Impact factor for the ionospheric total electron content response to solar flare irradiation

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[1] On the basis of ionospheric total electron content (TEC) enhancement over the subsolar region during flares, and combined with data of the peak X-ray flux in the 0.1–0.8 nm region, EUV increase in the 0.1–50 and 26–34 nm regions observed by the SOHO Solar EUV Monitor EUV detector, also with the flare location on the solar disc, the relationship among these parameters is analyzed statistically. Results show that the correlation between ionospheric TEC enhancement and the soft X-ray peak flux in the 0.1–0.8 nm region is poor, and the flare location on the solar disc is one noticeable factor for the impact strength of the ionospheric TEC during solar flares. Statistics indicate clearly that, at the same X-ray class, the flares near the solar disc center have much larger effects on the ionospheric TEC than those near the solar limb region. For the EUV band, although TEC enhancements and EUV flux increases in both the 0.1–50 and 26–34 nm regions have a positive relation, the flux increase in the 26–34 nm region during flares is more correlative with TEC enhancements. Considering the possible connection between the flare location on the solar disc and the solar atmospheric absorption to the EUV irradiation, an Earth zenith angle is introduced, and an empirical formula describing the relationship of TEC enhancement and traditional flare parameters, including flare X-ray peak and flare location information, is given. In addition, the X-ray class of the flare occurring on 4 November 2003, which led the saturation of the X-ray detector on GOES 12, is estimated using this empirical formula, and the estimated class is X44.


1. Introduction

[2] As one of the fastest and severest solar events, the solar flare, which is mainly classified according to the peak flux of soft X-rays in the 0.1–0.8 nm region measured on the GOES X-ray detector, has a great influence on the earth upper atmosphere and ionosphere. During a flare, the extreme ultraviolet (EUV) and X-rays emitted from the solar active region ionize the atmospheric neutral compositions in the altitudes of ionosphere to make the extra ionospheric ionization that causes many kinds of sudden ionospheric disturbance phenomenon (SID), which are generally recorded as sudden phase anomaly (SPA), sudden cosmic noise absorption (SCNA), sudden frequency deviation (SFD), shortwave fadeout (SWF), solar flare effect (SFE) or geomagnetic crochet, and sudden increase of total electron content (SITEC) [Donnelly, 1969; Mitra, 1974]. The mechanism and the affected strength about these SID phenomena have been studied thoroughly from 1960s and summarized by Mitra [1974] and more recently by Davies [1990]. Although the increase of electron density during a flare appears in all ionospheric subregions, it is usually accepted that the SPA and SCNA are closely related with the increase of electron density in the ionospheric D region which is ionized mainly by the extra sudden increase of X-ray during solar flares, and the strength of the SPA and SCNA have good correlation with the X-ray flux [Itkina, 1978; Liu et al., 1996; Thomson et al., 2005]. Nevertheless, the increase of electron density in the F region mainly due to the flare extra ionization of EUV radiation is thought to be responsible for a large fraction of the SITEC, so that the SITEC can be used as an index to represent the response of the ionospheric F region to solar flares [Mendillo et al., 1974].

[3] Ionospheric variation during solar flares is closely connected with the flare additional increase of irradiation flux from X-ray to EUV. The study of the ionospheric variation with the flare irradiation is one of the key issues for better understanding the photochemical process and also for improving the accuracy of the space weather prediction. Nevertheless, it was found that the flares exhibit obvious difference in solar irradiation spectra even for the same level flares classified according to the peak X-ray flux in the 0.1–0.8 nm region observed in GOES detector [Tsurutani et al.,...
2009; Woods et al., 2004, 2006]. For the flares in the same X-ray level, the spectrum in EUV band may be significantly different. From the point of the flare effect on ionosphere, this difference in solar flare irradiation will certainly bring about the obviously different ionospheric TEC response. This brings about the difficulty for estimating the ionospheric response to solar flares. On the basis of the relationship between the SPA or SCNA phenomenon connected with the sudden variation of electron density in ionospheric D region and the solar extra irradiation in X-ray band during flares, the behavior of the ionospheric D region can be revealed from the temporal variation of the soft X-ray flux correctly [Itkina, 1978; Thomson et al., 2005]. As for SITEC, its complicated dependence on the solar irradiation in the bands ranged from X-ray to EUV makes the poor prediction of the SITEC. Because of the flare to flare difference in irradiation spectrum, it is difficult to estimate the value of SITEC just on the basis of solar irradiation flux in some limited bands [Le et al., 2007; Leonovich et al., 2010; Tsurutani et al., 2009]. Undoubtedly, the observations in the fine structure of solar irradiation spectra can promote the accuracy of SITEC estimation. In recent years, many space projects focusing on the solar irradiation in different bands have been put forward and the data in different X-ray and EUV bands can be obtained gradually [Brekke et al., 2000; Judge, 1998; Drobnes, 2005; Woods et al., 2005]. These data conditions promote the further study of the ionospheric response to solar flares [Tsurutani et al., 2009].

