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Special Section:
Advances in Deep Learning for Satellite Data Analysis and Interpretation

Key Points:

- The ionospheric total electron content (TEC) variation due to four solar eclipse events over Ethiopia region was studied for the first time
- Solar eclipses lowered the value of TEC up to 38% during various eclipse events over Addis Ababa and Bahir Dar stations in Ethiopia
- The rate of reduction of TEC was found to depend on path of eclipse, magnitude, local time, and location of the station

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Variation in Total Electron Content Over Ethiopia During the Solar Eclipse Events

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Abstract This work studies variations of ionospheric total electron content (TEC) during four distinct solar eclipse events over the Ethiopia region. Dual-frequency global positioning system (GPS) data obtained from UNAVCO over Addis Ababa (9.036°N, 38.76°E) and Bahir Dar (11.6°N, 37.34°E) stations are used to examine the ionospheric variability during two annular solar eclipses on 15 January 2010 and 1 September 2016, a partial solar eclipse on 4 January 2011, and a hybrid solar eclipse (the eclipse path starts out as annular but later changes to total) on 3 November 2013. The results show a significant decrease in TEC values during the occurrence of the solar eclipses. Specifically, the TEC values are reduced to −20% and −10% during the annular eclipse on 15 January 2010, −33% and −38% during the partial solar eclipse on 4 January 2011, −26% and −24% during the annular solar eclipse on 1 September 2016, over the Addis Ababa and Bahir Dar stations, respectively. There is only minimal change in TEC of −8% and −9% at Addis Ababa and Bahir stations, respectively, during the 3 November 2013 solar eclipse even if the obstruction rate is high over the study area. Furthermore, the study shows that the spatial gradient of TEC reduction varies at different locations, which is attributed to the distinct amount of reduction in solar radiation reaching the Earth's surface, resulting in reduced photo-ionization. Overall, this study provides insightful information about the behavior of the ionospheric TEC during solar eclipses over Ethiopia and emphasizes the use of dual-frequency GPS data in tracking the variations of the TEC.

1. Introduction

Solar eclipse is an interesting astronomical event where the Moon aligns with the Sun and the Earth, blocking the Sun's light (Carter, 2015). A total solar eclipse occurs when the disc of the Moon completely blocks out the disc of the Sun. However, only a portion of the sun is blocked out during partial and annular eclipses (Möllmann & Vollmer, 2006; Reddy, 2012). During a total eclipse, the totality can last from a few seconds to about 7 min, depending on various factors such as the Moon's distance from Earth and the Earth's rotation. The degree of coverage during partial eclipse depends on the observer's location within the eclipse path (Silwal et al., 2021).

The ionosphere, a region of the Earth's upper atmosphere, is ionized by solar radiation, resulting in the presence of free electrons. During a solar eclipse, the Earth's ionosphere experiences significant effects, including total electron content (TEC), plasma frequency, and radio propagation (Ding et al., 2010; Miller, 2001; Şentürk et al., 2021; Silwal et al., 2021). TEC refers to the measurement of the number of free electrons present in a unit cross-sectional area from the Earth's surface to the top of the ionosphere (Ghimire et al., 2022; Sharma et al., 2010). The main effect of a solar eclipse on the ionospheric TEC is a reduction in electron density (Krankowski et al., 2006; Le et al., 2020). As the Moon blocks the Sun's radiation, there is a decrease in the ionization and subsequent electron production in the ionosphere (Vyas & Sunda, 2012). This reduction in electron density leads to a decrease in TEC values during the eclipse period (Cherniak & Zakharenkova, 2018; Pradipta et al., 2018; Sharma et al., 2010). This decrease in TEC during the eclipse period can have significant effects on radio wave propagation and communication systems (Dear et al., 2020; Le et al., 2020). It leads to signal attenuation, causing a decrease in signal strength, as well as signal delay, impacting accurate timing applications (Uryadov et al., 2016). Communication systems relying on ionospheric propagation may experience disruptions, increased noise, and signal degradation (Dear et al., 2020; Evans, 1965; Ryba & Taylor, 1991). Ionospheric scintillation, characterized by rapid fluctuations in signal amplitude and phase, can also occur (Ya'acob

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et al., 2014). Thus, the decrease in TEC and the effects of TEC changes during eclipses is important for improving communication system resilience and advancing our knowledge of ionospheric dynamics.

