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# Simultaneous ionospheric *E*- and *F*-layer perturbations caused by some major earthquakes in India

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**Abstract**

The variation in nighttime ionospheric *E*- and *F*-region critical frequencies (*foEs* and *foF*2) is examined for the months of August 1988, September 1993 and May 1997 in which major earthquakes ($6<M<6.6$) occurred in Indian seismic zones of Bihar-Nepal border, Latur in West India, and Jabalpur in Central India. The ionospheric data are obtained from Ahmedabad (latitude 23.01°N, longitude 72.36°E). The percent deviations of *foF*2 and *foEs* from their monthly median are determined for pre-midnight (18:00-00:00 h LT) and post-midnight (00:00-06:00 h LT) periods and studied over a span of 20 days before the occurrence of earthquakes. The results show that *foF*2 are reduced in both the time sectors prior to the occurrence of main shocks. In pre-midnight sector the reduction is between 24 and 30%, 0 to 4 days before the main shocks and in the post-midnight sector it is between 18 and 26%, 1 to 15 days before the main shocks. The *foEs* show enhancements by 100 to 155% during the same periods. The effects of magnetic storms (*Kp* and *Dst* variations) on the data are identified clearly but they do not vitiate the effects of earthquakes. The earthquake related anomalies are interpreted in terms of electromagnetic coupling between the lithosphere and ionosphere during earthquakes preparation processes.

**Key words** *ionosphere* – E- *and* F-*layers* – *earthquakes-magnetic storm* – foF2 *and* foEs

## 1. Introduction

Ever since Davies and Baker (1965) reported the first seismo-ionospheric anomalies related to Alaskan earthquake, several workers have attempted to study this problem using ground and satellite based observations. However, some convincing evidences of this phenomenon have come rather recently (Pulinets *et al.*, 1991, 1994; Ruzhin and Depueva, 1996) in which it has been found that the seismic effect on ionospheric *F*2-layer is observed in terms of reduction in morning time *foF*2 about a week before the occurrence of the earthquakes and this phenomenon may be observed over a wide ionospheric area covered by 30° latitude and 60° longitude. More recently similar studies have been made by Liu *et al.* (2000, 2001), Chuo *et al.* (2002) and Singh *et al.* (2004) in which they have reported afternoon reductions in *foF*2 also apart from morning time reductions. Anomalies in *foF*2 and Total Electron Content (TEC) have also been reported by Devi *et al.* (2001, 2004) prior to the occurrence of earthquakes. They have shown that both positive and negative ionospheric effects develop prior to an earthquake depending on the epicenter position with respect to the observing site.

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Several workers have also reported the ionospheric anomalies in *E*-layers prior to the occurrence of earthquakes (Gokhberg *et al.*, 1988; Liperovski *et al.*, 1992; Pulinets *et al.*, 1994; Ondoh, 2000; Ogawa *et al.*, 2002). Recently, Ondoh and Hayakawa (1999), Ondoh (2003) and Singh and Singh (2004) have made an elaborate study of this problem and have shown anomalous *foEs* increases 2-20 days before the occurrence of earthquakes.

Although, many workers have examined the effects of earthquakes on ionospheric *E*- and *F*-layers separately as stated above there is no report of simultaneous observations of *E*- and *F*- layer perturbations related to seismic activities. In the present paper, we examine this problem in detail by considering three major earthquakes that occurred in India in recent years. Our results show simultaneous earthquake induced changes in the *E*- and *F*-layers which are reflected by simultaneous reductions in *foF*2 and enhancements in *foEs*.

## 2. Ionospheric, earthquake and magnetic storm data

The ionospheric data have been obtained from Physical Research Laboratory, Ahmedabad (latitude 23.01°N, longitude 72.36°E), India where a digital ionosonde has been in operation for a long time. The data recorded at this station includes *foF*2, *foEs*, *hpF*2 and median values for respective months. The earthquake data have been obtained from India Meteorological Department, New Delhi, India. Since ionospheric anomalies appear during or after the occurrence of magnetic storms also it is worthwhile to examine the *foF*2 and *foEs* changes in relation to magnetic storms also. For this purpose, we consider *Kp* index and *Dst* index data, which have been obtained from Indian Institute of Geomagnetism, Colaba, Mumbai, India and World Data Center C2, Kyoto University, Kyoto, Japan respectively.

## 3. Results and discussion

Six major earhquakes have occurred in India during the last 15 years. They include Bihar-Nepal earthquake (20 August, 1988), Uttarkashi earthquake (20 October, 1991), Latur earthquake (30 September, 1993), Jabalpur earthquake (22 May, 1997), Chamoli earthquake (29 March, 1999) and Bhuj earthquake (26 January, 2001). In order to examine the effects of these earthquakes on *E*- and *F*-regions of the overhead ionosphere we have attempted to analyze the ionospheric data obtained from Ahmedabad. Unfortunately, *foEs* data are available corresponding to three earthquakes only, which are Bihar-Nepal earthquake, Latur earthquake and Jabalpur earthquake, and hence in the present study we consider the *F*- and *E*-regions anomalies corresponding to these earthquakes only. The locations of these three earthquakes are shown in the map of fig. 1 by solid circles and abbreviated words as BHR-NPL, LTR and JBL respectively. The location of Ahmedabad from where the ionospheric data have been obtained is also shown in the same figure by abbreviated word AHD. Other details of these earthquakes such as the date and time of occurrence, geographic location, magnitude, depth and distance from Ahmedabad are shown in table I.

