Investigation of the relationship between the spatial gradient of total electron content (TEC) between two nearby stations and the occurrence of ionospheric irregularity

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Abstract. The relation between the occurrence of ionospheric irregularities and the spatial gradient of total electron content (TEC) derived from two nearby located stations (ASAB:4.34°N, 114.39°E and DEBK: 3.71°N, 109.34°E, geomagnetic), located within the equatorial region, over Ethiopia, during the post-sunset hours was investigated. Different instruments and techniques have been applied to study the behavior of ionospheric irregularities. In this study, the Global Positioning System (GPS) based derived TEC during the year 2014 obtained from the two stations were employed to investigate the relationship between the gradient of TEC and ionospheric irregularity occurrence. The spatial gradient of TEC ($\Delta TEC/\Delta lon$) and its standard deviation over 15 min $\sigma(\Delta TEC/\Delta lon)$ derived from GPS-TEC were used in this study. The rate of change of TEC derived indices ($ROTI$, $ROTI_{ave}$) are also utilized. Our results revealed that most of the maximum enhancement/reduction in $\Delta TEC/\Delta lon$ are noticeable during 19:00 - 24:00 LT hours. In some cases, the peak values in the spatial gradient of TEC are also observed during daytime and post-midnight hours. The enhancement in the intensity of $\sigma(\Delta TEC/\Delta lon)$ observed after post-sunset show similar trends with $ROTI_{ave}$, and was stronger/weaker during equinoctial/solstice months. The observed enhancement in the intensity of $\sigma(\Delta TEC/\Delta lon)$ in equinoctial season show an equinoctial asymmetry where the March equinox was greater than September equinox. The gradient in TEC and $ROTI_{ave}$ observed during the evening time period also show similar trends with equatorial electric field (EEF) but after 1-2 hrs. The relationship between $\sigma(\Delta TEC/\Delta lon)$ and $ROTI_{ave}$ correlate linearly with correlation coefficient of C = 0.7975 and C = 0.7915 over ASAB and DEBK, respectively. The vast majority of the maximum enhancement/reduction in the spatial gradient of TEC observed during the evening time period may be associated with ionospheric irregularities/equatorial plasma bubbles. In addition to latitudinal gradients, the spatial/longitudinal gradient of TEC has a significant contribution to the computation of TEC fluctuations. The spatial gradient of TEC/electron density near solar-terminator obtained from two nearby located Global Navigation Satellite System (GNSS) receivers may be used as an alternative method to estimate the strength of the zonal electric field.

Key words: Spatial gradient of TEC, $ROTI_{ave}$, ionospheric irregularities

1 Introduction

The ionosphere, which consists of free electrons and ions, frequently experiences irregular electron density. After sunset, the ionospheric plasma interchange instabilities present in the equatorial/low-latitude ionosphere generate large-scale depletions in the ambient electron density which leads to the formation of plasma density irregularities that affect radio communication and navigation system (Basu and Basu, 1981). The generation of the plasma irregularities can be related to the decrease in plasma production immediately after sunset and the fast recombination rate in the E-region ionosphere, which results in a steep electron density gradient. The large enhancement of F region vertical plasma drift in the evening hours due to the presence of enhanced eastward electric field was thought to control the generation of plasma density irregularities (Fejer, 1991; Fejer et al., 2008). This pre-reversal enhancement (PRE) vertical plasma drift moves the F region to higher altitudes (Abdu et al., 2009). When the altitude of F-region is high enough to overcome recombination effects, the Rayleigh-Taylor (R-T) instability mechanism initiates growth in plasma fluctuations. The R-T instability is considered primary responsible for the generation of ionospheric plasma density irregularities or plasma bubbles in equatorial and low-latitude region (Rao et al., 2006a; Fejer et al., 1999). Kelley (2009) reported that the existence of equatorial plasma bubbles (EPBs) is attributed to the instability of the R-T plasma which is triggered by the intensification of the eastward equatorial electric field just before its reversal. The characteristics of ionospheric scintillation and ionospheric irregularities over the equatorial and low-latitude region in different longitudinal sectors during different solar and geomagnetic activities have been studied (e.g., Burke et al., 2004; Paznukhov et al., 2012; Oladipo and Schuler, 2013a; Seba and Tsegaye, 2015). Various instruments such as all-sky imager (Wiens et al., 2006), and very high-frequency radar observation (e.g., Otsuka et al., 2009; Ajith et al., 2016) have been used utilized to study the behavior of ionospheric irregularities and related scintillations. Recently, Global Navigation Satellite System (GNSS) signal analysis is an important tool to study the behavior of ionospheric irregularities (e.g., Pi et al., 1997; Nishioka et al., 2008; Watthanasangmechai et al., 2016; Magdaleno et al., 2017) because of its growing application in civilian and military applications.

The inhomogeneity of ionospheric electron distribution can cause sudden, rapid and irregular fluctuations of the amplitude and phase of the received signals, known as ionospheric scintillation (Wernik and Liu, 1974). This inhomogeneity, i.e, spatial plasma density/TEC gradient, is higher at low-latitude region because of geomagnetic storms, equatorial spread F (ESF) and Appleton ionospheric anomaly. As the GNSS signals pass through the ionosphere, the ionospheric irregularities also cause the delay of signals. The classification of the spatial electron density/TEC gradients can be given as latitudinal (north-south) and longitudinal (east-west) (Jakowski et al., 2004). It is normally found in the literature that the spatial plasma density gradients can be represented by means of TEC changes per latitude or longitude (TECU/deg) or by their changes in distance (TECU/km). In addition to causing an integrity threat for life-safety application to air traffic management (Luo et al., 2002; Lee et al., 2011; Rungraengwajiake et al., 2015), the ionospheric TEC gradient is also unfavorable for communication, and surveillance system which depends on trans-ionospheric signal propagation (Foster, 2000). Radicella et al. (2004) and Nava et al. (2007) also presented the contribution of the horizontal gradients of vertical TEC to positioning error. The characteristics of horizontal ionospheric density gradients and their effects on trans-ionospheric radio wave propagation have been studied at different

latitudes (Jakowski et al., 2005; Radicella et al., 2004). It has been reported that the majority of large/steep gradient TEC gradients are associated with equatorial plasma bubbles (Pradipta and Doherty, 2016). Rao et al. (2006a) estimated ionospheric spatial gradient from F-region peak electron density (NmF2) data using a chain of radio soundings. Based on the GNSS data acquired by dense distribution of receivers over Brazilian longitude sector, Cesaroni et al. (2015) highlights the relationship
5   between intensity and variability of TEC gradients and the occurrence of ionospheric scintillation.

     Previous studies attempt to explain the relation between the latitudinal (N-S) gradient of TEC surrounding the anomaly region and ionospheric scintillation over different sectors (Mendillo et al., 2001; Valladares et al., 2001; Rao et al., 2006b; Ray et al., 2006; Muella et al., 2008). Mendillo et al. (2001) pointed out that equatorial ionization anomaly (EIA) strength at sunset is the best available precursor for pre-midnight ESF. Using latitudinal distribution of TEC measurements at about 20:00 LT,
10   Valladares et al. (2001) observed a high crest-to-trough ratio prevalent to ESF days. Recently, Seba et al. (2018) investigated the relation between equatorial ionization anomaly and night time ESF over East Africa longitudinal sector using data from ground-based Global Positioning System (GPS) stations and a horizontal meridional neutral wind model. To identify signals which severely suffer from ionospheric gradient, Ravi Chandra et al. (2009) and Rungraengwajiake et al. (2015) used rate of change of TEC (ROT) and rate of change of TEC index (ROTI). From the definition, however, ROTI mixes both the spatial and
15   temporal gradients of TEC variations. To show the relation between EIA and ESF, Seba et al. (2018) used ROTI and crest-to-trough ratio. Even though, the characteristics of ionospheric irregularities/plasma bubbles over equatorial/low-latitude region of Africa under different solar and geomagnetic activities were discussed (Seba and Tsegaye, 2015; Seba and Nigussie, 2016; Mungufeni et al., 2016; Kassa and Damtie, 2017; Olwendo et al., 2018; Bolaji et al., 2019; Dugassa et al., 2019), a limited number of studies have been carried out over the region relating the latitudinal/longitudinal gradient of TEC/plasma density
20   and the occurrence of ionospheric irregularities.

     The PRE of eastward electric field is one of the most important features of the equatorial ionosphere which uplift the F-layer and create a conducive condition for irregularity formation under R-T instability mechanism. The causes of the enhanced horizontal electric field have been discussed and modeled in several articles (e.g, Rishbeth, 1971; Farley et al., 1986b; Eccles, 1998; Kelley et al., 2009). Longitudinal gradient of integrated Pederson conductivity that exist across sunset terminator affects
25   the strength of PRE and the generation of ionospheric irregularities (Tsunoda, 1985). However, it is not easy to obtain the longitudinal gradient of electron density over Africa longitude sector as radar, ionograms and/or incoherent scatter measurement are not available and study the relationship between the electron density gradient and occurrence of ionospheric irregularities. It is generally known that TEC is the integral of electron density, so closely located GPS receivers would help us to examine the strength of the zonal electric field and investigate the relation between the gradient of TEC and occurrence of irregularity.
30   Investigating the relationship between the spatial gradient of TEC and occurrence of ionospheric irregularity using ground GPS-TEC receiver from two nearby located stations is the aim of the current study. The relation between the daytime eastward equatorial electric field derived from the equatorial electric field (EEF) model and the daytime equatorial electrojet (EEJ) obtained from ground based magnetometer measurements were also discussed. The study is the first of its kind in the African sector to present the relation between the spatial gradient of TEC and occurrence of ionospheric irregularities. The gradients

of plasma density might be considered as an important parameter in the modeling of ionospheric irregularities and mitigating positioning errors on GNSS based application.

