monitoring and forecasting capabilities.

2. Data and Methods

2.1. Study Area and Observation Sites

This study investigates the performance of the IRI-2020 and AfriTEC ionospheric models in predicting TEC variations over Ethiopia during geomagnetically disturbed conditions in 2016. TEC predictions from both models were compared with GPS-derived TEC observations from five IGS stations located across Ethiopia: Addis Ababa (ADIS), Asosa (ASOS), Bahir Dar (BDMT), Nazret (NAZR), and Negele (NEGE). The geographical and geomagnetic coordinates, as well as elevation for each station, are presented in Table 1 and study area map in Figure 1.

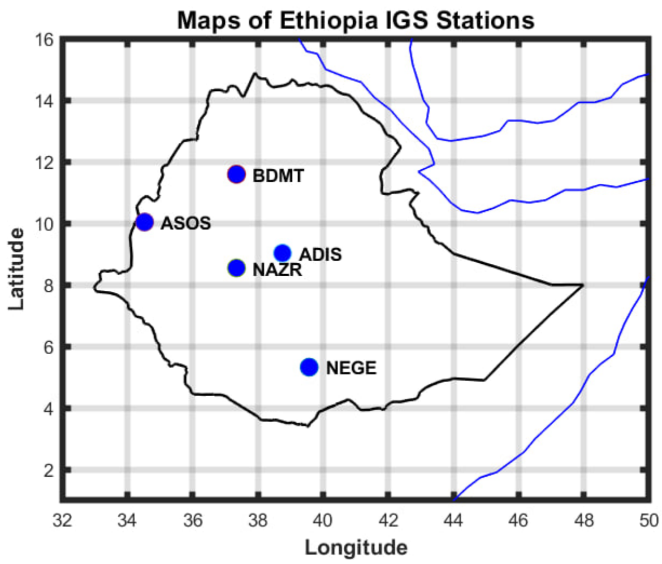


Figure 1. *Study area map with IGS stations in Ethiopia.*

Table 1. *The Geographical Positions and IGSS Code of the Ground-Based Stations in the Ethiopian Sectors.*

Country	IGSS Code	Geog Lat	Long	Mag Lat	Long	Elevation
Ethiopia	ADIS	9.03°N	38.76°E	24.1°N	121.4°E	2355m
Ethiopia	ASOS	10.04°N	34.53°E	1.54°N	106.86°E	1570m
Ethiopia	BDMT	11.59°N	37.35°E	2.67°N	109.12°E	1840m
Ethiopia	NAZR	8.55°N	39.27°E	-0.63°N	111.32°E	1712m
Ethiopia	NEGE	5.33°N	39.58°E	-3.69°N	113.20°E	1475m

2.2. Model Data Sources

2.2.1. IRI-2020

The International Reference Ionosphere (IRI-2020) model data were accessed via the official IRI Web Service (https://irimodel.org). This empirical global model provides electron density profiles based on a long-term database of ionospheric measurements (Bilitza et al., 2018).

2.2.2. AfriTEC

The AfriTEC model is a regional TEC model developed by Daniel Okoh (2024) for Africa, covering latitudes from $-40°$ to $+40°$ and longitudes from 20°W to 60°E. Model outputs are generated via a MATLAB toolbox accessible through MATLAB Central (https://www.mathworks.com/matlabcentral/fileexchange/69257-african-gnss-tec-afritec-model). Inputs to the model include location (latitude and longitude), date, and station ID. AfriTEC utilizes GNSS data from African stations to improve TEC predictions for the continent.

2.3. Geomagnetic Index Data

The Disturbance Storm Time (Dst) index, which quantifies the severity of geomagnetic storms, was obtained from the OMNIWeb database (https://omniweb.gsfc.nasa.gov) and the World Data Center at Kyoto University (http://wdc.kugi.kyoto-u.ac.jp/dstae/index.html). Periods with Dst ≤ -50 nT were considered geomagnetically disturbed for this study.

2.4. TEC Data and Processing

The GPS-TEC data were obtained from the International GNSS Service (IGS) network via several repositories, including UNAVCO (http://www.unavco.org), SOPAC (http://sopac.ucsd.edu), AFREF (http://www.afrefdata.org/), and IGS (http://www.igs.org/network). The data were retrieved in RINEX format and processed into vertical TEC using the GPS-TEC analysis application developed by Gopi Seemala (https://seemala.blogspot.com/). This tool uses dual-frequency GNSS signals to compute slant TEC, which is then converted to vertical TEC through mapping functions.

2.5. Model Performance Evaluation

To evaluate model performance, we used the Root Mean Square Error (RMSE) between predicted and observed TEC [20]. According to Petropoulos & Srivastava [18], to assess the effectiveness of AfriTEC and IRI models in predicting the TEC with GPS-TEC measurement data, Root Mean Square Error (RMSE), was used and is calculated as:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\text{TEC}_{\text{pred},i} - \text{TEC}_{\text{obs},i})^2} \quad (1)$$

Here, TEC_{pred} and TEC_{obs} denote predicted and observed TEC values, and N is the total number of observations. Model comparisons were carried out for diurnal, monthly, and seasonal TEC variations under both quiet and disturbed geomagnetic conditions.

3. Results and Discussion

3.1. The Geomagnetic Dst Index Value at Disturbed Time for 2016

The Disturbance Storm Time (Dst) index plot for 2016 shows multiple instances of geomagnetic activity, with several periods where the index drops below -50 nT, indicating moderate to intense storm conditions. Given the objective of this study, this result provides a foundation for evaluating how well these models capture ionospheric responses to storm events as shown in Figure 2. The fluctuations in the Dst index highlight the presence of geomagnetic storms, which are known to significantly impact TEC variations in the ionosphere. The accuracy of the models in predicting TEC during these events is crucial for assessing their reliability for space weather applications in East Africa. Since AfriTEC is primarily a quiet-time model and IRI-2020 has an optional storm-time mode, the study should determine whether the models effectively replicate TEC disturbances observed in GPS-TEC measurements. If discrepancies are found, they may indicate limitations in the models' ability to incorporate storm-induced ionospheric dynamics over the Ethiopian sector. A detailed statistical comparison, including RMSE analysis, will help quantify these differences and provide insights into model improvements for better regional TEC predictions.

3.2. The Diurnal, Monthly & Seasonal Performance of AfriTEC, IRI-2020, & GPS_TEC

The performance of AfriTEC, IRI-2020, and GPS-TEC was evaluated on diurnal, monthly, and seasonal timescales to assess how well the models capture ionospheric TEC variations over Ethiopia, particularly during geomagnetically disturbed periods. According to the following results, AfriTEC showed better agreement with GPS-TEC in tracking diurnal, monthly, and seasonal TEC variations, especially under disturbed conditions. IRI-2020, while useful for global applications, lacked precision in capturing localized ionospheric disturbances in Ethiopia. These findings highlight the importance of regional ionospheric models like AfriTEC for improving space weather predictions and GNSS-based applications in equatorial regions.

