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Effect of solar flares on ionospheric TEC at Varanasi, near EIA crest, during solar minimum period

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A solar flare is a sudden release of energy usually near a complex group of sunspots. The interaction of solar flare radiations with constituents of ionosphere produces immediate increase in the electron density in the ionosphere. The present paper describes the effect of solar flare on ionospheric total electron contents (TEC) using global positioning system (GPS) data recorded at Varanasi, a station situated near equatorial ionization anomaly (EIA) crest region during solar minimum period. In this study, total four flares have been selected to study the effect of solar flares on ionosphere during the year 2008, which is a solar minimum period. The enhancements on ionospheric TEC have been observed during the period of solar flares. The maximum enhancement of TEC during solar flare compared to quiet mean TEC up to 24 TEC units have been observed. A significant enhancement in TEC is observed at regions around the EIA crest region during the flare in association with: (a) the flare related EUV flux enhancement and consequent increased production of ionization, and (b) changes in the equatorial electrodynamics. The magnitude of enhancement in ionospheric TEC appears to be dependent on the class of the solar flare.

Keywords: Ionospheric total electron content (TEC), Solar flare, EUV flux, Sudden ionospheric disturbances (SID)

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1 Introduction

A solar flare can be defined as the sudden and explosive release of energy (~10^{19} – 10^{25} J) from a localized active region of the Sun usually near a complex group of sunspots, mainly in the form of electromagnetic radiation across the entire spectrum[1]. Solar flares and coronal mass ejections (CMEs) are the result of the sudden release of magnetic stresses accumulated for some period of time in the lower solar atmosphere[2]. The enhancement of X-ray and ultraviolet (UV) emission observed during chromospheric flares on the Sun immediately causes an increase in electron density in the ionosphere. These density variations differ for different altitudes and are called sudden ionospheric disturbances (SID)[3-5]. These disturbances have important effects on radio communications and navigations over the entire radio spectrum[5]. SIDs are generally recorded as the short wave fadeout (SWF)[6], sudden phase anomaly (SPA)[7], sudden frequency deviation (SFD)[8-9], sudden cosmic noise absorption (SCNA)[10], sudden enhancement/decrease of atmospherics (SES)[11] and sudden increase in total electron content (TEC)[12,13]. Most of the work on SID studies has been summarized in thorough reviews[5,14]. In the early years, the most common technique to study the ionospheric solar flare effects is to examine Doppler (frequency) shift in signals transmitted by Doppler sounding systems. However, owing to the high-frequency band (HF, 3–30 MHz) (Ref. 15) used, the Doppler sounding system observation generally suffers from the short wave fadeout and often no data were recorded even during the midway of the flare occurrence[5,9]. A serious limitation of methods based on analyzing VHF signals from geostationary satellites is their small and ever decreasing (with time) number and the non-uniform distribution in longitude. A, further, highly informative technique is the method of incoherent scatter (IS)[12,16]. However, the practical implementation of the IS method requires very sophisticated, expensive equipment. The IS method's time resolution is inadequate for the study of ionospheric effects from solar flares. The time of electron density enhancement in the E and F1 regions during impulsive flares can be 2-3 min.

Consequently, none of the above mentioned existing methods can serve as an effective basis for the radio detection system to provide a continuous global SID monitoring with adequate space-time resolution. Furthermore, the creation of these facilities requires development of special equipments including powerful radio transmitters. It is also significant that when using the existing methods, the inadequate spatial aperture gives no way of deducing the possible spatial inhomogeneity of the X-ray and UV flux.

The advent and evolution of a Global Positioning System (GPS) opened up a new era in remote sensing of the ionosphere because of its high resolution and precision[17-19]. Scientists report global views of ionospheric solar flare effects by means of the GPS technique[20-22]. Liu *et al.*[22] proposed two GPS observed quantities, the TEC and its time rate of change (rTEC), for observing ionospheric solar flare effects. They found that ionospheric responses of the two quantities depend on the local time of observation (or hour angle) and the most pronounced solar flare effects are in the mid-day region. They, further, showed theoretically that the rTEC stands for the frequency deviation of the GPS signals and is well correlated to Doppler shift in signals transmitted by Doppler sounding systems. Instead of the global view of a particular event, Zhang *et al.*[20] examined several flare events and found that for the similar classes, flares occurring near the solar meridian result in stronger ionospheric responses.