It may be noted that the ionospheric parameters show considerable variations following geomagnetic storms. The ionospheric responses to such storms are of negative kind and large at high and middle latitudes while they are modest and of positive kind at low latitudes especially during daytime hours. During nighttime, both positive and negative responses are possible at low and equatorial latitudes (Lakshmi *et al.*, 1983, 1997). Here, it may also be mentioned that Jain and Singh (1977) and Jain *et al.* (1979) have studied the low and equatorial latitude ionospheric changes during the period of magnetic storms and have shown that these ionospheric regions are influenced significantly during prolonged magnetic disturbances only and there is almost negligible variation during isolated storms. Furthermore, it may be pointed out here that the ionospheric station Ahmedabad is located close to the anomaly crest region and shows mixed response to magnetic storms and, sometimes, significant variations even during quiet periods. However, in the present study adequate care has been taken to see that the ionospheric departures due to magnetic storms and unknown reasons do not vitiate the main focus of our discussion.

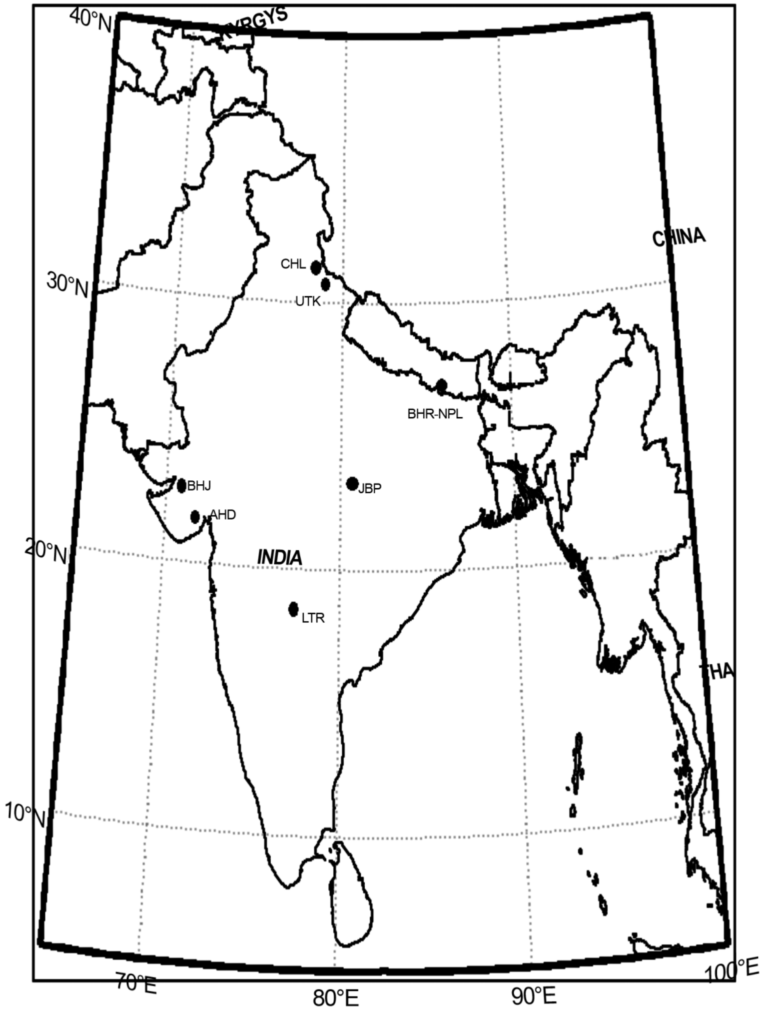


**Fig. 1.** Map of India showing the locations of three major earthquakes (solid circles). Also shown is the location of ionospheric station Ahmedabad (AHD).

**Table I.** Details of the three earthquakes considered.

| Date of occurrence | Location | Time (IST)* | Latitude (°N) | Longitude (°E) | Magnitude | Depth | Distance from AHD (km) |
|---|---|---|---|---|---|---|---|
| 20/08/1988 | BHR-NPL border | 23:09 h | 26.72 | 86.63 | 6.6 | 35 | 2500 |
| 30/09/1993 | Latur | 03:55 h | 18.07 | 76.62 | 6.3 | 12 | 1100 |
| 22/05/1997 | Jabalpur | 03:25 h | 23.08 | 80.06 | 6.0 | 35 | 1600 |

* IST = UT + 5.50 h.

