Association of Total Electron Content (TEC) and f_oF2 variations with earthquake events at the anomaly crest region

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Abstract
The paper attempts to identify ionospheric parameters in association with earthquake at anomaly crest station through VHF Radio Beacon data and ground based ionosonde measurements while the Total Electron Content (TEC) parameters from RB observations are based mainly on data taken over Guwahati (26.2°N, 91.75° E), f_oF2 data used in the analysis were collected at Ahmadabad (23.01°N, 72.36°E). The paper describes methods and techniques adopted to examine modifications on these parameters if any, due to earthquake preparatory processes at equatorial anomaly crest stations. The mechanism of inducement of density changes in the ionosphere is sought through the generation of strong fountain effect possibly by the development of electric field during the earthquake preparatory process.

Key words *earthquake – TEC – f_oF2 – anomaly*

1. Introduction

Earthquake-induced effects are diverse in nature and their manifestations are observed right from the Earth crust to thousands of kilometres up in the atmosphere. Conventional seismic monitoring along with knowledge of earthquake-associated phenomena like electromagnetic emissions, lithosphere-ionospheric coupling processes (Gokhberg *et al.*, 1982; Oraevsky *et al.*, 1994; Larkina *et al.*, 1989; Hayakawa, 1999) are now widely utilized to disclose an association between the processes.

Anomalous behavior of the ionosphere prior to an earthquake was reported as early as 1929. Since then, observations on the changes in ionospheric parameters like f_oF2, f_oEs, Total Electron Content (TEC) and characteristics of turbulences have been examined, to understand if there is any earthquake induced information and to devise some predictor parameters (Wolcott *et al.,* 1969; Parrot and Mogilevsky, 1989; Blaunstein, 1999; Devi *et al.,* 2001) within these variables.

However, analyses and co-relative works for identifying earthquake precursors remain a challenging problem because of the complexity of their very nature.

In this paper ionospheric parameters TEC and f_oF2 of anomaly crest stations like Guwahati (26.2°N, 91.75°E) and Ahmedabad (23.01°N, 72.36°E) are examined, associating a number of earthquake cases. As physical and dynamic processes of the high, mid, low and equatorial latitude ionosphere are of different nature, we will restrict our analysis to the low latitude equatorial anomaly region only.

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2. Background

Some of the strongest earthquakes of the world occurred on this region in the years 1548, 1596, 1642, 1663, 1897, 1875, though their exact magnitudes are not known. Some events of known intensity are those of the years 1897 (M = 8.7), 1918 (M = 7.6), 1930 (M = 7.1), 1950 (M = 8.7) and 1988 (M = 7.3). Because of the high seismic propensity of this zone, prediction of earthquakes in this region has become a necessity. Though a few short-term predictions based on statistical study have been made, these were observed to be false alarms.

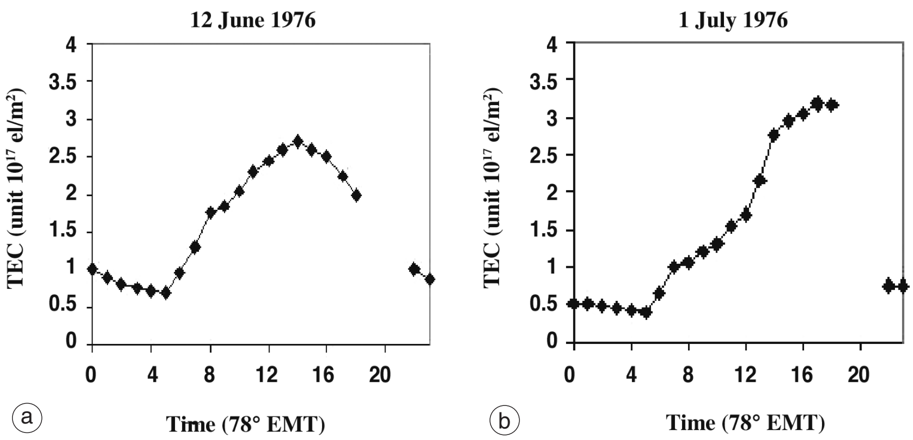

Fig. 1a,b. TEC variations during low solar activity period over Guwahati: a) a quiet day feature; b) a disturbed day TEC character. Note: the large enhancement in ionization density after sunset during the *D*-day.