In the past, various studies have been conducted on the impact of solar eclipses on ionospheric TEC over different locations of the Earth (e.g., Dear et al., 2020; Eisenbeis & Occhipinti, 2021; Evans, 1965; Ghimire et al., 2022; Idosa Uga & Beshir Seba, 2023; Le et al., 2020; Reddy, 2012; Ryba & Taylor, 1991; Sharma et al., 2010; Silwal et al., 2021, and references therewith). Eisenbeis and Occhipinti (2021) used data of ∼110 GNSS stations to study ionospheric irregularity during the 2 July 2019 solar eclipse. They found 25%–40% decrement in TEC during the Eclipse period. Hoque et al. (2016) studied ionospheric changes during the 20 March 2015 solar eclipse over European region and found the reduction of up to 6 TEC units. Şentürk et al. (2021) observed decrement of ionospheric TEC up to 50% during the 21 June 2020 solar eclipse over Northern Europe. Sharma et al. (2010) observed reduction in ionospheric TEC even during the morning eclipse over Indian region. Observations during the total solar eclipse on 21 August 2017, by Pradipta et al. (2018), over North America using global positioning system (GPS) TEC and ionosonde data showed substantial reductions (33%–45%) in TEC and ionospheric plasma densities due to the eclipse. Ghimire et al. (2022) studied the ionospheric responses to the solar eclipse on 22 July 2009 over Nepal region. They found that the TEC deviated between 1 and 5 TECU from the mean vertical total electron content (VTEC) value of the five quietest days. Silwal et al. (2021) studied 15 January 2010 and 21 June 2020 solar eclipses and finds that the measure of the decrease in TEC is proportional to the obscuration of the lunar disc. Vyas and Sunda (2012) investigated the solar eclipse and related ionospheric TEC fluctuations across Indian stations on 15 January 2010. They observed that all of the stations in the path of the eclipse showed signs of the eclipse's impact on the diurnal changes of TEC. By causing localized counter-electrojets, atmospheric gravity waves, and a reduction in the intensity of solar radiation, the solar eclipse changed the ionospheric behavior along its route. Krankowski et al. (2008) studied the variation in TEC during the total solar eclipse on 3 October 2005 in Europe. They found that the eclipse's effects could be clearly seen in TEC fluctuations for certain satellite passes as well as daily variations. Across a wide area, the steady TEC fall and subsequent rise of the trough-like oscillations were seen during the eclipse, with the decrement rate of 3–4 TEC unit over the study region.

The rate of the TEC reduction depends on various factors, including the duration and type of eclipse (partial or total), the location of the observer, the ionospheric conditions, and the altitude of the ionospheric layers affected by the eclipse. Thus, in the past, numerous works have been done for evaluating ionospheric TEC changes during the eclipse events over different parts of the globe. In this paper, we examine the behavior of ionospheric TEC during four solar eclipse events on 15 January 2010, 4 January 2011, 3 November 2013, and 1 September 2016, over Ethiopia region for the first time. The paper is organized as follows. We describe data and methodology in Section 2. We discuss our results in Section 3. Finally, we conclude our findings in Section 4.

2. Data and Methods

2.1. Events Information

We study ionospheric TEC variability during the four eclipse events over two stations, Addis Ababa (Oromia) and Bahir Dar (Amhara) regions, of Ethopia. The geographical information of these stations are shown in Table 1. On 15 January 2010, an annular solar eclipse took place, reaching its maximum at 07:06:33 Universal Time (UT) with a magnitude of 0.9190. Lasting 3 hr and 11 min and 8 s, it was predicted to be the longest annular eclipse of the century. In Ethiopia, specifically in Addis Ababa, the eclipse was visible as a partial solar eclipse with 60.56% coverage and a magnitude of 0.7018. It began at 7:14:32 LT (4:14:32 UT), reached its maximum at 8:38:53 LT (5:38:53 UT), and ended around 10:26:11 LT (7:26:11 UT). In Bahir Dar, another Ethiopian station, the partial solar eclipse had 54.29% coverage and a magnitude of 0.6474. It started at 7:16:56 LT (4:16:56 UT), reached its maximum at 8:38:50 LT (5:38:50 UT), and finished at about 10:22:16 LT (7:22:16 UT). On 4 January 2011, a partial solar eclipse occurred. In Addis Ababa, it was visible as a partial solar eclipse with 2.93% coverage and a magnitude of 0.0856, starting at 7:43:25 a.m. (10:43:25 LT), reaching its maximum at 8:27:52 a.m. (11:27:52 LT), and ending around 9:13:30 p.m. (12:13:30 LT). Similarly, in Bahir Dar, it had 7.00% coverage and a magnitude of 0.1541, commencing at 7:29:14 UT (10:29:14 LT), reaching its maximum at 8:27:02 UT (11:27:02 LT), and ending at about 9:27:08 UT (12:27:08 LT). On 3 November 2013, a hybrid solar eclipse occurred with a magnitude of 1.0159, visible as a partial solar eclipse in Addis Ababa with 82.50% coverage and a magnitude of 0.8614. It began at 1:14:13 UT (4:14:13 LT), reached its maximum at 2:24:12 UT (5:24:12 LT), and ended around 3:02:08 UT (6:02:08 LT). In Bahir Dar, it had 71.87% coverage and a magnitude of 0.7765, starting at 1:11:58 UT

Table 1
Geographical Information of the Stations

Stations	Geogr. lat.	Geogr. long.	Geomag. lat.	Geomag. long.	Local time
Addis Ababa	9.036°N	38.76°E	−0.27°N	110.51°E	UT+3
Bahir Dar	11.6°N	37.34°E	2.23°N	109.04°E	UT+3

(4:11:58 LT), reaching its maximum at 2:24:12 UT (5:24:12 LT), and concluding at about 3:04:44 UT (6:04:44 LT). An annular solar eclipse occurred on 1 September 2016, visible in Addis Ababa as a partial solar eclipse with 33.85% coverage and a magnitude of 0.4539. It began at 7:05:12 UT (10:05:12 LT), reached its maximum at 8:35:37 UT (11:35:37 LT), and ended around 10:10:46 UT (13:10:46 LT). In Bahir Dar, it had 28.37% coverage and a magnitude of 0.401, starting at 7:03:33 UT (10:03:33 LT), reaching its maximum at 8:28:16 (11:28:16 LT), and ending at about 9:58:28 UT (12:58:28 LT) hours. The eclipse period information over the studied stations, including the time period and magnitude, are presented in Table 2. The relationship between LT and UT for the Ethiopian region is given by,

$$LT = UTC + 3 \tag{1}$$

The information of all eclipse are accessed from the websites: https://www.timeanddate.com/eclipse/solar/2010-january-15, https://www.timeanddate.com/eclipse/solar/2011-january-4, https://www.timeanddate.com/eclipse/map/2013-november-3, and the https://www.timeanddate.com/eclipse/solar/2016-september-1, respectively.