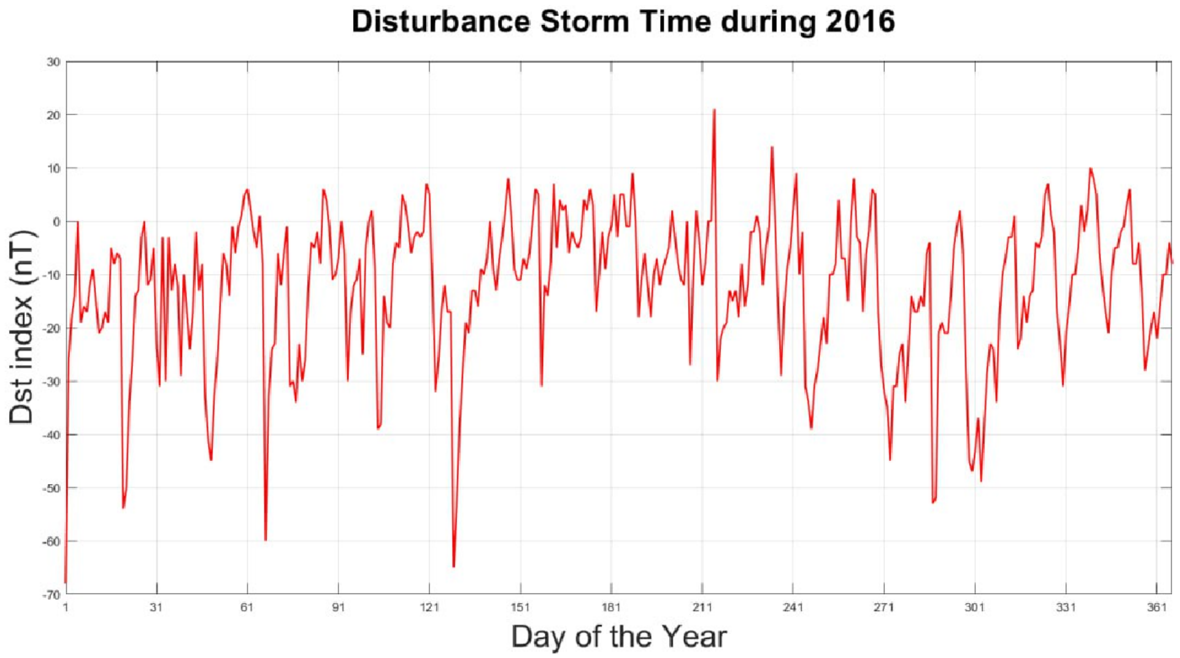


Figure 2. *Disturbance Storm Time (Dst) index variations during 2016, illustrating geomagnetic activity throughout the year.*

3.2.1. The Diurnal Performance of AfriTEC, IRI-2020, and GPS_TEC Variation in Ethiopian

The diurnal variation of TEC is primarily driven by solar radiation, with TEC values increasing during the daytime and decreasing at night. The study found that AfriTEC better captured the daytime peak TEC values, though slightly overestimated by AfriTEC, whereas IRI-2020 consistently underestimated TEC, particularly during peak solar activity hours. GPS-TEC exhibited the highest values, indicating that both models underrepresent the peak ionospheric response during disturbed periods in Figures 3, 4 and 5.

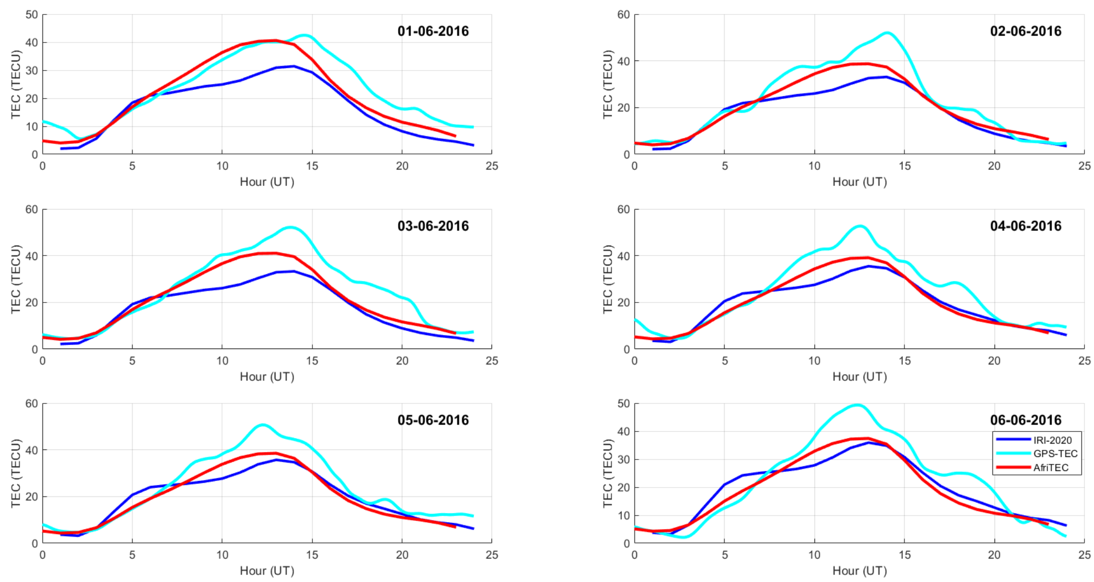


Figure 3. *Diurnal Variation of Consecutive Disturbed Days at the ADIS Station from 01-06-2016 to 06-06-2016.*