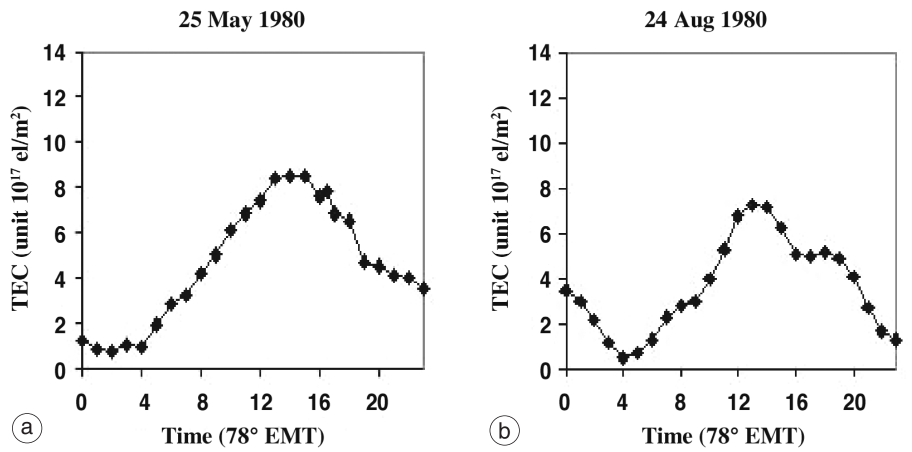

Fig. 2a,b. Same as in fig. 1a,b but for high solar activity periods: a) the usual quiet day diurnal variation and (b) one of the typical disturbed day TEC pattern. Note: the initial decay rate on *D*-day is arrested by post sunset enhancement.

3. Observations

3.1. *TEC and earthquake events*

Our attempts to understand the association between columnar electron content behaviour and earthquake events are discussed here through a few observations. This work is based on Faraday Rotation (FR) data collected through satellite Radio Beacon (RB) signal from ATS-6 (frequency 144 MHz, position 35°E) for low solar activity periods and from ETS II (frequency 136.11 MHz, position at 130°E) for high solar activity periods. Before attempting to identify earthquake-induced imprints on TEC profiles, as it is necessary to have a knowledge on the relation of TEC with solar and geomagnetic parameters, we show in figs. 1a,b and 2a,b a few profiles observed over Guwahati at different solar and geomagnetic situations. It is seen that during high solar activity periods (1979-1981) TEC is at least 2 fold higher (fig. 2a,b) than at low solar epoch of 1975-1976 as in fig. 1a,b, indicating the need to realize the role of background density while assessing possible earthquake-induced features. In fig. 1a, the TEC profile of June 12, 1976 while represents quiet day (*Q*-day), the profile of July 1, 1976 features a disturbed day (*D*-day). A large increase in ionization density even after sunset hours is a significant point to be noted in the *D*-day, indicating processes other than normal ones are active on such days. Depending on the solar-geomagnetic conditions, it is observed that the TEC profile shape of *D*-day changes (Devi *et al.,* 2002). In fig. 2a,b, we present one *Q*-day event (May 25, 1980) and a *D*-day TEC profile (24 August 1980) of high solar periods. Here too, on the *D*-day the initial decay rate is arrested by injection of extra ionization. Keeping these features in mind, we take the following approaches while examining possible seismo-ionospheric effects though this parameter. Five most quiet day TEC values are first identified and their average figure is taken as a base of TEC free from geomagnetic disturbances. We select a period of 30 days preferably keeping earthquake day as the centre while selecting the *Q*-day base. Further, as *Q*-day TEC also show day to day fluctuations, their maximum and minimum excursions from the base are determined. We have taken any deviation in TEC over this excursion limits as an index of anomaly. Thus, deviations in TEC from the base during and pre-earthquake days are evaluated. Attempts are then made to associate such excursions with earthquake events. Further, extensive study on magnetic storm-induced TEC behaviour over this station has been made (not discussed here) to omit the magnetic storm afflicted TEC data while making this selection.