2 Data and analysis method

The GNSS data used for this study were obtained from University NAVSTAR Consortium (UNAVCO) database (http://www. unavco.org/). We used data from two receiver stations located in the East African region at Debark (Geog. Lat. 13° N, Geog. Long. 37.65° E, Geomag Lat. 4.13° N) and Asab (Geog. Lat. 13° N, Geog. Long. 42.65° E, Geomag. Lat. 4.85° N) for the period 2014. The receiver-independent exchange (RINEX) observation files obtained from the IGS website were processed by the GPS-TEC application software developed at Boston College (Seemala and Valladares, 2011). The TEC analysis software uses the phase and code values for both L1 and L2 GPS frequencies to eliminate the effect of clock errors and tropospheric water vapor to calculate relative values of slant TEC (Sardón and Zarraoa, 1997; Arikan et al., 2008). In order to avoid the multipath effects, different authors have used observation data above certain cutoff mask ranging from 15° to 35° (Chu et al., 2005; Mushini and Pokhotelov, 2011). In the current study, an elevation cutoff mask of 30° was used for all the VTEC computed. Table 1 gives the list of all the stations for which data has been used in this study.

There are two independent ways of estimating the TEC gradient values using ground based GPS receiver data (e.g., Lee et al., 2007, 2010). The first method uses a pair of closely-spaced receiver stations, looking at the same GPS satellite to calculate the difference in TEC values between the two neighboring ionospheric piercing points (IPP) at any given time. The second method uses a single GPS receiver station to infer the spatial TEC gradient values based on the observed temporal rate of change in TEC. In the current study, we have applied the first method to obtain the spatial gradient of TEC. Using the computed VTEC determined from the two receiver stations, the spatial gradient of TEC (difference of TEC between two stations per longitudinal separation) was computed for every time and then we analyzed its diurnal, monthly and seasonal variations. The two stations are located nearly along the same geographic latitude with longitudinal separation of about $\sim 5°$ or corresponding spatial separation of 535.7 km. Stations with the same latitude were selected to examine only the contribution of the longitudinal gradient of TEC to the generation of ionospheric irregularities expressed by ROTI. Vertical TEC (VTEC) values obtained by averaging the VTEC over 30 min intervals for a satellite and then averaged over all satellites in view are used in the computation of the gradient of TEC. The spatial gradient of TEC utilized in this study were computed using Eq. (1) (Lee et al., 2007; Ravi Chandra et al., 2009; Cesaroni et al., 2015).

$$Spatial\ gradient\ of\ TEC(t) = \frac{VTEC_{asab}(t) - VTEC_{debk}(t)}{\Delta lon} = \frac{\Delta TEC}{\Delta lon} \tag{1}$$

where Δlon represents the difference in the longitude between the two stations. In this study, we applied standard deviation of the spatial gradient of TEC over 15 min, $\sigma(\Delta TEC/\Delta lon)$, to examine the relation between spatial gradient (zonal or E-W gradients) of TEC and occurrence of ionospheric irregularities.

The time variation of TEC also known as rate of change of TEC (ROT) and its derived indices are a good proxy for the phase fluctuation, which is a measure of large-scale ionospheric irregularities (Aarons et al., 1997) were used in this study. These kinds of indices can be used to characterize all the known features of equatorial spread F (ESF) (Mendillo et al., 2000). The rate of change of TEC (ROT) is given by

$$ROT = \frac{TEC_k^i - TEC_{k-1}^i}{t_k^i - t_{k-1}^i} \tag{2}$$

where i is the visible satellite and k is the time of epoch and ROT is in units of TECU/min. The ROTI is defined as the standard deviation of ROT over a 5-min period and mathematically given by Eq. (3) (Pi et al., 1997; Bhattacharyya et al., 2000; Nishioka et al., 2008). Usually, ROTI > 0.5 TECU/min indicates the presence of ionospheric irregularities at scale lengths of a few kilometers (Ma and Maruyama, 2006).

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2} \tag{3}$$

Oladipo and Schuler (2013b) employed the idea of Mendillo et al. (2000) to obtain a new index called $ROTI_{ave}$ index given in Eq. (4). $ROTI_{ave}$ index is the average of ROTI over 30 min interval for a satellite and then averaged over all satellites in view. The index gives average level of irregularities over half an hour. Recently, $ROTI_{ave}$ has been applied to demonstrate and explain the level of ionospheric irregularities over low-latitude/equatorial region of Africa (Oladipo et al., 2014; Bolaji et al., 2019; Dugassa et al., 2019). In this study, the rate TEC fluctuation index (ROTI) and ($ROTI_{ave}$) (Pi et al., 1997; Oladipo and Schuler, 2013b; Oladipo et al., 2014) were used to observe the occurrence of ionospheric irregularities.

$$ROTI_{ave}(0.5hr) = \frac{1}{N} \sum_{n=1}^{N} \sum_{i=1}^{k} \frac{ROTI(n, 0.5hr, i)}{k} \tag{4}$$

where n is the satellite number, $0.5hr$ is half an hour (0, 0.5, 1,... 23.5, 24 UT), i is the 5 min section within half an hour (i = 1, 2, 3, 4, 5, 6), N is the number of satellites observed within half an hour and k is the number of $ROTI$ values available within half an hour for a particular satellite. According to Oladipo and Schuler (2013b), the value of $ROTI_{ave} < 0.4$, $0.4 < ROTI_{ave} < 0.8$ and $ROTI_{ave} > 0.8$, respectively represents the background fluctuation, existence of phase fluctuation, and severe phase fluctuation activities. These threshold values were used to observe the relation between the occurrence of ionospheric irregularities and the spatial gradient of TEC.

The magnetic data used in this study are obtained from International Real-Time Magnetic Observatory Network (INTER-MAGNET) and Africa-Meridian B-field Edication and Research (AMBER) installed in Addis Ababa (AAE, 9.0° N, 38.8° E, 0.2° N, geomagnetic) and Adigrat (ETHI, 14.3° N, 39.5° E, 6.0° N, geomagnetic), respectively. It provides one minute

values of the northward (X), eastward (Y), vertical (Z) components of the Earth's magnetic field, from where the horizontal component (H) is computed using Eq. (5).

$$H = \sqrt{X^2 + Y^2} \tag{5}$$

To avoid different offset values of different magnetometers, the nighttime baseline values in the H component (Eq. 6) are first obtained for each day and subtracted from the corresponding magnetometer data sets to obtain the hourly departure of H denoted ΔH expressed by Eq. (7). The baseline value was defined as the average of the H component night time (23:00 - 02:00 LT) value of the Earth's magnetic field.

$$H_o = \frac{H_{23} + H_{24} + H_{01} + H_{02}}{4} \tag{6}$$

where H_{23}, H_{24}, H_{01}, and H_{02} are respectively the hourly values of H at 23:00, 24:00, 01:00 and 02:00 in local time (LT).

$$\Delta H(t) = H(t) - H_o \tag{7}$$

where t is the time in hours ranging from 01:00 to 24:00 LT. The hourly departure ΔH is then corrected for the non-cyclic variation using (Eq. 8). This correction was proposed previously by Rastogi et al. (2004) who defined non-cyclic variation as a phenomenon in which the value at 01:00 LT is different from that of local midnight (24:00 LT).

$$\Delta c = \frac{\Delta H_{01} - \Delta H_{24}}{23} \tag{8}$$

The hourly departure of H (ΔH) corrected for the non-cyclic variation corresponding to magnetometer data set gives the solar quiet variation (Sq) values as shown in Eq. (9):

$$Sq(t) = \Delta H(t) + (t-1) * \Delta c \tag{9}$$

where t = 1 to 1440.

The equatorial electrojet current (EEJ) produces a strong enhancement in the H-component magnetic field measured by magnetometers located within $\pm 5°$ of the magnetic equator. Measurements of this magnetic field perturbation in equatorial magnetometers could provide a direct measure of the daytime equatorial electrojet (EEJ) and have strong relationships with dayside vertical velocity ($\boldsymbol{E} \times \boldsymbol{B}$ drift) (Anderson et al., 2004, 2006; Yizengaw et al., 2012). The equatorial stations respond primarily to the EEJ and also to the ring current and the global quiet time Sq current system. However, ground magnetometers just outside the extent of the EEJ ($\sim 6° - 9°$, off the dip equator) exhibit exact response to the ring and Sq currents, but near-zero response to the EEJ. To obtain the contribution of H-component field to the EEJ current, we subtract the H-component

value recorded at the off the equator ($\sim 6° - 9°$ geomagnetic) from H-component value measured at the magnetic equator, using Eq. (10). The subtraction has been made to remove the contribution of the ring current and global Sq dynamo from the H-component.

$$\Delta H = \Delta H_{AAE} - \Delta H_{ETHI} \tag{10}$$

5 where ΔH_{AAE} and ΔH_{ETHI}, respectively, show the hourly departure of H over Addis Ababa and Adigrat, .

Table 1. Location information and the type of data used in this study.

Name of stations	Code	Geo. lon	Geo. lat	Geom. lon	Geom. lat	Data
Asab, Eritrea	ASAB	$42.65°$ E	$13°$ N	$114.34°$ E	$4.85°$ N	GPS-TEC
Debark, Ethiopia	DEBK	$37.65°$ E	$13°$ N	$109.24°$ E	$4.13°$ N	GPS-TEC
Addis Ababa, Ethiopia	AAE	$38.77°$ E	$9.04°$ N	$110.47°$ E	$0.18°$ N	Magnetometer
Adigrat, Ethiopia	ETHI	$39.46°$ E	$14.28°$ N	$111.06°$ E	$5.80°$ N	Magnetometer

The other data source used in this study is the Real-time model of the Ionospheric Electric Fields (http://geomag.org/models/PPEFM/RealtimeEF.html). The Prompt Penetration Electric Field Model (PPEFM) (Manoj and Maus, 2012) is a transfer function model which models the daily variations coming from the solar wind, which are mapped in the interplanetary electric field (IEF) data. Eight years IEF data from the ACE satellite, radar data from Jicamarca Unattended Long-Term studies of

10 the Ionosphere and Atmosphere (JULIA) system, and magnetometer data from the CHAMP satellite were used to derive the transfer function. Using the real-time data from ACE satellite, the transfer function models the current variations in the equatorial ionosphere. The model takes time and location as input parameters and calculates the best estimates of the equatorial electric field. The model outputs provide the electric field generated as a result of the convective electric field, quiet time electric field, and both. In the present study, we have used only the background quiet-time electric field to examine the relation between

15 the equatorial electric field (EEF) and the spatial gradient of TEC derived from the two nearby stations.