[Matsoukas et al. [1972] studied the correlative relationship between the solar radio bursts and SITEC by grouping the flares according to their solar radio flux and flare locations. They found that the flares near the solar meridian line (flare longitude) had stronger effect on the SITEC than the flares near the solar limb region. Furthermore, Donnelly [1976] proved this relationship and clearly concluded that the solar flare EUV irradiation had strong center to limb effects, while there was essentially none for X-rays. Through the study of the ionospheric TEC during different solar flares, the different responses of the ionospheric TEC to the same level solar flares classified according to the soft X-ray peak flux have been noted [Afraimovich et al., 2002; Zhang et al., 2002]. Case studies showed that besides the solar X-ray peak flux, the parameter of the flare location on the solar disc was also important to reveal the effective strength of the ionospheric response to solar flares [Zhang et al., 2001; Zhang and Xiao, 2003, 2005; Tsurutani, 2005; Tsurutani et al., 2006]. More recently, by comparing the SITEC values and the solar irradiation flux increase in soft X-ray and EUV bands during several extreme solar flares occurred in the last solar cycle, Tsurutani et al. [2009] examined the flare-ionosphere connection, and found the strong spectral variability from flare to flare. Tsurutani et al. [2009] suggested that the continuous full solar flare spectrum was necessary to understand this connection. Although the concept that ionospheric response is connected with the solar flare location is accepted, the clear relationship between ionospheric TEC enhancement and flare location has not been revealed yet. Undoubtedly, case studies and statistical analysis are helpful to reveal the relationship between ionospheric TEC enhancement and the flare location quantitatively.

[During the period from 28 October to 4 November 2003, a large number of extreme solar events occurred and triggered a nearly continuous series of geophysical disturbances [Gopalswamy et al., 2005]. Particularly, two flares on 28 October and 4 November 2003 were focused [Zhang and Xiao, 2005; Tsurutani, 2005; Tsurutani et al., 2006; Thomson et al., 2004; Brodrick et al., 2005]. Especially, during the flare on 4 November 2003, the GOES-12 X-ray detector was saturated by the extreme X-ray flux. Its level was first classified as X 28 by extrapolation (http://www.swpc.noaa.gov/ftpmenu/warehouse/2003.html). And then, on the basis of the ionospheric response in D region to this flare, the flare level was estimated using the measurement of SPA and SCNA effect [Thomson et al., 2004; Brodrick et al., 2005]. The flare’s level was estimated as high as X 45 (from SPA) and X 36 (from SCNA).

[As introduced above, compared with the ionospheric D region response to flares, the response of the ionospheric SITEC to flares is more complicated owing to the extra atmospheric ionization ranging in the height from ionospheric D to F region by wide bands of irradiation from X-ray to EUV. In this study, by choosing the X-level flares occurred in the last solar cycle from 1998 to 2006, the relationships among the ionospheric TEC enhancement and the flare location, flare X-ray peak level, the SOHO Solar EUV Monitor (SEM) EUV flux increase in the 0.1–50 and in 26–34 nm regions will be analyzed statistically. Furthermore, an empirical formula connected the SITEC, the flare peak flux in the 0.1–0.8 nm region and its location on the solar disc will be developed.

2. Data and Methods

[The flares occurred from 1998 to 2006 are sampled under the following criteria: (1) the class of the flare is larger than X1.0; (2) the information of flare peak flux, flare’s beginning, peak, and ending time, flare’s location on the solar disc are complete; (3) the time interval between flare’s beginning and peak time is less than 30 min; and (4) the corresponding EUV flux measurements from SOHO SEM during every flare period are available.