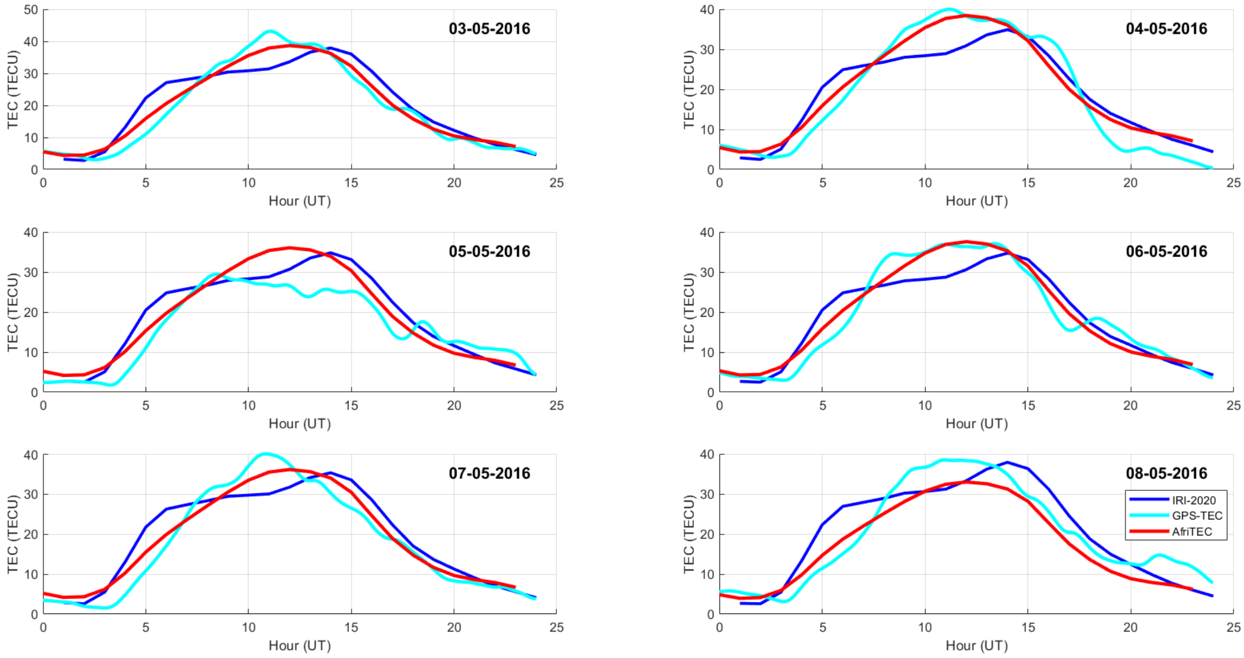


Figure 4. *Similar to 3 but for ASOS station from 03-05-2016 to 08-05-2016.*

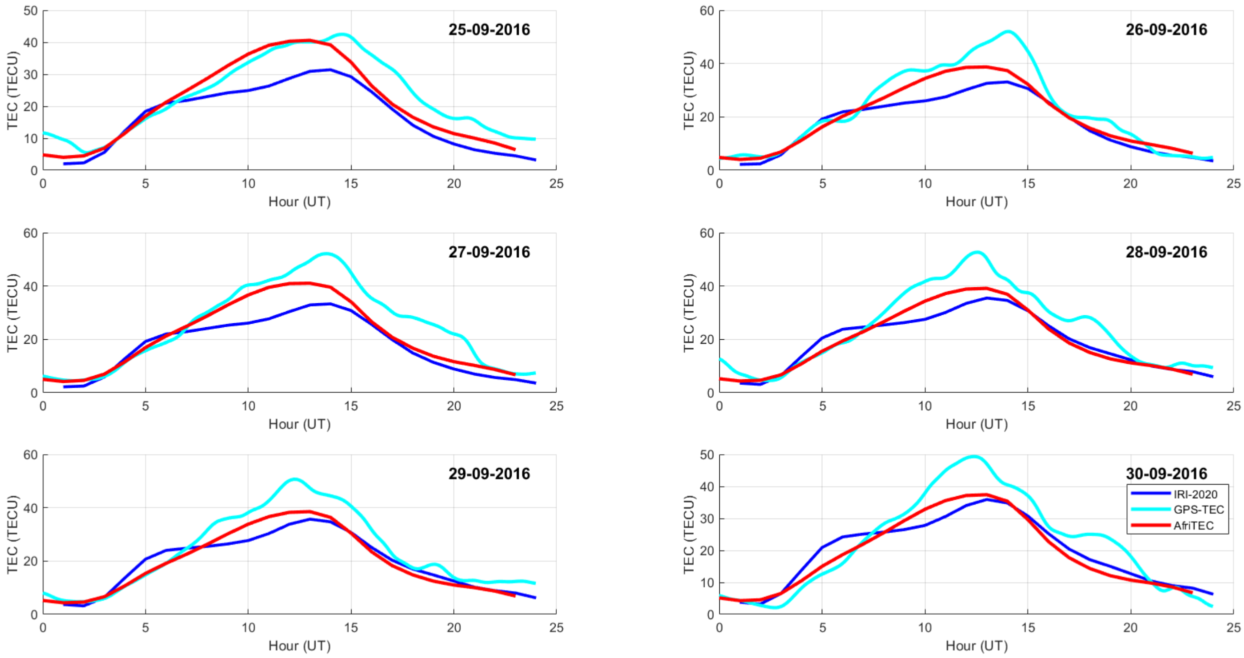
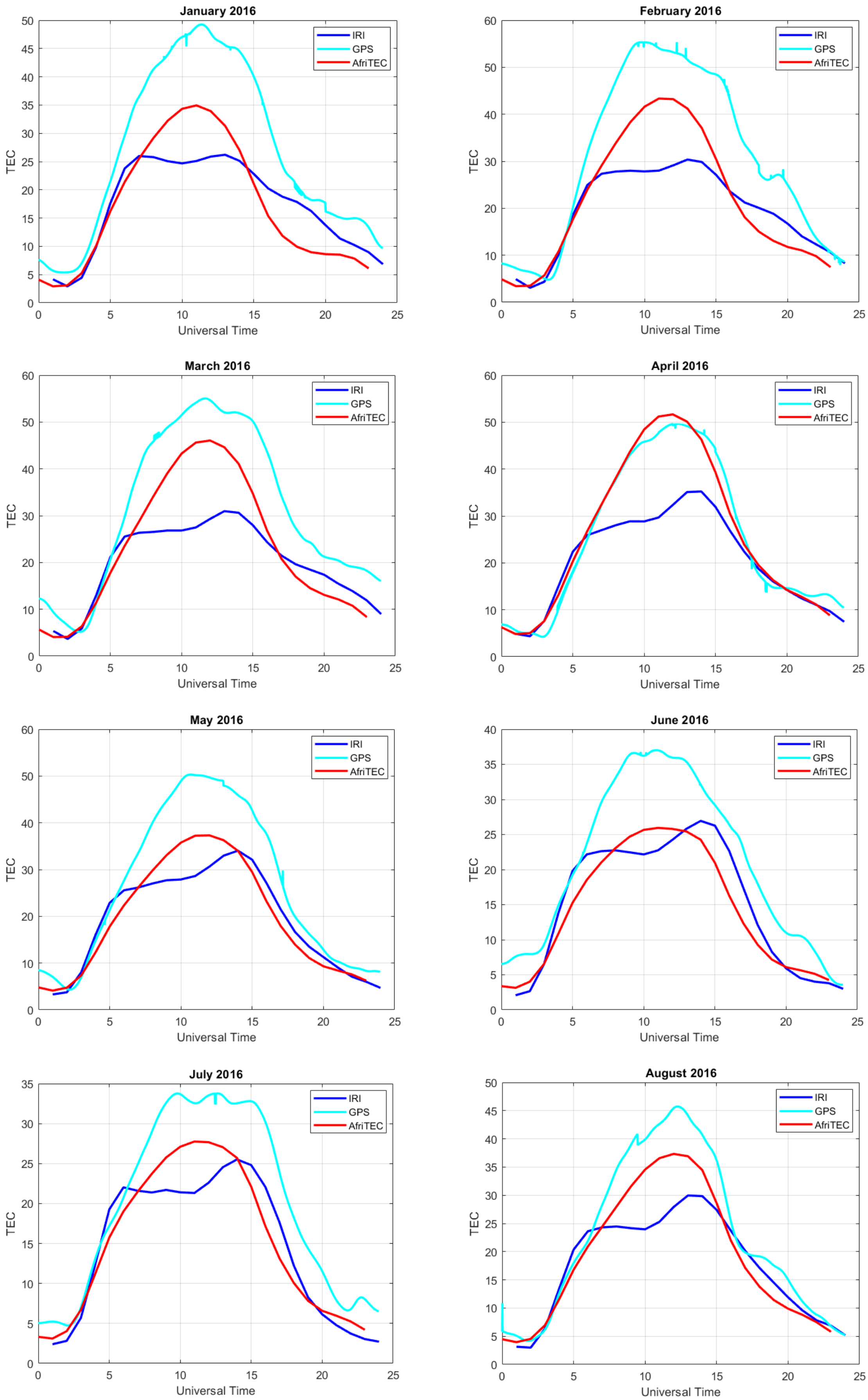


Figure 5. *Similar to 3 but for BDMT station from 25/09/2016 to 30/09/2016.*

3.2.2. Monthly Variations of Measured GPS-TEC, AfriTEC & IRI-2020 in Ethiopian Sectors

The Monthly Performance refers to the evaluation of the IRI-2020 and AfriTEC ionospheric models in predicting TEC variations over Ethiopia during geomagnetically disturbed periods in Figures 6, 7, and 8. The study compares the model-derived TEC values with GPS-TEC observations across different months in 2016, assessing their accuracy and discrepancies. Key findings indicate that while both models generally follow the monthly TEC trends, AfriTEC shows a closer correlation with GPS-TEC data, particularly during peak solar activity hours, whereas IRI-2020 tends to underestimate TEC variations. The analysis provides insights into how ionospheric response fluctuate on a monthly basis and the reliability of these models in capturing such changes. Monthly comparisons revealed that TEC variations exhibited distinct trends throughout the year, with notable differences between the models.