The real-time model of electric field have been used for different case studies over different sectors to observe the influence of prompt penetration electric field (PPEF) on the variations of total electron content and the occurrence of ionospheric irregularities (Nayak et al., 2017; Dugassa et al., 2019). However, this model has not been applied yet to explain the electrodynamic phenomena over African low-latitude region. To use the PPEF model in this region, we presented its relationship with equato-

20 rial electrojet (EEJ), an indicator of the eastward electric field, during the daytime period over the equatorial region of Africa based on ground-based magnetometer measurements (Rastogi and Klobuchar, 1990; Anderson et al., 2002; Yizengaw et al., 2014). Over East Africa longitude, two magnetometer stations, one at Adigrat (ETHI, $14.3°$ N, $39.5°$ E, $6.0°$ N, geomagnetic) and the other at Addis Ababa (AAE, $9.0°$ N, $38.8°$ E, $0.2°$ N, geomagnetic) exist. ETHI and AAE stations belong to AMBER

network (Yizengaw and Moldwin, 2009) and INTERMAGNET, respectively. It has been reported that the strength of EEJ before sunset has a correlation with the generation of ESF during nighttime period preceded by rise in the F-region (Dabas et al., 2003; Uemoto et al., 2010; Ram et al., 2007). The relation between the EEF obtained from the real-time electric field model and ΔH were determined. The EEF derived from the real-time electric field model were used in this study to explain the

5 influence of equatorial electric field on nighttime variations of the spatial gradient of TEC and the occurrence of ionospheric irregularities. The temporal resolution of EEF was 5 min and that of ΔH was 1 min. To make their resolution consistent, 5 min average of ΔH of each of the selected quiet days were computed. In this study, ΔH derived from the H-component of the geomagnetic field of the two stations during quiet days of the year 2012 were used. In this year, we have a large number of magnetometer measurements relative to other years. From each month of year 2012, the five quiet international days (total of

10 38) obtained from (http://wdc.kugi.kyoto-u.ac.jp/qddays/index.html) were selected to show the correlation between ΔH and EEF. Since the EEJ is a day time phenomenon, only the daytime values of EEF and ΔH during (07:00 to 17:00 LT) were examined.

3   Results and Discussions

3.1   Relation between the day-time Equatorial Electrojet (EEJ) and Equatorial Electric Field Model (EEFM)

15 Figure 1a presents the diurnal variation of EEF and EEJ current signature of H-component of geomagnetic field on 26 March 2012. As can be seen in Figure 1a, during the daytime period (07:00 - 17:00 LT), the ΔH and EEF show similar trends. The relationship between the strength of daytime EEJ derived from ΔH and EEF obtained from equatorial electric field model was shown in Figure 1b. To show the reliability of EEF model over East African sector, we presented the relationship between ΔH and EEF for five (5) international quiet days of each month of year 2012. In the analysis, we considered the daytime (07:00 -

20 17:00 LT) value of ΔH and EEF. As depicted in Figure 1b, during daytime period, the ΔH correlate positively and linearly with EEF with correlation coefficient, C = 0.60. Manju et al. (2012) obtained an excellent agreement with observations at the Indian and South American sectors. Different techniques have been utilized to estimate the ionospheric electric field (e.g., Hysell and Burcham, 2000; Anderson et al., 2002; Alken et al., 2013; Dubazane and Habarulema, 2018). Anderson et al. (2002) proposed ΔH deduced from ground-based magnetometers as a proxy of equatorial electrojet current. They reported that the vertical

25 plasma drifts observed from Jicamarca incoherent scatter radar (ISR) has a positive and linear relation with ΔH and henceforth the ΔH was widely taken as a substitution for the EEF. Anderson et al. (2006) and Yizengaw et al. (2011) also reported a strong relation between the dayside vertical velocity ($\boldsymbol{E} \times \boldsymbol{B}$ drift) and ΔH. Alken et al. (2013), on the other hand, estimates the EEF using CHAMP satellite derived latitudinal current profiles of daytime EEJ along with ΔH measurements from ground magnetometer stations and they showed that any pair of ground magnetometer stations capture the day-to-day strength of the

30 EEJ.

The daytime eastward equatorial electric field (EEF) in the ionospheric E-region plays an important role in equatorial iono- spheric dynamics. It is responsible for driving the EEJ current system, equatorial vertical ion drifts, and the equatorial ionization

anomaly. The EEJ is a strong ionospheric current along the magnetic equator driven by the day side eastward electric field. Studies also show that the daytime electrodynamics play a decisive role in the initiation of post-sunset ESF (e.g., Mendillo et al., 2001; Valladares et al., 2001, 2004). The connection between the occurrence of ESF during the evening sector preceded by the rapid rise in F-layer and the strength of EEJ before sunset has been presented (Dabas et al., 2003; Burke et al., 2004; Kelley, 2009; Uemoto et al., 2010; Ram et al., 2007). Sreeja et al. (2009) reported observational evidence for the plausible linkage between the daytime EEJ related electric field variations with the postsunset F-region electrodynamics. Furthermore, Hajra et al. (2012) indicate that the afternoon/evening time variation of the eastward electric field as revealed through EEJ seems to play a dominant role in dictating postsunset resurgence of EIA and consequent generation of spread-F irregularities. Since the equatorial electric field derived model (EEF) correlate moderately with ΔH over East Africa longitudinal sector, we could use the real-time EEF model over equatorial/low-latitude region of Africa to explain some special features of ionospheric phenomena like plasma density irregularities and the positive/negative in the spatial gradient of TEC between the two stations.
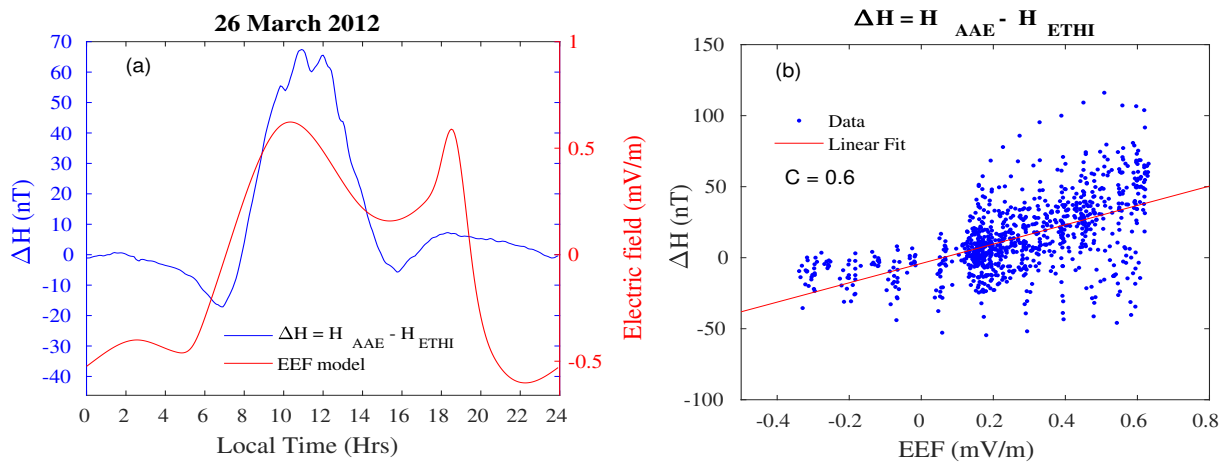
Figure 1. (a) Example showing the diurnal variation of Equatorial Electric field (EEF) Model (red curve) and ΔH (blue curve) during 26 March 2012 and (b) The correlation between the equatorial electrojet (EEJ) and quiet-time equatorial electric field model (EEF) during day-time (07:00-17:00 LT) period for quiet days of year 2012. The red line shows the linear fit of data points.

3.2 Relation between the equatorial electric field (EEF), the spatial gradient of TEC and occurrence of ionospheric irregularity

Figure 2 (a-l) shows the diurnal variation of the quiet-monthly mean of spatial gradient of TEC (blue curves) and EEF (along $\sim 40°$ E) (red curves) in the year 2014. We superimpose EEF and spatial gradient in TEC to observe the effect of EEF on the variability of the gradient in TEC and/or occurrence of ionospheric irregularities. In the computation of the spatial gradient of TEC (using Eq. 1), negative/positive values in the gradient of TEC may be observed during the nighttime or daytime. Both the negative and positive differences of TEC between the two stations show the gradient of TEC. It is obvious that positive/negative gradient in TEC is obtained when the minuend is larger/smaller than the subtrahend. A positive/negative

gradient in TEC denotes an enhancement/reduction in TEC or electron density over ASAB relative to DEBK. Gradient in TEC is positive when TEC over ASAB is greater and is negative when TEC over DEBK is greater. This difference may be attributed to different physical processes, like neutral winds and plasma drift. In this study, the term maximum enhancement/reduction in the gradient of TEC (in terms of magnitude) were used when the nighttime value of gradient of TEC was larger than the daytime value. There were also cases when the gradient in TEC during the daytime was greater than nigh time values. It can be seen from Figure 2 (red curves) that around evening hours, enhancement in EEF were observed in the equinoctial months and was relatively weak during the June and December solstices. It has been stated that an enhanced eastward electric field will be produced from the electrodynamical interaction of the eastward thermospheric wind with the geomagnetic field around the dip equator at the sunset terminator when longitudinal gradient conductivity exist between the high-conducting day side ionosphere and the low-conducting night side ionosphere (Batista et al., 1986; Heelis et al., 1974). Most of the enhancement/reduction in the TEC gradient was observed in the pre-midnight (19:00 - 24:00 LT) and postmidnight (24:00 - 06:00 LT) but after 1-2 hr of the post-sunset enhancement of the equatorial electric field. During the nighttime period, the maximum enhancement/reduction in spatial gradient of TEC found mostly in the range between 5.0 TECU/deg and -5.0 TECU/deg. A variation in the spatial gradient of TEC observed in the pre-midnight may be due to the plasma bubbles (Ratnam et al., 2018). In some days, the spatial gradient of TEC observed during the daytime was relatively small compared to the evening time hours. The maximum enhancement/reduction in the gradient of TEC and the peak in the EEF observed during the pre-midnight period was significant during the equinoctial months. After post-sunset period, the maximum enhancement/reduction in the gradient of TEC in solstice months was small compared to equinoctial months, when PRE electric field observed in the evening period was minimum. Yoshihara et al. (2005) confirm the larger ionospheric gradients during summer and followed by autumn. The ionospheric gradients are less during winter as compared to summer and autumn. The enhancement/reduction in the gradient of TEC observed in the evening period could be related to the PRE in a zonal electric field.