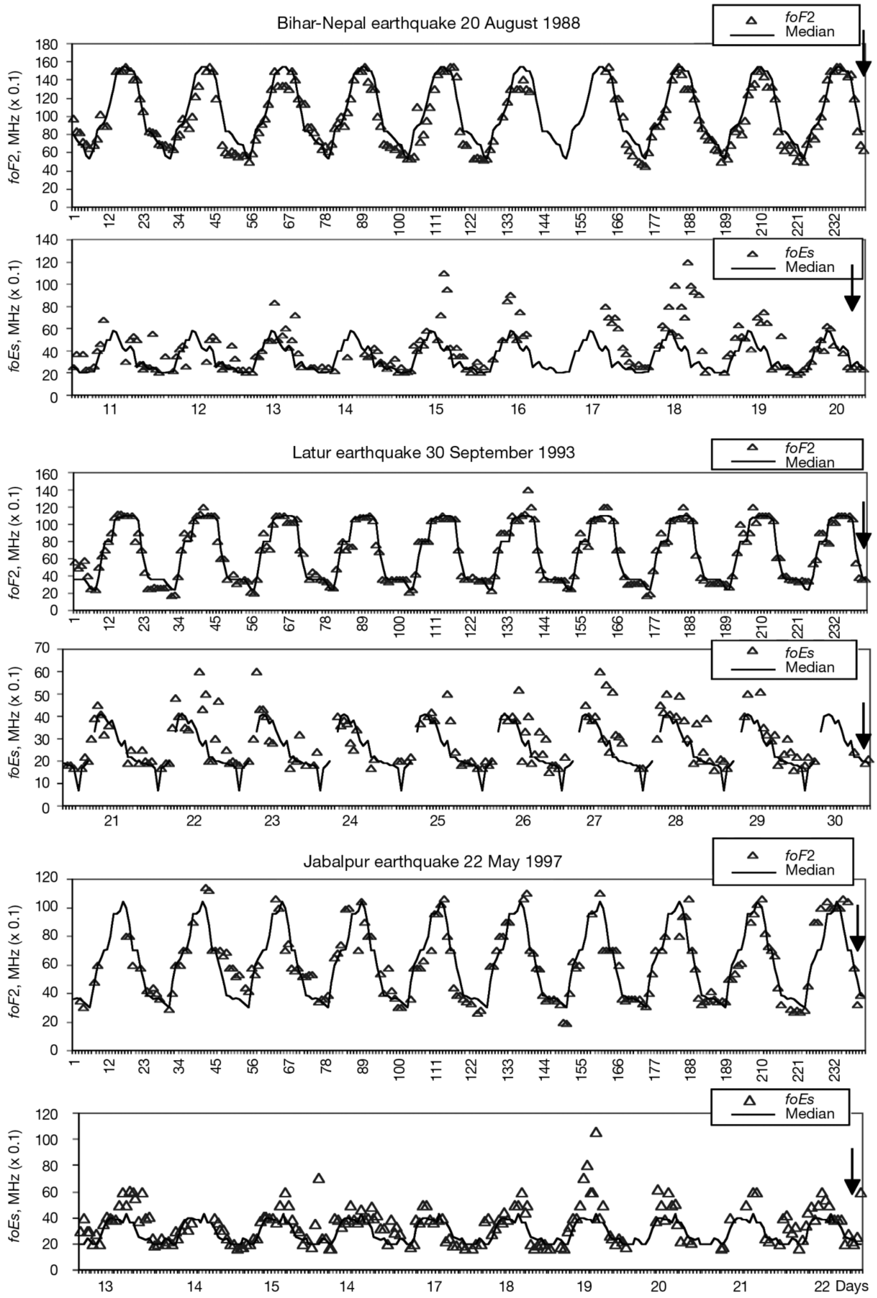


**Fig. 2a.** The variations of monthly median of *foF*2 and *foEs* (shown by solid curves) and hourly measured values (shown by open triangles) for ten days before the occurrence of the earthquakes in the months of August, 1988 (top two panels), September, 1993 (middle two panels) and May, 1997 (bottom two panels). Monthly median is repeated on each day. The inverted arrows indicate the days of the earthquakes.