2.2. Data Set

In this study, we use GPS-TEC data over two stations of Ethiopia, Addis Ababa (ADIS) and Bahir Dar (BDAR). We select four solar eclipse events, 15 January 2020; 4 January 2011; 3 November 2013; and 1 September 2016, occurred during Solar Cycle 24. The ionospheric TEC data are downloaded from the UNAVCO (University NAVSTAR Consortium) website (https://www.unavco.org/data/gps-gnss/data-access-methods/dai1/dai1.html). We also use the Operating Mission as Nodes on the Internet website system (https://omniweb.gsfc.nasa.gov/) to access the data of the solar wind parameters such as z-component of interplanetary magnetic field (IMF Bz) and solar wind speed (Vsw), and geomagnetic indices, Kp, Ap, Dst, and AE, during the considered events. The change in total electron content (DTEC) and spatial gradient TEC are calculated to evaluate the variation in TEC during these events over the study area.

2.3. Estimation of STEC and VTEC

Slant TEC (STEC) is the integrated electron density along the signal path from a satellite to a receiver on the ground. It is measured in terms of TEC, generally expressed in TEC units (TECu). The STEC between a GPS satellite (S) and a ground-based receiver (R) can be expressed as (Sun et al., 2017),

Table 2
Eclipse Information

Eclipse	Station	Obscuration	Magnitude	Duration	Start time (UT)	Maximum (UT)	End time (UT)
15 January 2010	ADIS	60.56%	0.7018	3 hr 11 min 39 s	4:14:32 a.m.	5:38:53 a.m.	7:26:11 p.m.
	BDAR	54.29%	0.6474	3 hr 5 min 20 s	4:16:56 a.m.	5:38:50 a.m.	7:22:16 p.m.
4 January 2011	ADIS	2.93%	0.0856	1 hr 30 min 5 s	7:43:25 a.m.	8:27:52 a.m.	9:13:30 a.m.
	BDAR	7.00%	0.1541	1 hr 57 min 54 s	7:29:14 a.m.	8:27:02 a.m.	9:27:02 a.m.
3 November 2013	ADIS	82.50%	0.8614	2 hr 10 min 53 s	1:14:13 p.m.	2:24:12 p.m.	3:02:08 p.m.
	BDAR	71.87%	0.7765	2 hr 10 min 58 s	1:14:13 p.m.	2:24:12 p.m.	3:02:08 p.m.
1 September 2016	ADIS	33.85%	0.4539	3 hr 5 min 34 s	7:05:12 a.m.	8:35:37 a.m.	10:10:46 a.m.
	BDAR	28.37%	0.401	2 hr 54 min 55 s	7:03:33 a.m.	8:28:16 a.m.	9:58:28 a.m.

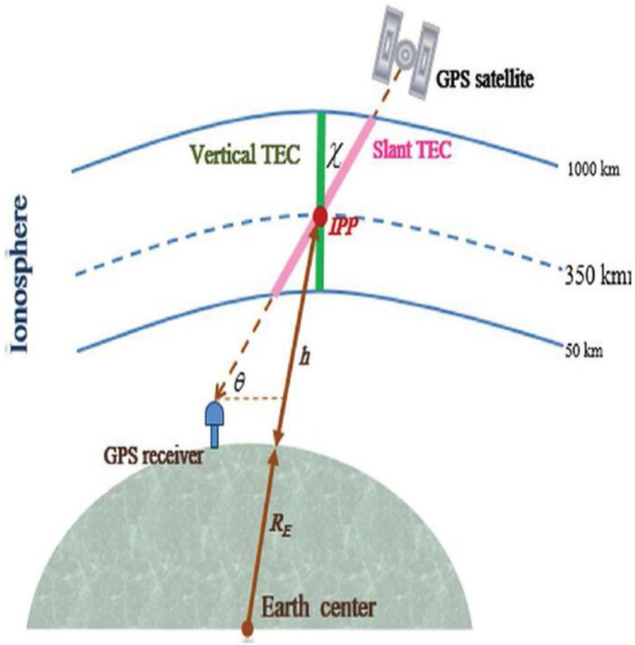

Figure 1. Vertical value of total electron content obtained from slant total electron content. (Source: Thai GNSS and Space Weather Information Data Center, http://iono-gnss.kmitl.ac.th/).

$$STEC = \int_R^S Ndl \tag{2}$$

where l is the direction from the receiver to the satellite, and N is the location-dependent electron density expressed in electron per meter cube. The STEC also can be computed using pseudo-range and phase data as (Bagiya et al., 2009; Ghimire et al., 2022; Idosa et al., 2023),

$$STEC = \frac{1}{40.3} \times \left(\frac{1}{L1^2} - \frac{1}{L2^2}\right)^{-1} \times (P1 - P2) + TEC_{CAL} \tag{3}$$

where L1 and L2 are two L-band frequencies, having respective frequencies of 1,575.42 MHz and 1,227.60 MHz, that are transmitted by each GPS satellite. A dual-frequency GPS receiver examines the difference in ionospheric delay between the L1 and L2 signals as the GPS signal travels through the ionosphere to estimate the TEC value (Bagiya et al., 2009). $P1$ is the Pseudo range at $L1$, $P2$ is the Pseudo range at $L2$, and TEC_{CAL} is the bias error correction (Fayose et al., 2012).