Figure 3a,b shows two representative cases for low solar activity period. The two cases are so selected that they represent two basic features of earthquake-time density variation. Considering the type I behavior, we take the December 6, 1975 earthquake event. A clear increase in TEC prior to the earthquake days is noted in this case. This earthquake occurred at 11:15 h (92° East Meridian Time, EMT) with epicentre at 17.42°N (119.68°E). The figure also shows maximum and minimum excursion values of *Q*-days from its mean value, along with diurnal TEC variations of December 6. Magnitudes of daytime electron content on the two days show a clear high, relative to average quiet day TEC from the 30 day period.

As an example of type II, fig. 3b represents features of the July 21, 1976 earthquake, when a significant depletion in TEC values are noted prior to and during the event. This earthquake occurred at 21:10 h (92°EMT) on that day with its epicenter at 24.78°N (98.70°E). The TEC pattern was the reverse of what was received on 6th December. In the pre-event time, a decrease of density is noted at the latitude of Guwahati and the density dips far below the minimum excursion bar of quiet day TEC mean.

However, such strong changes may not be clear when solar activity and background density both are high. As an example, we take the TEC values say for July 29, 1980 (fig. 4), when two consecutive earthquakes are recorded at 18:20 h (92°EMT) and 20:58 h (92°EMT) with epicenters at 29.33°N (81.26°E) and 29.60°N (81.09°E). On this occasions increase in density at Guwahati though appreciable from early morning hours, the large changes in TEC as observed in the low solar period are not so appar-

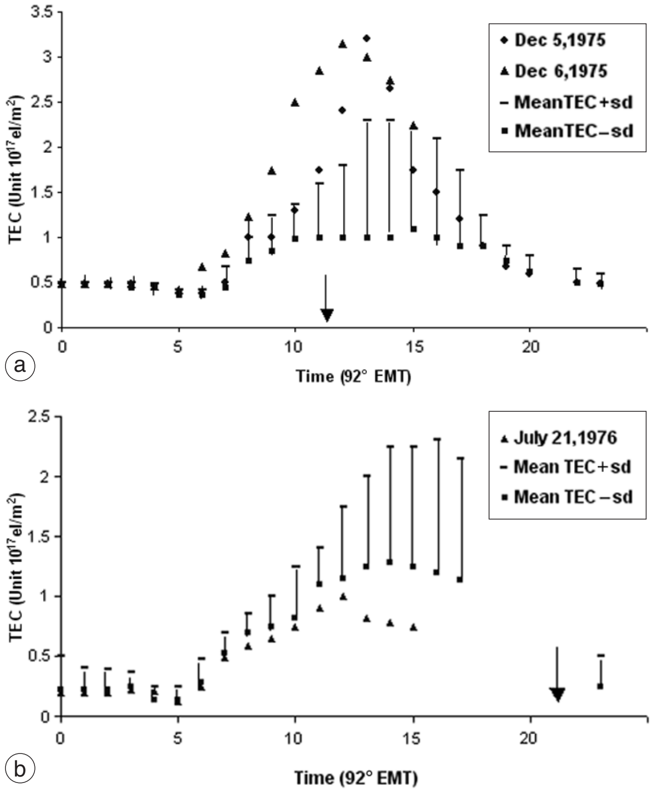

Fig. 3a,b. Plots showing variations in TEC (taken over Guwahati) from the *Q*-day base, during low solar activity period. Earthquakes occurred on (a) December 6, 1975 and (b) July 21, 1976. Earthquake commencement times are shown by arrowheads in the figure. The vertical bars give the excursion of standard deviation of *Q*-day TEC from the base.