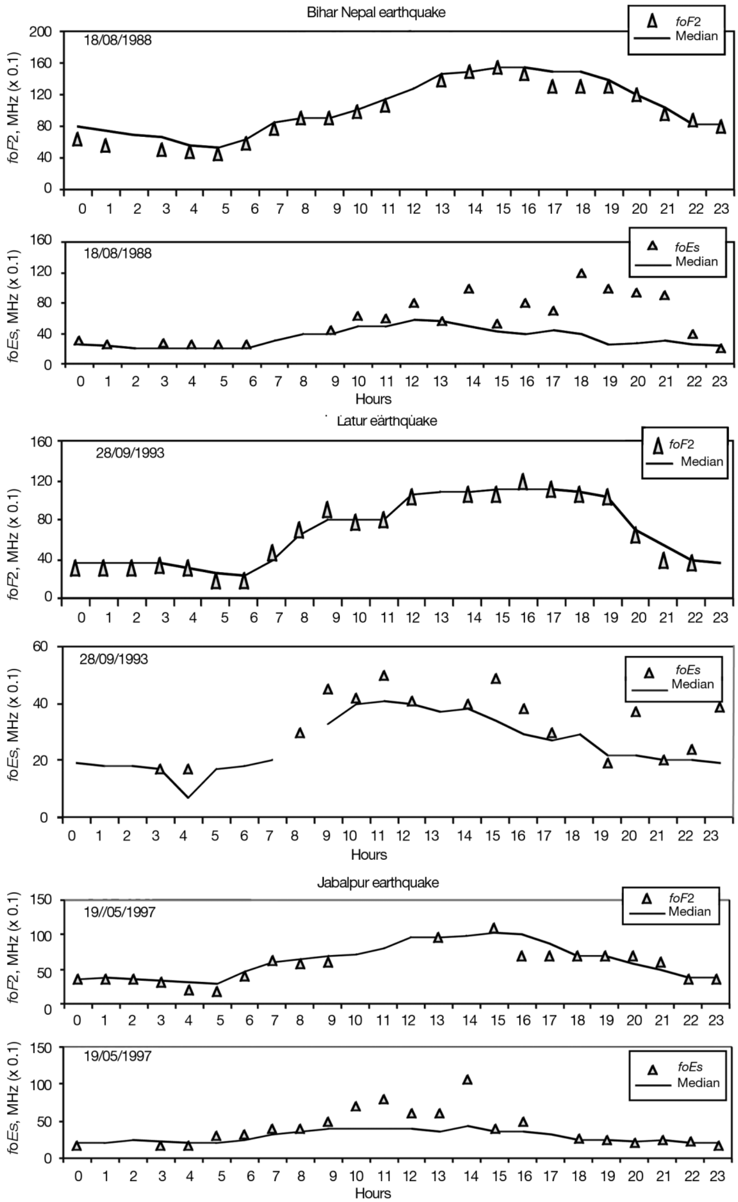


**Fig. 2b.** Temporal variation of monthly median *foF*2 and *foEs* (solid curves) and hourly measured values (open triangles) on the days of observed anomalies corresponding to the earthquakes under consideration.

Figure 2a shows the daily variations of *foF*2 and *foEs* corresponding to three earthquakes under consideration. The *foF*2 and *foEs* data are shown by triangles whereas monthly medians are shown by solid lines. The data are shown for 10 days before the occurrence of the respective earthquakes. The days of earthquakes are shown by inverted arrows in all the panels. From a glance at the top two panels which correspond to Bihar-Nepal earthquake of 20 August, 1988 we see that there is a maximum reduction in morning time *foF*2 from median values on 18 August, whereas there is a maximum enhancement in *foEs* on the same day. Since there is no major magnetic storm in this month before the earthquake (as shown ahead) it may be inferred that *foF*2 and *foEs* are influenced by the earthquake giving rise to peak anomalies 2 days before the occurrence of the earthquake. Further, it will be shown that *foF*2 and *foEs* indicate decreasing and increasing trends respectively starting from 03 August itself thereby showing the influence of earthquakes from 18 days before its occurrence. The middle two panels correspond to Latur earthquake of 30 September 1993. Here, the *foF*2 is lowest in the morning of 28 September whereas *foEs* is enhanced during the midday and evening hours of 27 and 28 September. There is a reduction in *foF*2 and corresponding enhancement in *foEs* on 22 September also which may be attributed to a magnetic storm that occurred on 20 September (discussed ahead). The bottom two panels correspond to Jabalpur earthquake of 22 May 1997. In this case the *foF*2 has gone lowest and *foEs* largest on 19 May 1997 about three days before the occurrence of the earthquake. The figure shows enhancements in *foEs* on 13 and 15 May also. The enhancement on 15 May may be attributed to severe magnetic storm ($Kp = 7$, $Dst = -116$), which occurred on the same day. The reason for the enhancement on 13 May is not known, but it may not be attributed to the storm of 1 May because the effect of such isolated storms cannot affect the ionosphere so late. To identify the times of occurrence of the anomalies (reduction in *foF*2 and enhancement in *foEs*) occurring on 18 August 1988, 28 September 1993 and 19 May 1997 as shown in fig. 2a we plot the temporal variation of *foF*2 and *foEs* data along with their median values in fig. 2b. The results of maximum deviation and times of occurrence are presented in table II. Here it may be noted that percent reduction in morning time *foF*2 and enhancements in *foEs* are the largest as compared to other days. Further, the *foEs* data presented in the table II on 18 August during afternoon hours shows a value of 296% where as in the abstract we have mentioned the maximum enhancement of 155%. This result should not be taken as contradictory because the data presented in the abstract have resulted from the running mean which will be made clear ahead.