Afraimovich[23] and Afraimovich *et al.*[24-26] developed a new methodology of a global detection of ionospheric effects from solar flares and presented data from first GPS measurements of global response of the ionosphere to powerful impulsive flares of 23 September 1998, 29 July 1999 and 28 December 1999 to illustrate the practical implementation of the proposed method. They found that fluctuations of TEC, obtained by removing the linear trend of TEC with a time window of about 5 min, are coherent for all stations and line-of-sight (LOS) on the dayside of the Earth. The time profile of TEC responses is similar to the time behaviour of hard X-ray emission variations during flares in the energy range 25-35 keV, if the relaxation time of electron density disturbances in the ionosphere of order 50-100 s is introduced.

Most of the studies on the solar flare effects in the ionosphere have been with the solar flares of class X and M during solar maximum period. Information regarding the effects of weak solar flares during solar minimum period in the ionosphere over the EIA crest region is lacking. In the present study, perhaps for the first time, attempt has been made to study the response of ionosphere during the weak solar flares of C and B class during the solar minimum period over the EIA crest region.

In this paper, the effects of solar flares on ionospheric TEC during low solar activity period of year 2008 have been presented. The TEC is derived using high resolution and precision GPS measurements obtained at Varanasi, a low latitude station situated at the EIA crest region.

2 Ionospheric TEC measurements

The slant total electron content (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. The total number of free electrons is proportional to the ionospheric differential delay between L1 (1575.42 MHz) and L2 (1227.60 MHz) signals

$$STEC = \int Ne(l)dl \qquad \ldots (1)$$

where, N_e, is the electron density; and 1 TEC unit = 10^{16} electrons m^{-2}.

The slant total electron content (STEC) estimated from GPS data recorded in RINEX format (Trimble 5700 receiver) with a time resolution of 30 s at the low latitude station Varanasi is converted into vertical total electron content (VTEC) according to Rama Rao *et al.*[27]:

$$CTEC = \left(STEC - [b_R + b_S]\right) / S(\theta_l) \qquad \ldots (2)$$

where, b_R and b_S, are receivers and satellite biases, respectively; θ_l, the elevation angle of the satellite in degrees; S (θ_l), the obliquity factor with zenith angle χ at the ionospheric pierce point (IPP); and VTEC, the vertical TEC at the IPP. The obliquity factor S (E_l) (or mapping function) is defined as[28-29]:

$$S(\theta_l) = \frac{1}{\cos(\psi)} \left\{ 1 - \left(\frac{R_E \cos(\theta_l)}{R_E + h} \right)^2 \right\}^{-1/2} \qquad \ldots (3)$$

where, R_E, is the mean Earth's radius in km; h, the height of the ionospheric shell above the Earth's surface; ψ, the zenith angle; and θ_l, the elevation angle of satellite in degree. Here, satellite elevation angle greater than 30° has been taken. The latitudes and longitudes of ionospheric pierce points (IPPs) have been calculated from the RINEX navigation message data by using standard coordinate transformation formulae and corrections in satellite orbits[30].

3 Results and Discussions

A solar flare typically produces immediate increases in the ionospheric ionization of varying degree at different heights, which are called the sudden ionospheric disturbances (SIDs) or the ionospheric solar flare effects[3-4]. In the present study of ionospheric solar flare effects through variation of ionospheric TEC, four different solar flare events during the solar minimum period for the year 2008 have been chosen.

3.1 Solar flare on 3-5 November 2008

A weak solar flare of class B occurred during 3-5 November 2008. The top panel of Fig. 1 shows the global solar X-ray flux observed from 1.5 to 12.4 keV (1-8.0 A°) and 3.1 - 24.8 keV (0.5 – 4.0 A°) during 3-5 November 2008. The detailed descriptions of the solar flares are given in Table 1. The middle panel of Fig. 1 shows the variation of mean TEC for quiet period and variation of TEC for the period 3-5 November 2008. The lowest panel shows the change in TEC during these periods.