[Then the increase of EUV flux in the 0.1–50 and 26–34 nm regions are derived from SEM observation (available at http://www.usc.edu/). According to the flare peak time, the subsolar region where solar zenith angle in the earth surface is less than 10° in the flare peak time is determined, and the GPS data observed in this region during flare time are collected from IGS network (available at http://sopac.ucsd.edu). The temporal resolution of the GPS data is usually 30 s. All stations use high-precision, dual-frequency GPS receivers, which can provide carrier phase and pseudorange measurements in two L band frequencies \( f_1 = 1575.42 \text{ MHz}, f_2 = 1227.60 \text{ MHz} \). Using these four measurements, combining the geometrical relation of the satellite, ionosphere, and receiver, a precision TEC can be derived at every observational epoch [Lanyi and Roth, 1988; Hofmann-Wellenhof et al., 1992; Mannucci et al., 1998]. For each GPS station, at least four vertical TEC values with a different ionospheric penetration point (IPP), which is the point of intersection of the line of sight and the ionospheric shell (usually assumed to be 400 km), can be derived for an interval of 30 s. Since this study is focused on ionospheric disturbances caused by flare radiation, only relative TEC changes or TEC enhancements during the flare are useful,
and the relative accuracy of the TEC is 0.02 total electron content unit (1 TECU = 10^{16} \text{ el m}^{-2}) [Hofmann-Wellenhof et al., 1992]. As an example for the procedure of data analyzing, the ionospheric TEC curves calculated from the GPS data observed in GALA station (0.74°N, 269.70°E) during the flare on 6 April 2001 were given in Figure 1. By applying the TEC deriving method for all collected GPS data corresponding to each flare, the temporal TEC curves during each selected flare like showed in Figure 1 are obtained. After that, the TEC enhancement values related to flare extra irradiation are derived from each ionospheric TEC curve by removing the influence of the background solar disc irradiation, the final TEC enhancement value is obtained by averaging all TEC enhancement value from all ionospheric TEC curves obtained over the subsolar region [Zhang and Xiao, 2003].

By above procedures, the data set including the ionospheric TEC enhancement and the corresponding flare irradiation increases in different spectral band are obtained and all total 66 flares that meet the above constraint conditions are studied in this paper.

3. Results and Analysis

3.1. Examples of the Different Impact Strength on Ionospheric TEC for Solar Flares With the Same X-ray Class

Figure 2 gives the ionospheric TEC curves derived from the GPS data during six solar flares that are selected according to their class and location information. The triangles in Figure 2 mark the local noon of GPS station where the GPS data observed. The parameters of these flares, the corresponding ionospheric TEC enhancements and the information of GPS site are listed in Table 1. These six flares are classified into three groups on the basis of their X-ray peak flux. The two flares in each group have the same level of the peak X-ray flux but different solar location. The different strength of the ionospheric TEC response to the flares with the same X class can be seen clearly in Figure 2. On the whole, the flares nearer to the solar center exhibit stronger impact on the ionospheric TEC. It is known that the solar irradiation in the band of soft X-ray and EUV is responsible for the ionospheric TEC enhancement due to the sudden increase of the electron density in the whole ionospheric height [Donnelly, 1976; Tsurutani et al., 2009]. So this different response revealed in Figure 2 manifests the difference in EUV irradiation flux for every flare pair.

3.2. Statistical Relationship Among the Ionospheric TEC Enhancement, Flares’ Irradiation Flux, and Their Location on the Solar Disc

[11] The dependence of the flare irradiation impact on ionospheric TEC can be revealed more clearly by analyzing the flares grouped according to their X-ray peak level. According to their X-ray peak flux, the flares less than X4.0 are divided into four groups: (X1.0–X1.1), (X1.4–X1.8), (X2.3–X2.8), (X3.0–X3.9). Figure 3 shows the relationship between the TEC enhancement values (represented as DTEC) and the flares longitude (relative to solar center meridian line) during the flares in these four groups. It can be seen that the TEC enhancement is related to the flares longitude. Statistically, the larger the longitude, the smaller the TEC enhancement. This dependence should manifest the variation of EUV irradiation flux with flare location.