In order to make the earthquake induced anomalies more clear and distinct from those arising due to storm and other unknown factors we have made a thorough analysis of the data by following a procedure in which we have calculated the percent reduction in hourly *foF*2 and percent enhancement in hourly *foEs* relative to monthly median values. We have chosen the data for the period 18:00-06:00 h, LT only and divided them into two sectors, pre-midnight (18:00-00:00 h) and post-midnight (00:00-06:00 h). This period of the data has been chosen to avoid complications arising due to variations in photoionisation intensity during daytime (Michel Parrot, personal communication, Bhopal, 17 November 2003). Since the data are not continuous and there are some intermittent gaps, we have taken

**Table II.** Details of times and maximum deviation of *foF*2 and *foEs* observed during the anomalies.

| Days of anomaly | Maximum reduction in *foF2* | | | | Maximum enhancement in *foEs* | | | |
|---|---|---|---|---|---|---|---|---|
| | Morning hours | | Afternoon hours | | Morning hours | | Afternoon hours | |
| | Time (h) | Reduction (%) | Time (h) | Reduction (%) | Time (h) | Enhancement (%) | Time (h) | Enhancement (%) |
| 18/08/1988 | 03:00 | 26.4 | 18:00 | 13.3 | 03:00 | 40.0 | 19:00 | 296.0 |
| 28/09/1993 | 05:00 | 32.0 | 21:00 | 29.6 | 04:00 | 142.8 | 23:00 | 105.0 |
| 19/05/1997 | 04:00 | 37.5 | 17:00 | 20.4 | 05:00 | 50.0 | 14:00 | 146.5 |

six days running mean of the peak reduction in *foF*2 and peak enhancement in *foEs* for both the pre-midnight and post-midnight data. The variations of percent reduction in *foF*2 and enhancement in *foEs* are shown for 20 days before the occurrence of each earthquake in the top two panels of fig. 3a-c. The solid circles correspond to pre-midnight data and solid squares