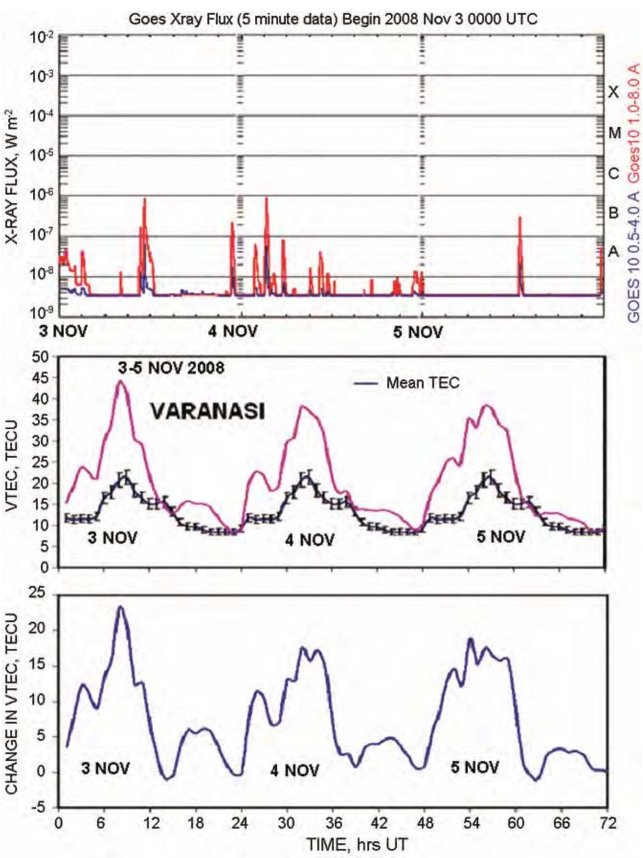

Fig. 1 — Variation of X-ray flux during solar flare (top panel), variation of VTEC and quiet mean VTEC (middle panel), and change in VTEC (bottom panel), for the period 3-5 November 2008 (vertical bar shows standard deviation for estimated mean TEC)

From Fig. 1, it is clear that the enhancement of X ray emissions observed during the solar flares on the Sun causes an increase in electron density in ionospheric TEC. From the Table 1, it is found that a C 1.0 class solar flare started at 03:17 hrs UT on 4 November, it had its maximum at 03:30 hrs UT, and ended at 03:36 hrs UT. The beginning of increment in the value of TEC has been around 04:00 hrs UT (middle panel). The maximum enhancement is approximately 35 TECU around 06:00 hrs UT. On the whole, there is an increment of approximately 15 TECU in the value of TEC (lowest panel). The TEC enhancements observed could be due to the enhancements in the extreme EUV radiations associated with the solar flare[31-32] and also the changes in the overall ionospheric dynamics/electrodynamics.

Also from the Table 1, it is found that a solar flare of class B 3.4 occurred on 5 November 2008. This solar flare started at 12.52 hrs UT, had its maximum at 12:56 hrs UT and ended at 13:03 hrs UT. The middle panel of the Fig. 1 shows that during this period, there is also an increment in the value of VTEC (around 20 TECU).

3.2 Solar flare on 2-4 January 2008

A solar flare of class C 1.2 occurred on 2 January 2008. The descriptions of these solar flares are tabulated in Table 2. The top panel of Fig. 2 shows the global solar X-ray flux observed from 1.5 to 12.4 keV (1-8.0 A°) and 3.1 - 24.8 keV (0.5–4.0 A°) for the period 2-4 January 2008. The middle panel of Fig. 2 shows the variation of mean TEC for quiet periods and variation of TEC for the period

Table 1 — Details of solar flare during 3-5 November 2008

Date	Time, hrs UT			Class of flare
	Begin	Maximum	End	
03 Nov 2008	10:42	10:46	10:48	B2.9
03 Nov 2008	11:15	11:19	11:22	C1.6
03 Nov 2008	22:45	22:56	23:03	B2.4
04 Nov 2008	03:17	03:30	03:36	C1.0
04 Nov 2008	05:37	05:41	05:44	B1.0
05 Nov 2008	12:52	12:56	13:03	B3.4
05 Nov 2008	23:44	23:46	23:49	A8.4

Table 2 — Details of solar flare during 2-4 January 2008

Date	Time, hrs UT			Class of flare
	Begin	Maximum	End	
02 Jan 2008	06:51	10:00	11:23	C1.2
04 Jan 2008	03:05	03:12	03:19	B1.8

2-4 January 2008. The lowest panel shows the change in TECU during these periods.