[12] The EUV data from SEM are often used for modeling solar irradiation spectrum [Judge, 1998]; the data can also be used in the solar irradiation variation during solar flare period. Figure 4 shows the irradiation flux measurements of soft X-ray in the 0.1–0.8 nm region obtained from GOES and EUV flux in the 0.1–50 and 26–34 nm regions detected in SEM during a flare on 15 April 2001. This is another example which indicates that the increase of the corresponding solar irradiation flux related to the solar flare can...
be derived from this kind of flux curves. Here, it should be noticed that the postflare increases in the EUV band shown in Figure 4 is due to the contamination of the flare energetic particles impinging upon the SEM detector. In the same way, the relationships between the TEC enhancement and the EUV enhancement in the 0.1–50 and 26–34 nm regions during the flares in the group (X1.0–X1.1) are given in Figure 5, respectively. It shows that the EUV enhancement during flares in the same X-ray class varies greatly, ranging from 1.4 to 3.0 unit for EUV band in the 0.1–50 nm region and 0.1–0.6 unit for the EUV band in the 26–34 nm region (1 unit = 10^{10} photons m^{-2} s^{-1}). That illustrates the flare to flare difference in different solar flare irradiation bands. Even so, as can be expected, the TEC enhancement caused by the flares’ irradiation is positively correlated with the EUV flux enhancement.

Figure 6 shows the corresponding relationship between the flare longitude and the EUV flux enhancement in group (X1.0–X1.1). Similar to the TEC enhancement, the EUV flux enhancement related to the same X-ray class flare varies with the solar flare longitude, and the nearer to the solar center, the larger the EUV enhancement. It can also be seen that the different ionospheric response exists even for the flares with the same flare longitude and the same X-ray class. That also illustrates the variability of the irradiation spectrum of flare to flare.

Table 1. Parameters of Flares, Ionospheric TEC Enhancement, and the GPS Site Information Used in Figure 2

<table>
<thead>
<tr>
<th>YYMMDD</th>
<th>Start Time (UT)</th>
<th>End Time (UT)</th>
<th>Peak Time (UT)</th>
<th>Flare Longitude (deg)</th>
<th>Flare’s X-ray Class</th>
<th>ΔTEC/TECU</th>
<th>GPS Site</th>
<th>Site Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>981122</td>
<td>1610</td>
<td>1632</td>
<td>1623</td>
<td>89</td>
<td>X2.5</td>
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<td>areq</td>
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<td>1521</td>
<td>1513</td>
<td>07</td>
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<td>braz</td>
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<tr>
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<td>1900</td>
<td>1847</td>
<td>64</td>
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<td>ispa</td>
<td>−27.1</td>
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<tr>
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<td>1420</td>
<td>1435</td>
<td>1430</td>
<td>09</td>
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<td>1124</td>
<td>1110</td>
<td>08</td>
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<tr>
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<td>1803</td>
<td>1740</td>
<td>77</td>
<td>X17.0</td>
<td>3.70</td>
<td>bogt</td>
<td>4.6</td>
</tr>
</tbody>
</table>

*aYYMMDD, year, month, day; read 981122 as 22 November 1998.

3.3. Relationship Among Solar Irradiation in Different Spectral Bands

From the results illustrated above, we can see that the positive relationship between the TEC enhancement and the EUV flux increase exists statistically but is also scattered obviously. Figure 7 gives the relationship between the EUV enhancement in the band of 0.1–50 nm and the EUV in the band of 26–34 nm during the flares in the X1.0–X1.1 class. That shows the obvious flare to flare difference in solar flare irradiation spectrum in EUV band. Because the spectrum that can ionize the atmospheric component ranges from soft X-ray to EUV, the solar flare flux in any spectral band cannot represent the impact strength of the flare to ionospheric TEC effectively. So it is meaningful to give a convenient flare irradiation proxy by analyzing the relationship between the TEC enhancement and the corresponding flare’s parameters.

Figure 8 shows the relationship between the TEC enhancement and the soft X-ray peak flux derived from all selected solar flares in this study. Because the information of the flares’ locations is not taken into consideration, their correlation is poor, which is understandable based on the analysis above. Therefore, different from the flare’s effect on the ionospheric electron density in D region, the soft X-ray peak flux parameter is not enough to describe the strength of the sudden increase of ionospheric TEC caused by the flare extra irradiation.