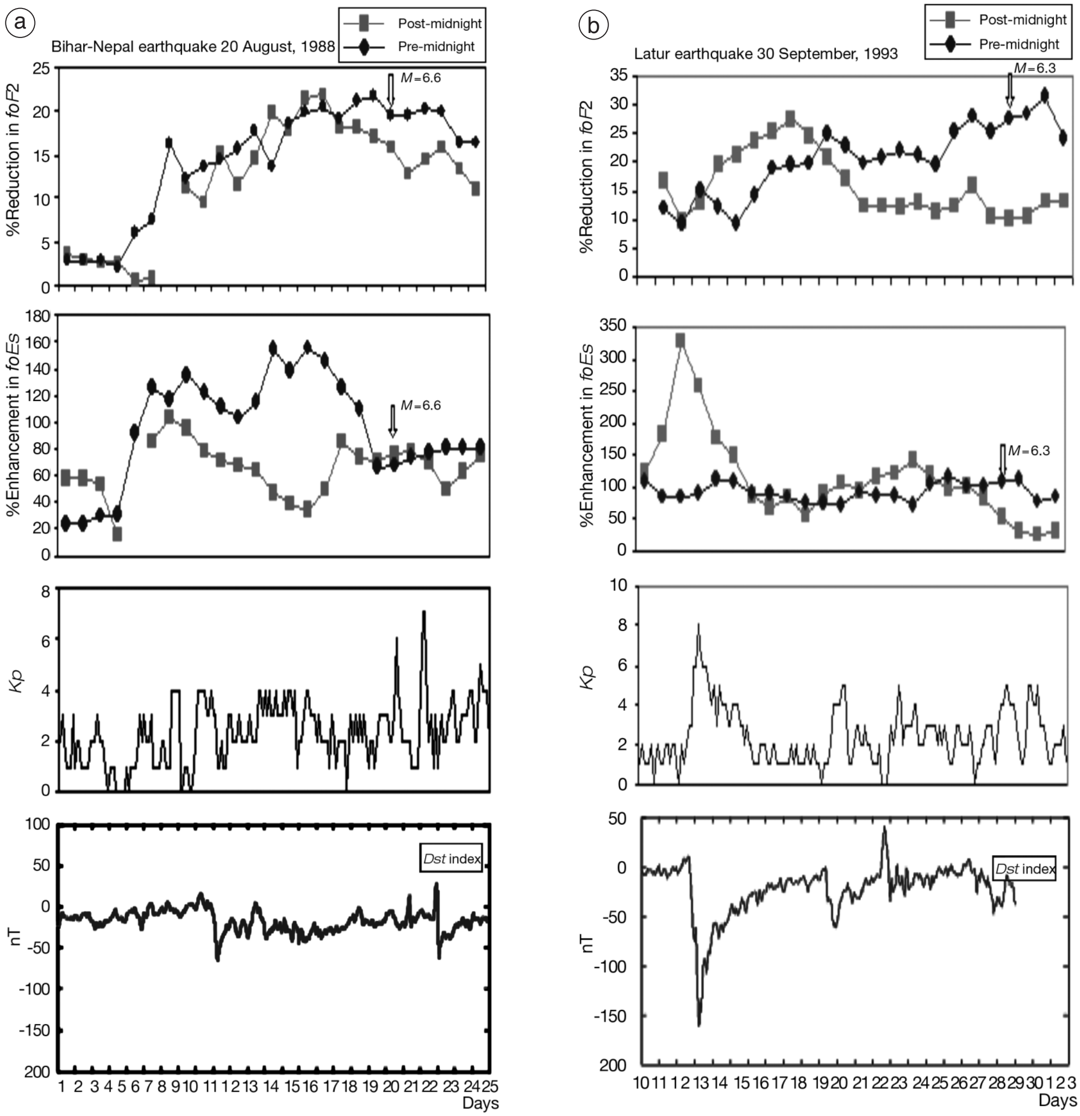


**Fig. 3a,b.** a) *Top* – six days running mean of the peak percent reductions during pre-and post-midnight sectors in *foF*2 for 25 days in the month of August 1988. The earthquake (*M*=6.6, shown by downward arrow) occurred at a ) Bihar-Nepal Border on 20 August 1988. *Second* – same as in top panel but for enhancements in *foEs*. *Third* – *Kp* index variation. *Bottom* – *Dst* index variation on the days under consideration. b) The same as (a) but for Latur earthquake (*M*=6.3) which occurred on 30 September 1993.

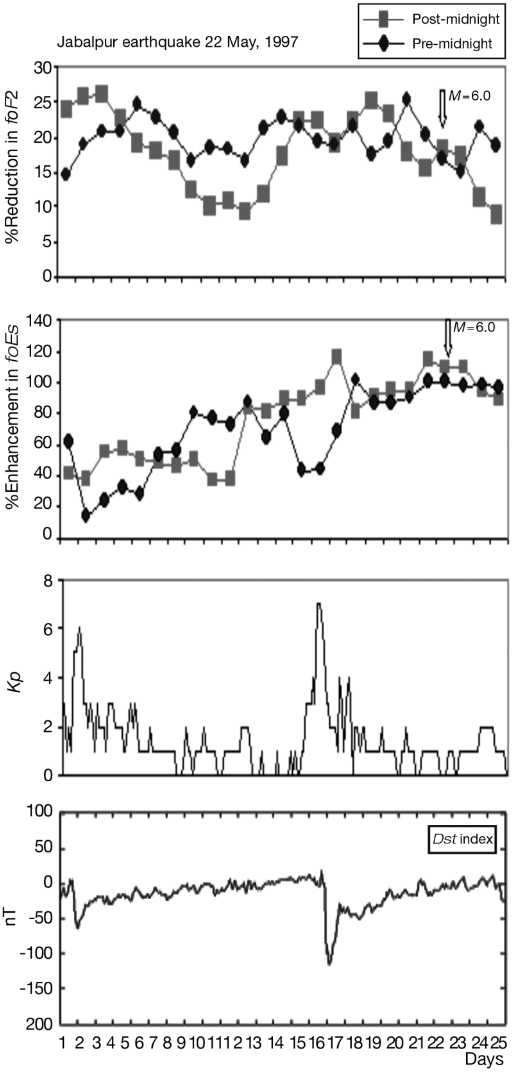


**Fig. 3c.** The same as fig. 3a but for Jabalpur earthquake ($M=6.0$) which occurred on 22 May 1997.

correspond to post-midnight data. The days of the earthquakes are shown by inverted arrows with the magnitude of the earthquakes indicated nearby. In the bottom two panels of these figures we show the variation of the magnetic storms by three hour *Kp* indices and corresponding *Dst* indices. Here, it may be noted that $Kp \leq 4$, $4 \leq Kp \leq 6$ and $Kp \geq 6$ indicate quiet, moderate and severe magnetic storms respectively. The magnetic storm condition is also denoted in terms of *Dst* index and the value of $Dst \leq -50$ nT represents minor storms. In general, the low latitude ionosphere is influenced by large reductions in *Dst* ($Dst \leq -100$) only (B.M. Reddy, pers. comm., November 2003).