From the Table 2, it is known that a C1.2 class solar flare occurred on 2 January 2008. This solar flare began at 06:51 hrs UT, had its maximum at 10:00 hrs UT and ended at 11:23 hrs UT. From Fig. 2, it is found that during this period, there is a small decrease in the value of TEC from mean TEC.

3.3 Solar flare on 24-26 March 2008

An intense solar flare of class M 1.7 occurred on 25 March 2008. The detailed descriptions of the solar flares are given in Table 3. The top panel of Fig. 3 shows the global solar X-ray flux observed in the range 1.5-12.4 keV (1-8.0 A°) and 3.1-24.8 keV (0.5–4.0 A°) for the period 24-26 March 2008. The middle panel of Fig. 3 shows the variation of mean TEC for quiet periods and variation of TEC for the period 24-26 March 2008. The lowest panel shows the change in TECU during these periods.

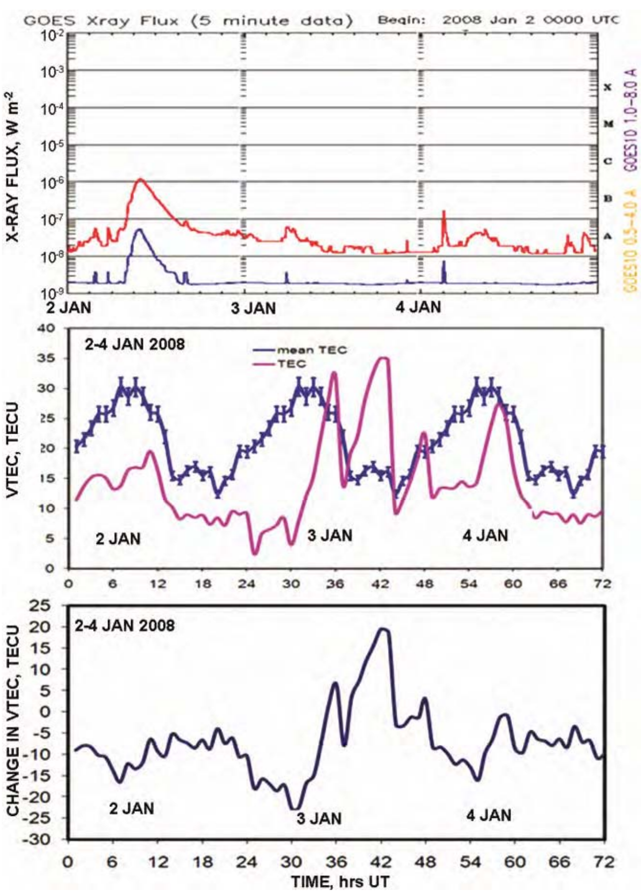

Fig. 2 — Variation of X-ray flux during solar flare (top panel), variation of VTEC and quiet mean VTEC (middle panel), and change in VTEC (bottom panel), for the period 2-4 January 2008 (vertical bar shows standard deviation for estimated mean TEC)

From Fig. 3, it is clear that the enhancement of X-ray emissions observed during the solar flares on the Sun causes an increase in electron density in ionospheric TEC[32]. From the Table 3, it is found that M1.7 class solar flare began at 18:36 hrs UT, had its maximum at 18:56 hrs UT, and ended at 19 hrs UT. Due to maximum at 18:56 hrs UT, there is the beginning of increment in the value of TEC around 22:00 hrs UT (middle panel), this increment attains a maximum value of approximately 50 TEC unit around 06:00 hrs UT on 26 March. So, there is an increment of approximately 18 TECU in the value of TEC (lowest panel).

