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Equatorial Influence of Sunspot Number (SSN) on Total Electron Content (TEC) at the Moderate Phase of the Solar Cycle

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ABSTRACT

The sunspot number (SSN) is a standard indicator of solar activity and a recognised driver of ionospheric Total Electron Content (TEC). This study assesses how strongly SSN is reflected in GPS-derived TEC at eight equatorial and low-latitude stations in the Northern Hemisphere (geomagnetic latitudes 1.12°N to 26.58°N) during 2013, a year of moderate activity in Solar Cycle 24 with a mean monthly SSN of 64.7. For each station, monthly mean TEC from the five international quietest days of every month was compared with monthly SSN through linear regression and the Pearson correlation coefficient (r). Seven stations show positive correlations (r = 0.12 to 0.36), while SHEB shows a negligible negative value (r = −0.09). The largest coefficients occur at NAMA (0.36), ASAB (0.30) and BDMT (0.30). Stations within 12° of the geomagnetic equator average r ≈ 0.22, compared with r ≈ 0.14 for those beyond 20°. In a year of moderate solar activity, SSN therefore leaves a weak to moderate, latitude-dependent imprint on equatorial TEC, alongside substantial local and seasonal influences.

Keywords: *Sunspot number; Total Electron Content; equatorial ionization anomaly; moderate solar activity; GPS-TEC; Solar Cycle 24*

1. Introduction

TEC is the integrated electron density along the path between a satellite and a receiver, counted per square metre of cross-section and expressed in TEC units (1 TECU = 10^{16} electrons per square metre). It determines the size of the ionospheric delay imposed on GNSS signals, understanding how it varies is a practical requirement for accurate positioning, navigation and communication (Rabiu et al., 2014).

Near the geomagnetic equator, the daytime eastward electric field raises plasma to greater heights, from where it diffuses along magnetic field lines toward higher latitudes. This fountain process leaves a density trough over the equator, flanked by two crests that typically lie within about ±15° to ±20° of the magnetic equator, a structure known as the Equatorial Ionization Anomaly (EIA) (Appleton, 1946; Balan et al., 2018). The position and intensity of the crests shift with local time, season and solar activity. Low latitudes are consequently the region where TEC responds most strongly to the Sun, and also where it is most variable.

Solar activity is commonly expressed through indices such as the sunspot number (SSN) and the 10.7 cm radio flux, F10.7, which are among the most widely used (Tapping, 2013). Sunspots mark cooler, magnetically active patches of the solar surface, and their count follows the roughly 11-year cycle in the Sun's ultraviolet output. Higher SSN should therefore be accompanied by greater ionization and larger TEC. Consistent with this, GPS-TEC at equatorial stations in Nigeria and Peru rose from the minimum to the ascending phase of Solar Cycle 24 (Akala et al., 2013), and solar-cycle variation of TEC has been examined at Birnin Kebbi in northern Nigeria (Ogwala et al., 2019). The usefulness of SSN, F10.7 and photon flux for modelling and predicting TEC has also been evaluated with machine-learning methods (Benoit & Petry, 2021). Most comparisons contrast high with low solar activity (Jonah et al., 2015) or concentrate on the rising and declining phases of the cycle (Oron et al., 2013; Ogwala et al., 2022), and TEC over Nigeria has been characterised for 2011, a year with a sunspot number of 55.7 (Rabiu et al., 2014). To the authors' knowledge, studies devoted specifically to the SSN dependence of equatorial TEC across a latitude chain in a year of intermediate activity are comparatively few.

This paper addresses that gap by relating TEC to SSN at eight equatorial and low-latitude Northern Hemisphere stations in 2013, a year of moderate solar activity, with a mean monthly SSN of 94.9 (Table 1).

2. Data and Methodology

2.1 TEC data and stations

TEC for 2013 was derived from GPS receivers at eight stations in the African and Arabian sector, spanning geomagnetic latitudes of 1.12°N to 26.58°N. They are Addis Ababa (ADIS) and Bahir Dar (BDMT) in Ethiopia, Asab (ASAB) and Sheb (SHEB) in Eritrea, NAMA and TAYS in Saudi Arabia, and

Rabat (RABT) and Tetouan (TETN) in Morocco (Table 2). So that geomagnetic storms would not distort the comparison, each month was represented by its five international quietest days (IQDs). Hourly TEC on those days was averaged to give one quiet-time monthly value per station.

2.2 Sunspot number

The monthly SSN values for 2013 are given in Table 1. They increase from 84.3 in April to 107.6 in December, which defines the range of solar activity available for the comparison. The mean of the twelve monthly values is 94.9.

Table 1: Monthly sunspot number (SSN) for the year 2013 (WDC–SILSO. (2025).

Month	**SSN**	**Month**	**SSN**
January	86.6	July	94.6
February	86.1	August	99.0
March	84.4	September	104.7
April	84.3	October	107.0
May	87.0	November	106.9
June	90.9	December	107.6

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2.3 Correlation analysis

At every station, the twelve monthly TEC values were plotted against the corresponding monthly SSN and a least-squares line was fitted. The Pearson correlation coefficient (r) was used to describe the relationship: its sign shows whether TEC rises or falls with SSN, and its magnitude shows how closely the points follow a straight line.

