

Studies of Total Electron Content variations at low-latitude stations within the Equatorial Ionization Anomaly zone

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Abstract: The total electron content (TEC) is an important parameter to monitor for possible space weather impacts. The radio waves that pass through the earth's ionosphere travel more slowly than their free space velocity due to group path delay of the ionosphere. This group path delay is directly proportional to the TEC of the ionosphere. Using dual frequency GPS receiver at low latitude stations of Ile-Ife (7.52°N, 4.28°E), Addis Ababa (9.04°N, 38.77°E) and Bangalore (13.03°E, 77.57°E), all located within 0 - 15°N of the equatorial anomaly region, the measurement of ionospheric TEC for 2012 has been carried out. The data from the three stations were used to study the diurnal, monthly and seasonal variations of TEC. The diurnal variations maximize between 10:00 – 16:00UT, 08:00 – 14:00UT and 06:00 – 12:00UT for Ile-Ife, Addis Ababa and Bangalore stations respectively. The diurnal variations showed wave-like perturbation during disturbed and quiet periods at Bangalore and Addis Ababa stations. The monthly average TEC variations showed that the month of March recorded the highest TEC value of ~59TECu at about 16:00UT in Ile-Ife station, while TEC at Addis Ababa and Bangalore maximize in October with ~72TECu and 65TECu at about 11:00UT and 09:00UT respectively. Seasonal variations showed that TEC maximizes during the equinoctial months and least in summer, over the three stations. Geomagnetic storms enhance TEC variations in the three stations.

Keywords: EIA, GPS, Ionosphere, Low-latitude, TEC

I. Introduction

The atmosphere is influenced by the dynamic and violet sun in various ways. The sun's surface occasionally erupts, sending a large part of the solar atmosphere (solar wind) streaming away at high speed. These events are called coronal mass ejections (CMEs). CME that enters the earth's magnetic field may cause geomagnetic storms which usually occur in conjunction with ionospheric storms. The ionosphere, the earth's upper atmosphere, is partially ionized by the solar radiation such as extreme ultra violet (EUV) and x-ray radiations.

At low-latitudes, during the day, one of the most prominent features in the ionosphere is the equatorial ionization anomaly (EIA). This feature is distinguished by higher plasma density on both sides of the equator, rather than that at the equator itself. The equatorial anomaly is formed as a consequence of $E \times B$ upward plasma drifts associated with an eastward E-field and a northward horizontal B-field. The lifted plasma then diffuses downward along the geomagnetic field lines due to the gravitational force and the plasma pressure gradient, and this results in ionization enhancements on both sides of the magnetic equator ($\pm 15^\circ$ in the latitude)^[1].

In the measurement of the magnitude of ionization in the ionosphere, TEC is used. The TEC is the number of electrons present along a path between a radio transmitter and receiver. Radio waves are affected by the presence of electrons. The more electrons in the path of the radio wave, the more the radio signal will be affected. For ground to satellite communication and satellite navigation, TEC is a good parameter to monitor for possible space weather impacts. The TEC in the ionosphere is modified by changing EUV radiation, geomagnetic storms and the atmospheric waves that propagate up from the lower atmosphere. The propagation of radio waves is affected by the ionosphere. The velocity of radio waves changes when the signal passes through the electrons in the ionosphere. The total delay suffered by a radio wave propagating through the ionosphere depends on the frequency of the radio wave and the TEC between the transmitter and the receiver. The change in the path and velocity of radio waves in the ionosphere has a big impact on the accuracy of satellite navigation systems such as GPS/GNSS. Neglecting changes in the ionospheric TEC can introduce tens of meters of error in the position calculations.

Ariyibi, et al.^[2] studied the diurnal variation of TEC over Ile-Ife using GPS data. They observed that diurnal TEC is enhanced as a result of geomagnetic storm. The effect of geomagnetic storm over Ile-Ife was also studied by Ariyibi et al.^[3]. They concluded that the value of TEC varies widely from low TEC value before dawn to a very high value during the daytime. Chauhan, et al.^[4] studied diurnal and seasonal variation of TEC at Agra in India and observed that the mean TEC varies from pre-dawn minimum to an afternoon maximum and then decreases. The low values were observed in winter while high values were observed in equinox and summer months, and there was an absence of winter anomaly. The variability of TEC over the West African

equatorial region was reported by Bolaji, et al.^[5] and results showed that the value and diurnal range variation is consistently lower in the June solstice than in other seasons during both high and low solar activities. Bhattacharya^[6] also reported that in India, TEC is depleted at the equator and enhanced at regions located 15° South and North of the magnetic equator and this raises the TEC gradient.

The study in this paper is related to the TEC variations in 2012 for three stations located within 0 – 15° N of EIA zone. The ionization in this zone is known to be high compared to relatively moderate levels of electron content in the mid-latitudes. The study therefore sets out to investigate the day-to-day, month-to-month, seasonal and annual variations in TEC at these stations and how the variability can affect users of satellite based navigation systems at low latitudes.

II. Material And Methods

Total electron content (TEC) are obtained from GPS data measured by NovAtel GSV400B GPS SCINDA receivers situated at Obafemi Awolowo University, Ile-Ife, Nigeria (Geomagnetic cords: Lat 7.52°N and Long 4.28°E); Addis Ababa University, Addis Ababa, Ethiopia (Geomagnetic cords: Lat 9.04°N , Long 38.77°E) and Indian Institute of Science, Bangalore, India (Geomagnetic cords: Lat 13.03°E, Long 77.57 °E). Fig. 1(a) shows the location of the study areas on the world map and within the EIA zone (15°N). Since the poles move slowly according to secular variation of the geomagnetic field, the coordinates also varies from year to year. Fig. 1(b) shows the latitudinal and longitudinal locations of the study areas in 2012 using 'geomagnetic dipole coordinate'. The GPS SCINDA is a real-time GPS data acquisition and ionospheric analysis system, and computes ionospheric parameters S_4 and TEC using the full temporal resolution of the receiver. The TEC is computed from the combined L_1 (1575 MHz) and L_2 (1228 MHz) pseudo ranges and carrier phase, and the scintillation index, S_4 , is the statistical measure of the intensity of the amplitude scintillation of the L_1 frequency (1575 MHz) GPS signals. The equipment is suited for studying several parameters simultaneously.