Also, from the Table 3, it is found that a solar flare of class B7.6 occurred on 26 March 2008. This solar flare started at 21:12 hrs UT, had its maximum at 21:29 hrs UT and ended at 21:40 hrs UT. From the middle panel of the Fig. 3, it is found that during this period, there is also an increment in the value of VTEC (around 5 TECU).

3.4 Solar flare on 3-5April 2008

Two solar flares of class C1.2 occurred on 3 April 2008. The description of this solar flare is presented in Table 4. The top panel of Fig. 4 shows the global solar X-ray flux observed from 1.5 to 12.4 keV (1-8.0 A°) and from 3.1 to 24.8 keV (0.5–4.0 A°) for the

Table 3 — Details of solar flare during 24-26 March 2008

Date	Time, hrs UT			Class of flare
	Begin	Maximum	End	
24 Mar 2008	01:17	01:20	01:23	B1.7
24 Mar 2008	02:37	02:44	02:53	B5.1
24 Mar 2008	03:00	03:05	03:07	B4.2
24 Mar 2008	04:50	04:55	04:59	B1.7
24 Mar 2008	07:59	08:18	08:34	B3.3
24 Mar 2008	10:13	10:17	10:21	B1.1
24 Mar 2008	14:03	14:10	14:12	B2.6
24 Mar 2008	16:13	16:18	16:27	B1.2
24 Mar 2008	17:18	17:21	17:23	B1.3
24 Mar 2008	19:47	19:51	19:53	B1.9
25 Mar 2008	04:49	04:56	05:04	B4.7
25 Mar 2008	07:52	08:02	08:11	B1.8
25 Mar 2008	11:18	11:25	11:32	B1.7
25 Mar 2008	14:49	14:52	14:54	B2.3
25 Mar 2008	17:34	17:38	17:41	B2.1
25 Mar 2008	18:26	18:29	18:31	B1.8
25 Mar 2008	18:36	18:56	19:13	M1.7
26 Mar 2008	11:21	11:25	11:30	B1.8
26 Mar 2008	18:51	19:19	19:26	B1.3
26 Mar 2008	21:12	21:29	21:40	B7.6

period 3-5 April 2008. The middle panel of Fig. 4 shows the variation of mean TEC for quiet periods and variation of TEC for the period 3-5 April 2008. The lowest panel shows the change in TECU during these periods.

From the Table 4, it is found that two C1.2 class solar flare occurred on 3 April 2008. This first solar flare began at 01:12 hrs UT, had its maximum at 01:24 hrs UT and ended at 01:36 hrs UT. The second solar flare on 3 April 2008 of class C1.2 began at 02:18 hrs UT, had its maximum at 02:27 hrs UT, and ended at 02:35 hrs UT. Also, from the Table 4, it is found that a solar flare of class B1.3 occurred on 5 April 2008. This solar flare began at 11:02 hrs UT, had its maximum at 11:06 hrs UT, and ended at 11:10 hrs UT. For this flare, due to maximum around 11:06 hrs UT, there is beginning of increment in the value of TEC around 04:00 hrs UT (middle panel), this increment attains a maximum value of approximately 40 TEC unit around 06:00 hrs UT. So, there is an increment of approximately 5 TECU in the value of TEC (lowest panel).