January 2016
February 2016
March 2016
April 2016
May 2016
June 2016
July 2016
August 2016
TEC
Universal Time
IRI
GPS
AfriTEC
0
5
10
15
20
25
30
35
40
45
50
60

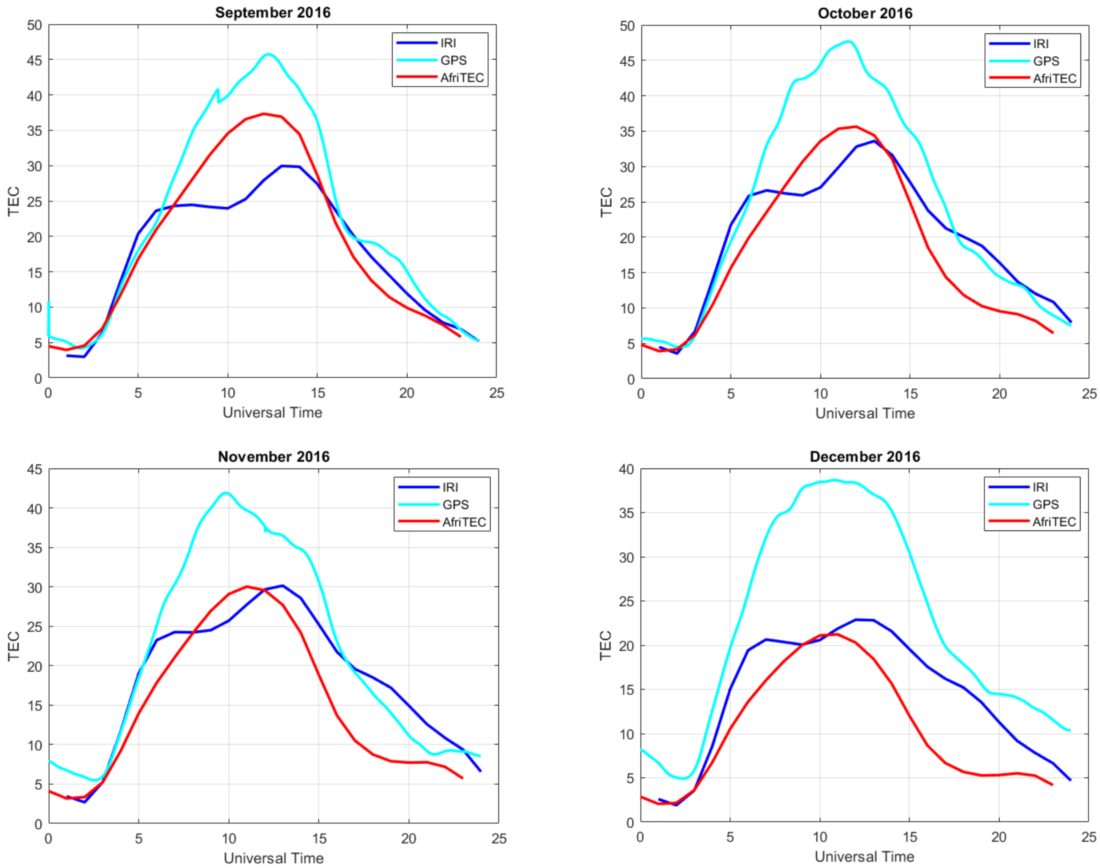
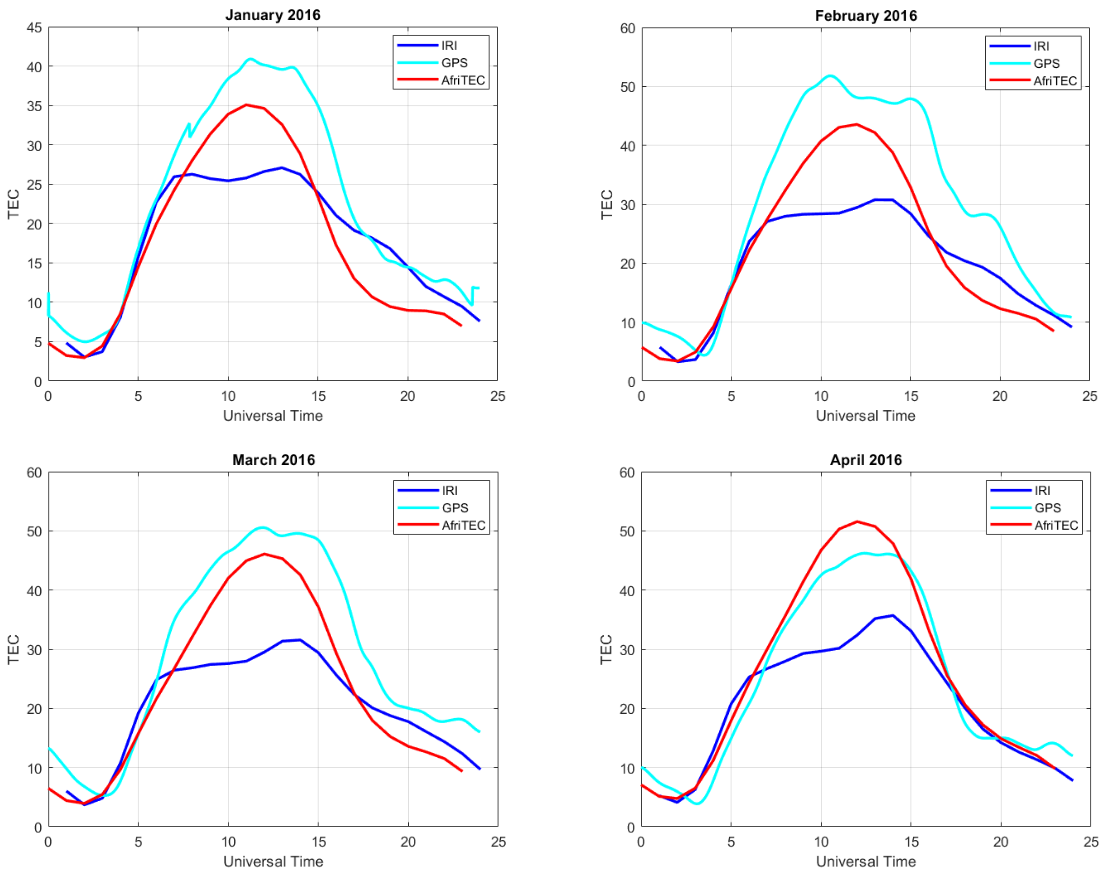


Figure 6. *Monthly Variation of TEC (TECU) Vs Hour (UT) at Addis Ababa Station During Five Disturbed Days in Each of the Twelve Months.*