Figures 3 (a - d) shows the diurnal variation of the spatial gradient of TEC (blue curve) and $ROTI_{ave}$ (red and black curves) over ASAB and DEBK stations. The $ROTI_{ave}$ values in each panel was greater than 0.4 TECU/min, a threshold value showing the presence of irregularities in the pre-midnight hours. Likewise, maximum enhancement/reduction in the gradient of TEC were observed during pre-midnight and post-midnight periods. It is evident from Figure 3 during nighttime period (after 18:00 LT) that the pattern of ROTI (observed in both stations) and the spatial gradient in TEC show a kind of similar trend. Different researchers used the concept of ionosphere spatial gradient based on multi-GNSS observations within a small scale region to provide corrections and integrity information to the Ground-Based Augmentation System (GBAS) (Rungraengwajiake et al., 2015; Saito and Yoshihara, 2017). They attribute the large ionosphere spatial gradient to the TEC enhancements and the ionosphere irregularities. Saito and Yoshihara (2017) associated spatial gradient in ionospheric TEC with plasma bubbles. Sun et al. (2013) examined the relationship between the storm-enhanced plasma density (SED)-associated irregularities (ROTI) and TEC gradients over continental United States (CONUS) during the geomagnetic storms. Rungraengwajiake et al. (2015) analyzed plasma bubbles at postsunset equinox time and observed the higher scales in east-west gradient compared with north-south gradients for GBAS system, however, Cesaroni et al. (2015) reported that north-south gradient in TEC correlates well
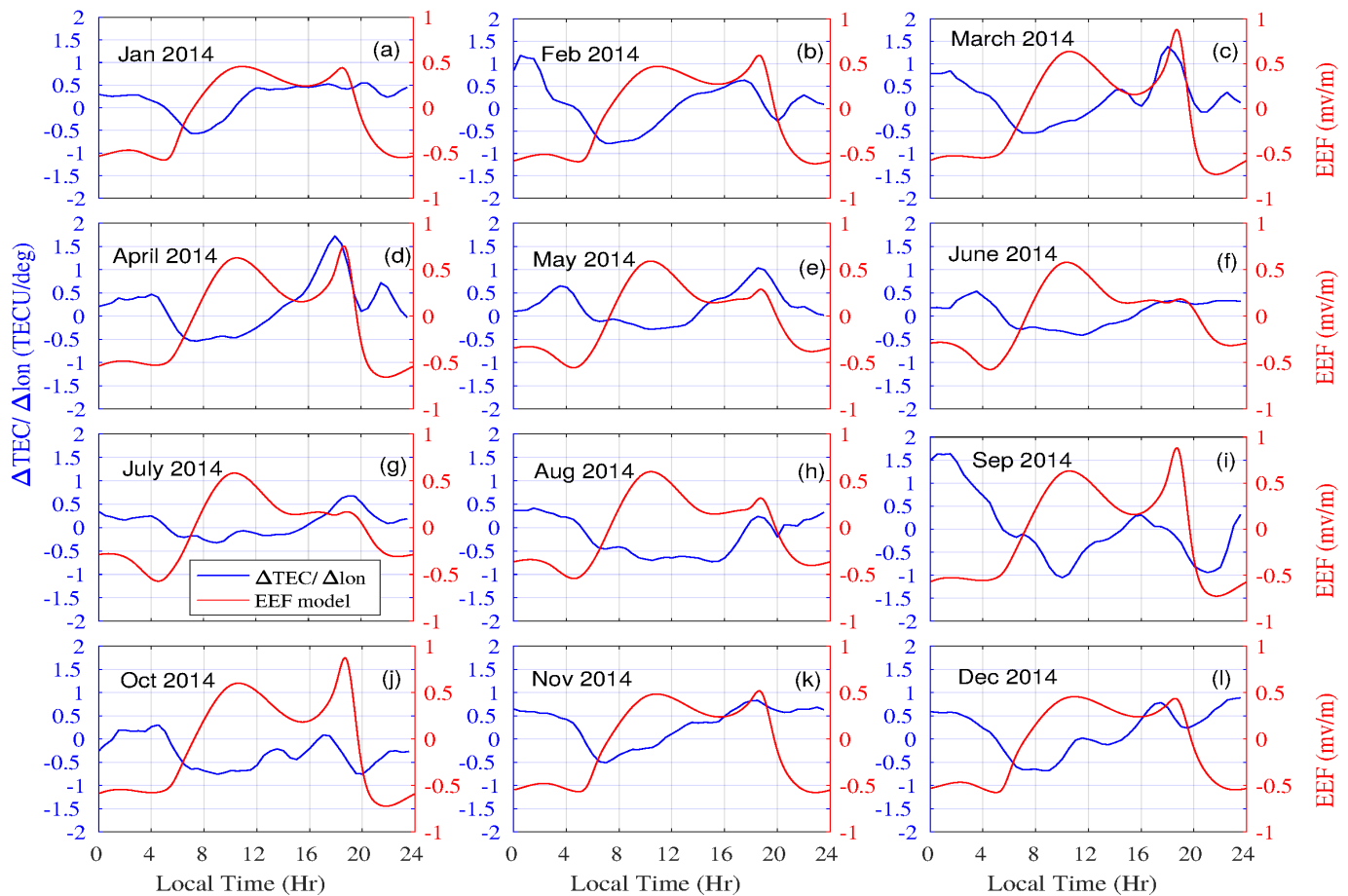
Figure 2. Comparison of Quiet-Monthly Mean of EEF derived from real-time electric field model at about ($\sim 40°$ E) and spatial gradient of TEC between ASAB and DEBK in the year 2014.

with ionospheric scintillation than the east-west gradient of TEC. The plasma density variability, either the spatial and/or temporal, causes not only the GNSS-based positioning error but also radio wave scintillation.

The maximum enhancement/reduction in the gradient of TEC and the associated ionospheric irregularity during the post-sunset period could be explained by ionospheric electrodynamics. It is well known that Earth's equatorial ionosphere presents dynamically temporal and spatial variations. The electrodynamics of low-latitude ionosphere after sunset is influenced by F-region dynamo which is governed by a longitudinal gradient of the electrical conductivity and thermospheric zonal wind (Crain et al., 1993). Anderson et al. (2004) showed that the scintillation activity is related to the maximum $E \times B$ drift velocity between 18:30 LT and 19:00 LT. Mendillo et al. (2001) have pointed out that the best available precursor for pre-midnight equatorial spread F (ESF) is the equatorial ionization anomaly (EIA) strength at sunset, which is in turn influenced by the magnitude of PRE. Using differential TEC profiles, TEC (at 18:00 hr) - TEC (at 20:00 hr), Valladares et al. (2004) explained that the PRE

of the vertical drift would re-energize the fountain effect. The postsunset EIA produces a large plasma density gradient from the trough region to th crest region. Takahashi et al. (2016) observed a most steep in TEC gradient with a difference of 30-50 TECU from the inside to outside plasma bubbles.
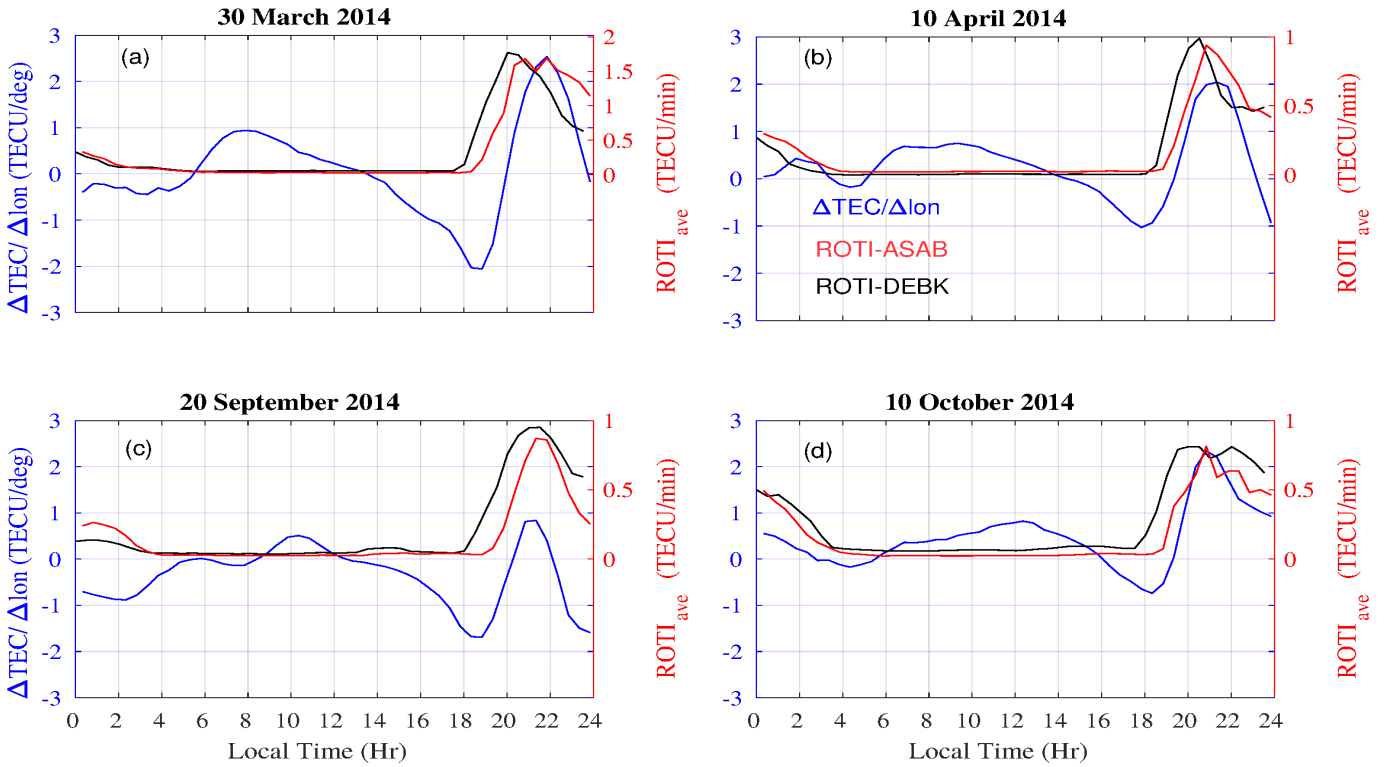
Figure 3. Typical examples of diurnal variation in the spatial gradient of TEC (blue curve) and the ROTI over ASAB (red curve) and DEBK (black curves) on a) 30 March 2014, b) 10 April 2014, c) 20 September 2014 and d) 10 October 2014.