3. Results and Discussion

3.1 Direction and strength of the response

Figure 1 presents the TEC–SSN scatter plots for the eight stations, each with its fitted line and coefficient, and Table 2 lists the coefficients in order of increasing geomagnetic latitude.

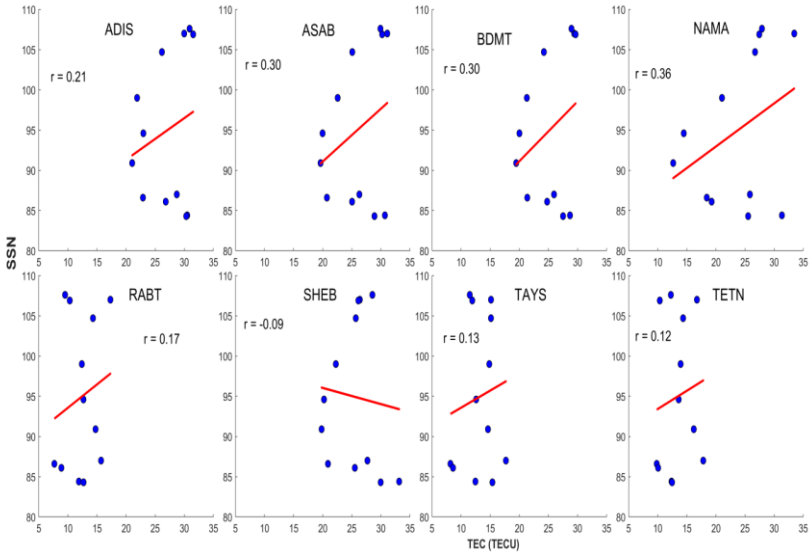


Figure 1: TEC plotted against sunspot number (SSN) at the eight stations, with least-squares lines (red) and correlation coefficients (r).

Table 2: Station coordinates and correlation coefficient (r) between TEC and SSN, 2013.

Station / Country	**Code**	**Geographic latitude (°N)**	**Geomagnetic latitude (°N)**	**r (TEC–SSN)**
Addis Ababa, Ethiopia	ADIS	9.04	1.12	0.21
Bahir Dar, Ethiopia	BDMT	11.59	2.80	0.30
Asab, Eritrea	ASAB	13.06	4.92	0.30
Sheb, Eritrea	SHEB	15.85	7.43	−0.09
Saudi Arabia	NAMA	19.20	11.49	0.36
Saudi Arabia	TAYS	28.50	20.86	0.13
Rabat, Morocco	RABT	33.99	23.86	0.17
Tetouan, Morocco	TETN	35.56	26.58	0.12

TEC rises with SSN at seven of the eight stations, in line with the expectation that stronger solar ultraviolet and extreme ultraviolet emission produces more ionization. The coefficients are nevertheless modest, lying between −0.09 and 0.36. NAMA has the highest value (r = 0.36), followed by ASAB and BDMT (r = 0.30 each). ADIS (r = 0.21) and RABT (r = 0.17) are weakly positive, and TAYS (r = 0.13) and TETN (r = 0.12) are very weakly positive. SHEB is the only station with a negative coefficient (r = −0.09); the value is so close to zero that it signals the absence of a clear relationship rather than a genuine inverse one.

3.2 Latitudinal dependence

Averaging the coefficients gives r ≈ 0.22 for the five stations within 12° of the geomagnetic equator (ADIS, BDMT, ASAB, SHEB and NAMA) and r ≈ 0.14 for the three beyond 20° (TAYS, RABT and TETN). The SSN signal in TEC is thus somewhat stronger across the equatorial and low-latitude belt, where background TEC is larger and both photoionization and fountain transport are more effective. NAMA, at 11.49°N geomagnetic latitude, is the station nearest to the expected EIA crest position (about ±15° to ±20°) and gives the highest coefficient, which suggests that TEC close to the crest is particularly sensitive to changes in solar activity. At the higher-latitude stations the weak response indicates that regional ionospheric dynamics, geomagnetic activity, local time and season matter more than SSN.

The ordering with latitude is not strictly monotonic. SHEB (7.43°N) lies among stations with positive coefficients yet shows none, pointing to local influences at that site during the study period. Denser latitudinal coverage and a longer record would be needed to separate such local effects from the general trend.

3.3 Comparison with earlier studies

The positive but modest TEC response to SSN agrees in sign with the increase of equatorial TEC with solar activity reported for Lagos and Pucallpa (Akala et al., 2013) and with the examination of solar-cycle TEC variation at Birnin Kebbi (Ogwala et al., 2019). A weak positive correlation has likewise been reported between F10.7 and TEC perturbations over Uganda during the ascending phase of the cycle (Andima et al., 2015), although that study concerned perturbations rather than TEC itself. Weak or occasionally negative coefficients at individual stations can arise from geomagnetic disturbance, a delay between solar forcing and ionospheric response, and limitations of the measurements. Geomagnetic storms in particular strongly affect TEC at equatorial and low latitudes (Mishra et al., 2020) and produce TEC anomalies and irregularities over Africa (Anoruo et al., 2022). Because this study correlates one monthly value per station with monthly SSN, such influences are averaged together, which lowers the coefficients.