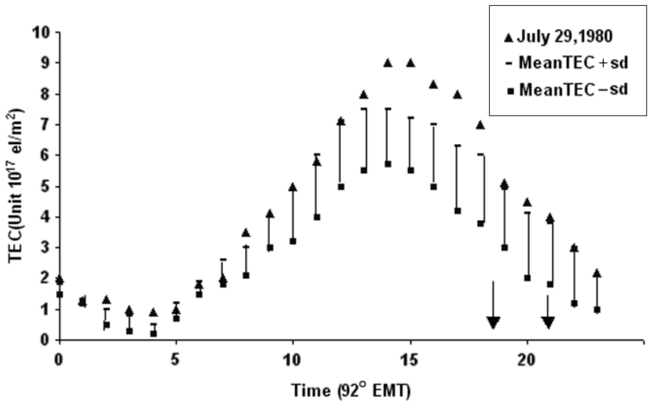

Fig. 4. Same as in fig. 3a,b but for high solar activity earthquake event. The event shown is for 29 July, 1980. Earthquake occurrence times are shown by arrowheads. The vertical bars give excursion of standard deviation of *Q*-day from the base.

ent probably because of high background density conditions. In this case, the epicenter lies at 5° away from the sub ionospheric point of the satellite which is at 24.12°N, 95.71°E.

Results of this nature are presented elsewhere (Devi *et al.*, 2001). The analysis therefore indicates that both positive and negative ionospheric effects can be seen prior to an earthquake, and an association between ionospheric effects and its epicenter position cannot be ruled out.

3.2. *f_oF2 as precursor of earthquake*

The changes in critical frequency of *F*-layer received from ground-based ionosonde at Ahmedabad are next examined to disclose variations in f_oF2 if any, during the earthquake preparatory process. For this purpose, hourly f_oF2 data for 15/10 days prior to an event are considered. Further, we examine the magnitude and development of bite out, as a result of a fountain effect another input along with temporal changes in f_oF2 prior to an earthquake. A few representative cases in F_of2 features and generation of anomaly before earthquake events are described below.

Two events presented in fig. 5 are for April 6 (epicenter at 26.19°N, 96.87°E) and April 27 (epicenter at 13.07°N, 119.54°E), 1994. The dark shades indicate strong density zones, prior to an earthquake and a signature of bite out is seen as two black areas around noon. It is also to be noted that the background density during this month is fairly large and ionization density needs to be sufficiently strong to exhibit the signature of bite out effect. Arrowheads in the figure indicate time (78°EMT) of occurrence of the earthquake. The absence of data is also marked.

Figure 6 presents a representative event of a summer case where the earthquake occurred on July 30, 1996 at 23:08 h (78°EMT) with its epicenter at 14.51°N (119.95°E). Here, strong density regions and anomaly (*i.e.* bite out) were not seen many days earlier, but a high density zone is formed two days before the event and anomaly effect is detected 6 h before earthquake.

Interestingly, all these cases (shown as representatives of different seasons) indicate generation of strong density along with bite out, which must have sources other than the normal ionizing