Sardon, et al.^[7] reported that if accurate estimates of the ionospheric TEC are to be made, the differential instrumental biases must be removed. The TEC along the GPS ray path from a satellite to a receiver is known as slant TEC (STEC). STEC is the measure of the total number of free electrons in a column of the unit cross-section along the path of the electromagnetic wave between the satellite and the receiver. It can also be obtained from the difference between the

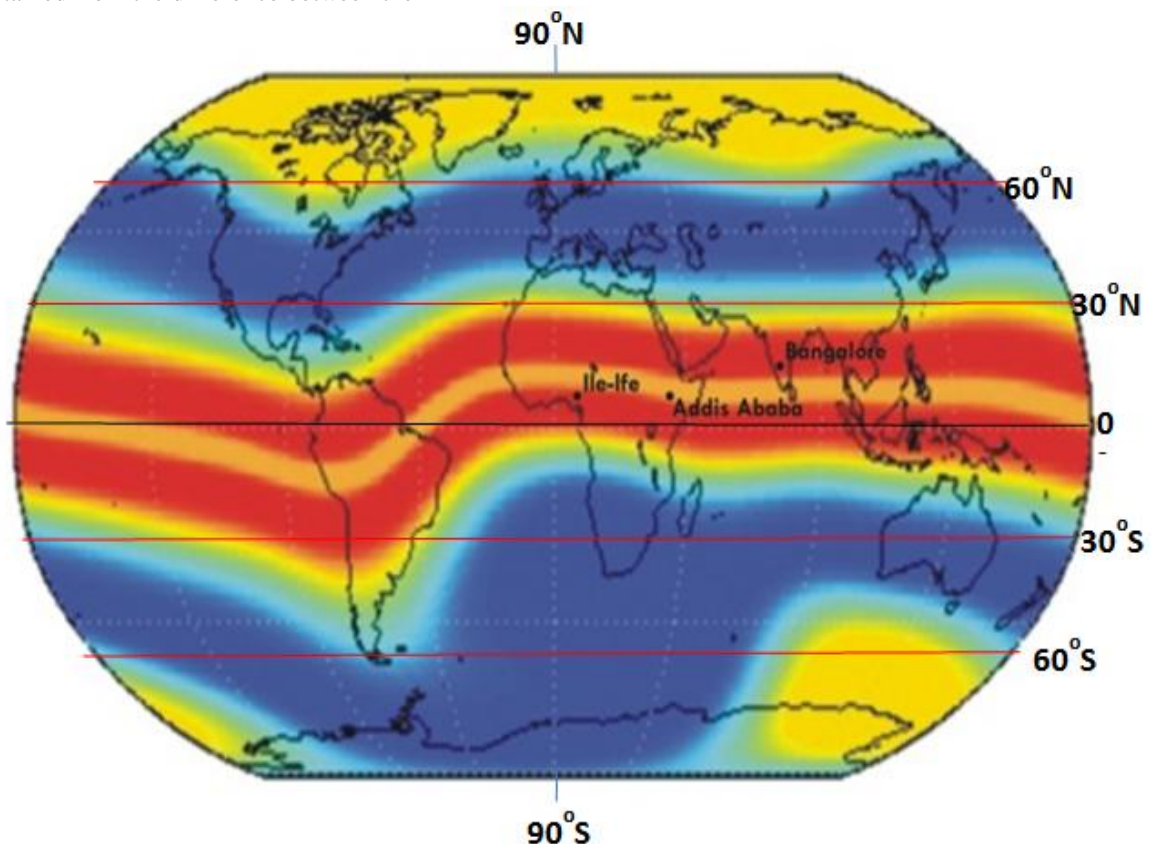


Fig. 1(a): The map of the world showing the study areas (Adapted from Kintner et al.^[8])

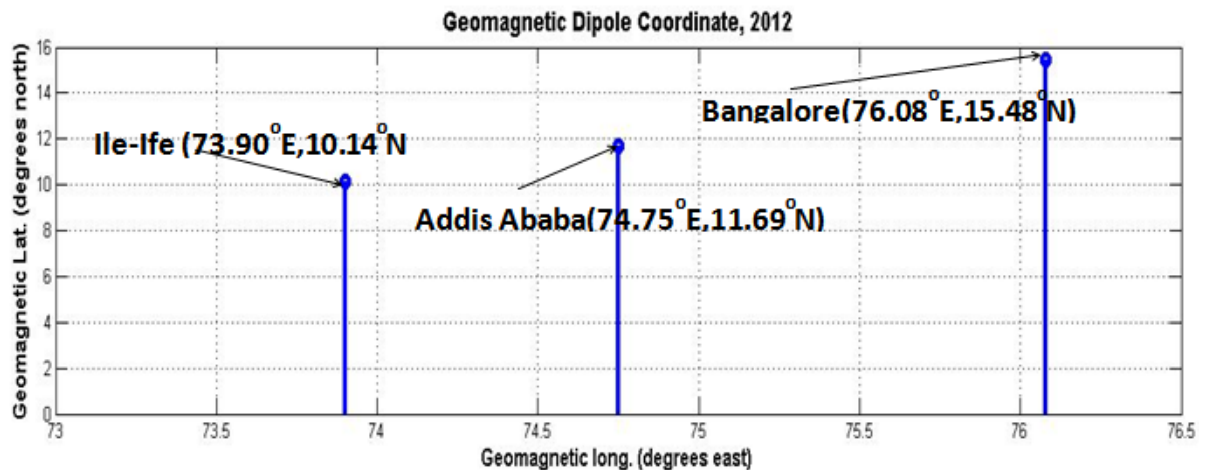


Fig. 1(b): The latitudinal and longitudinal locations of the study areas

pseudo ranges (P_1 and P_2), and the difference between the phases (L_1 and L_2) of the two GPS signals^{[9][10]}. The relevant equations are:

$$STEC = \frac{1}{40.3} \times \left(\frac{1}{L_1^2} - \frac{1}{L_2^2} \right)^{-1} \times (P_1 - P_2) + TEC_{cal} \quad (1)$$

where P_1 is pseudo range at L_1 ; P_2 is pseudo range at L_2 ; TEC_{cal} is the user - defined TEC offset. As STEC is dependent on the ray path geometry through the ionosphere, it is desirable to calculate an equivalent vertical value of TEC, which is independent of the elevation of the ray path. The vertical TEC is obtained by taking the projection from the slant to vertical using a thin shell model, assuming a height of 350 km following the techniques given by Klobuchar^[10]

$$vTEC = STEC \times \cos\left(\sin^{-1}\left(\frac{R_e \cos\theta}{R_e + h_{max}}\right)\right) \quad (2)$$

where $R_e = 6378$ km, $\theta =$ elevation angle of GPS satellite at the ground station and h_{max} is the height of ionospheric penetration point (IPP) usually assumed to be 350 – 400 km.

The analysis of the TEC data from the three stations were carried out using the GPS-TEC analysis application software, version 2.2^[11]. This program gives plots of vertical TEC on the screen and writes ASCII output files which are used for further analysis of the data. It calculates TEC from the observation data of GPS Rinex, Novatel (reads only ID43 records), SCINDA (scn files) and Leica binary files.

III. Results And Discussion

The results presented here are from the analysis of TEC values measured by three independent GPS receivers situated at different locations at low latitudes. The analyses of diurnal, monthly and seasonal variations of TEC for January – December 2012 have been made.

3.1. Diurnal Variation of TEC

To investigate the diurnal variations in vertical TEC, the daily average TEC variations for some disturbed days have been compared with that for some quiet periods.

