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Response of High Latitude Ionospheric TEC to Enhanced Radiation Fluxes during the Major Solar Flare Events

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Abstract

We have investigated the response of ionosphere to major solar flare events that occurred during 1998 to 2011. The effect of enhanced radiation fluxes in the X-ray and EUV band on the GPS derived Total Electron Content (TEC) is examined. The data of X-ray flux from Geostationary Operational Environment Satellite (GOES) and EUV flux from Solar EUV Monitor (SEM) onboard SOHO spacecraft were correlated with the Total Electron Content (TEC) data of a high latitude station, Davis (68.57^{0}S, 77.96^{0}E). We found that peak intensities of X-ray and EUV flux correlate very well with the peak values of TEC. We also studied the correlation of peak enhancement of these fluxes with the peak enhancement of TEC and found that peak enhancement of these fluxes correlate highly with the peak enhancement of TEC than with the peak values themselves. It is also found that correlation is extraordinarily improved when these fluxes are multiplied by Cos(CMD) where CMD is Central Meridian Distance on the solar disc, thereby showing that the location of flares on the solar disc plays an important role while investigating the ionospheric influences of solar flares.

Keywords: Ionosphere; TEC; CMD; Solar Flare.

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1. Introduction

The solar flares are accompanied by release of large amount of energy. The energy released during solar flares is in the form of radiations across entire electromagnetic spectrum. When the radiation impinges on the earth's ionosphere, several ionospheric disturbances are produced by increasing the ionization level. How much effect a flare can produce on the ionosphere depends on the strength of the flare as well as on the location of the flare on the solar disc. The solar flares occurring near the central meridian produce much stronger impact than those occurring at the solar limb [1]. The effect of flare

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location on the ionosphere can be taken care of by adjusting the flux to Central Meridian Distance (CMD), i.e. by multiplying the fluxes with Cos(CMD) as shown in this study as well as some other studies conducted in the past [1, 2]. The amount of fluxes during the flares varies considerably. But still there is no method by which we can take care of the variation of fluxes in flares while investigating the ionospheric influences of solar flares. Several studies have been conducted in the past to investigate the ionospheric influences of solar flares and many interesting facts have been discovered.

The effects of the solar flares on the ionosphere have been studied in the past and well reviewed by Mitra [3] and Davies [4]. It has been found that the value of fmin (frequency of minimum reflection of D layer) increases during the flares and in the case of large flares there can be a complete radio blackout [5, 6]. These disruptions or fadeouts occur as result of increased absorption of radio waves due to increased flare time ionization in the D region. The huge X-ray flux emitted during flares is responsible for causing these fadeouts as the major portion of the flux is able to penetrate to the D region. In upper ionosphere (F layer) the increase in ionization occurs mainly as a result of EUV flux. It has been reported that the critical frequency of F2 layer as measured by ground based Ionosondes gets largely increased during the periods of solar flares due to enhanced EUV flux [7]. The electron densities of E and F1 layers also show a sharp enhancement during the periods of extreme solar events [8]. A number of studies carried out using GPS derived Total Electron Content have shown that the value of TEC follows a large enhancement during the case of solar flares [9, 10]. Also it has been shown by Tsurutani *et al.* [2] and Mahajan *et al.* [10] that if these fluxes are adjusted to Cos(CMD) where CMD is Central Meridian Distance that takes care of flare location on solar disc, the correlation is greatly improved.

In this paper we have examined the response of ionosphere during twenty X class solar flares that occurred during the 1998 to 2011. We report a very good correlation of solar X-ray flux and EUV flux with the GPS derived Total Electron Content (TEC). We also validate the findings of Tsurutani *et al.* [2] and Mahajan *et al.* [10].

2. Event Selection

We have selected twenty X-class solar flares that occurred during 1998 to 2011. The selection of solar flares was made on the basis of following criteria:

- Their visibility at the selected GPS station i.e Davis (68.570S, 77.960E).
- The availability of various data sets.

The catalog of all the solar flares, selected by using the above criteria, is provided in the Table 1 along with their various characteristics.