In the evening sectors, the vertical drift enhancement is of particular significance as it is the major drivers for the generation of ESF (Farley et al., 1970; Woodman, 1970; Basu et al., 1996; Fejer et al., 1999; Martinis et al., 2005). Tulasi Ram et al. (2006) reported that the rapid enhancement of post-sunset of the zonal electric field leads to a large vertical plasma drift ($E \times B$), thereby lifting the F-layer to higher altitudes resulting in a condition conducive for the generation of ESF. Ionospheric irregularities are mostly observed over equatorial/low-latitude region an hour or two hours after the PRE. Rastogi and Woodman (1978) showed ESF can appear at any time of the night other than the post-sunset period following the abnormal reversal of the vertical F-region drifts to an upward direction, with a delay of about 1-2 hr. As illustrated in Figure 2, the influence of post-sunset enhancement in the zonal electric field on the maximum enhancement/reduction in the spatial gradient of TEC during the post-sunset period can be seen. This could indicate the maximum enhancement/reduction in the spatial gradient of TEC and the occurrence of ionospheric irregularities have some degree of relationship.

Figures 4 (a-h) indicate representative cases showing the diurnal variation of $ROTI_{ave}$ over ASAB (red curve) and DEBK (black curve) and $\sigma(\Delta TEC/\Delta lon)$ (blue curve) when the occurrence of ionospheric irregularity present (left panel) and absent (right panel). It is clearly observed from Figures 4 (a-d) that intensity level of $ROTI_{ave}$ was greater than 0.4 TECU/min indicating the presence of ionospheric irregularities. Figures 4 (e-h), on the other hand, indicate examples when the presence of occurrence of ionospheric irregularities are absent, where the value of $ROTI_{ave}$ was less than 0.4 TECU/min. $ROTI_{ave} \geq$ 0.4 TECU/min indicate the presence of ionospheric irregularities (Oladipo and Schuler, 2013b; Oladipo et al., 2014). As can be seen from Figure 4 (blue curves), the intensity level of $\sigma(\Delta TEC/\Delta lon)$ observed in the evening period was higher when the occurrence of ionospheric irregularity present (Figure 4, left panels) than when the occurrence of irregularity absent (Figure 4, right panels). It is evident from the figures that the strength of $\sigma(\Delta TEC/\Delta lon)$ observed on the nighttime period was greater than the daytime value, as $ROTI_{ave}$ does. The post-sunset plasma bubble irregularities are generated at the bottom side of the F-layer by the sunset enhancement of the zonal electric field called pre-reversal enhancement caused by the the combined action of an eastward thermospheric wind and the longitudinal gradient in ionospheric conductivity that exist along sunset terminator (Rishbeth, 1971; Fejer et al., 1999). It is well documented that plasma bubble development depends on the linear growth rate for generalized R-T instability process, the flux tube integrated Pedersen conductivity that controls the non-linear development, and density perturbations that are needed to act as a seed to trigger the instability growth. The density gradient control the intensity of the PRE through the E regions electrodynamical coupling process and the generation of equatorial plasma bubbles (Abdu et al., 2009). Background electron density and its distribution in the ionosphere affects the formation of ionospheric irregularities. The intensity level of $\sigma(\Delta TEC/\Delta lon)$ obtained from two nearby located stations observed near sunset terminator, related with the longitudinal gradient of ionospheric conductivity, could indicate the presence/absence of large-scale ionospheric irregularities. Cesaroni et al. (2015) reported a strong relation between the standard deviation of gradient of TEC and occurrence of ionospheric scintillation.

Figure 5 (a-d) illustrates examples showing the diurnal variation of $\sigma(\Delta TEC/\Delta lon)$ and $ROTI_{ave}$ during some of selected geomagnetic storm days. These storm days are categorized as moderate magnetic storms (-100 nT $\leq$ Dst $\leq$-50 nT) (Loewe and Prölss, 1997; Echer et al., 2013). When the presence of ionospheric irregularity are observed ($ROTI_{ave} \geq$ 0.4 TECU/min), the magnitude of $\sigma(\Delta TEC/\Delta lon)$ in the post-sunset period show enhancement (for example, 13 September 2014) and when its occurrence suppressed ($ROTI_{ave} <$ 0.4 TECU/min), the magnitude of $\sigma(\Delta TEC/\Delta lon)$ reduced (for example, 19 February and 27 August 2014). On these days, the spatial gradient in TEC ($\Delta TEC/\Delta lon$) observed during the daytime hours show maximum enhancement/reduction. The influence of geomagnetic storm on the occurrence irregularities have been studied (e.g., Aarons, 1991; Oladipo and Schuler, 2013a; Kassa and Damtie, 2017). The triggering/inhibition effect of storm on the generation of ionospheric irregularities could be related to the magnitude and direction of z-component of interplanetary magnetic field (Biktash, 2004). The enhancement/reduction in spatial gradient of TEC in the daytime period during geomagnetic storm day appears to show inhibition of ionospheric irregularities. On the other hand, the enhancement/reduction in the $\sigma(\Delta TEC/\Delta lon)$ observed during nighttime period indicate the presence/absence of ionospheric irregularity. It is evident from Figures 4 and 5 that the spatial gradient of TEC, $\sigma(\Delta TEC/\Delta lon)$, obtained from two closely located stations could show the presence and absence of ionospheric irregularities.
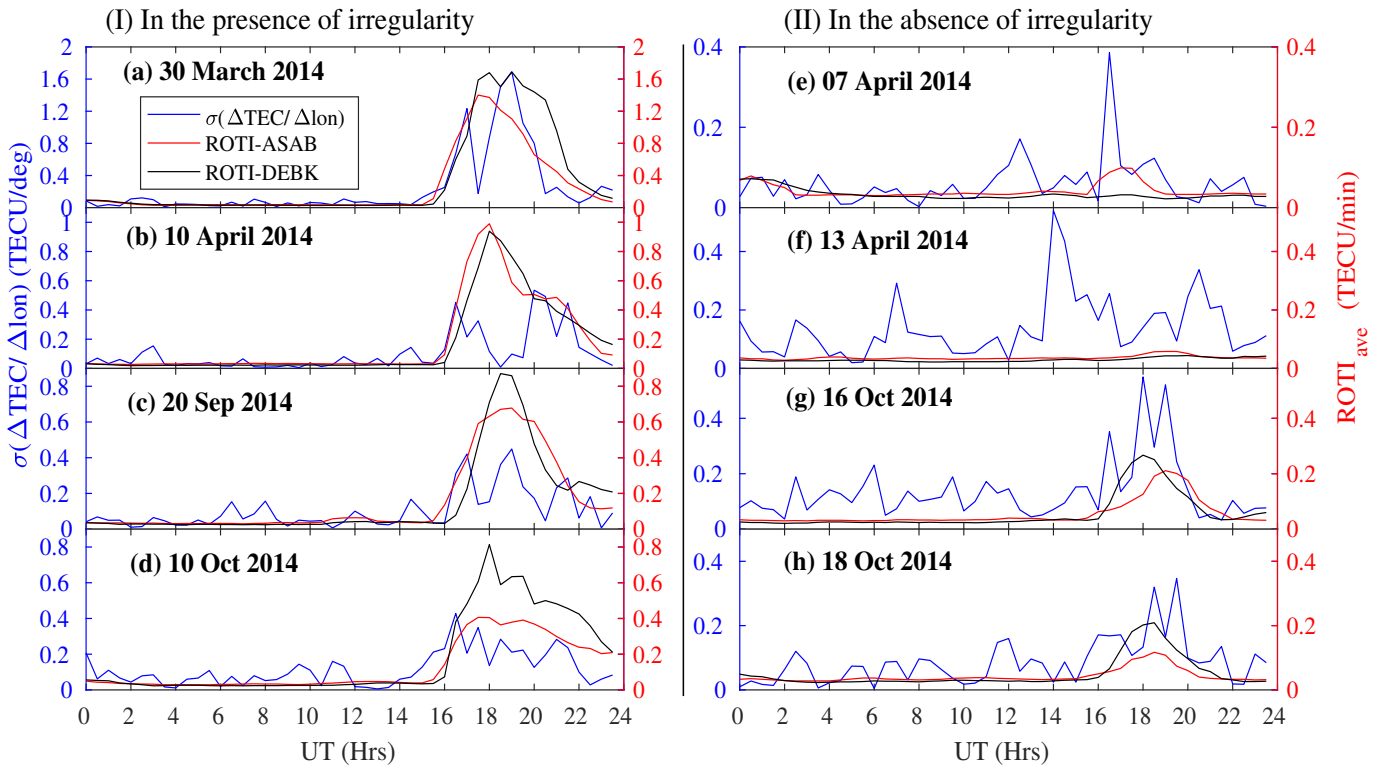
Figure 4. Typical examples showing the diurnal variation of $\sigma(\Delta TEC/\Delta lon)$ (blue curve) and $ROTI_{ave}$ over ASAB (red curve) and DEBK (black curves) (I) in the presence of ionospheric irregularities on (a) 30 March 2014, (b) 10 April 2014, (c) 20 September 2014 and (d) 10 October 2014 (II) in the absence of ionospheric irregularities on (e) 07 April 2014, (f) 13 April 2014, (g) 16 October 2014 and (h) 18 October 2014. Local time (LT) = UT + 3 hr.