Fig. 2 compared the diurnal variation of TEC during the geomagnetic storm period of 7 – 11 March 2012, with the diurnal variation of TEC for the quiet periods of 1- 5 May 2012 for two stations, Ile-Ife and Bangalore. There was no TEC data for May 2012 in Addis Ababa station. The Dst indices for the corresponding periods are also shown in the 1st panel of the figure. The minimum Dst on the storm day was -131nT while the Dst values on the quiet days ranges from -20 to 18nT. The diurnal variation of TEC is compared with the monthly mean for each month, shown by blue line. It can be seen that there was an enhancement in the vertical TEC on days 8, 9 and 10 of March 2012, with day 9 having the highest TEC value of about 70 TECu in Ile-Ife station. The maximum TEC value for the mean TEC is about 56 TECu for the same station. For Bangalore, there was significant enhancement only on the day of the storm. The maximum diurnal TEC value was about 71 TECu against 60 TECu for the monthly mean TEC on the storm day. However, before and after the storm, the daily values are approximately equal to the monthly mean, just as it is the case for the quiet period of 1 – 5 May 2012 shown in fig. 2b. This situation is the same for the two stations; Ile-Ife and Bangalore.

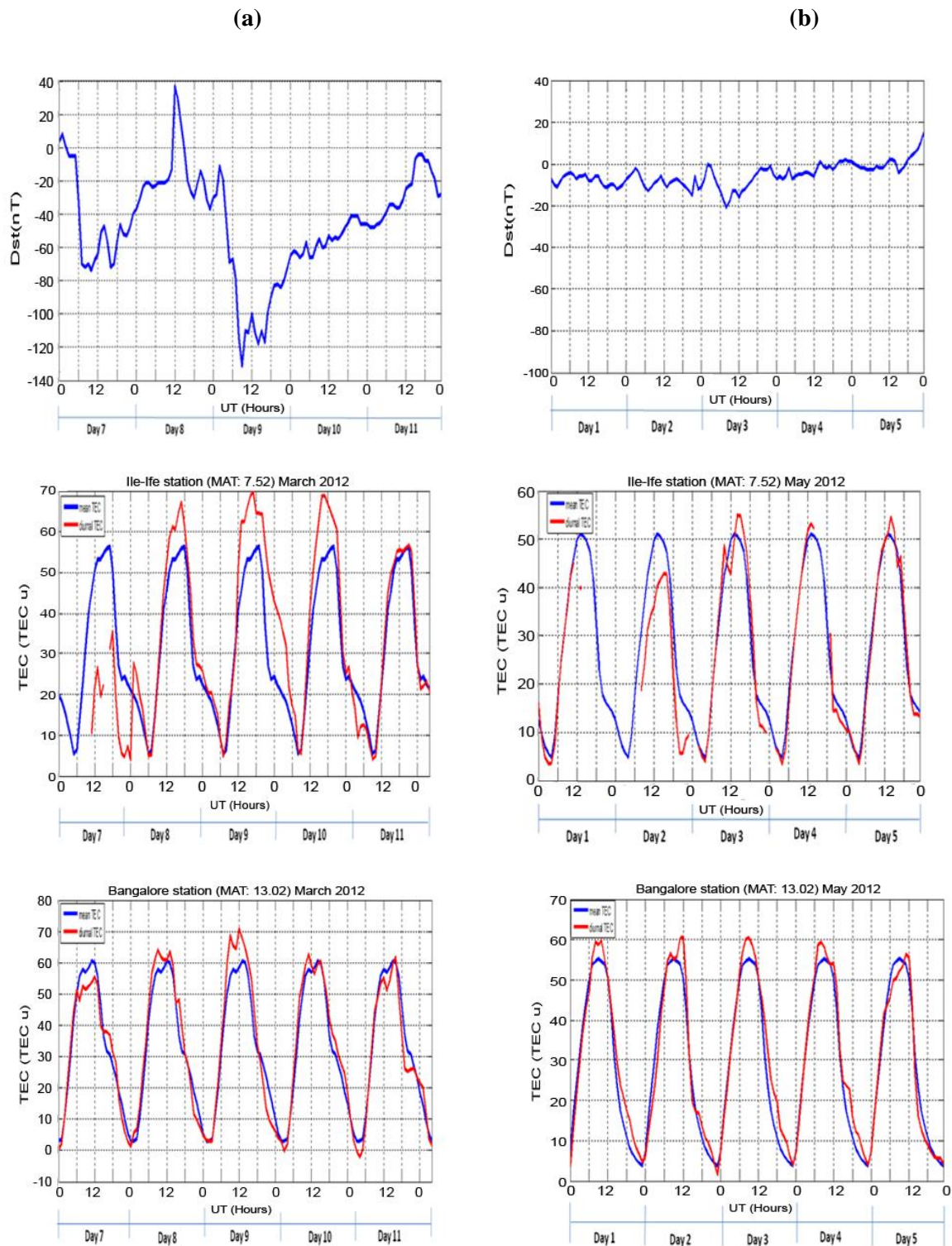


Fig. 2: The diurnal variation of TEC: (a) Depicts the storm event of 9 March 2012, with Ile-Ife station in the 2nd panel and Bangalore station in the 3rd panel. (b) Depicts the quiet period in May 2012, with the Ile-Ife station in the 2nd panel and Bangalore station in the 3rd panel. In both cases, the corresponding Dst index is presented in the 1st panel.

Fig. 3 compared the diurnal variations of TEC during the geomagnetic storm period of 29 September to 3 October 2012, with the diurnal variations of TEC for the quiet periods of 26 - 30 August 2012 for the three stations. The Dst indices for the corresponding periods are also shown in the 1st panel of the figure. The minimum Dst on the storm day was -120nT while the Dst values on the quiet days ranges from -16 to 10nT. The diurnal variation of TEC (in red line) is compared with the monthly mean for each month (in blue line). It can be

seen from the figure that there was an enhancement in the vertical TEC on the storm day, while the TEC values for the other days were almost equal for the three stations. This was not the case during the quiet periods. The monthly mean TEC and the diurnal TEC were almost equal for all the days. The storm that occurred on 9 March and 1 October 2012 was preceded by storm sudden commencement (SSC) at about 03:00UT on 9 March and 23:00UT on 29 September respectively, marking the beginning of the main phase of the storm. The main phase ended with minimum Dst values of -120nT and -131nT for 9 March and 1 October respectively. This is an indication of the penetration of high latitude convection electric field to the low latitude stations of African and