An analogous vertical value of TEC (VTEC), which is independent of the height of the wave path, is determined based on the geometry of the path of the wave through the ionosphere as shown in Figure 1. According to Klobuchar (1987), the VTEC can be calculated by projecting from the slant to the vertical using the thin shell model and assuming a height of 350 km as,

$$VTEC = STEC \times Cos(\chi) \tag{4}$$

where,

$$Sin(\chi) = \frac{R_E}{R_E + h} Cos\theta \tag{5}$$

$$Cos\chi = \sqrt{1 - \left(\frac{R_E}{R_E + h} Cos\theta\right)^2} \tag{6}$$

Using Equation 5 in Equation 3, the VTEC takes the form,

$$VTEC = STEC \times Cos\left[Sin^{-1}\left(\frac{R_E\, Cos\theta}{R_E + h}\right)\right] \tag{7}$$

where; χ is the Zenith angle (degree), θ is an elevation angle of the satellite (degree), R_E is Earth's radius (6,378.137 km), h is the height of the ionospheric layer (assuming that the height at 350 km).

2.4. Deviation in TEC (DTEC)

Using the observational data from the considered stations, during the event period and quiet period, the difference in TEC (DTEC) is computed using the following equation (Idosa & Shogile, 2023),

$$DTEC\% = \frac{TEC_{eclipse} - TEC_{quiet}}{TEC_{quiet}} \times 100\% \tag{8}$$

where, $TEC_{eclipse}$ and TEC_{quiet} are the TEC values during the eclipse and quiet period, respectively. For the quiet-time TEC, similar to Silwal et al. (2021), we took a mean TEC of top five quietest days of the month, accessed from the World Data Center for Geomagnetism, Kyoto (https://wdc.kugi.kyoto-u.ac.jp/).

Table 3
Summary of Variations of Total Electron Content Over Both Stations During Eclipse Day

Eclipse day	Stations	DTEC %	(Time)
15 January 2010	ADIS	−20	(06:30 UT)
	BDAR	−10	(07:30 UT)
4 January 2011	ADIS	−33	(06:30 UT)
	BDAR	−38	(07:00 UT)
3 November 2013	ADIS	−8	(14:25 UT)
	BDAR	−9	(14:20 UT)
1 September 2016	ADIS	−26	(08:32 UT)
	BDAR	−24	(08:40 UT)

2.5. Spatial Gradient

A spatial gradient, also known as "spatial derivatives," is the rate at which a particular scalar physical quantity changes in relation to the location coordinates (Haupt, 2002). We employed a spatial gradient approach to understand the behavior of ionospheric TEC (the decrease in TEC) over two selected stations using their longitudinal coordinate separations. In this method, if the spatial gradient value (TEC in TECU/long) is low, the station with the greater geographic longitude is more highly affected by the solar eclipse than the station with the lower geographic longitude. But if the spatial gradient value (TEC in TECU/long) is high, the station with the greater geographic longitude is less affected by the solar eclipse than the station with the lower geographic longitude. The spatial gradient TEC is calculated using the formula expressed as (Idosa & Shogile, 2022),

$$Spatial\ Gradient = \frac{TEC_A - TEC_B}{\Delta L} \quad (9)$$

where TEC_A and TEC_B are TEC over Addis Ababa and Bahir Dar stations, respectively. ΔL is the geographic longitudinal difference between the two stations.

3. Results and Discussions

In this section, we discuss the ionospheric TEC variation over two stations of Ethiopia during the four solar eclipse events of Solar Cycle 24. Table 3 summarizes the observed TEC decrement rates.

3.1. Geomagnetic Activity Levels

The ionospheric irregularities are mainly caused due to the solar activities. We aim to estimate accurate depletion level of TEC over Ethopia due to the Eclipse events. We want our events do not influence by major geomagnetic activities. From Figures 2 and 3, we see no significant disturbances before, during, and after the Eclipse events of 15 January 2010, 4 January 2011, and 3 November 2013. For these events, the interplanetary magnetic field data ranging between −5 and 5 nT. Solar wind speed lies between the 400–500 km/s. The Kp index is settled below 30. The SYM-H value is no less than −20. The maximum AE index is reached up to 400 nT only. However, for the eclipse event of 1 September 2016, we observe some disturbances. The IMF-Bz fluctuates between −5 and 5. The solar wind speed started to increase from the 12:00 UT in 1 September and reached to around 650 km/s on 2 September. SYM-H value cross the value of −50 nT indicating the moderate storm. The increment of AE index more than 1,000 nT, indicating this event was disturbed by the geomagnetic activity. The calculated TEC depletion for this event also may have contribution of TEC variation due to the moderate storm. The contribution in TEC fluctuations due to these separate phenomenon is very complex, we still considered this event to examine the TEC responses for such type of events.

3.2. TEC Variation Before, During, and After the Eclipse Day

Figures 3a–3h shows the diurnal variations of ionospheric TEC over Addis Ababa and Bahir Dar before, during, and after the solar eclipse day. The values of ionospheric TEC before and after the eclipse day over both station show larger values than the TEC during the Eclipse day. The ionospheric TEC values during the eclipse day shows a clear signature of decrement of it over both stations. The eclipse takes longer to pass over Addis Abeba than Bahir Dar station at different eclipse events. Thus we see slight difference in TEC decrement trend. A trough-like depression in the TEC curve over the two GPS stations, which is indicative of the eclipse effect, shows the impact of a rapid reduction in the sun's ultra-violet irradiation on the dissipated electron content in the ionosphere over the sector (Airapetian et al., 2020). The effects of a solar eclipse on TEC is due to the reduction in solar radiation, which lowers the ionospheric TEC, the decreased total electron concentration is consequently observed over both stations. Our plots show similar trend in TEC variation as in the previous studies (Cherniak & Zakharenkova, 2018; Jenan et al., 2021).