Figures 6 (a-d) respectively, show the annual variation of $ROTI_{ave}$ (over ASAB and DEBK), spatial gradient of TEC ($\Delta TEC/\Delta lon$) and its standard deviation $\sigma(\Delta TEC/\Delta lon)$ in the year 2014. The intensity level of $ROTI_{ave}$, $\Delta TEC/\Delta lon$, and $\sigma(\Delta TEC/\Delta lon)$ are indicated in the color bar. As stated by Oladipo and Schuler (2013b), the value of $ROTI_{ave} \geq 0.4$ TECU/min shows the presence of ionospheric irregularity. The occurrence of ionospheric irregularities at the two stations, as indicated by intensity level of $ROTI_{ave}$, was predominantly observed in the pre-midnight periods, mainly between 19:00 LT and 24:00 LT. The large-scale ionospheric irregularities, which are responsible for the scintillation of trans-ionospheric signals at GNSS frequencies, are more pronounced during post-sunset hours. The observed phase fluctuation shows monthly variations and there is also a seasonal trend in the occurrence of ionospheric irregularity. Strong and weak ionospheric irregularities are observed in March equinox and in June/July solstices, respectively.

It can be seen from Figure 6c that positive/negative values in the gradient of TEC were observed. Gradient in TEC is positive when TEC/electron density over ASAB is higher, and is negative when TEC/electron density over DEBK is higher. Maximum enhancement/reduction in the gradient of TEC was observed mostly during the post-sunset (18:00 - 24:00 LT) and
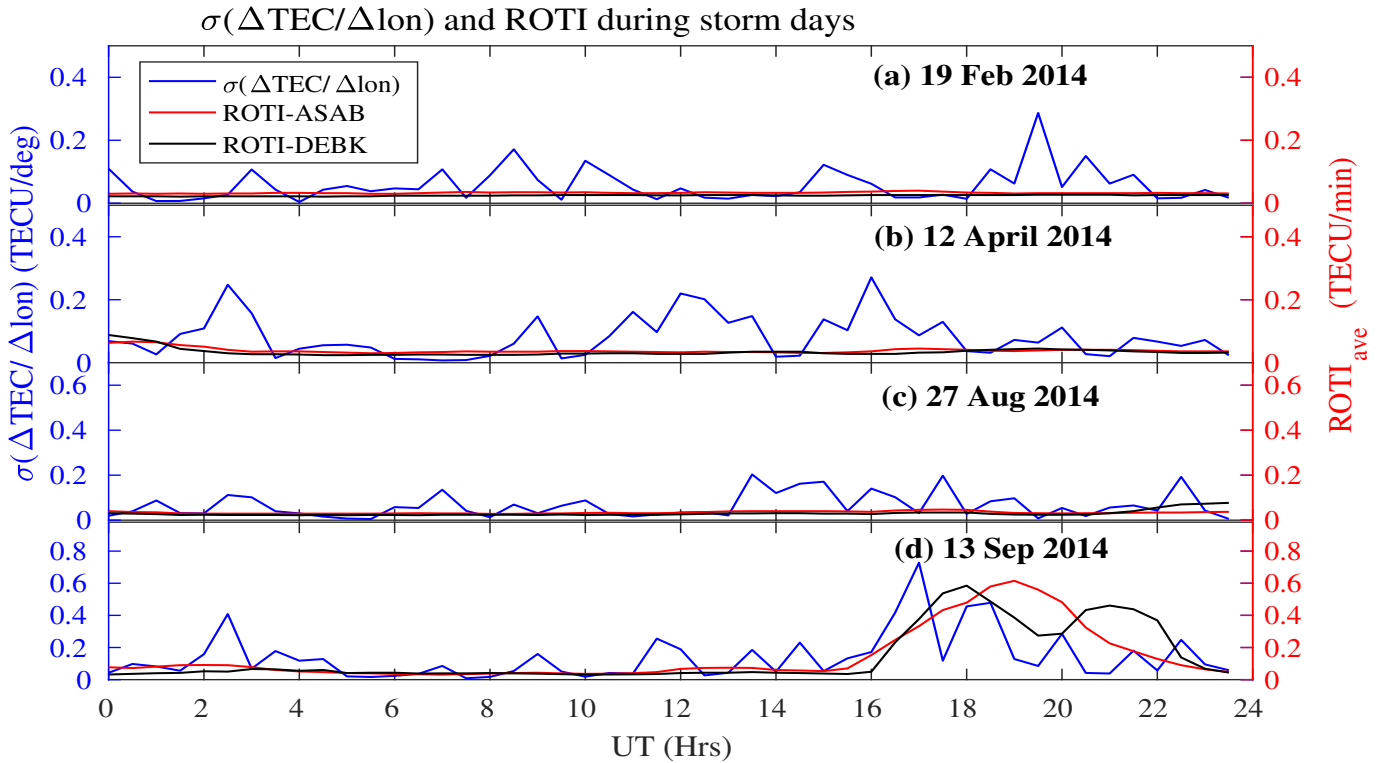
Figure 5. Representative examples showing diurnal variation of $\sigma(\Delta TEC/\Delta lon)$ (blue curves) and $ROTI_{ave}$ over ASAB (red curves) and DEBK (black curves) during geomagnetic storm days (a) 19 February 2014 (b) 12 April 2014 (c) 27 August 2014 and (d) 13 September 2014. Local time (LT) = UT +3 hr.

post-midnight (24:00 - 06:00 LT) period. Equation (1) was applied to all days (364 days) of year 2014 in computing the spatial gradient of TEC. Out of the total observed daily maximum value of the gradient of TEC, about 194 days (in percent about 53%) of them fall in this time period. There was also a case where the maximum enhancement/reduction in the value of the gradient of TEC were observed in the early morning period. In Figure 6d the diurnal, monthly and seasonal variation in the standard
5   deviation of spatial gradient of TEC, $\sigma(\Delta TEC/\Delta lon)$, was clearly observed and its variation show similarity with variation of $ROTI_{ave}$. Maximum enhancement in $\sigma(\Delta TEC/\Delta lon)$ was observed in the evening time period, 19:00 - 24:00 LT. The seasonal variation in $\sigma(\Delta TEC/\Delta lon)$ also appears frequently in equinoctial months, but rarely in solstice months. Such kind of occurrence variation could be related to the magnitude of $\boldsymbol{E} \times \boldsymbol{B}$ drift. Cesaroni et al. (2015) also found seasonal variation of the TEC spatial gradients and they reported that it is larger during the equinoctial seasons than in the solstice seasons.

10   Figures 6 (e-h) respectively, show the daily maximum values of $ROTI_{ave}$ (over ASAB and DEBK), spatial gradient of TEC ($\Delta TEC/\Delta lon$) and standard deviation of spatial gradient of TEC $\sigma(\Delta TEC/\Delta lon)$, respectively, in the year 2014. As can be observed from Figures 6 (right panel), the daily maximum value of $ROTI_{ave}$, $\Delta TEC/\Delta lon$ and $\sigma(\Delta TEC/\Delta lon)$ shows
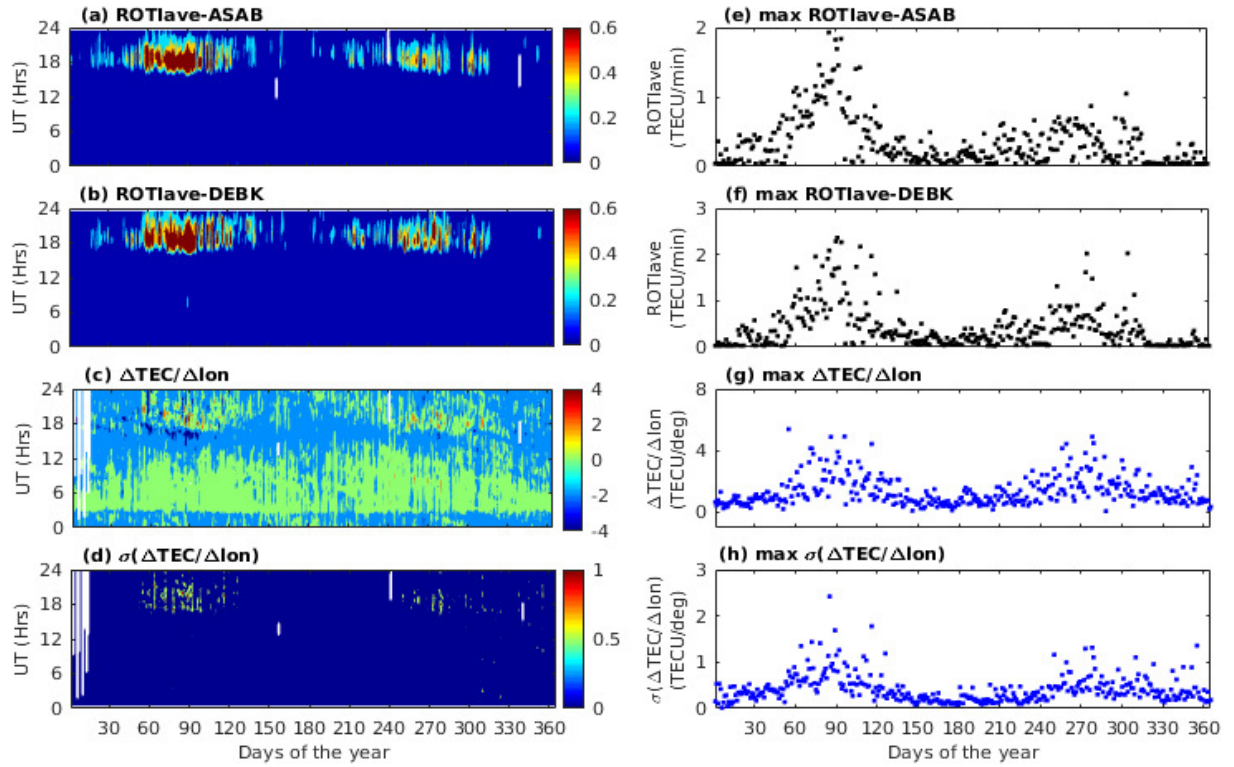
Figure 6. Annual and daily maximum value variation of (a,b) $ROTI_{ave}$ over Asab (ASAB), (c,d) $ROTI_{ave}$ over Debark (DEBK), (e,f) spatial gradient of TEC ($\Delta TEC/\Delta lon$), (g,h) standard deviation of gradient of TEC $\sigma(\Delta TEC/\Delta lon)$ in year 2014. The $ROTI_{ave}$ in TECU/min and $\Delta TEC/\Delta lon$ in TECU/deg is indicated in color bar. Local time (LT) = UT + 3 hr.

monthly and seasonal variations, and an equinoctial asymmetry is also observed. The daily maximum value of $\Delta TEC/\Delta lon$ and $\sigma(\Delta TEC/\Delta lon)$ shows similar trends with the daily maximum value of $ROTI_{ave}$ observed over ASAB and DEBK stations. The trend they show has similarity with the time of occurrence of maximum enhancement/reduction, monthly and seasonal variations. Moreover, the seasonal variation observed in both variables exhibits equinoctial asymmetry, where the

5   March equinox was greater than September equinoxes. The mechanism of generation of the enhancement in vertical drift just after sunset was detailed by Farley et al. (1986b). The magnitude of peak vertical drift is known to control the seasonal and day-to-day variations in the occurrence of equatorial spread F (Manju et al., 2009; Tulasi Ram et al., 2006).