From fig. 3a it may be seen that there are enhancements in percent reduction in *foF*2 and enhancements in *foEs* from 3 August itself about 18 days before the occurrence of the earthquake and the effect is reflected in both the pre and post-midnight data of *foF*2 and in pre-midnight data of *foEs*. The largest enhancement in pre-midnight *foF*2 reduction amounts to 24%, one day before the earthquake whereas the same in post-midnight hours amounts to 26%, four days before the earthquake. The maximum enhancements in *foEs* of 155% on 15 August and 102% on 7 August are observed in pre and post-midnight data respectively. During the periods of these enhancements the magnetic condition was quiet. Hence, the anomalies may be attributed to the earthquake only. The magnetic storms occurred on 20 and 21 August, after the occurrence of the earthquake, which may not influence the ionosphere in advance. It may be mentioned here that the days of maximum enhancement in reduction of *foF*2 and maximum enhancement in *foEs* as seen in this as well as in the next two figures do not match exactly with those shown in fig. 2. This discrepancy has been produced by taking the six days running mean of the data, otherwise the days of anomalies remain unchanged. Figure 3b presents the results corresponding to Latur earthquake. The top two panels show that there are large enhancements in reduction in *foF*2 between 17 and 23 September and large enhancements in *foEs* on 15 September (which appears on 13 September because of six days running mean), which may be attributed to the severe magnetic storm of 13 September ($Kp=8$, $\Sigma Kp=48$). However, the enhancements in reduction in *foF*2 and enhancements in *foEs* during 25-30 September may be attributed to the earthquake of 30 September only. Maximum enhancements in *foF*2 reductions are observed on 28 September by 18% in post-midnight data and by 30% on 30 September in the pre-midnight data. In case of *foEs*, maximum enhancements of 140% on 25 September and of 117% on 27 September are observed in post and pre-midnight data respectively. The moderate magnetic storms ($Kp=5$) on 20, 23 and 30 September are unlikely to influence the data as stated before that only severe and prolonged magnetic storms are found to influence the low latitude ionosphere. Figure 3c shows the results corresponding to the Jabalpur earthquake of 22 May 1997. In this month two magnetic storms ($Kp=6.7$) occurred on 1 and 15 May 1997. The *Dst* variation shows the values −63 and −116 on these two days respectively. As shown in the top panel of the figure, there are increases in *foF*2 reductions during 4-9 May as well as on 16 and 18 May. These increases in reductions may be attributed to the storms of 1 and 15 May respectively. However, the maximum enhancement in reduction in the pre-midnight data by 25% on 20 May and by 18% on 22 May may possibly be due to the earthquake that occurred on 22 May. The second panel shows that there is a gradual increase in *foEs* in both the pre and post-midnight data starting from 2 May to 21 May, up to one day before the occurrence of the earthquake. The maximum enhancement in post-midnight data on 21 May is 114% whereas in pre-midnight data it is 100%. This gradual increase in *foEs* from nearly 20 days before may be due to the earthquake of 22 May. The transient increase in *foEs* during 16-17 May may be attributed to the storm of 15 May.

From the results presented in fig. 3a-c it may be seen that the effects of earthquakes on *foF*2 and *foEs* data corresponding to Latur and Jabalpur earthquakes are not as much convincing as that related to Bihar-Nepal earthquake presented in fig. 3a. One reason for this is that there occurred magnetic storms during the period of analysis in the later two cases, which complicated the data whereas there was no magnetic storm in the first case. However, this ambiguity can be eliminated if we look at the diurnal variation in *foF*2 and *foEs* of fig. 2 where enhancements and reductions are visible very clearly.

In order to give further support to our results mentioned above we have carried out more rigorous statistical analysis. We have employed the past 10 years of data corresponding to the months in which *foF*2 and *foEs* data have been analyzed in fig. 3a-c. Out of the bulk of 10 years data we have picked up only those, which corresponded to the same months and the years in which the Sun spot numbers were almost similar. For example, in the case of Bihar-Nepal earthquake the lowest *foF*2 was found to be on 18 August 1988 two days before the occurrence of the earthquake. Hence, we have considered the same day data in the years 1978, 1984, 1993, 1998 and 1999, which corresponded approximately to similar Sun spot numbers. Then we determine the deviation of *foF*2 from monthly median ($\Delta foF2$) for each hour of the days. From these data, mean (m) and standard deviation ($\sigma$) were calculated. Similar calculations have been made for *foEs* also. The variations of $m$ and $m\pm\sigma$ along with $\Delta foF2$ and $\Delta foEs$ corresponding to each earthquake are shown by different notations in fig. 4. From this figure it is seen that $\Delta foF2$ is deviated out of $m+\sigma$ in the morning (04:00-07:00 h) in all the cases. The deviation is also seen in the afternoon (17:00-19:00 h) and in the late evening hours (21:00-23:00 h). The *foEs* deviations are mostly in the pre-midnight hours in all the cases except in Jabalpur case in which it is deviated during afternoon also. These results are in agreement with the results presented in fig. 3a-c.

The anomalous state of the ionosphere during seismic activities as presented above has been interpreted by several workers in terms of lithosphere-ionosphere coupling produced by earthquake-induced electric fields, which are generated from internal gravity waves. These electric fields can penetrate the ionospheric *F*- and *E*-region heights and bring out changes in the electron density profile due to $E\times B$ drift (Kim and Hegai, 1999; Sorokin and Chmyrev, 1999). The enhancement or depression in *foF*2 values may be attributed to positive or negative direction of electric fields. The effect of distant earthquakes on ionospheric data over Ahmedabad may be interpreted in terms of $E\times B$ drift of an electron stream upward over the epicenter of earthquakes which may then move towards or away from Ahmedabad depending upon positive or negative direction of electric fields or neutral winds causing enhancement or depres-