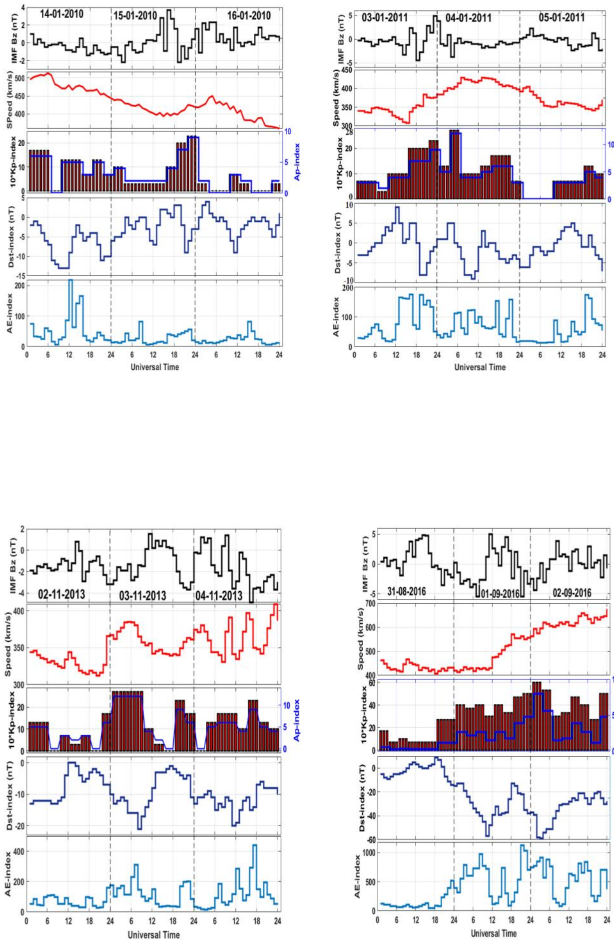

Figure 2. Variations of solar wind parameters before, during, and after the solar eclipse days on 14–16 January 2010 (upper left), 3–5 January 2011 (upper right), 2–4 November 2013 (lower left), and 31 October–2 September 2016 (lower right).

3.3. Deviation in TEC During the Eclipse Day (Comparison With the Quiet Day)

The TEC during the quiet day is compared with the TEC during the Eclipse day, using Equation 7, to find the deviation in TEC (DTEC). We observe the TEC values reduces during the eclipse period in comparison to the mean quietest days. During a solar eclipse, TEC fluctuations in the Earth's ionosphere are governed by intricate physical processes. The primary factor is the momentary occlusion of solar radiation when the Moon comes between the Earth and the Sun. This eclipse-induced reduction in solar radiation leads to decreased ionization within the ionosphere, resulting in a reduction in TEC (Dear et al., 2020; Silwal et al., 2021). Additionally, the diminishing solar Extreme Ultraviolet (EUV) radiation and changes in ionospheric absorption contribute to TEC variability (Ghimire et al., 2022; Le et al., 2020). Concurrently, alterations in temperature and ionospheric dynamics due to the eclipse can impact electron densities and ion-electron recombination rates, further influencing TEC (Senapati et al., 2020). Local geographical factors and diurnal ionospheric variations can modulate these effects (Bagiya et al., 2009; Reddy, 2012; Sharma et al., 2010). Figure 4 depicts the DTEC over Addis Ababa and Bahir Dar stations during all four eclipse events. Figures 4a and 4b shows that on 15 January 2010 annular solar eclipse event, the DTEC is about −20% and −10% around the end of the eclipse over Addis Ababa and Bahir Dar station, respectively. Figures 4c and 4d depicts the DTEC during 4 January 2011, partial eclipse. −33% TEC over Addis Ababa and −38% TEC over Bahir Dar station is reduced during this event. We notice that the TEC started decreasing before the eclipse at both stations for this event. Since this eclipse was occurred during early morning hours, solar radiation is just starting to reach the Earth's ionosphere, and the ionization levels may be lower compared to later in the day. This can lead to a decrease in TEC. We found minimal change in TEC at both stations during the total solar eclipse event of 3 November 2013 as shown in Figures 4e and 4f. The TEC decrement rate are 8% and 9% at Addis Ababa and Bahir Dar, respectively. Although it was one of the powerful eclipse worldwide, the obstruction rate over the selected stations are small. The result shows that the degree of the lunar disc's obscuration, which is strongly related to the creation of electrons through the photo-ionization process, is proportional to the decline in the vertical value of the TEC. During the 1 September 2016 solar eclipse, as shown in Figures 4g and 4h, we observe the DTEC of about −26% and −24% over Addis Ababa and Bahir Dar stations, respectively. The apparent fluctuation throughout the eclipse period showed the consistent trends with previous works on ionospheric irregularities due to the solar eclipse (Silwal et al., 2021; Tripathi et al., 2022). It is also observe that during 4 January 2011, and 1 September 2016, eclipse periods, the region of drop in TEC is not symmetric in latitude, but the area of highest decline has a greater obstruction magnitude in the range of 0.0856–0.4539. Notably, during the event of 1 September 2016, there is a substantial decrease in TEC following the eclipse period. This decrease is attributed to a moderate storm, occurred around 09:30 UT on 1 September 2016, which is expected to have caused negative ionospheric disturbances leading to the reduction in TEC during daytime as shown in Figures 4g and 4h. On 1 September 2016, moderate storm occurred during the end hours of the eclipse; thus, we expect some contribution of this storm on the TEC decrement due to eclipse over Ethiopia region. Furthermore, when closely examining DTEC in %, we observe periods in which there are significant increases/decreases in TEC during non-eclipse period compared to eclipse periods. The day-to-day variability of TEC is a complex and intriguing area of ongoing research. Thus, in this work, our primary focus is on the eclipse period only.