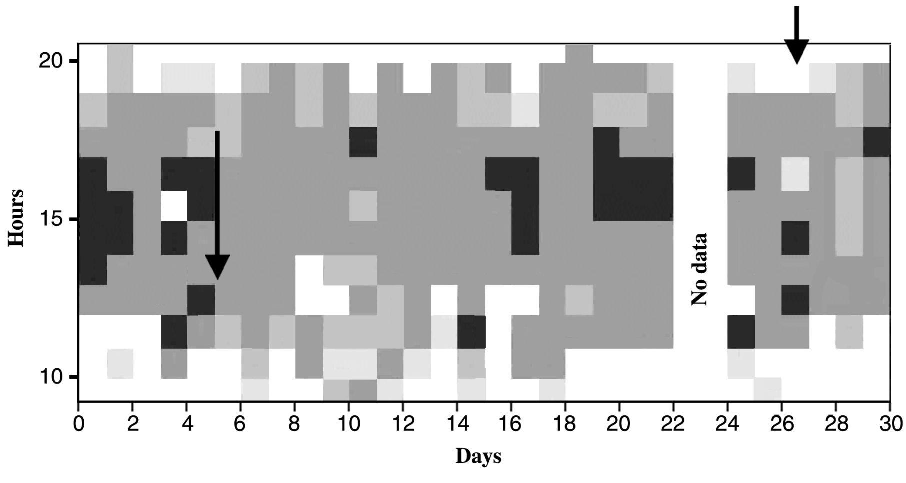

Fig. 5. f_oF2 variation pattern over the anomaly crest station of Ahmedabad before and during earthquakes of April 6 and 27, 1994. The arrowheads give the time of commencement of earthquakes. The density magnitude is defined by gray shades. Black zone is for frequencies > 11.00 MHz. Early morning data are not shown in the figure. High density zones and bite outs are present before and during the events.

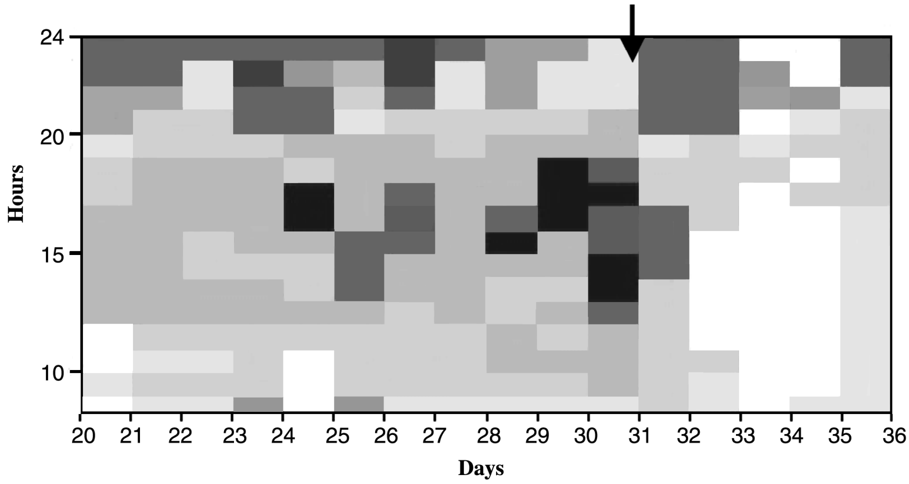

Fig. 6. One more case showing f_oF2 variations, prior to and during the 30.7.1996 earthquake. In this case the darkest region is for frequencies > 10.50 MHz. Presence of bite out is to be noted before the earthquake event.