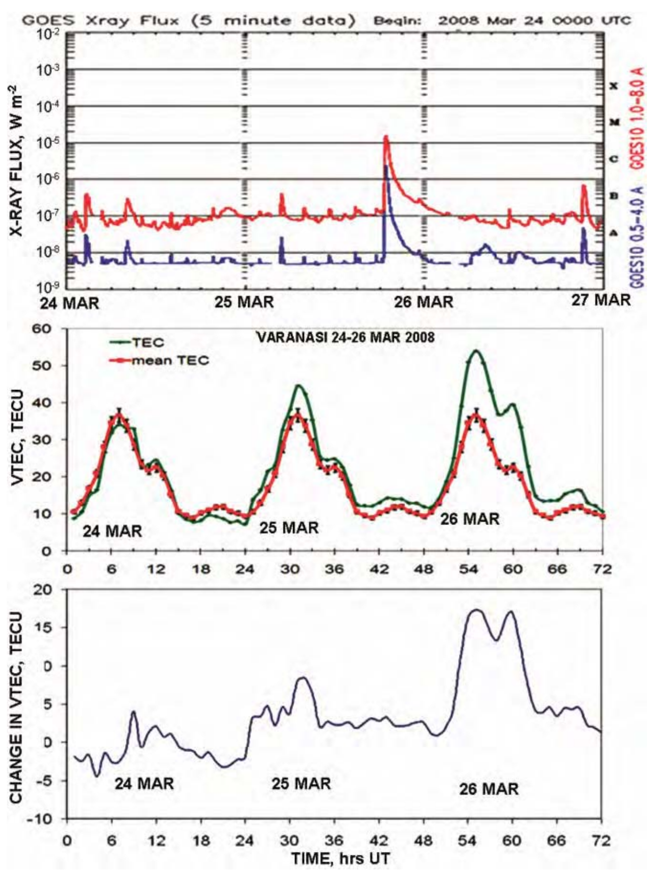

Fig. 3 — Variation of X-ray flux during solar flare (top panel), variation of VTEC and quiet mean VTEC (middle panel), and change in VTEC (bottom panel), for the period 24-26 March 2008 (vertical bar shows standard deviation for estimated mean TEC)

Thus it is found that solar flare events investigated here revealed increase in the overall VTEC. Mitra[14] has published an excellent review on the ionospheric effects of solar flares. As discussed earlier and mentioned by Tsurutani *et al*.[31], the impulsive ionization of the flare radiation causes enhanced ionization over a broad altitude range from the D-region (80–100 km altitude) all the way to the F-region (the F-region peak is at about 300 km altitude). As mentioned by Papagiannis[32], most of the SIDs are directly related to the ionization of the D-layer, which is the result of the X-ray burst from the solar flare. During quiet days, the D-region is maintained by the Lyman (121.6 nm) emission from the Sun and by the galactic cosmic rays (lower D-region). The quiet Sun emits practically no X-rays below 1 nm and therefore, all the solar X-rays are stopped above the D-region. The X-ray emission from a flare, however, extends easily into the 0.1 nm range, which can reach the D-region and increase its electron density by at least one order of magnitude. A significant enhancement in TEC observed at regions around EIA crest region during the solar flares are due to the enhancements in the extreme EUV radiations associated with the solar flare and consequent increased production of ionization[31-34]. This can also be explained by the movement of the F-layer in terms of the movement of the regions with higher electron density. The enhancements in TEC observed in the present investigations are related to the ionospheric electron density changes as a result of the additional ionization, due to the solar flare extreme EUV (Ref. 31).

Liu *et al.*[22] have also investigated solar flare signatures of the ionospheric GPS total electron content and have reported that the maximum value of the TEC increase solely depends on the flare class, while the

Table 4 — Details of solar flares during 3-5 April 2008

Date	Time, hrs UT			Class of Flare
	Begin	Maximum	End	
03 Apr 2008	01:12	01:24	01:36	C1.2
03 Apr 2008	02:18	02:27	02:35	C1.2
03 Apr 2008	05:55	05:59	06:12	B1.2
03 Apr 2008	15:27	15:31	15:33	B1.0
03 Apr 2008	15:51	15:57	16:00	B2.9
03 Apr 2008	19:44	19:51	19:58	B1.9
03 Apr 2008	20:20	20:24	20:28	B2.3
04 Apr 2008	01:47	01:57	02:08	B5.0
04 Apr 2008	14:57	15:01	15:05	B1.2
04 Apr 2008	18:06	18:10	18:14	B2.7
05 Apr 2008	11:02	11:06	11:10	B1.3