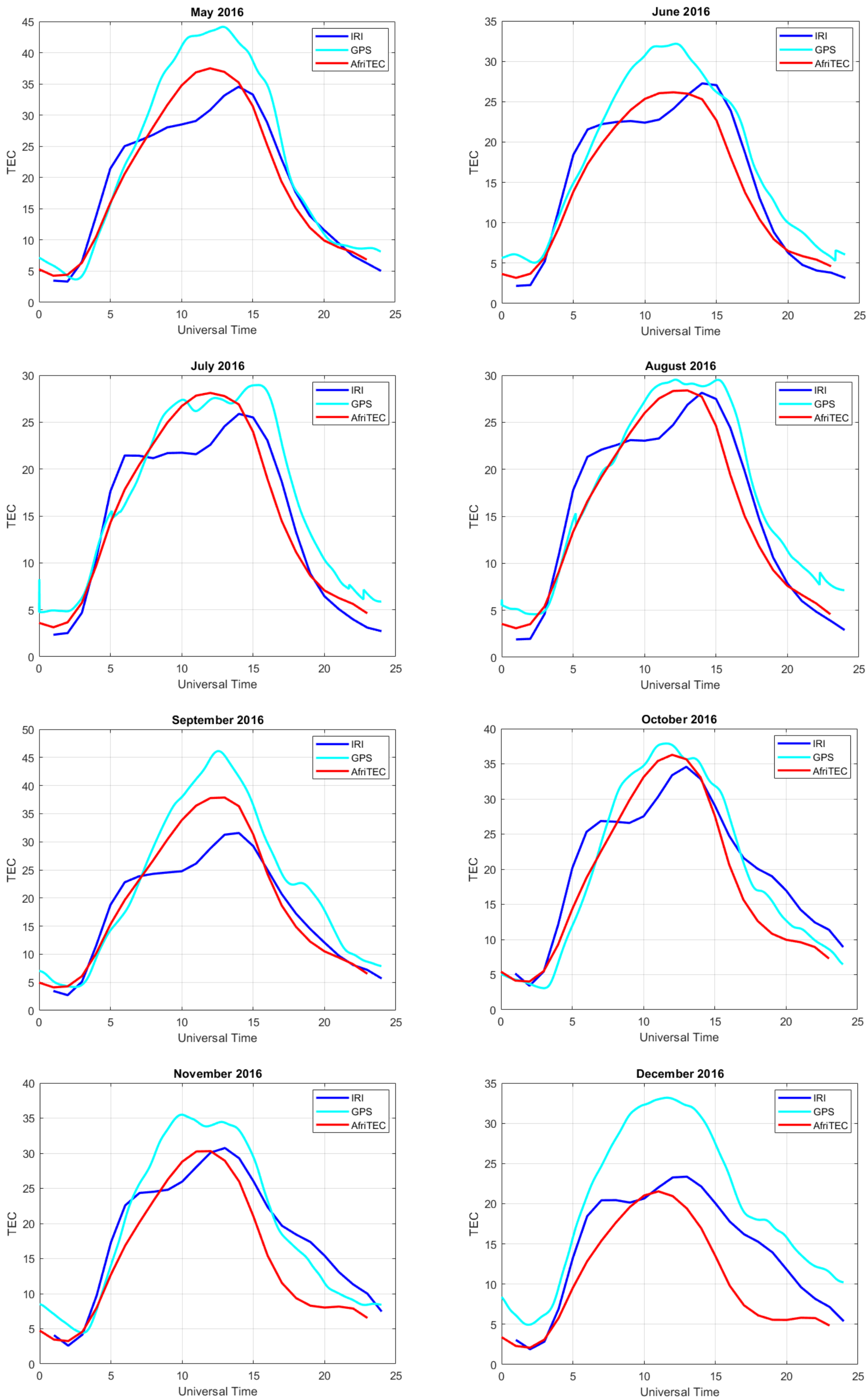
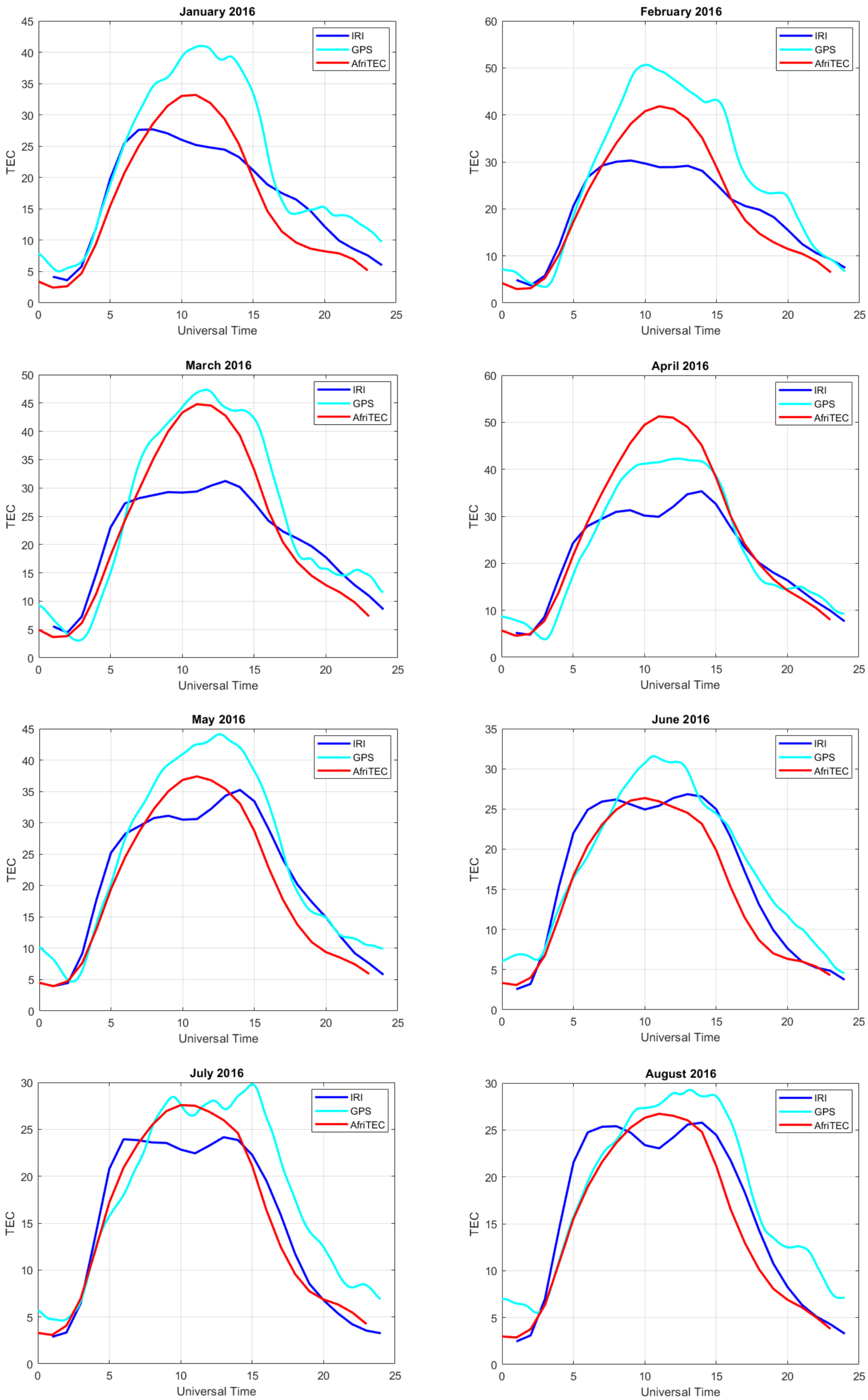


Figure 7. *Similar to 6 but for Asosa station in 2016.*


January 2016
February 2016
March 2016
April 2016
May 2016
June 2016
July 2016
August 2016
IRI
GPS
AfriTEC
TEC
Universal Time