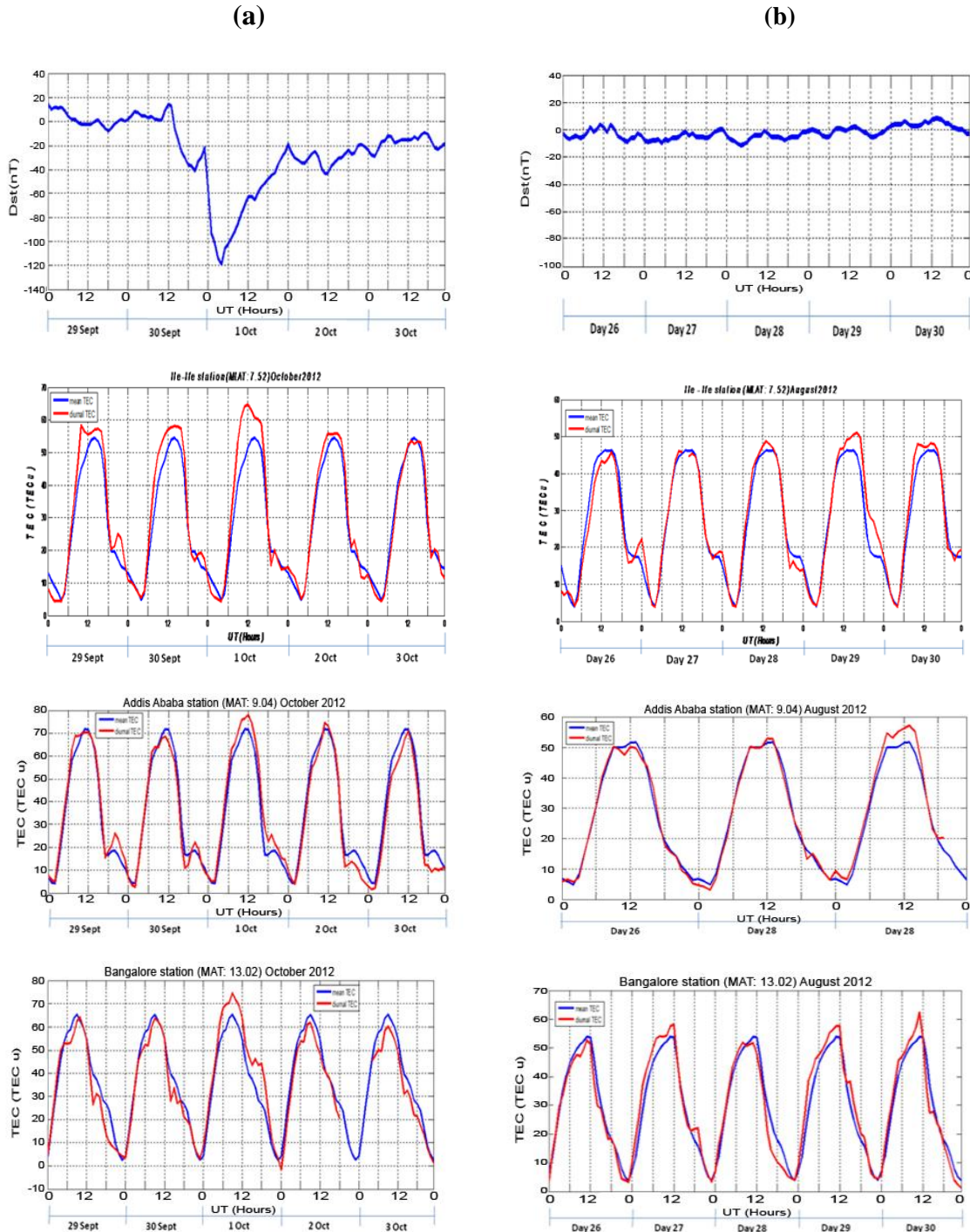


Fig. 3:The diurnal variation of TEC: (a) Depicts the storm event of 1 October 2012, with Ile-Ife station in the 2nd panel, Addis Ababa station in the 3rd panel and Bangalore station in the 4th panel. (b) Depicts the quiet period in August 2012, with the Ile-Ife station in the 2nd panel and Addis Ababa station in the 3rd panel. In both cases, the corresponding Dst index is presented in the 1st panel.

Indian sectors. As it was reported by Basu et al.^[12] and Forster and Jakowski^[13] of a significant enhancement of ring current during the main phase of a storm, the investigation of diurnal variation of TEC revealed an enhancement in TEC during geomagnetic storms. Also, comparing the three stations, two in Africa and one in India, it revealed that the enhancement in TEC during storms was more at Addis Ababa and least at Ile-Ife. This suggests that TEC variations do not depend solely on the sector.

Another feature of interest as observed (fig. 4 and 5) was a wave-like perturbation and multiple peaks on the two stations of Addis Ababa and Bangalore for both disturbed and quiet days. Ile-Ife has relatively smooth variations with respect to time. It has been reported of such wave-like features during geomagnetic storms in Indian sector^[14] and in the South American region^[12]. They proposed that storm shocks might have induced the wave-like perturbations in TEC, which indicate the presences of gravity wave type perturbations in the ionosphere. The perturbation of such was attributed to prompt penetration of high-latitude electric fields to lower latitudes. D'ujanga et al.^[15] observed such wave-like perturbation in two stations of East Africa during the recovery phase of a storm. This study reveals such wave-like perturbation at Bangalore and Addis Ababa stations during both disturbed and quiet periods, with Ile-Ife station having relatively smooth variation. The deriving force for such feature on quiet days are yet not understood.