     Figure 7 depicts the quiet-monthly mean of $ROTI_{ave}$ (over ASAB and DEBK) (red and black curves) and $\sigma(\Delta TEC/\Delta lon)$ (blue curve) in the year 2014. The enhancement/reduction in the intensity of $\sigma(\Delta TEC/\Delta lon)$ show similar trends with

10    $ROTI_{ave}$, and was stronger/weaker during equinoctial/solstice months. Equinoctial asymmetry both in $ROTI_{ave}$ and $\sigma(\Delta TEC/\Delta lon)$ was also evident from Figure 7, where March equinoxes was stronger than September equinoxes. As expected, the TEC spatial gradients are also found to be larger during the equinoctial seasons than in the solstice seasons.
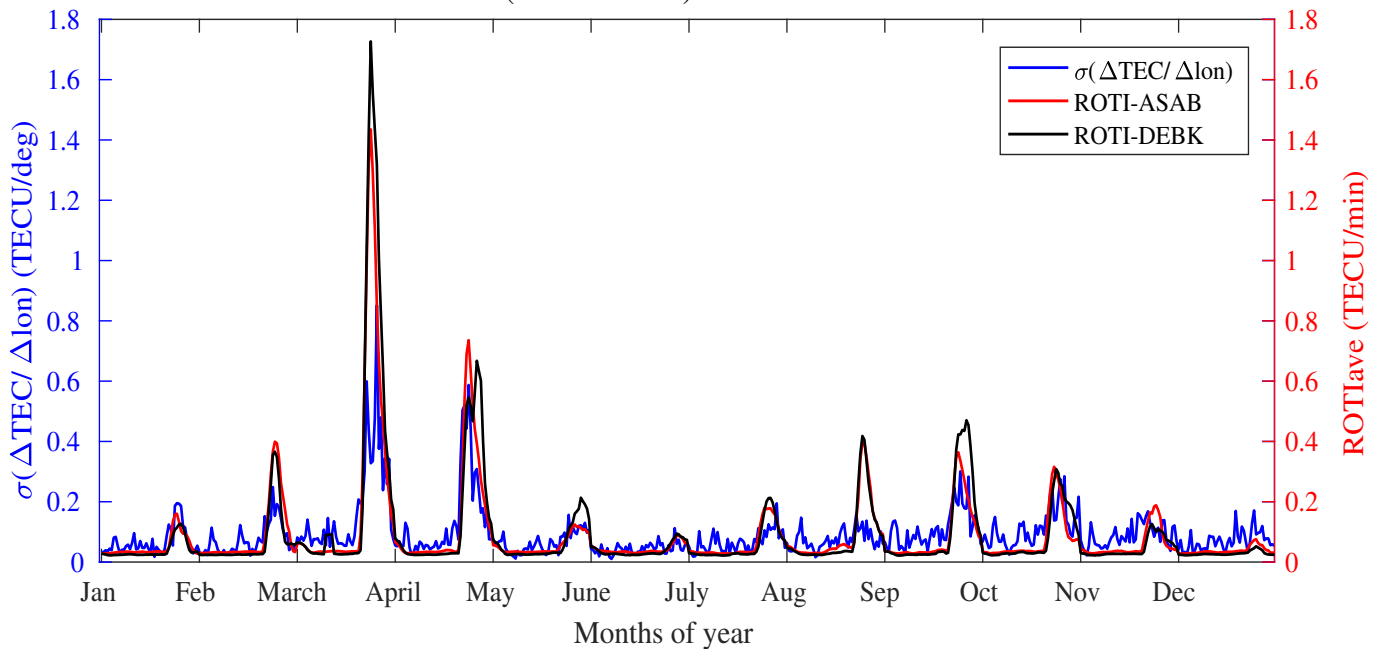
Figure 7. Seasonal variation of $ROTI_{ave}$ over ASAB (red curve), $ROTI_{ave}$ over DEBK (black curve), and $\sigma(\Delta TEC/\Delta lon)$ (blue curve) in the year 2014

Figure 8 shows relationship between the standard deviation of spatial gradient of TEC $\sigma(\Delta TEC/\Delta lon)$ and $ROTI_{ave}$ (over ASAB and DEBK) in the year 2014. The daily maximum values of $\sigma(\Delta TEC/\Delta lon)$ and $ROTI_{ave}$ were considered to examine their correlation. The correlation coefficient between $\sigma(\Delta TEC/\Delta lon)$ and $ROTI_{ave}$ is about 0.7915 (in ASAB) and 0.7975 (in DEBK), respectively. Studies indicate that the gradient of TEC can be computed from a pair of closely-spaced receiver stations ($< 2^o$) such that the two receivers share the same GPS satellite. In our case, however, the two stations are separated by 5°. The moderate correlation obtained might be attributed to the wider longitudinal separation (5°) between the two stations. The other factor for the moderate correlation between the gradient of TEC and occurrence of ionospheric irregularities might be the way ROTI was computed (since ROTI contains both the spatial and temporal variation in TEC). It is well known that ROT is the combination of the spatial and temporal gradients. However, by giving less attention to the spatial gradient effect, previous authors often use $\Delta TEC/\Delta t$ to examine the fluctuation in TEC. It is not only the temporal variation of TEC that contribute to the fluctuation in the phase and amplitude of the signals but also the spatial gradient of TEC. The computed correlation coefficient between the TEC gradient and ROTI, here, gives an indication of the contribution of the spatial gradient of TEC to ROTI (or ROT) usage. This can give the case where the spatial gradient of TEC between two nearby located stations can be used as an indicator of occurrence of ionospheric irregularities. Every night time enhancement/reduction in the gradient of TEC may not be a guarantee to indicate the occurrence/non-occurrence of ionospheric irregularities. However, there are cases which show the occurrence of irregularities over both stations (ASAB and DEBK) when the night time enhancement/reduction

in the TEC gradient were observed. Hua and Chunbo (2009) discussed the relation between ROTI index, ionospheric TEC gradient and vertical TEC. Cesaroni et al. (2015) also described the importance of the information provided by the TEC gradients variability and the role of the meridional TEC gradients in driving scintillation. By comparing the zonal and the meridional components of average and standard deviation of ΔTEC, Cesaroni et al. (2015) reported that the North-South (N-S) gradients of TEC are significantly larger than their East-West (E-W) counterparts, regardless of the season. Saito and Yoshihara (2017) associated extreme ionospheric total electron gradient with plasma bubbles for GNSS Ground-Based Augmentation System and they obtained a largest ionospheric gradient of about 3.38 TECU/km. It is suggested that when scintillation events are investigated ionospheric TEC gradient is also one of considerable parameters.
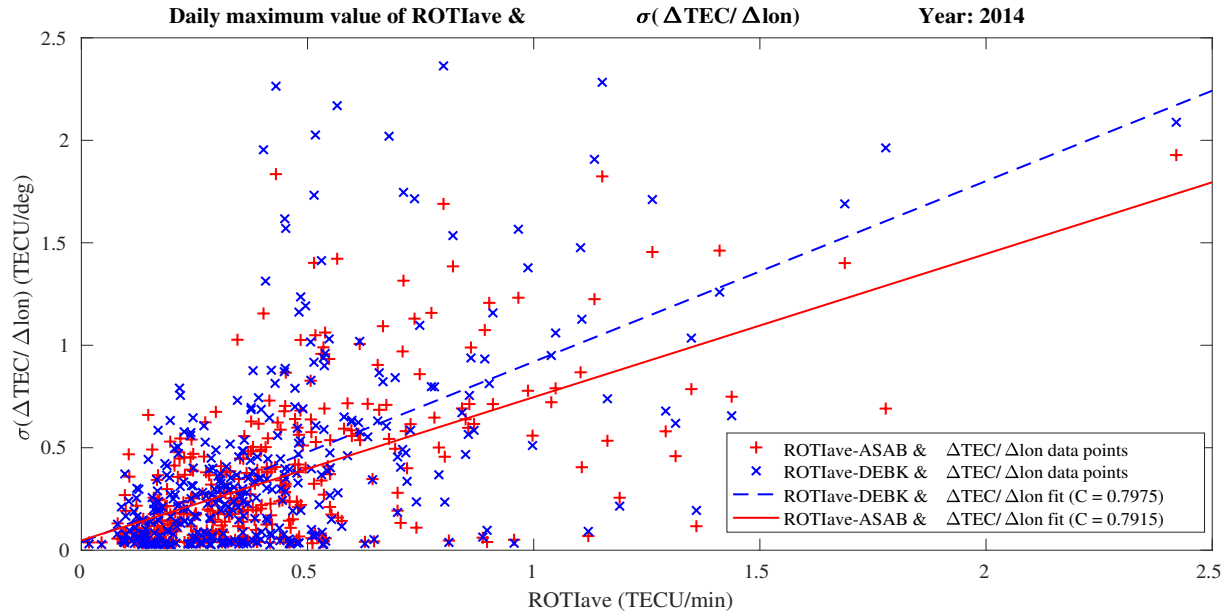
Figure 8. Relation between the daily maximum value of $\sigma(\Delta TEC/\Delta lon)$ and the daily maximum value of $ROTI_{ave}$ over ASAB (red, +) and DEBK (blue, x) in the year 2014. The blue broken and solid red lines indicate the linear fit between the daily maximum value of $\sigma(\Delta TEC/\Delta lon)$ and $ROTI_{ave}$ for ASAB and DEBK, respectively.