3.4. Spatial Gradient TEC During the Solar Eclipses

The distance between Addis Ababa and Bahir Dar is approximately 322 km (200 miles), with a longitudinal separation of about 1.41°E between the two stations. Although obstruction rate is one of the major factors, other

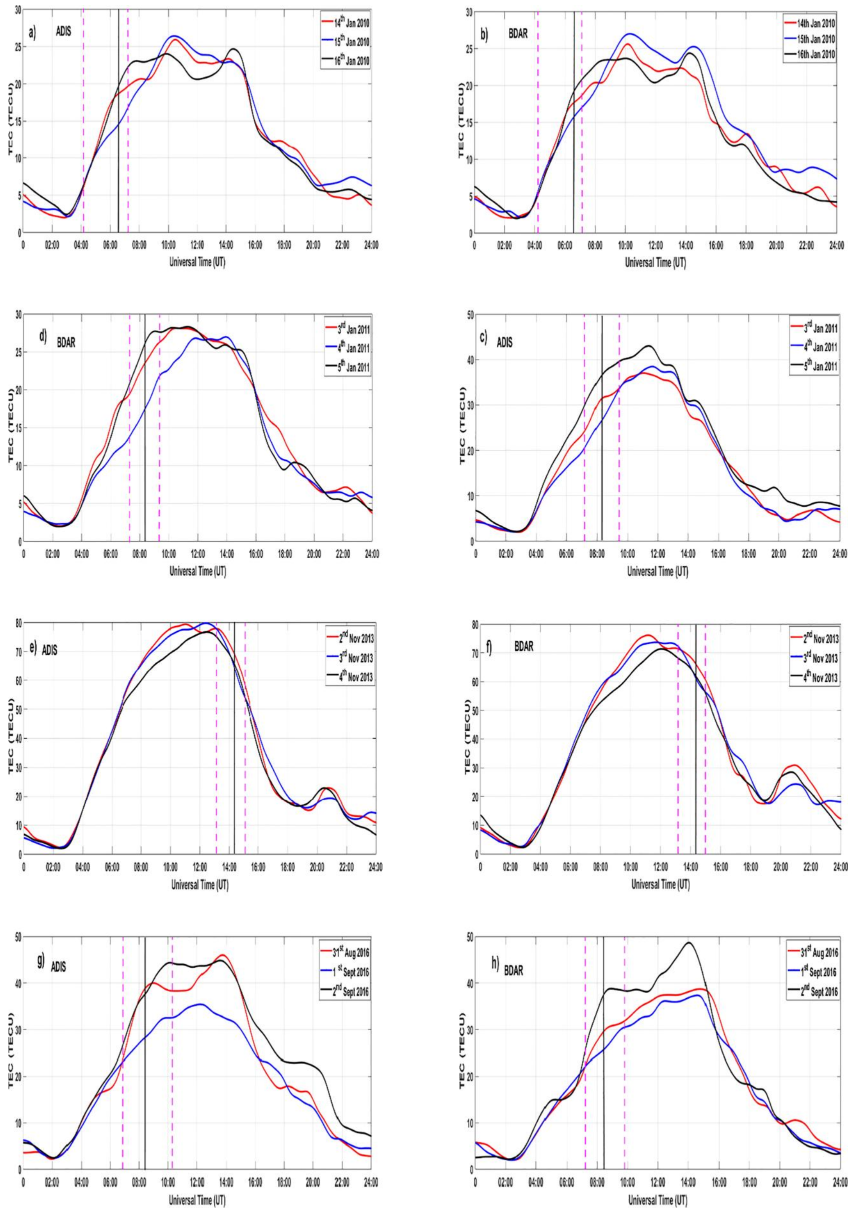

Figure 3. Diurnal variations of total electron content before, during, and after the solar eclipse days on 14–16 January 2010, 3–5 January 2011, 2–4 November 2013, and 31 October–2 September 2016, over Addis Ababa and Bahir Dar stations. The pink dashed lines represent the eclipse start and end times. The black solid line represents the maximum eclipse time.

parameters such as geographical location, LT, etc., also plays and important role for the rate of reduction in TEC during eclipse time. Spatial Gradient TEC refers to the rate at which TEC changes with respect to spatial location. It is a parameter used to describe how the electron density varies across different locations in the ionosphere (Hoque et al., 2016). It is calculated by determining the change in TEC over a given distance. A positive spatial gradient indicates an increase in TEC with increasing distance, while a negative spatial gradient indicates a decrease in TEC with increasing distance. We calculate the spatial gradient of TEC during eclipse events using Equation 9. The data for vertical TEC measurements at one-minute resolution for both stations are averaged to estimate the spatial gradient of TEC (Cesaroni et al., 2015; Chandra et al., 2009). Figure 5a–5d illustrates the variations in TEC spatial gradients over Addis Ababa and Bahir Dar during the eclipse days. In Figure 5a, the spatial gradient TEC variations is shown during the solar eclipse day on 15 January 2010. Particularly, during eclipse time, we see significant difference in TEC, with gradient TEC value of −1.3 TECU/long. This indicates