![Figure 3](image-url)
Figure 9 gives the relationship between the TEC enhancement and the increases of the EUV flux in the 0.1–50 and 26–34 nm regions for all selected flare events. It has a better correlation than the X-ray flux that shown in Figure 8. It can be seen that the correlation between the TEC enhancement and the extra increase of EUV flux in the 26–34 nm region is much better than that of the EUV in the 0.1–50 nm region. This gives a clue that the extra increase of EUV flux in the 26–34 nm region can be used as a better parameter to estimate the sudden increase of the TEC than peak X-ray flux. Nevertheless, compared with the flare class represented by the soft X-ray peak flux in the 0.1–0.8 nm region, the EUV flux is much less provided to public so is inconvenient to obtain. Thus, in the practical utility, this correlational relationship may not be suitable for the manifestation of the flare irradiation effect on ionospheric TEC variation.

The flare class expressed in X-ray peak flux and its location on the solar disc are included in the flare list report that can be easily obtained from Space Weather Prediction Center (SWPC) web site. Donnelly [1976] owed the so-called center-to-limb effects of the EUV to the solar atmosphere absorption. Referring to the theory of the terrestrial atmosphere absorption to the solar irradiation ever used in the Chapman ionizing theory [Chapman, 1931], the Earth zenith angle (EZA) that represents the angle between the zenith direction of the flare location in solar surface and the direction of the line of sight from flare location to Earth is defined. The cosine of this angle is introduced to describe the real EUV flux reaching to the earth atmosphere. Then, the impact of the flare irradiation to the ionospheric TEC can be described as a factor “ImF” that is the product of X-ray peak flux and the cosine of EZA. Figure 10 shows the relationship of the TEC enhancement and the ImF. It can be seen that the TEC enhancement exhibits a very good linear correlation with the factor ImF. The fitting equation to describe this relationship is as followed:

\[ DTEC = 0.89 \times P_{X-ray} \times \cos(\phi) \cos(\lambda) + 0.04 \]  

Figure 4. Irradiation flux measurements of soft X-ray in the 0.1–0.8 nm region and EUV flux in the 0.1–50 and 26–34 nm regions during a flare on 15 April 2001. The units of the EUV flux are 10^{10} photons cm^{-2} s^{-1}.

Figure 5. Relationship between the TEC enhancement and the EUV enhancement in the (left) 0.1–50 and (right) 26–34 nm regions during the flares in the X1.0–X1.1 class. The units of the EUV flux are 10^{10} photons cm^{-2} s^{-1}.
DTEC represents the TEC enhancement due to flare extra irradiation, the unit of DTEC is TECU. PX-ray represents the X-ray peak flux in unit of the $10^{-4}$ W m$^{-2}$, $\varphi$ is the solar flare latitude, and $\lambda$ is the flare longitude usually given in the SWPC flare list report. The $\cos(\varphi)\cos(\lambda)$ is the cosine of EZA derived according to the geometrical relationship among the Sun, flare and the Earth. Because the flare’s X-ray class and its location on the solar disc are the elementary parameters in the flare list report, the empirical relationship between the factor ImF and TEC enhancement is useful for estimating the flare’s impact to ionospheric TEC enhancement. However, this relationship can also be used to deduce flare class information under some special conditions, such as X-ray detector failure or saturation.

3.4. Estimation of the X-ray Class for the Flare on 4 November 2003

As mentioned in section 1, the flare on 4 November 2003 saturates the X-ray detector in GOES 12. SWPC estimates this flare class as X28 according to the X-ray flux tendency before the saturation. Using the long-range VLF measurement, Thomson et al. [2004] gave the class of this flare X45. Also using riometer measurements at 20.1 MHz, Brodrick et al. [2005] suggested that X38 seems to be more suitable class for this flare. The similar estimation for this flare can also be done using equation (1). Figure 11 is the temporal ionospheric TEC curves obtained near the subsolar region during this flare. The TEC enhancement value is 4.55 TECU that derived from TEC curves. According to the SWPC flare list report, the flare location is S19°W83°. The flare X-ray class is calculated according to equation (1), and the class of the flare using this estimation method is X44.