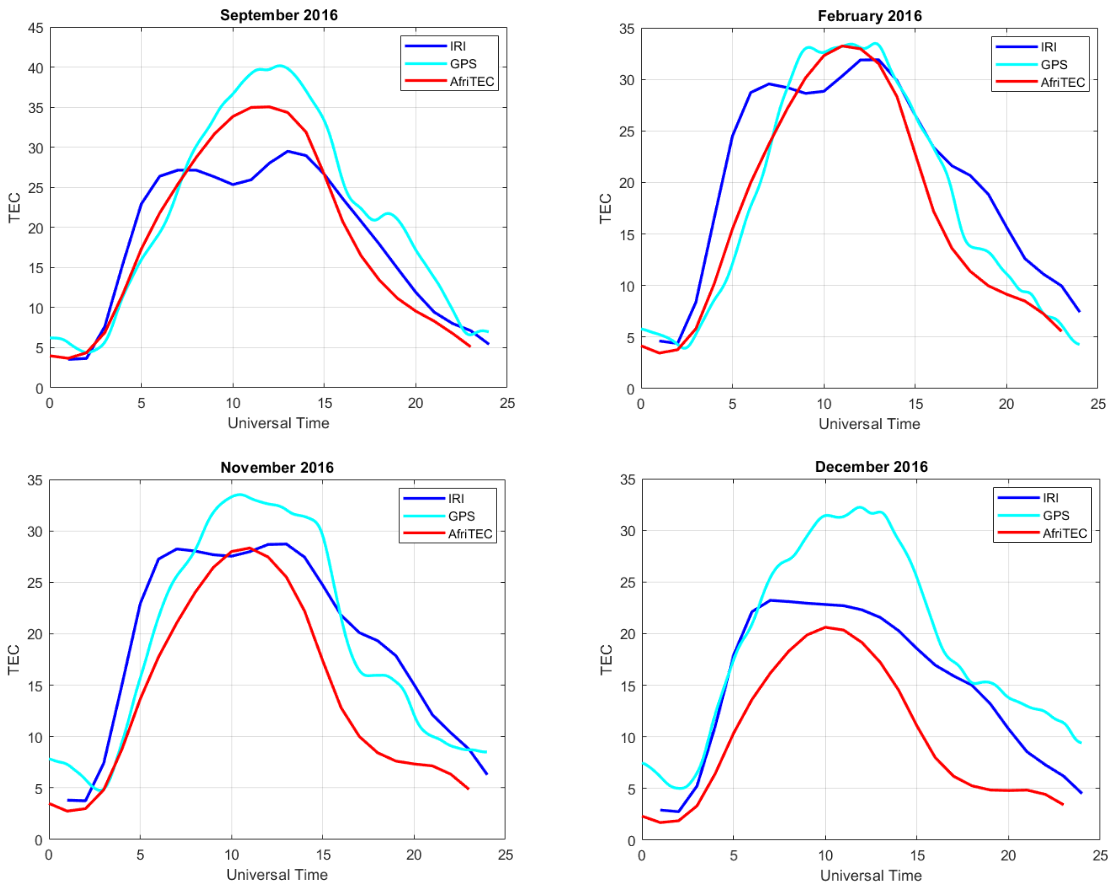


Figure 8. *Similar to 6 but for Negele station in 2016.*

3.3. The Seasonal Results in Ethiopian Sectors

Table 2. *Seasonal variation of RMSE values between AfriTEC and IRI-2020 models compared with GPS-TEC observations in the Ethiopian sector. The first row corresponds to the March equinox, the second to the June solstice, the third to the September equinox, and the final row to the December solstice for each station.*

Stations Name	RMSE-AfriTEC	RMSE-IRI
ADIS station	10.82	6.07
	3.32	2.84
	5.80	4.16
	4.25	4.66
ASOS station	5.72	5.57
	3.18	2.75
	3.85	3.73
	14.21	4.57
BDMT station	4.99	4.30
	10.33	2.74
	5.68	2.55
	9.60	5.06
NAZR station	9.34	10.98
	7.93	2.86
	5.88	4.75
	7.74	8.74
NEGE station	5.02	5.59
	6.74	2.11
	7.30	3.88
	8.54	4.94

Seasonal variations in the ionosphere are driven by solar activity, geomagnetic influences, and atmospheric dynamics 9, and 10. In equatorial regions like Ethiopia, ionospheric response fluctuate significantly between different seasons due to variations in solar radiation, geomagnetic disturbances, and electrodynamic processes such as the Equatorial Ionization Anomaly (EIA). TEC exhibits distinct seasonal patterns, influenced primarily by changes in solar zenith angle, ionospheric dynamics, and geomagnetic conditions. The study evaluates TEC variations across different seasons in Ethiopia using the AfriTEC and IRI-2020 models compared with GPS-TEC data in Table 2.

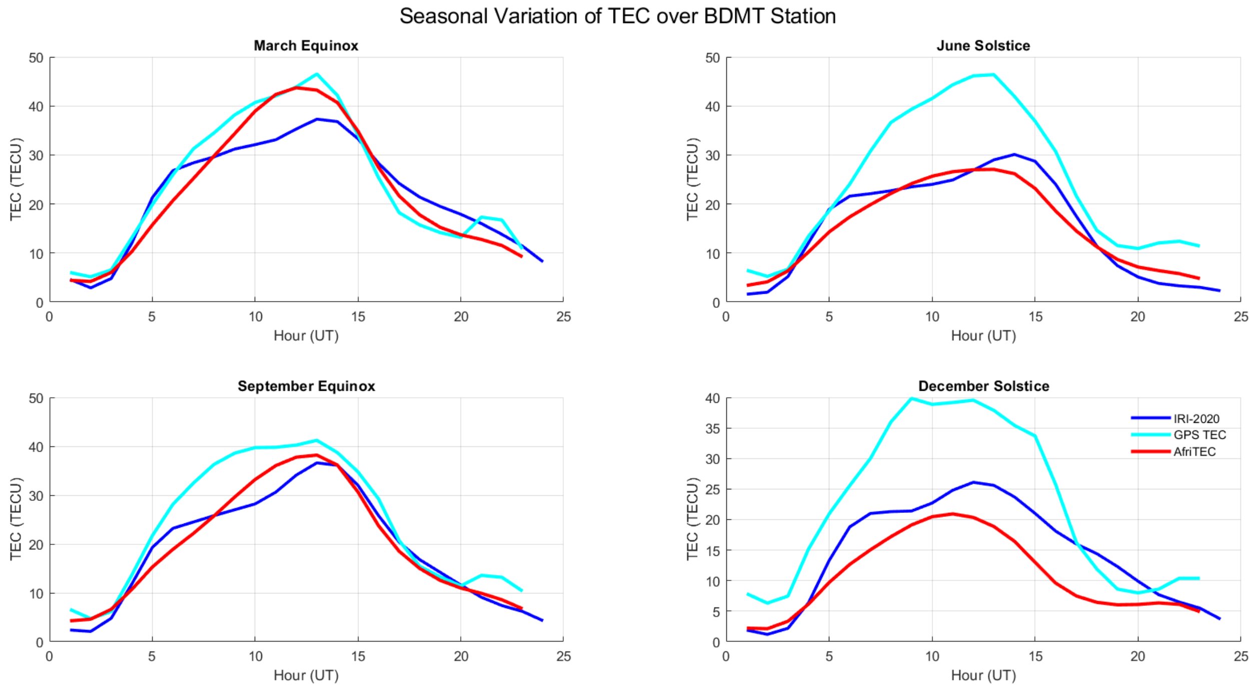


Figure 9. *Seasonal variation of TEC over the BDMT station during 2016.*

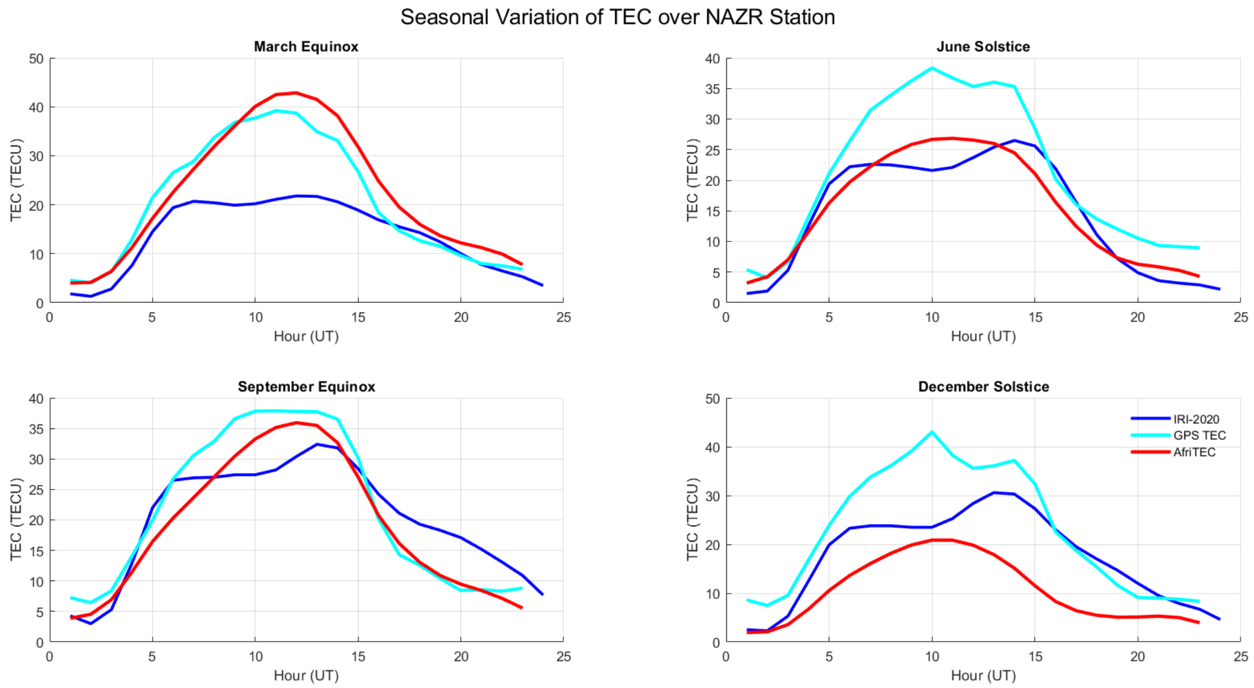


Figure 10. *Seasonal variation of TEC over the NAZR station during 2016.*

3.4. Discussion

The disturbed time corresponds to periods of increased geomagnetic activity that impact ionospheric electron density. During these periods, real-time measurements (GPS) often show enhanced TEC values compared to model predictions, especially in equatorial & low-latitude regions like Ethiopia.