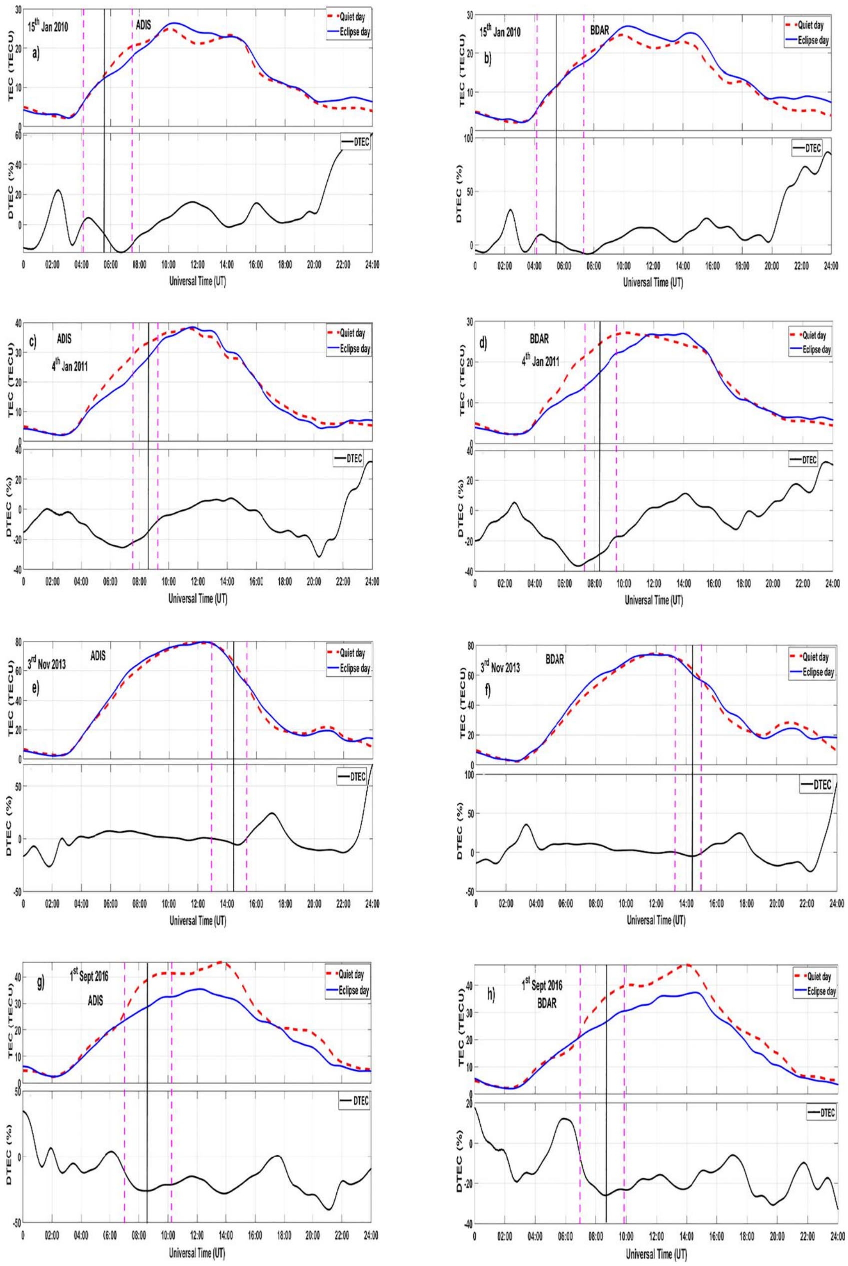

Figure 4. Deviation in total electron content over Addis Ababa and Bahir Dar stations during 15 January 2010, 4 January 2011, 3 November 2013, and 1 September 2016 eclipse events.

that the TEC rates at these two stations are dissimilar, and they are not equally affected by the eclipse event. On 4 January 2011 (Figure 5b), during a partial solar eclipse event, Addis Ababa station is significantly more affected compared to Bahir Dar station, as evidenced by the gradient TEC variation ranging from 1.3 to 2.5 TECU/long during the eclipse period, attributed to the event occurring during the daytime. We notice this value more increased to 3 TECU/long after the eclipse end, indicating the effect is more stronger during post-eclipse period. On 3 November 2013 (Figure 5c), during a hybrid solar eclipse, the difference in TEC change at both stations is very less pronounced compared to the eclipse on 4 January 2011. The value of gradient TEC is ranging between −0.3 and −0.9 TECU/long during the eclipse time. Note that, as there is no significant DTEC during this event, this value of gradient TEC is might not be associated with TEC change due to eclipse rather it is a normal day-to-day gradient TEC. During the September 2016 eclipse, the gradient TEC during the eclipse period is in a range of very high value, indicating a larger difference in TEC change over these stations. A significant dip in gradient