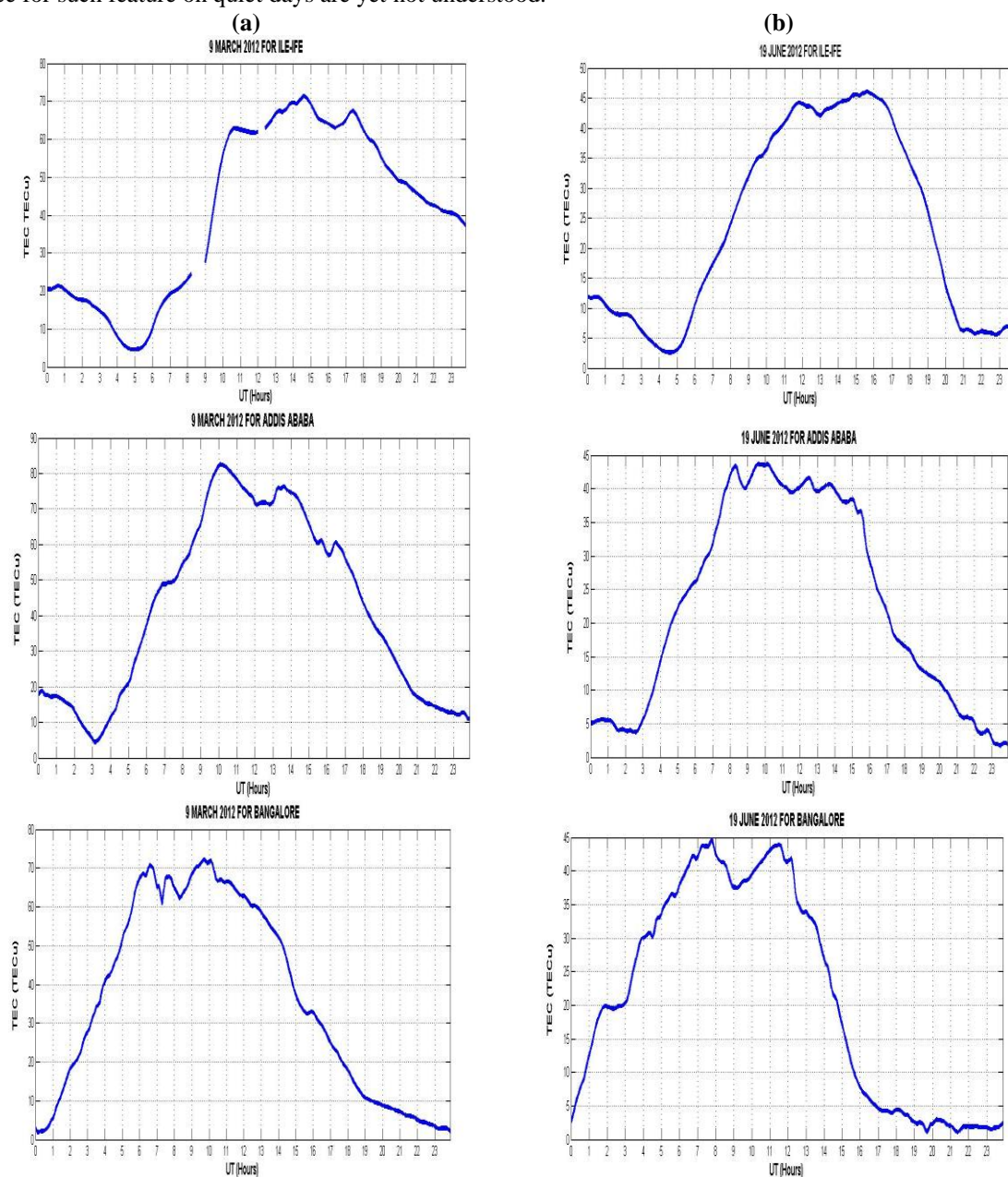


Fig. 4:The diurnal variation of TEC indicating wave-like perturbation: (a) disturbed day of 9 March 2012 and (b) quiet day of 19 June 2012.

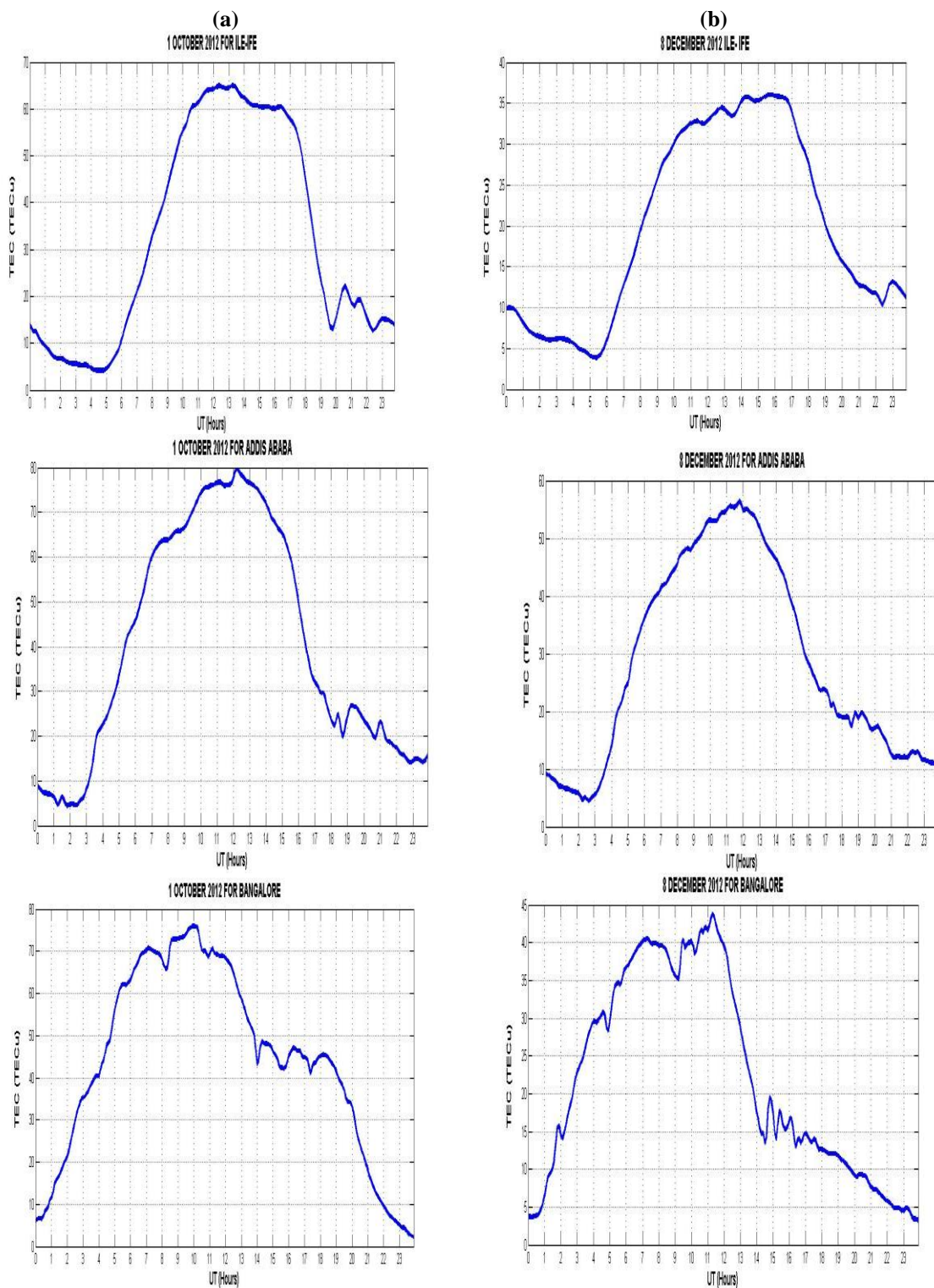


Fig. 5:The diurnal variation of TEC indicating wave-like perturbation: (a) disturbed day of 1 October 2012 and (b) quiet day of 8 December 2012.

3.2 Monthly variation of TEC

The monthly variation in TEC as shown in figure 6 in the three stations revealed the three segments expected of low-latitude stations: the build-up region, afternoon plateau and decay region. In Ile-Ife station, the month of March recorded the highest peak TEC of ~59TECu at about 16:00UT, followed by April with maximum TEC value of ~57TECu at about 15:00UT. The month of December recorded the least peak TEC of ~37TECu at about 14:00UT. In Addis Ababa station, the month of October recorded the highest peak TEC of ~71TECu at about 11:00UT, followed by March and April, with Peak TEC of ~68 and 67TECu respectively at about 11:00UT. The least peak TEC of ~48TECu at about 12:00UT was observed in August and July. In Bangalore station, the month of October recorded the highest peak TEC of ~65TECu at about 09:00UT, followed by September and April with TEC values of ~62TECu and 60TECu respectively. December recorded the lowest peak TEC of ~40TECu during the afternoon maximum.