4. Conclusion

The effect of sunspot number on TEC was examined at eight equatorial and low-latitude Northern Hemisphere stations during 2013, a year of moderate solar activity. TEC is weakly to moderately and positively correlated with SSN at seven stations (r up to 0.36) and shows no meaningful relationship at the eighth (r = −0.09). The response is stronger on average at the five stations within 12° of the geomagnetic equator than at the three beyond 20°, and is highest at NAMA, the station closest to the EIA crest. SSN is therefore a contributing but not dominant influence on equatorial TEC at the moderate phase of the solar cycle, with local geophysical factors, season and geomagnetic conditions also playing substantial roles. These findings can inform ionospheric modelling and the design of satellite navigation and communication systems in the equatorial belt, and should be tested with multi-year data spanning several phases of the cycle.

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Conflict of interest

The authors declared no any competing interests.

References

Akala, A. O., Seemala, G. K., Doherty, P. H., Valladares, C. E., Carrano, C. S., Espinoza, J., & Oluyo, S. (2013). Comparison of equatorial GPS-TEC observations over an African station and an American station during the minimum and ascending phases of solar cycle 24. *Annales Geophysicae*, 31, 2085–2096. https://doi.org/10.5194/angeo-31-2085-2013

Andima, G., Jurua, E., Amabayo, E. B., & Habarulema, J. B. (2015). Statistical analysis of TEC perturbations over a low latitude region during 2009–2013 ascending solar activity phase. *Advances in Space Research*, 56(11), 2542–2551.

Anoruo, C. M., Rabiu, B., Okoh, D., Okeke, F. N., & Okpala, K. C. (2022). Irregularities in the African ionosphere associated with total electron content anomalies observed during high solar activity levels. *Frontiers in Astronomy and Space Sciences*, 9, https://doi.org/10.3389/fspas.2022.947473.

Appleton, E. V. (1946). Two anomalies in the ionosphere. *Nature*, 157, 691. https://doi.org/10.1038/157691a0

Balan, N., Liu, L., & Le, H. (2018). A brief review of equatorial ionization anomaly and ionospheric irregularities. *Earth and Planetary Physics*, 2(4), 257–275. https://doi.org/10.26464/epp2018025

Benoit, A. G. M. d. S., & Petry, A. (2021). Evaluation of F10.7, sunspot number and photon flux data for ionosphere TEC modeling and prediction using machine learning techniques. *Atmosphere*, 12(9), Article 1202. https://doi.org/10.3390/atmos12091202

Jonah, O. F., de Paula, E. R., Muella, M. T. A. H., Dutra, S. L. G., Kherani, E. A., Negreti, P. M. S., & Otsuka, Y. (2015). TEC variation during high and low solar activities over South American sector. *Journal of Atmospheric and Solar-Terrestrial Physics*, 135, 22–35. https://doi.org/10.1016/j.jastp.2015.10.005

Mishra, R. K., Adhikari, B., Chapagain, N. P., Baral, R., Das, P. K., Klausner, V., & Sharma, M. (2020). Variation on solar wind parameters and total electron content over middle- to low-latitude regions during intense geomagnetic storms. *Radio Science*, 55, Article e2020RS007129. https://doi.org/10.1029/2020RS007129

Ogwala, A., Oyedokun, O. J., Ogunmodimu, O., Akala, A. O., Ali, M. A., Jamjareegulgarn, P., & Panda, S. K. (2022). Longitudinal variations in equatorial ionospheric TEC from GPS, Global Ionosphere Map and International Reference Ionosphere-2016 during the descending and minimum phases of Solar Cycle 24. *Universe*, 8(11), 575. https://doi.org/10.3390/universe8110575

Ogwala, A., Somoye, E. O., Ogunmodimu, O., Adeniji-Adele, R. A., Onori, E. O., & Oyedokun, O. (2019). Diurnal, seasonal and solar cycle variation in total electron content and comparison with IRI-2016 model at Birnin Kebbi. *Annales Geophysicae*, 37, 775–789. https://doi.org/10.5194/angeo-37-775-2019

Oron, S., D'ujanga, F. M., & Ssenyonga, T. J. (2013). Ionospheric TEC variations during the ascending solar activity phase at an equatorial station, Uganda. *Indian Journal of Radio & Space Physics*, 42(1), 7–17.

Rabiu, A. B., Adewale, A. O., Abdulrahim, R. B., & Oyeyemi, E. O. (2014). TEC derived from some GPS stations in Nigeria and comparison with the IRI and NeQuick models. *Advances in Space Research*, 53, 1290–1303.

Tapping, K. F. (2013). The 10.7 cm solar radio flux (F10.7). *Space Weather*, 11(7), 394–406. http://doi.org/10.1002/swe.20064

WDC–SILSO. (2025). Yearly mean total sunspot number and monthly smoothed total sunspot number data series. Royal Observatory of Belgium. https://www.sidc.be/SILSO/datafiles