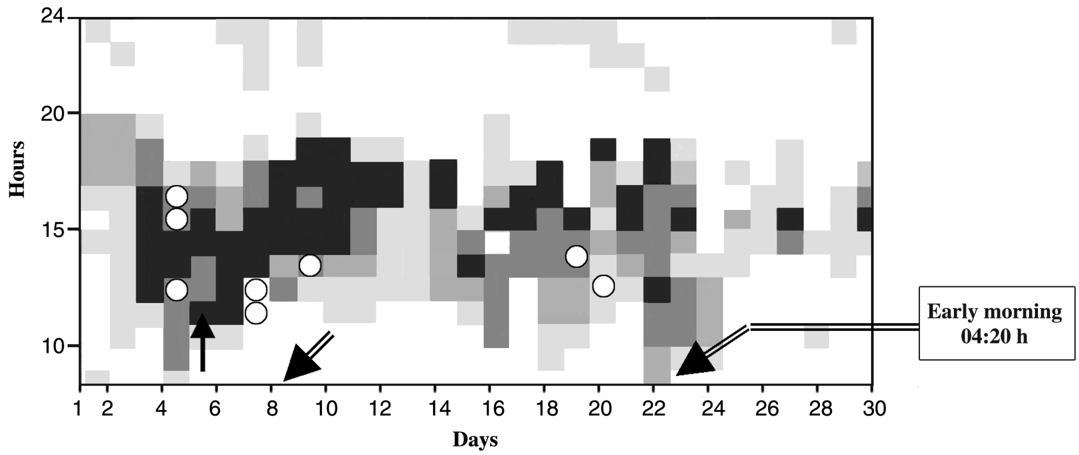

Fig. 7. Same as in figs. 5 and 6 but for three consecutive summer earthquake events for May 5, 8 and 22 of 1997. The arrowheads indicate the occurrence time of each earthquake event. Here the black zone is for frequencies > 10.00 MHz. White circles indicate absence of data. Though bite out is not prominent, high density zones up to day 23 are significant.

process. However, these features may not be well reflected in all cases especially when we have a succession of tremors at frequent intervals as shown in fig. 7 for May 1997, where there were three earthquakes of magnitudes of 5.5-6.0, on 5th, 8th and 21st day. The 5th May quake was observed at 11:15 h (78°MT), with epicenter at 14.91°N (119.89°E). High density zones are seen prior to the quake day but due to non availability of data at 13, 15 and 16 h on day 4, it is difficult

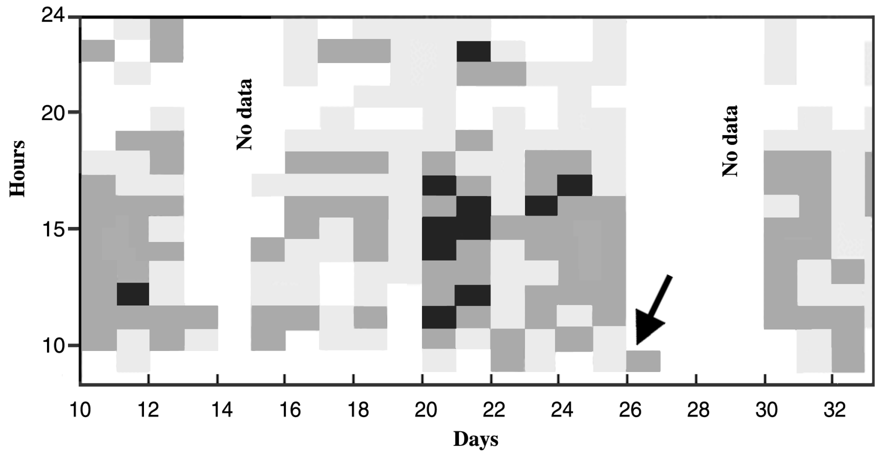

Fig. 8. A case of very strong earthquake of M = 8.1 experienced around Ahmedabad on 26 January, 2001. The large density contours followed by depletion in density prior to the event (at 09:00 h, 78°EMT) are clearly seen. Here the black region corresponds to frequencies > 11:50 MHz. Due to mass destruction no f_oF2 data are available just from the onset of the event for 3 days.

to make a statement on bite out. However, on the day of the event a bite out is observed. On May 8, another tremor was detected at 08:23 h (78°EMT) with epicenter at 24.89°N (92.25°E). Strong density zones in noon and afternoon hours, prior to the earthquake day are clearly seen in the ionogram. But, we cannot say if bite out was present because of want of data during noon hours, however bite out was seen after the earthquake. So, is the case with the event of May 22, when the tremor occurred at about 04:00 h. However, we cannot make a statement on bite out on May 19, 20 and 21, as there were no continuous data. The high density regions in noon and afternoon periods as noted almost on all days from May 3 to 23rd, subside after May 23rd.

The overall pattern described above seems to be maintained during major earthquakes too, one such event is shown in fig. 8.