4. Discussion and Conclusions

The behavior of the ionosphere during solar flares is controlled by many factors. These factors include the solar zenith angle, the neutral composition distribution, the ionization and recombination process, the temporal evolution of flare burst and the solar irradiation spectrum from X-ray to EUV. Case studies for the ionospheric response to solar flares in the sunlit hemisphere show that the value of SITEC is correlative with local solar zenith angle [Zhang et al., 2002; Zhang and Xiao, 2003, 2005]. Although the response of the ionosphere to solar flares sometimes exhibits a little different strength in the summer-winter hemisphere owing to the asymmetrical distribution of atmospheric neutral compositions, on the whole, the smaller the solar zenith angle, the larger the value of the SITEC. In our study, only the GPS stations located in the subsolar regions in flare peak time are selected to derive the SITEC value. This selection ensures the consistency for the comparison of the TEC enhancement value for different flares.
Second, although the atmospheric ionization process in all ionospheric height caused by the extra flare irradiation is very quick, the timescale of the recombination process is very different. The recombination timescale of the electron in ionospheric D and E regions where molecular ions are predominant is an order of magnitude of minutes, but the recombination timescale of the atomic ion-predominant F region is an order of magnitude of hours, much larger than the timescale for the impulsive flare evolution. Therefore, the ionospheric TEC change determined by the variation of electron density in ionospheric F region is mainly controlled by the ionization process during impulsive solar flares. Certainly, the ionospheric TEC change is a height integration of ionization plus loss process, and the detailed loss process is also needed to have a better understanding of the ionospheric TEC variation caused by full solar irradiation spectrum [Le et al., 2007; Leonovich et al., 2010; Tsurutani et al., 2009].

Third, because the current information for solar flare irradiation is insufficient for fully revealing the ionospheric response, the flare to flare difference in the temporal evolution and in the irradiation spectrum makes the revealing of ionospheric variation caused by solar flare irradiation much difficult. Strictly, for a certain flare, the perfect ionospheric model combining the real time atmospheric neutral composition and the high-resolution solar irradiation spectrum is needed to reveal the ionospheric variation during flare period. Although the data in scattered solar irradiation data in X and EUV band can be available from some space-based observations [Brekke et al., 2000; Judge, 1998; Woods et al., 2005], it is still impossible to obtain the full spectrum data with enough resolution to meet the demand for revealing the ionospheric behavior during flares by ionospheric model simulation at present. However, by statistical analysis for the relationships among the ionospheric TEC and currently available flare information, some clear relationship between ionospheric TEC enhancement and the flare parameters can be obtained. In addition, the prediction for the ionospheric response to flare irradiation can benefit from this relationship. On the basis of the analysis mentioned above, we can make the following conclusions:

The correlation between ionospheric TEC enhancement and the soft X-ray peak flux in the 0.1–0.8 nm region is poor. The flare location on the solar disc is an important parameter to determine the impact strength of the ionospheric TEC response to solar flares. Statistically, for the flares with the same X-ray class, the flares near the solar disc center has stronger effect on the ionospheric TEC than that near the solar limb region. The relationship between TEC enhancement and the EUV flux increases in the 26–34 nm region during a flare is more correlative than that in the 0.1–0.8 and 0.1–50 nm bands. Given the possible connection between the flare location on the solar disc and the solar atmospheric absorption to the EUV irradiation, an Earth zenith angle (EZA) is introduced and an empirical relationship between the TEC enhancement and the increase of the EUV flux in the (left) 0.1–50 and (right) 26–34 nm regions for all selected flare events.

Figure 9. Relationship between the TEC enhancement and the increases of the EUV flux in the (left) 0.1–50 and (right) 26–34 nm regions for all selected flare events.

Figure 10. Relationship of the TEC enhancement and the “ImF” that is the product of X-ray peak flux and the cosine of the Earth zenith angle of solar flares.

Figure 11. Temporal ionospheric TEC curves obtained near the subsolar region during the flare on 4 November 2003.
formula describing the relationship of the TEC enhancement and traditional flare parameters is obtained. The X-ray class of the flares occurred on 4 November 2003 has been estimated using this empirical formula, and the estimated class is X44.

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