3.4.1. Comparison of IRI-2020 and AfriTEC Models with the GPS_TEC in Ethiopia

We checked how well the IRI-2020 and AfriTEC ionospheric models could predict the TEC during times when the geomagnetism in Ethiopia was changing by comparing their results with TEC observations made with GPS. The primary parameter, such as the TEC, which is vital for assessing the ionosphere's impact on GNSS signal delay, was analyzed to understand the ionospheric characteristics on F2-layer peak electron density (foF2) and its corresponding height (hmF2). Disturbed time can cause significant fluctuations in TEC, leading to errors in satellite navigation and communication. At these times, foF2 can undergo significant changes, affecting HF (high-frequency) radio communication. Variations in hmF2 can influence the propagation path of radio signals [13]. Disturbed time can cause fluctuations in hmF2, leading to altered signal paths and affecting the accuracy of ionospheric models. TEC is similar to vertical TEC; this parameter represents the TEC in a column from the ground to the top of the ionosphere and is essential for assessing ionospheric effects on satellite-based technologies, especially during disturbed periods when TEC can change rapidly [9, 21].

The results show that both models accurately capture the general diurnal and seasonal trends of GPS-TEC. However, notable discrepancies arise, especially during periods of geomagnetic disturbance. The AfriTEC model consistently exhibits a closer correlation with GPS-TEC observations compared to IRI-2020, which tends to underestimate TEC, particularly during peak solar activity hours [8]. AfriTEC slightly overestimates daytime TEC, while IRI-2020 underestimates it, indicating differing sensitivity to peak ionospheric activity, leading to significant deviations from observed GPS-TEC values. The overestimation in AfriTEC suggests its sensitivity to regional ionospheric disturbances, while the underestimation in IRI-2020 highlights its global nature, which does not fully account for localized equatorial anomalies [10].

3.4.2. Dst Index Variations in Ethiopia During Geomagnetically Disturbed Periods

The dst index measures the intensity of the ring current around Earth and the geomagnetic disturbance in nanoteslas (nT). The time with high negative disturbance storm time index values are correlated during the disturbed time. Positive values indicate weaker disturbance, while negative values indicate stronger disturbance [3]. The scale ranges from about +20 to -70 nanoteslas (nT). The figure 2 shows several significant dips below zero, indicating the occurrence of geomagnetic disturbance. More negative values represent strong geomagnetically disturbance. There are several periods where the dst index reaches values below -70 nT, indicating strong geomagnetic disturbance. The overall trend shows periodic disturbance with varying intensity levels throughout the year 2016 in Ethiopia.

3.4.3. Diurnal Analysis of IRI-2020 and AfriTEC Models with the GPS-TEC

The diurnal variation of TEC was analyzed using GPS-derived TEC, IRI-2020, and AfriTEC models over Ethiopia during five highly disturbed days in 2016. The results revealed that IRI-2020 consistently underestimated TEC values, particularly during peak solar activity hours, while AfriTEC tended to slightly overestimate TEC values during the daytime.

During the pre-dawn period (00:00 - 05:00 UT), all models showed low TEC values, approximately 5 TECU, with minimal variation. As solar radiation increased in the morning hours (05:00 - 10:00 UT), the TEC values rose sharply, with GPS-TEC showing the steepest increase, peaking at around 35 TECU, while IRI-2020 and AfriTEC exhibited lower peaks of 25-30 TECU. The midday peak (10:00 - 15:00 UT) was well captured by AfriTEC, although it slightly overestimated TEC, whereas IRI-2020 significantly underestimated the peak values. In the afternoon and evening hours (15:00 - 20:00 UT), both models showed a gradual decline in TEC, but GPS-TEC remained consistently higher than the model predictions. By nighttime (20:00 - 24:00 UT), TEC values returned to pre-dawn levels across all datasets.

The AfriTEC model closely followed the GPS-TEC trend, particularly in peak timing, demonstrating its ability to better capture localized ionospheric variations. However, its overestimation during peak hours suggests that the model may be highly sensitive to regional ionospheric disturbances. On the other hand, IRI-2020 smoothed out TEC fluctuations, failing to capture short-term variations effectively. The study also found that diurnal TEC variations were more pronounced on disturbed days, with GPS-TEC showing the highest values and sharpest increases, confirming the strong influence of solar and geomagnetic activity on ionospheric electron content [9].

Overall, the results indicate that AfriTEC outperforms IRI-2020 in representing TEC variations over Ethiopia during geomagnetic disturbances, particularly in capturing daytime peaks. However, both models require further improvements to better account for short-term ionospheric fluctuations in equatorial regions.

3.4.4. Monthly Performance of IRI-2020 & AfriTEC Models in Ethiopian Sectors

To avoid repetitive narratives, monthly TEC model performance is summarized in the following table. Each model's behavior (correlated, overestimated, underestimated) is listed by month. Commentary follows to highlight trends and key distinctions.

Table 3. *Summary of IRI-2020 and AfriTEC TEC Model Performance (January–December 2016).*

Month	IRI-2020	AfriTEC	GPS Correlation
January	Mixed (under/over)	Mixed (over/under)	Partial
February	Underestimated	Over/Underestimated	Early UT
March	Under/Overestimated	Under/Overestimated	Early UT
April	Underestimated	Slight overestimate near peak	Strong
May	Underestimated	Mixed (over/under)	Early/Late UT
June	Underestimated	Underestimated	Mid UT
July	Underestimated	Mixed	Partial
August	Under/Overestimated	Correlated/Underestimated	Late UT
September	Underestimated	Mixed	Correlated
October	Under/Overestimated	Underestimated	Mid UT
November	Under/Overestimated	Underestimated	Mid UT
December	Overestimated	Underestimated	Early UT

Table 3 presents the models' behavior in monthly plots. AfriTEC generally performs better than IRI-2020 in modeling TEC variations over Ethiopia, particularly during peak daytime hours. IRI-2020 tends to underestimate TEC values throughout most months, except in December, when it shows overestimation. AfriTEC occasionally overestimates during the day but aligns better with GPS measurements during early and late UT intervals. The highest correlation between GPS and AfriTEC is observed in April, while IRI-2020 consistently falls short of capturing the peak magnitudes, suggesting limitations in representing disturbed ionospheric response. Overall, GPS-derived TEC remains the most reliable indicator, especially during midday and geomagnetically active periods.