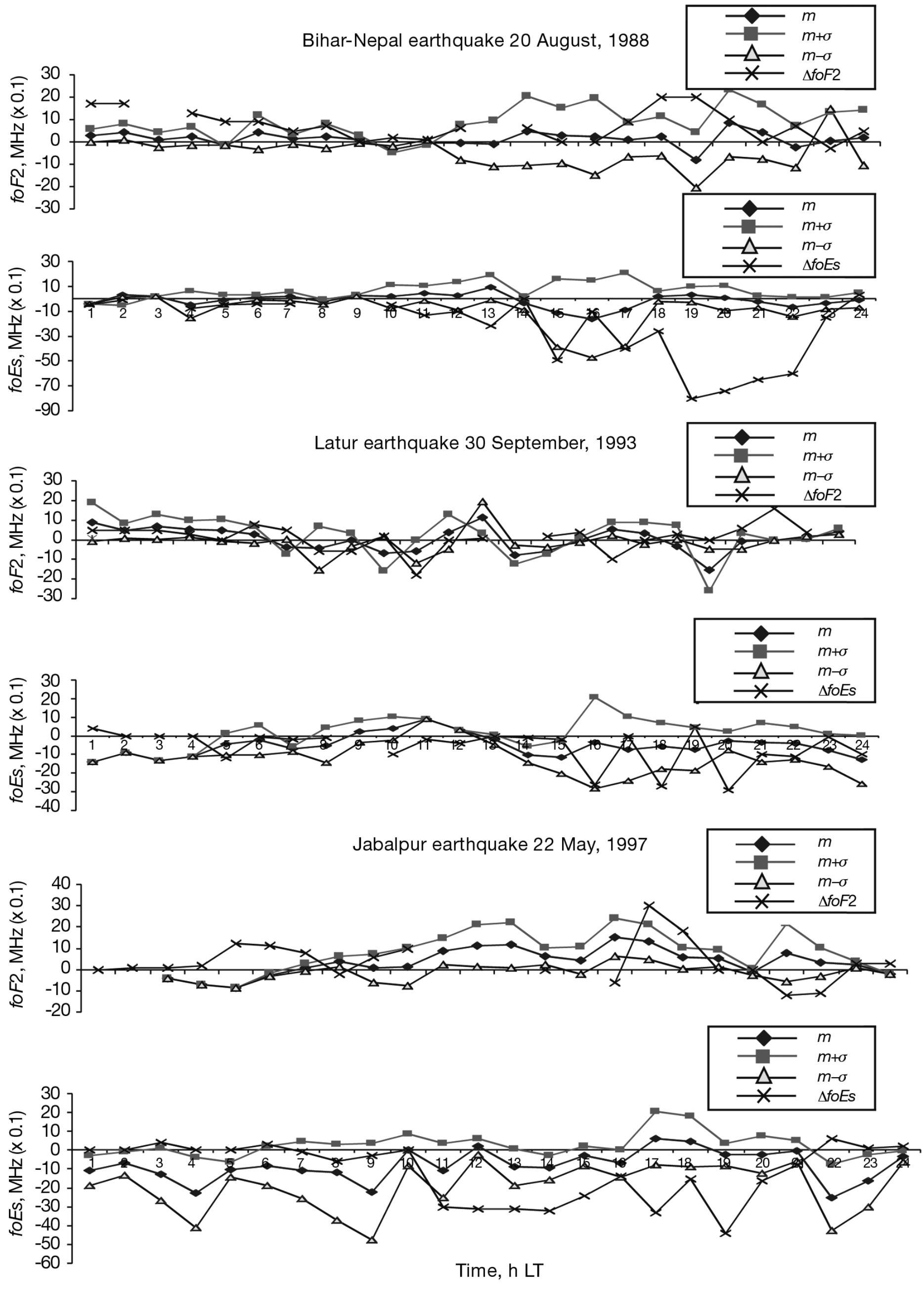


**Fig. 4.** Statistical results showing the deviation of *foF*2 and *foEs* from the monthly median on the day it was lowest in the month of the earthquake ($\Delta foF2$ and $\Delta foEs$). The mean ($m$) and standard deviation ($\sigma$) around mean ($m \pm \sigma$) are computed for the same days in the past ten years of data on which Sun spot numbers were nearly identical.

sion in *foF*2 data as discussed by other workers (Yoshimatsu, 1938; Ondoh, 1999). In case of anomalies at the *E*-layer heights, the upward $E \times B$ drift will be amplified thereby augmenting the density pumping process from the epicentral zone to off epicenter positions in the ionosphere (Ruzhin and Depueva, 1996). The other possibility of *E*-layer anomaly is *quasi*-static heating and production of additional ionization in the sporadic *E*-layers caused by cloud discharge in the atmosphere over seismic zones induced by seismic electric fields (Ondoh and Hayakawa, 2002; Ondoh, 2003). The *foEs* enhancements prior to the occurrence of large earthquakes have also been suggested due to radon emanations from seismic sources, which are carried upward by the electric fields and create additional ionization at the heights of *E*-layer (Ondoh and Hayakawa, 2002; Ondoh, 2003). Over all we expect that the reduction in *foF*2 and enhancements in *foEs* during the periods of earthquakes may probably be interpreted in terms of lifting of *F*- and *E*-layers due to $E \times B$ drift caused by a unidirectional electric field. In this mechanism the *F*2 peak will be lifted to a region of lower electron density whereas *Es*-layer will be lifted upward to a region of higher electron density producing reduction in *foF*2 and enhancement in *foEs* respectively.

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