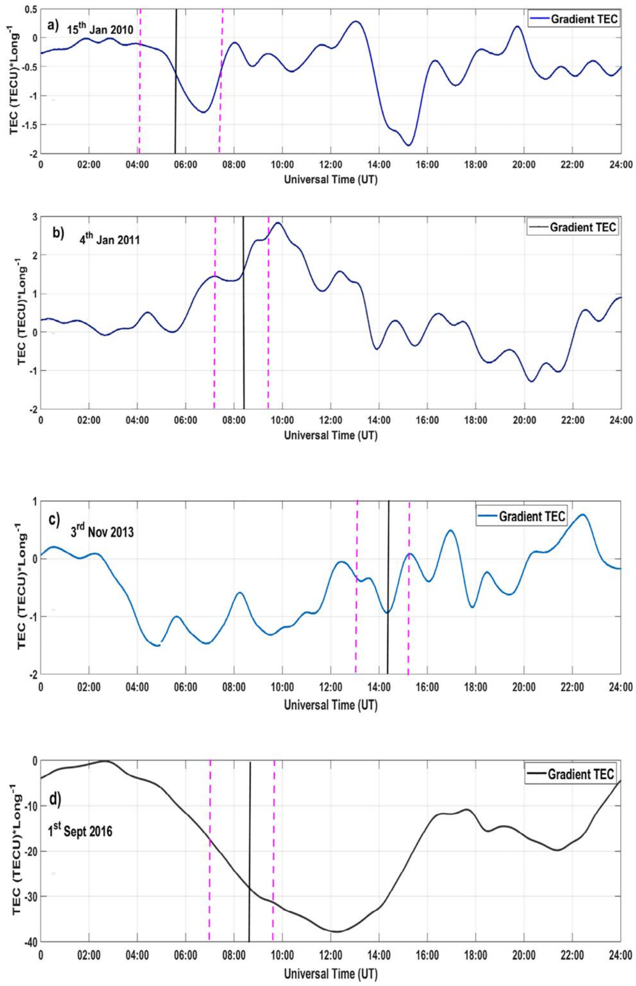

Figure 5. Spatial gradient total electron content between Addis Ababa and Bahir Dar before, during, and after the solar eclipse day on (a) 14–16 January 2010, (b) 3–5 January 2011, (c) 2–4 November 2013, and (d) 31 October–2 September 2016.

TEC was observed after noon on the eclipse day, attributed to a moderate storm that occurred at that time, highlighting the dissimilarity in TEC variation between these two locations. Overall, there is a significant difference in TEC during normal time as well as event time as the TEC change depend on geographical locations. Also, we noticed that as the eclipse path for these stations are varying, there is dissimilarity on DTEC as well as gradient TEC for both stations, supporting the common understanding that the solar eclipse's impact is weaker at a station outside the path of totality.

4. Conclusion

A study was conducted to analyze the impact of four solar eclipse events on ionospheric TEC over Addis Ababa and Bahir Dar stations of Ethiopia region for the first time. The result shows that during the eclipse period, there was a noticeable decrease in TEC values compared to the days preceding and following the eclipses. We compared the TEC during eclipse day with the quiet day to find the rate of deduction in TEC over both stations in Ethiopia during all four events. It shows that there was a reduction of TEC between −8% and −38% at both stations during studied eclipse events. These changes were attributed to the reduction in photo-ionization caused by the partial or complete blocking of the sun's radiation by the Earth during the eclipse. The deduction of TEC values during the eclipse found to depend on eclipse path, sun coverage, and magnitude of the eclipse. In addition, during the eclipse period, the variations in TEC exhibit a significant dependence on LT. In the context of early morning eclipse events, TEC variations can be influenced by the transition from nighttime to daytime conditions.

The ionosphere undergoes diurnal variations, and during the early morning hours, the onset of solar radiation is a key factor. TEC may exhibit a decrease as the ionosphere transitions from its nighttime state to daytime ionization levels. The magnitude and direction of TEC variations depend on the LT when the eclipse occurs. For regions experiencing the eclipse during different times of the day, the impact on TEC will vary accordingly. Temperature changes, which are often dependent on LT, can also contribute to TEC variations. The early morning hours may experience lower temperatures, affecting the ionization processes and leading to specific patterns in TEC changes. The LT dependence of TEC variations during an eclipse period adds a layer of complexity to the analysis. In the future, carefully considering the specific LT of the eclipse event and its correlation with ionospheric changes can be studied to provide a comprehensive understanding of TEC dynamics. The spatial gradient analysis shows that the fall in TEC during eclipse is not same over the stations. The eclipse found to have less impact at the stations far from the path of totality. As change in TEC vary at different locations, many researchers over the globe are trying to understand ionospheric dynamics during eclipse events conducting similar types of research over different regions of the Earth. Thus, it is crucial to understand its impact during the different events. In summary, the practical implications of observed ionospheric irregularities during solar eclipses are wide-ranging. They offer opportunities for better understanding the ionosphere's behavior and improving the robustness of technologies that rely on it, from communication systems to navigation, scientific research, and space weather forecasting. This knowledge ultimately enhances the resilience and reliability of systems operating in the ionosphere, benefiting various industries and scientific endeavors. This is the first study ever conducted on eclipse events over Ethiopia using the data from GNSS receiver stations. We believe this study will serve as a valuable reference for the study of ionospheric dynamics during the eclipse period in this region.

Data Availability Statement

The data analyzed in this study have been obtained from the International GNSS Service (Estey & Meertens, 1999) and the OMNIWeb data sets (King & Papitashvili, 2005) from https://omniweb.gsfc.nasa.gov/form/dx1.html. TEC data was processed using GPS-TEC analysis application (G. K. Seemala, 2023; G. Seemala & Valladares, 2011).

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