3.3. *Major earthquake*

On 26th January 2001, Ahmedabad region experienced a very strong earthquake of scale 8.1, and was followed by a number of tremors. It is interesting to note the high densities indicated by strong f_oF2 values prior to the event (fig. 8). Bite outs are also visible before quake days but high density contours disappeared shortly before the onset of earthquake. This decrease in density and the position of the epicentre of the earthquake (23.36°N and 70.33°E), is to be noted. Due to mass destruction, no ionospheric data were available just after the onset of earthquake, which continued for 3 days.

4. Discussion

Although ionospheric parameters behave in a complex manner, scientists have been attempting to associate some of their features with seismic events (Wolcott *et al.*, 1969; Hayakawa, 1999; Depueva and Rotanova, 2001). One of the approaches is by analysing the development and inhibition process of anomaly by mapping the magnitude and spread of its crest and trough, before and during earthquake events using topside ionospheric data (Depueva and Ruzhin, 1993, 1995). In this exercise too, we are trying to see the anomaly effect during the earthquake preparatory process. Increase in magnitude of TEC, which is observed to be higher than maximum excursion limits in day to day TEC fluctuations (figs. 1a,b and 2a,b), indicate that an inflow of ionisation might have taken place in the earthquake preparatory region from an additional source. Similarly, a decrease in TEC suggests that an outflow of ionization has taken place from the afflicted site.

Such changes in TEC variations for a number of strong earthquake events (Devi *et al.,* 2001) also indicate that high-density TEC contours are often associated with earthquakes having their epicenters near to the equator or away from the observational site. The study further indicates that TEC depletions (like the event of July 1976) are often observed when the epicenter lies very near to the observational site.

It is also observed from f_oF2 variations over Ahmadabad that enhancement as well as biteout are fairly well detected phenomena prior to an earthquake. But unlike the case of TEC, decrease in density is not clearly seen even if the epicenter lies near to the receiving site. However, for the major earthquake of January 2001, when its epicenter was at Ahmedabad, a decrease in density was detected prior to the event. The depletion features as observed in TEC are prolonged in comparison to what is seen through f_oF2. These enhancements (as well as depletion) in density values along with development of anomaly if considered as earthquake-induced perturbations in the atmosphere, an extra agent (besides the normal ionizing agencies) associated with the earthquake preparation processes in shaping density profiles has to be active. As $\boldsymbol{E}\times\boldsymbol{B}$ drift is one of the significant contributors in controlling density at anomaly crest stations like Ahmedabad and Guwahati (Devi *et al.,* 2002), it is necessary to invoke electric field triggered by earthquake preparatory processes that generate $\boldsymbol{E}\times\boldsymbol{B}$ drift (Depueva and Ruzhin, 1993, 1995). In fact, emission of ELF fields prior to earthquakes was also detected near the epicenter (Larkina *et al.*, 1983; Parrot and Magilevsky, 1989). Depletion and enhancements as seen on density profiles, may be the result of earthquake-associated $\boldsymbol{E}\times\boldsymbol{B}$ drift when electron density may flow into or out of the observing station depending on its location, if an electric field of sufficient magnitude is developed at the ionospheric heights. There are reports related to possible effects of earthquake generated electric fields at ionospheric heights (Gokhberg *et al.*, 1984; Parrot, 1995). Considering that such electric field does develop during earthquake preparatory processes and it penetrates to *E*-layer heights resulting in enhanced electrojet strength, the upward $\boldsymbol{E}\times\boldsymbol{B}$ drift will then be amplified. We therefore examine the effects of such field, reflected as bite outs in density profiles while dealing with f_oF2, as one of the inputs for identifying seismo-ionospheric effects. However, the anomaly effects generally being very regular and strong during equinoxial months, we have taken summer and winter events only, to avoid ambiguities in analysis and interpretation. In fact, the development or inhibition of anomaly during earthquake preparatory processes have also been examined by earlier workers (Depueva and Rotanava, 2001). While analysing topside electron density over a dip latitude zone of ± 30°, they showed that considerable changes in the development processes of the anomaly do take place prior to an earthquake and also that the position of the epicentre is critical in controlling the magnitude of anomaly. However the magnitude of such electric fields is still a question.

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