The variation of the monthly mean TEC for the above mentioned period of 12 months for the three stations are as shown in the contour plots of figs. 7. The features mentioned above are reflected very well in these figures. The minimum mean TEC was registered from 20:00 – 07:00UT, except in the months of March and April where the periods of 20:00 – 23:00UT recorded moderate mean TEC values in Ile-Ife station. The afternoon maximum was attained between the hours of 10:00 and 17:00UT. The months of June, July and August recorded moderate mean TEC values ranging from 41 – 43 TECu during the afternoon maximum (depicted in yellow colour in the diagram). The highest mean TEC values was recorded in the months of March, April, September and October, with values ranging from 51 -59 TECu. For Addis Ababa station, the afternoon maximum was attained between 10:00 and 14:00UT. In the months of June, July and August, the afternoon maximum recorded moderate mean TEC value, ranging from 42 – 47 TECu. The maximum mean TEC value for the afternoon maximum was attained in the months of March, April and October, with the value of ~71 TECu recorded in the month of October at about 11:00UT. In Bangalore station, the afternoon maximum was attained during 06:00 – 12:00UT and the minimum during night and early morning (16:00 – 02:00UT). The months of June, July and August recorded moderate mean TEC value during the afternoon maximum, as depicted in green colour. The maximum mean TEC during the afternoon maximum was recorded in the months of March, April, September and October 2012, with highest value of 65 TECu recorded in October at about 09:00UT.

In general, the variations in monthly mean TEC varied from month-to-month over all stations. The afternoon maximum was attained earlier at Bangalore, followed by Addis Ababa and then at Ile-Ife station. Addis Ababa station recorded the maximum mean TEC during the afternoon maximum over all the months, followed by Bangalore station and least at Ile-Ife station.

The day-to-day or month-to-month variability in TEC, which has also been observed by some authors^{[1][16]}, may be due to the changes in the activity of the sun itself and to the associated changes in the intensity of the incoming radiations and the zenith angle at which they are incident on the Earth's atmosphere. EEJ strength, Earth's magnetic field and the dynamics of the neutral wind are also some factors which may be responsible for this variability Rama Rao et al.^[1]. The results of variation in mean TEC over the low-latitude stations considered in this work showed that the variation in mean TEC is dependent on season, latitude and local time of occurrence.

3.3 Seasonal variation of TEC

Figs. 8 and 9 showed the seasonal variation of TEC in the three stations and the dependence of seasonal variation of TEC on locations respectively. The TEC variations attained maximum during the afternoon with equinoctial months (March, April, September and October) recording the highest TEC amplitude of ~68, 61 and 56TECu for Addis Ababa, Bangalore and Ile-Ife stations respectively. This was followed by the TEC amplitudes in winter (November, December, January and February), recording ~58, 50 and 47TECu for Addis Ababa, Bangalore and Ile-Ife respectively. Summer months (May, June, July and August) recorded the least TEC amplitudes of ~49TECu for Addis Ababa and Bangalore, while that for Ile-Ife was ~44TECu. In general, the morning rise to peak in the afternoon and then fall in TEC was sharp during the equinoctial months. Also, the production of O/N₂ was faster in winter than in summer. These could be explained using thermospheric neutral composition. Thermospheric neutral composition has a direct control on the seasonal variation of TEC. Rishbeth and Setty^[17] suggested that the seasonal changes result from changes in ratio of the concentration of atomic oxygen and molecular nitrogen in the F-region. During the daytime, the equator is hotter than the pole, therefore meridional wind flows towards the pole from the equator. This flow of meridional wind changes the neutral composition and O/N₂ decreases at equatorial and low latitude stations. The decrease is maxima in equinoctial months. At 350 km altitude (F2-layer), N₂ dissociation is the major process which removes ambient electrons. Hence, the decrease in O/N₂ ratio will result in higher electron density and therefore in equinox, TEC will be highest.

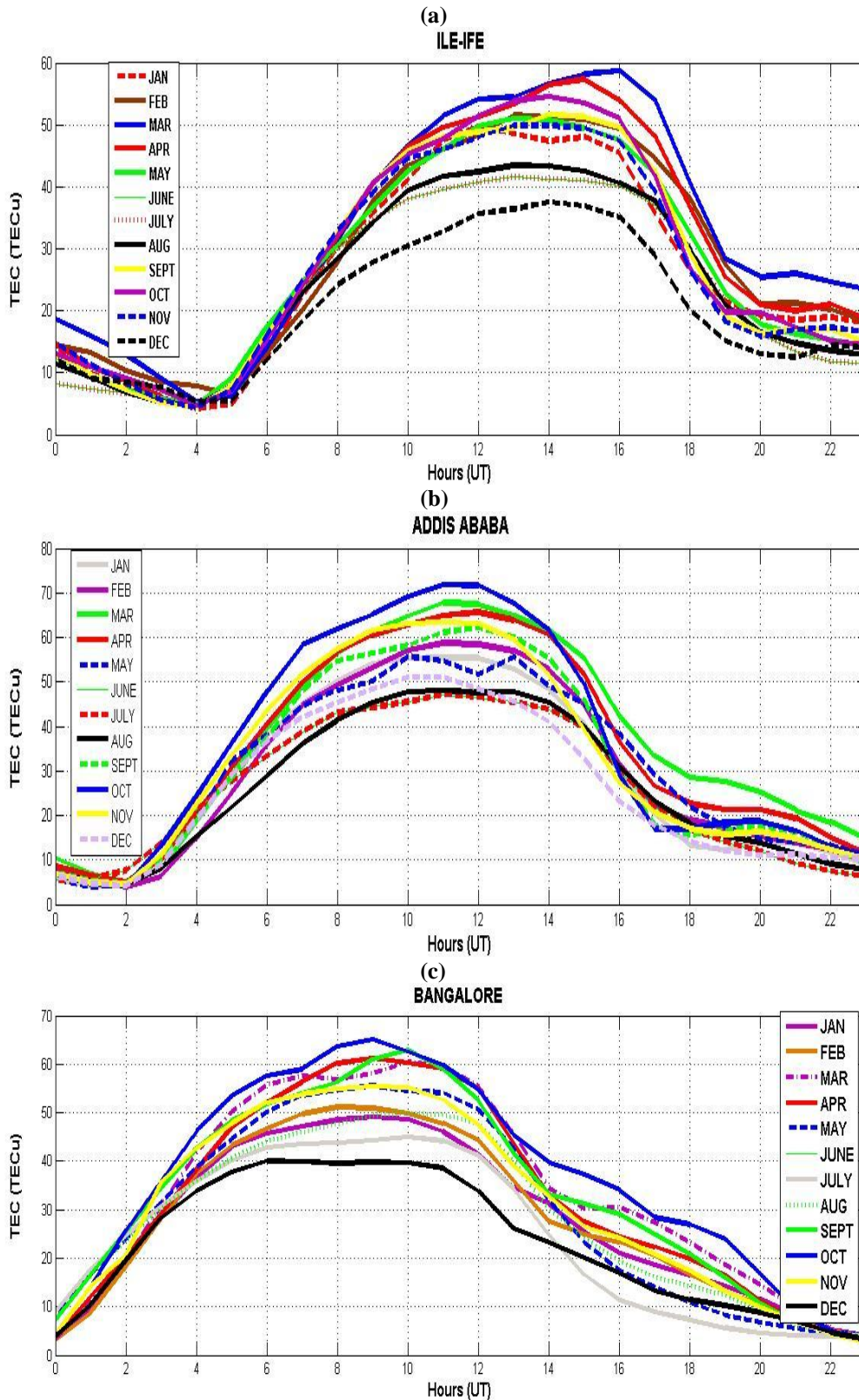


Fig. 6: The monthly variation of TEC for 2012: (a) Ile-Ife (b) Addis Ababa and (c) Bangalore