Figure 9 presents the percentage occurrence of ionospheric irregularities over ASAB (blue) and DEBK (red) in the year 2014. The observation of the percentage occurrence was made for all days of the year 2014 including both quiet and disturbed days. The percentage occurrence of irregularities was calculated by counting the number of days in a month with $ROTI_{ave} \geq$ 0.4 TECU/min and dividing by the number of days in a month for which the data are available, and multiplied by 100 % (Oladipo et al., 2014). Since the two stations are close to each other, the occurrence of ionospheric irregularities observed over both stations does not show major differences. Two peaks of irregularity occurrence were observed around the middle of the equinoxes (i.e., in March and September) at both stations. This could be related to the alignment of the magnetic field lines with a geographic meridian (Burke et al., 2004; Tsunoda, 2005, 2010). The seasonal variation of ionospheric irregularities

exhibits an equinoctial asymmetry in its occurrence especially at the two peaks (i.e., in March and September), where March equinox was greater than September equinox. The maximum $ROTI_{ave}$ observed over this station in the year 2014 was about 1.8 TECU/min in March 2014 and minimum level of $ROTI_{ave}$ was observed on December Solstice.

Based on a few station observations, earlier studies indicated the equinoctial asymmetry in the occurrence of L-band scintillations and they attributed to differences in the meridional winds during two equinoxes (e.g., Nishioka et al., 2008; Maruyama et al., 2009; Otsuka et al., 2006). Nishioka et al. (2008) have analyzed the occurrence characteristics of plasma bubbles using GPS-TEC obtained all over the globe and found equinoctial asymmetry in its occurrence. They have suggested that equinoctial asymmetry could be due to the asymmetric distribution of integrated conductivities during these periods. Using three ionosonde observations, Maruyama et al. (2009) reported that meridional wind is the key factor for the equinoctial asymmetry. Using multi-instrument observations, Sripathi et al. (2011) examined the equinoctial asymmetry in scintillation occurrence in the Indian sector and they suggested that the asymmetry in the electron density distribution and meridional winds as a possible causative mechanism. Manju et al. (2012) also reported equinoctial asymmetry in ESF occurrence and they discussed the possible role of asymmetric meridional winds. Manju and Haridas (2015) observed a significant asymmetry in the threshold height between the vernal equinox and autumn equinox and underlines the distinct differences in the role of neural dynamics in ESF triggering during the two equinoxes. Based on scintillation index (S_4) and GPS-TEC derived indices, the seasonal and equinoctial asymmetry in the occurrence of ionospheric irregularities over equatorial/low-latitude region of African were presented (Susnik and Forte, 2011; Paznukhov et al., 2012; Oladipo and Schuler, 2013b; Oladipo et al., 2014; Seba and Tsegaye, 2015; Mungufeni et al., 2016). By employing the horizontal wind model (HWM14), Seba et al. (2018) recently reported that the difference in the wind pattern between March and September is one of the factors for the equinoctial asymmetry. The local time and seasonal trends of occurrence of ionospheric irregularities observed in this study are similar to those reported in the previous studies (Aarons, 1993; Basu et al., 1988; Olwendo et al., 2013; Amabayo et al., 2014; Seba and Tsegaye, 2015). The equinoctial asymmetries in the occurrence of ionospheric irregularities observed in our case might also be due to the direction of the meridional winds during equinoxes over the stations.

In terms of diurnal, monthly, and seasonal behavior the enhancement/reduction in the spatial gradient of TEC and the occurrence of ionospheric irregularities appears to show similar trends. And, it is evident from the above result that the spatial gradient of TEC between two nearby located stations where the two receivers lie nearly along the same latitudes covey insight into the relation between large-scale ionospheric irregularity occurrence. The spatial gradient of electron density (TEC) near solar-terminator obtained from two nearby located GNSS receivers method may be an alternative method to estimate the strength of the zonal electric field. In the current study, the optimum distance between the two GNSS receivers and the threshold value of the gradient of TEC that could indicate the occurrence of ionospheric irregularities has not been considered. This will be considered in our future work.
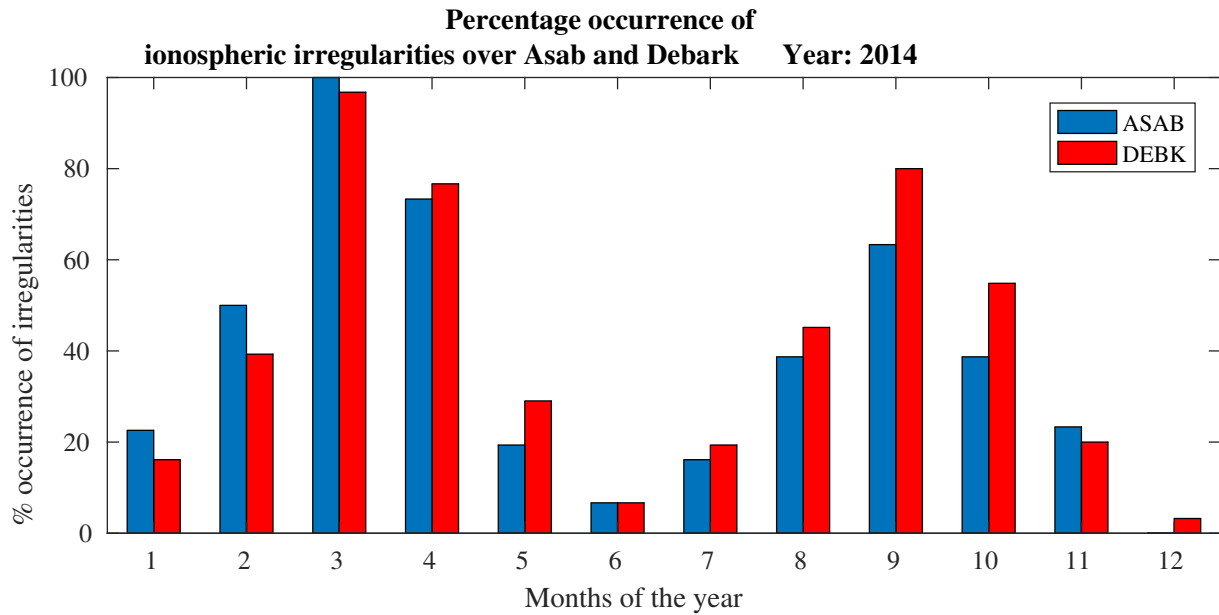
Figure 9. Percentage of occurrence of ionospheric irregularities over ASAB (red) and DEBK (blue) stations in the year 2014 based on $ROTI_{ave}$ index.

4 Conclusions

In this study, we present for the first time the relationship between the spatial gradient of TEC between two nearby located stations (ASAB and DEBK) and the occurrence of ionospheric irregularities over Ethiopia, an equatorial region, using ground based GPS-TEC observations. The following observations are the summery of our analysis. The daytime equatorial electrojet

5 (EEJ) derived from H-component of geomagnetic field and the real-time electric field (EEF) model (Manoj and Maus, 2012) correlates linearly and positively with correlation coefficient of C = 0.6. Most of the peak enhancement/reduction value of $\Delta TEC/\Delta lon$ and $\sigma(\Delta TEC/\Delta lon)$ was observed about 1-2 hrs later from post-sunset enhancement of equatorial electric field (EEF), which indicates that EEF and the spatial gradient of TEC has strong relationship. In terms of seasons and months, the nighttime pattern of the spatial gradient of TEC ($\Delta TEC/\Delta lon$) and its standard deviation $\sigma(\Delta TEC/\Delta lon)$ show similar

10 trend with $ROTI_{ave}$. The relation between the standard deviation of the spatial gradient of TEC, $\sigma(\Delta TEC/\Delta lon)$, and ionospheric irregularity occurrence indicated by $ROTI_{ave}$ are presented. The correlation coefficient between $\sigma(\Delta TEC/\Delta lon)$ and $ROTI_{ave}$ was about 0.7975 (in ASAB station) and 0.7915 (in DEBK station). Both $\sigma(\Delta TEC/\Delta lon)$ and $ROTI_{ave}$ show maximum enhancement/reduction during equinoctial/solstice months. Equinoctial asymmetry was also observed in both $\sigma(\Delta TEC/\Delta lon)$ and $ROTI_{ave}$, where March equinox was greater than September equinox. The intensity level of

15 $\sigma(\Delta TEC/\Delta lon)$ was stronger/weaker when the occurrence of ionospheric irregularity is present/absent. When the occurrence of ionospheric irregularities are suppressed (for example, during geomagnetic disturbed conditions), the nighttime peak value of $\sigma(\Delta TEC/\Delta lon)$ was smaller. Based on the above results, the strength of spatial gradient of TEC between the two

nearby located stations lying along the same geomagnetic latitudes could indicate the presence of large-scale ionospheric irregularities. The spatial gradient of TEC/electron density near-solar terminator obtained from two nearby located GNSS receivers method may be an alternative method to estimate the strength of the zonal electric field. The threshold value of the gradient of TEC and its standard deviation $\sigma(\Delta TEC/\Delta lon)$ and the minimum longitudinal separation between two stations that could led us to predict the occurrence of ionospheric irregularities are not addressed in the current study and this will be considered in the future investigation.

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Data availability

The data used in this study were obtained from ftp://cddis.gsfc.nasa.gov, http://geomag.org/models/PPEFM/RealtimeEF.html, http://magnetometers.bc.edu/index.php/, http://www.intermagnet.org/, and http://isgi.unistra.fr/data_download.php.

Competing interests

The authors declare that they have no conflict of interest.

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