3.4.5. Seasonal Analysis During a Disturbed Time in Case of Ethiopian Sectors

A seasonal analysis further highlights the models' performance. During the equinoxes (March/April and September/October), TEC levels are at their highest due to increased ionospheric activity. The AfriTEC model demonstrates a higher degree of variability, capturing abrupt changes in TEC better than IRI-2020. The latter exhibits a smoothed representation of TEC variations, failing to capture sudden peaks observed in GPS-TEC measurements. In contrast, during solstices (June and December), both models exhibit larger discrepancies from GPS-TEC. In December, AfriTEC significantly overestimates TEC, while IRI-2020 underestimates it. This suggests that AfriTEC is more sensitive to regional changes, while IRI-2020 is less responsive to geomagnetic disturbances in equatorial regions. In 2016, Ethiopia experienced several such disturbances. During the equinoxes (March/April and September/October), TEC typically peaks because of solar wind effects. In 2016, disturbed time caused sharp TEC changes. For summer (June-August), TEC is high, but disturbances can cause sudden drops followed by recovery. Winter (December-February) shows lower TEC, with significantly related fluctuations. Monthly predictions for 2016 showed elevated TEC in March/April and September/October with strong variability during disturbance. June-August had high TEC with sudden drops, while December had lower TEC but still saw sharp changes during disturbances [8].

The IRI-2020 model is a widely used global ionosphere model, providing estimates of parameters like electron density and TEC. It works well during quiet geomagnetic periods, but its predictions during disturbed time, such as the 2016 geomagnetic disturbed period, should be treated with caution as it does not directly account for disturbances effects. For Ethiopia, near the magnetic equator, the IRI- 2020 model predicts higher TEC values during the equinoxes (March/April and September/October) because of enhanced ionospheric activity. However, during a disturbed time in 2016, actual TEC could vary significantly from the model, showing sudden drops or spikes. In summer (June- August), TEC is high, but may cause rapid fluctuations, which the IRI- 2020 model doesn't fully capture. Winter (December- February) typically shows lower TEC values, but during disturbed time, the model might underestimate TEC changes caused by geomagnetic disturbances. Monthly predictions follow similar trends, with high TEC during equinoxes and moderate TEC during summer. The model may not accurately reflect the disturbed time variations observed in 2016, especially during storm periods. In summary, while IRI- 2020 provides a useful baseline for Ethiopia's TEC, its predictions during 2016 disturbed time, especially geomagnetic periods, are limited and need to be supplemented by observational data for better accuracy.

3.4.6. RMSE Results Analysis

In this study, the Root Mean Square Error (RMSE) is employed as statistical metrics to evaluate and compare the performance of the IRI-2020 and AfriTEC ionospheric models over Ethiopia during geomagnetically disturbed periods. RMSE is used to quantify the average magnitude of the differences between the model predictions and observed TEC values. It provides a direct measure of the models' accuracy, with lower RMSE values indicating better agreement with observed data. This is particularly important during disturbed conditions, where ionospheric response can deviate significantly from normal patterns. By using both RMSE and R, the analysis offers a comprehensive assessment of each model's capability, highlighting not only their numerical accuracy but also their effectiveness in reproducing the dynamic behavior of the ionosphere under disturbed conditions.

The study found that, when evaluated against GPS-TEC measurements, IRI-2020 exhibited the highest RMSE values, indicating its difficulty in accurately capturing TEC variations, particularly during geomagnetic disturbances. In contrast, AfriTEC achieved the lowest RMSE values, demonstrating superior predictive capability for TEC variations over Ethiopia, especially under disturbed conditions. Seasonal and diurnal variations in RMSE values were observed, with larger discrepancies notably occurring in December and June, suggesting that the models' performance varies across different timescales. Furthermore, AfriTEC showed a higher correlation with GPS-TEC compared to IRI-2020, indicating that it more accurately represented observed TEC variations in Ethiopia.

4. Conclusion

This study delivers a thorough, station by station assessment of the IRI-2020 and AfriTEC ionospheric models during geomagnetically disturbed times over Ethiopia. The principal conclusions are as follow:

1. *Model skill in disturbed ionospheres.* AfriTEC replicates the rapid, event driven swings in vertical TEC (vTEC) recorded by dual-frequency GNSS with markedly greater fidelity than IRI-2020. At NEGE, ADIS, NAZR, ASOS, and BDMT, AfriTEC preserves the steep dawn-to-mid-morning gradients (2-5 TECU) that accompany enhanced eastward electric fields, whereas IRI-2020 smooths these gradients and underestimates peak amplitudes by $\sim$ 15-30.
2. *Temporal resolution and application scope.* The pronounced agreement between AfriTEC and GNSS during the 05:00 11:00 UT window when navigation and HF links are most vulnerable renders AfriTEC the preferable model for high-resolution operational tasks (precise point positioning, time transfer, HF frequency management) in equatorial East Africa. IRI-2020, despite its muted response to storm-time forcing, provides a globally consistent baseline suitable for climatological studies and first-order corrections in regions lacking dense GNSS coverage.
3. *Error statistics.* Seasonal RMSE analysis confirms AfriTEC's advantage: a mean RMSE of 0.36 TECU versus 0.61 TECU for IRI-2020 under Dst from -70 to +20 nT. Largest performance gaps occur during the June and December solstices, when IRI-2020 undervalues post-sunset enhancements linked to prereversal electric field surges.
4. *Implications for space-weather services.* Accurate TEC specification is critical for mitigating range errors (>5 m) in GNSS and for frequency management in HF and VHF links across Ethiopia's mountainous terrain. Deploying AfriTEC in regional space-weather centres would therefore measurably enhance warning lead times and link reliability.

Overall, the evidence positions AfriTEC as the more reliable tool for operational forecasting and engineering applications in Ethiopia, while highlighting actionable pathways to elevate IRI-2020's performance under dynamic ionospheric conditions. Continuous regional validation remains indispensable for advancing model accuracy and, by extension, the robustness of navigation and communication infrastructures across East Africa.

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Abbreviations

EIA	Equatorial Ionization Anomaly
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HF	High Frequency
IRI	International Reference Ionosphere
RINEX	Receiver-Independent Exchange
RMSE	Root Mean Square Error
TECU	Total Electron Content Unit

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Author Contributions

Melaku B., edited and reviewed the paper, write, simulated the results, and compared the model. Dejene A., conceptualized the study, designed the research methodology, and supervised the project. Efrem A., collected and processed the ionospheric data, performed the model simulations, and conducted the statistical analyses. Gebre K., contributed to the interpretation of results. All authors were actively involved in refining the manuscript, and has taken responsibility for ensuring the accuracy and integrity of the work.

Data Availability Statement

The data used in this study are obtained from GNSS & International GNSS Services (IGS) GPS receiver stations within the East Africa region of Ethiopia sectors. These stations are Addis Ababa, Asosa, Bahir Dar, Nazireth, and Negele. The codes ADIS, ASOS, BDMT, NAZR, and NEGE are used to respectively represent the stations. The GNSS data available from University Navstar Consortium (UNAVCO) (http://www.unavco.org), South Pacific Applied Geoscience Commission (SOPAC) (http://sopac.ucsd.edu), African Geodetic Reference Frame (AFREF) (http://www.afrefdata.org/), International Global Navigation Satellite System service (IGS) (http://www.igs.org/network). The IRI team makes the latest IRI-2020 model data available online through the IRI-web service https://irimodel.org. The AfriTEC model represents the ionospheric GNSS TEC across the whole African continent spanning from latitudes -40^0 S to 40^0 N and longitudes 20^0 W to 60^0 E, of the IGS stations. The model has been developed by [7], using TEC data gathered from GNSS receivers in various African locales for TEC modeling across the continent. It obtained by inputting the year, month, day, latitude, longitude, stations ID through MatLab tool box & Central website (https://www.mathworks.com/matlabcentral/fileexchange/69257-african-gnss-tec-afritec-model's-tid=prof-contriblnk). This model analyzes variations of tec using gained GNSS data to simulate and predict tec variations in this work. The Dst is an index used to measure geomagnetic activity & data from OMNIWEB(https://omniweb.gsfc.nasa.gov/) which is used to observe the geophysical environment during disturbed conditions.

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Conflicts of Interest

The authors declare no conflicts of interest.

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