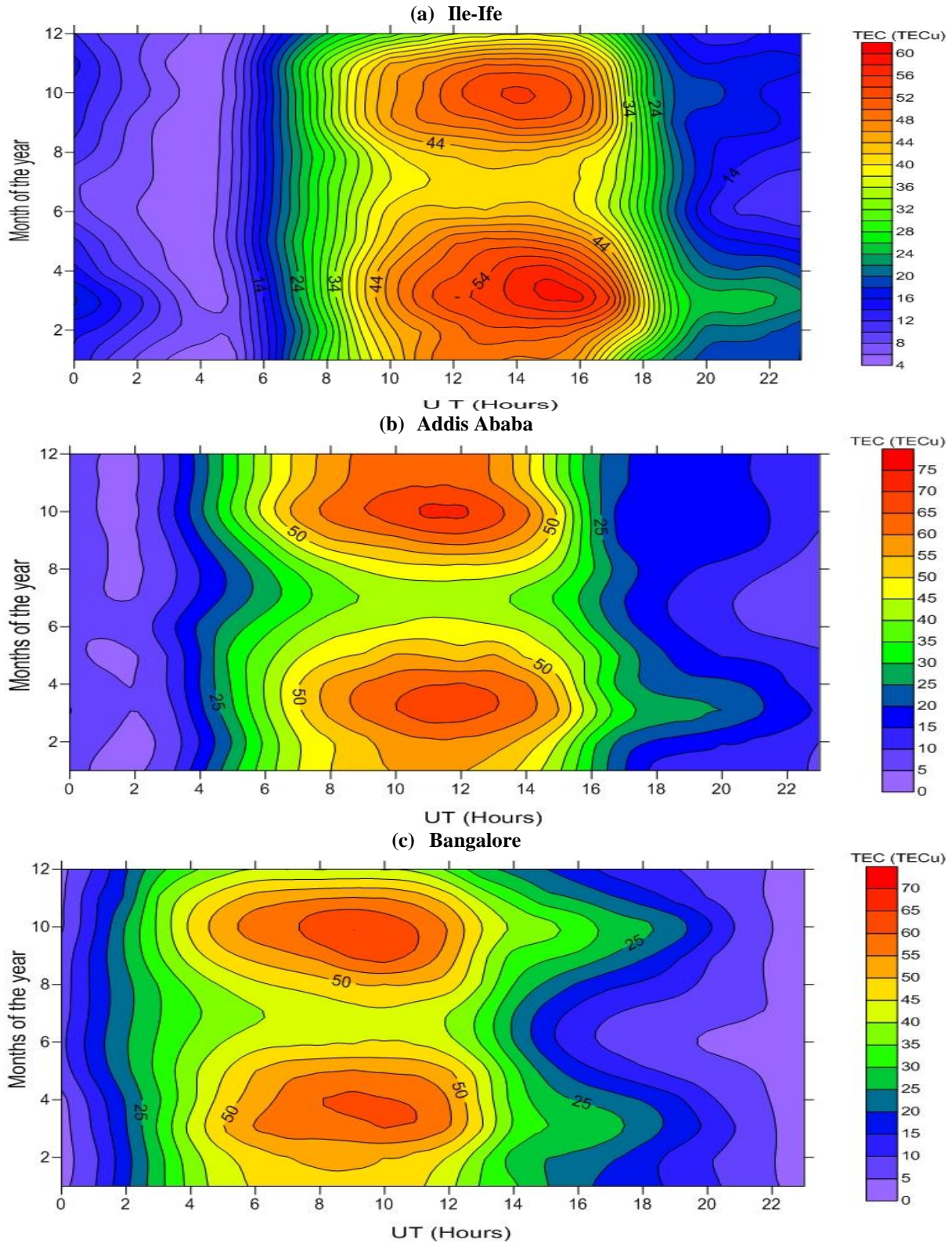


Fig. 7:Contour plots of monthly mean TEC variation at (a) Ile-Ife (b) Addis Ababa and (c) Bangalore