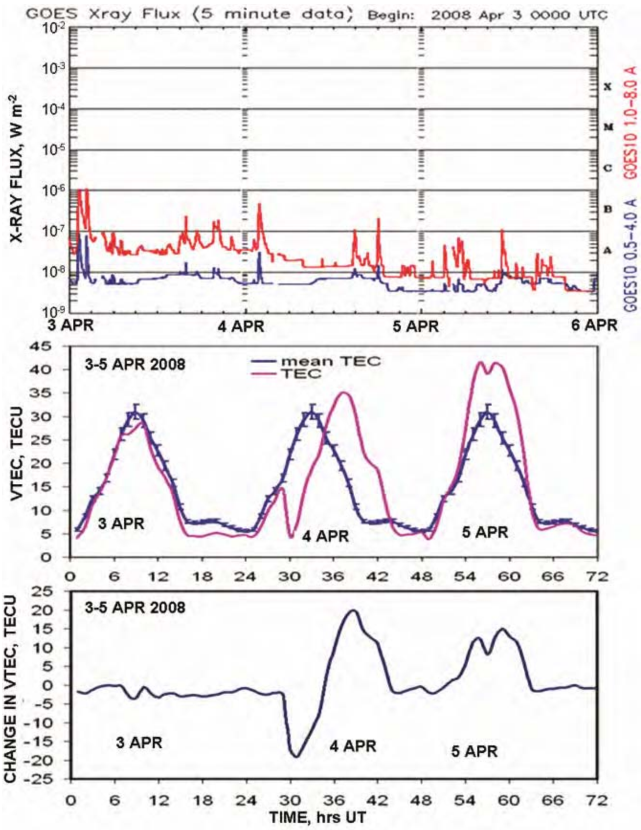

Fig. 4 — Variation of X-ray flux during solar flare (top panel), variation of VTEC and quiet mean VTEC (middle panel), and change in VTEC (bottom panel), for the period 3-5 April 2008 (vertical bar shows standard deviation for estimated mean TEC)

maximum rate of TEC change is related to not only the flare class but also to the time rate of change in the flare radiations. It appears that the GPS/TEC observations, which are due to the line-of-sight ultra high frequency propagation between a satellite and ground-based receiver, just reflect the electron density enhancements in the ionospheric region following a solar flare.

In the present study, large changes in the TEC (up to 24 TEC units) have been observed during the weak solar flares of C and B class during the solar minimum period over the EIA crest region. These large deviations from the mean TEC during weak solar flares of C and B class are entirely not due to solar flare effects. The major portion of these deviations from the mean TEC is due to the overall changes in the low latitude electrodynamics, i.e. fountain effect and the meridonal wind effects[34]. Only the minor deviations in TEC may correspond to the flare effects during daytime. The dawn-to dusk prompt penetration of electric fields to the low latitudes is directed eastward during the day and enhanced the low latitude E × B drift of the ionization. The uplifted plasma then diffuses along the magnetic field lines towards higher altitudes where recombination rates are smaller giving enhanced value of TEC. The other possibility is the storm induced equatorward winds which may lift the ionospheric layers to higher altitudes, where the recombination loss becomes smaller. This may result in increases of EIA peak densities. Over these enhanced TEC, some minor deviations in TEC of 4-5 TECU from the TEC of that day itself may correspond to the solar flare effects of these weak C and B class flares. A significant modulation of the equatorial electrojet (EEJ) associated currents systems by the flare related EUV flux enhancement in different longitudes have also been reported by Manju *et al.*[34].

The present results are important because perhaps for the first time, attempt has been made to analyze the GPS data in order to study the effect of weak solar flares of class C and B on variation of TEC, during the lowest solar activity period of 2008 in recent years.

4 Summary and Conclusions

In present work, the GPS-derived TEC response to weak solar flares during the solar minimum period at the EIA crest region has been presented. The TEC variations during four selected solar flares, which occurred during the solar minimum year 2008, have been presented. It is found that solar flares, in general, increased the value of VTEC. The maximum enhancement of TEC during solar flare compared to quiet mean TEC up to 24 TEC units have been observed even during the solar minimum period of 2008. However, these large deviations from the mean TEC during weak solar flares of C and B class are not due to solar flare effects alone. The enhancement is attributed to: (a) increased EUV radiation emitted during the flare and consequent increased production of ionization, (b) change in the low latitude electrodynamics/dynamics owing to the geomagnetic activity commenced following the flare events. Further, the magnitude of enhancement in ionospheric TEC is found to be dependent on the class of the solar flare. One realizes that there are large numbers of GPS sites measuring TEC, which provide an excellent chance to continuously monitor ionospheric solar flare effects at various local times, i.e. longitudes as well as latitudes. There is, further, need to simultaneously monitor the ionosphere response to solar flares with global GPS network.

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