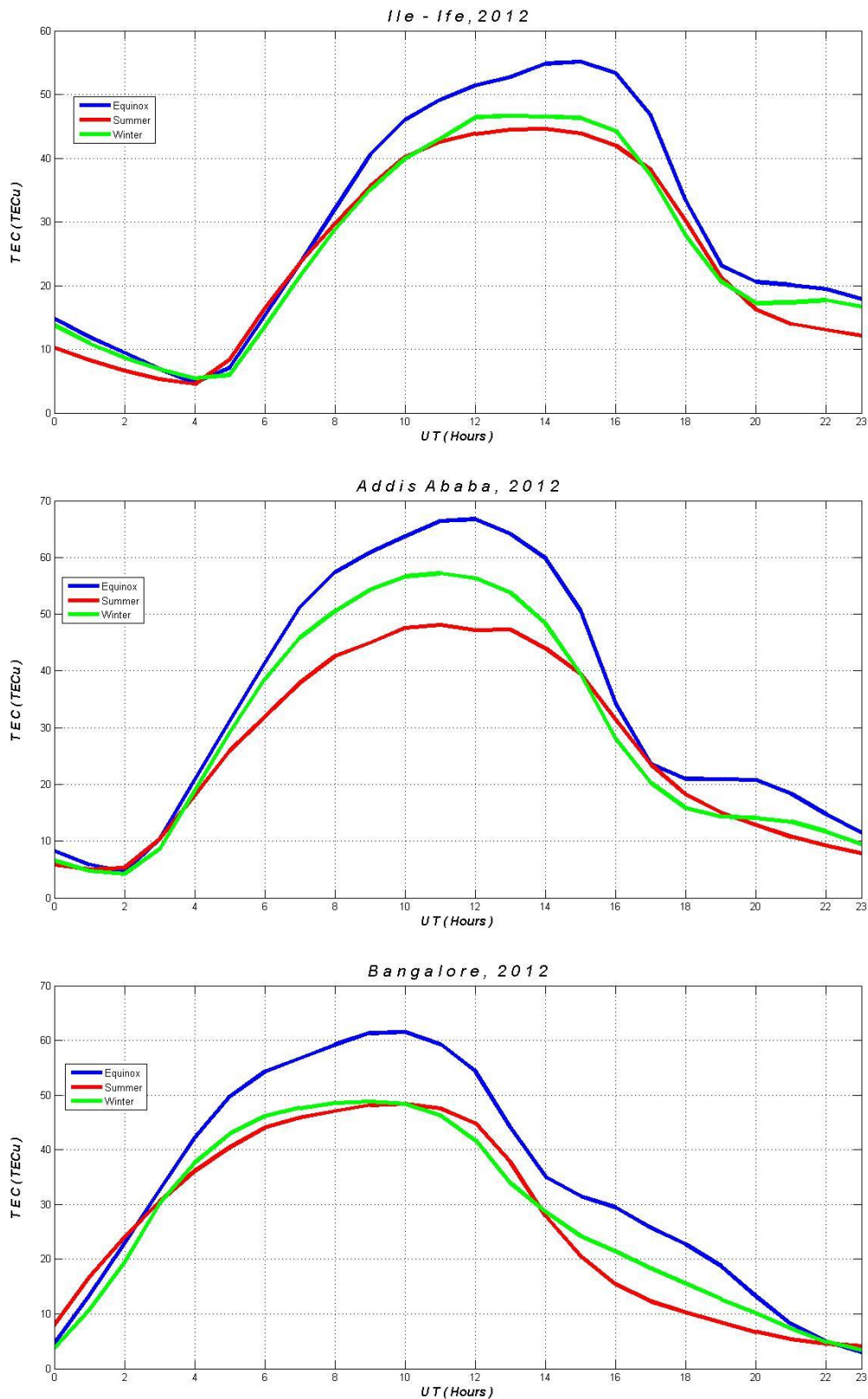


Fig. 8: The seasonal variation of TEC in 2012 for: (a) Ile-Ife (b) Addis Ababa and (c) Bangalore

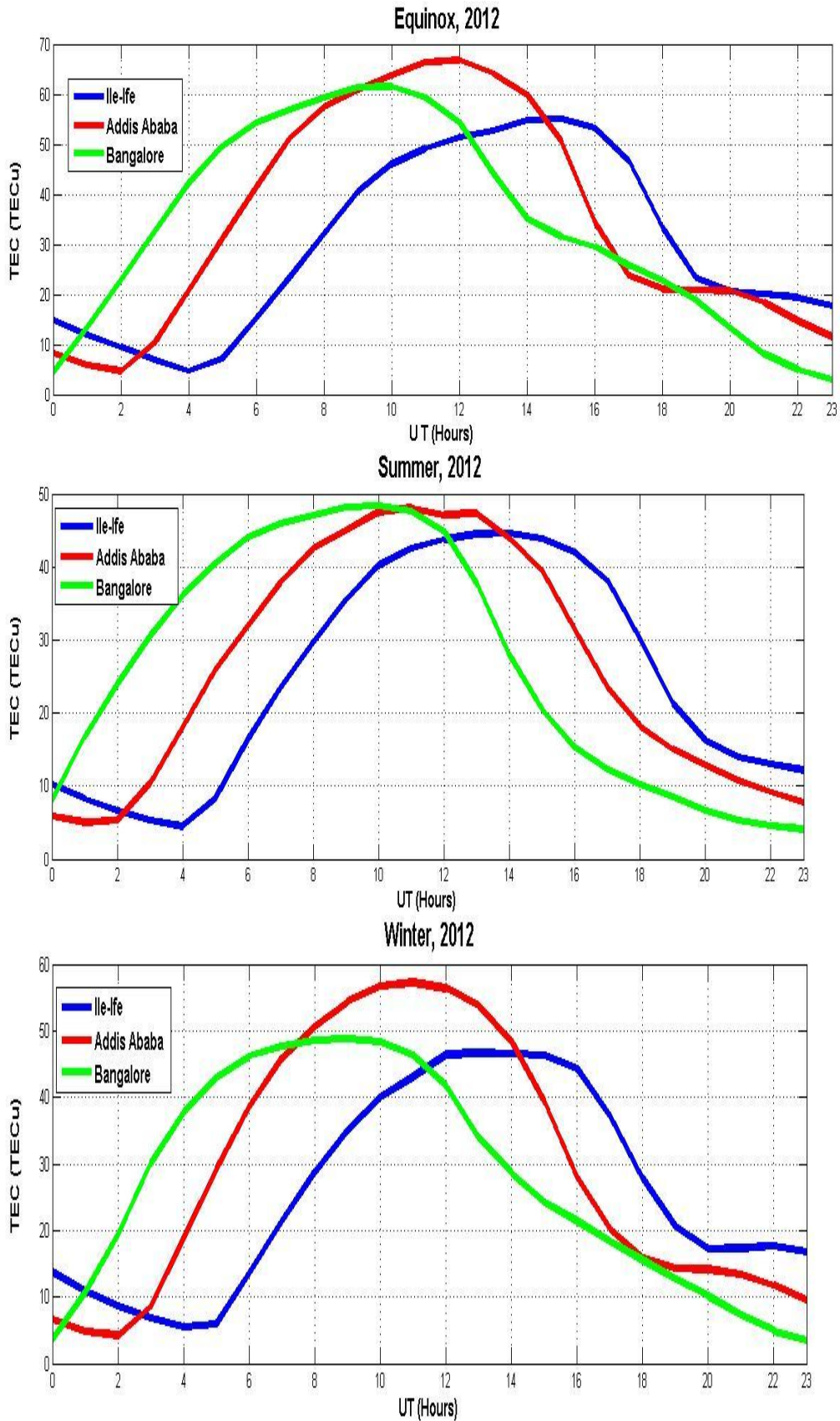


Fig. 9: The dependence of seasonal variation of TEC on location

IV. Conclusion

The diurnal, monthly and seasonal variations of TEC from the three stations of Ile-Ife (7.52°N, 4.28°E), Addis Ababa (9.04°N, 38.77°E) and Bangalore (13.03°E, 77.57°E), all located at the northern crest of equatorial ionization anomaly region have been studied for the period of January – December 2012. There was considerably TEC variations in the three stations, especially during geomagnetic storms. The diurnal variations reached maximum values between 10:00 – 16:00UT, 08:00 – 14:00UT and 06:00 - 12:00UT for Ile-Ife, Addis Ababa and Bangalore stations respectively. The diurnal variations at Bangalore and Addis Ababa exhibited wave-like perturbations during both disturbed and quiet periods, with greater effect at Bangalore station. The cause of the wave-like perturbations during quiet periods are not yet understood. The monthly variations showed that TEC maximizes during the equinoctial months over all the stations, followed by winter months. The observations showed that geomagnetic storms enhances the TEC and in comparison, Addis Ababa had higher TEC values, followed by Bangalore and least in Ile-Ife station. The observed TEC variations in the three stations suggest that space weather effects are likely to be felt more at Addis Ababa and least at Ile- Ife.

Acknowledgements

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