3. Data Sets and Sources

In our study for twenty X-class solar flares observed during 1998 to 2011, we have used three sets of data: (1) X-ray flux measured by X-ray sensors onboard Geosynchronous Operational Environmental Satellite GOES-10 (2) EUV flux measured by Solar EUV

Monitor (SEM) onboard SOHO spacecraft and (3) GPS derived Total Electron Content (TEC).

Instrument onboard GOES satellite provides high quality X-ray flux data. The X-ray flux data contains 5 minute and 1 minute averages of solar X-ray flux output in two pass bands 1-8 Angstrom and 0.5-4.0 Angstrom. In our study we have used 1-8 Angstrom X-ray flux. The data can be downloaded at NOAA's Space Environment Center (NOAA-SEC) URL [11]. In our study we have used existing 1 minute averaged values.

The SEM experiment measures EUV flux integrated in the two wavelength bands 26-34 nm (channel 1) and 0.1-50 nm (channel 0). In our study we have used 26-34 nm EUV flux. The SEM/SOHO fluxes have been used in several studies, especially for examining the effects of solar flares in the Earth's ionosphere [2, 9] and in the Martian ionosphere [1]. The SEM data can be downloaded from URL [12]. The data provided on the website is in three time resolutions viz 15 second average, 5 min average and 10 minute average. In our study we have used existing 15 second averaged values**.**

A network of GPS receivers is spread over the entire globe and data is recorded regularly. The data recorded at all the stations which form the part of International GPS Service (IGS) is freely available to users and can be downloaded from the URL [13]. The data downloaded from the web is in RINEX format, which is then processed by using appropriate tools to get the required Total Electron Content (TEC) and other important data sets.

Table 1. Catalog of all the selected flares along with their various characteristics.

Sl.	Event Date	ST(UT)	PT(UT)	ET(UT)	GOES Class	NOAA AR	Location
1	19 Oct 2001	0047	0105	0113	X1.6	9661	N16W37
2	22 Oct 2001	1744	1759	1814	X1.2	9672	S19E26
3	25 Oct 2001	1442	1502	1528	X1.3	9672	S19W26
4	11 Dec 2001	0758	0808	0814	X2.8	9733	N14E30
5	19 Oct 2003	1629	1650	1704	X1.1	10484	N05E54
6	23 Oct 2003	0819	0835	0849	X5.4	0486	S16E67
7	26 Oct 2003	0557	0654	0733	X1.2	0486	S15E32
8	26 Feb 2004	0150	0203	0210	X1.1	0564	N14,W28
9	30 Oct 2004	1138	1146	1150	X1.2	0691	N13,W13
10	07 Nov 2004	1542	1606	1615	X2.0	0696	N09,W08
11	10 Nov 2004	0159	0213	0220	X2.5	0696	N08,W50
12	01 Jan 2005	0001	0031	0039	X1.7	0715	N04,E20
13	13 Sep 2005	1919	1927	2057	X1.5	0808	S11,E17
14	13 Dec 2006	0214	0240	0257	X3.4	0930	S06W35
15	14 Dec 2006	2107	2215	2226	X1.5	0930	S05W47
16	15 Feb 2011	0144	0156	0206	X2.2	1158	S21W21
17	06 Sep 2011	2212	2220	2224	X2.1	1283	N14W16
18	07 Sep 2011	2232	2238	2244	X1.8	1283	N14W30
19	24 Sep 2011	0921	0940	0948	X1.9	1302	N13E46
20	03 Nov 2011	2016	2027	2032	X1.9	1339	N18E49

We have selected 20 major solar flare events that occurred during the period 1998 to 2011. The temporal variation of the GPS TEC is presented along with the changes in the X-ray and EUV fluxes as measured by GOES and SEM/SOHO, respectively. The temporal variation of TEC along with the variations in solar X-ray and EUV flux during 11 December 2001 flare event are shown in Fig. 1. Fig. 1 shows that the variation of TEC follows the similar pattern with the variations in both fluxes. As the fluxes increase due to solar flares the TEC also undergoes a considerable increase. There is delay of 20-30 minutes between the peak values achieved by fluxes and TEC, thus indicating that the effect of enhanced radiation fluxes is immediately felt in the ionosphere. For all selected events the variation of TEC with changes in X-ray and EUV fluxes follows similar pattern as shown in Fig. 1.

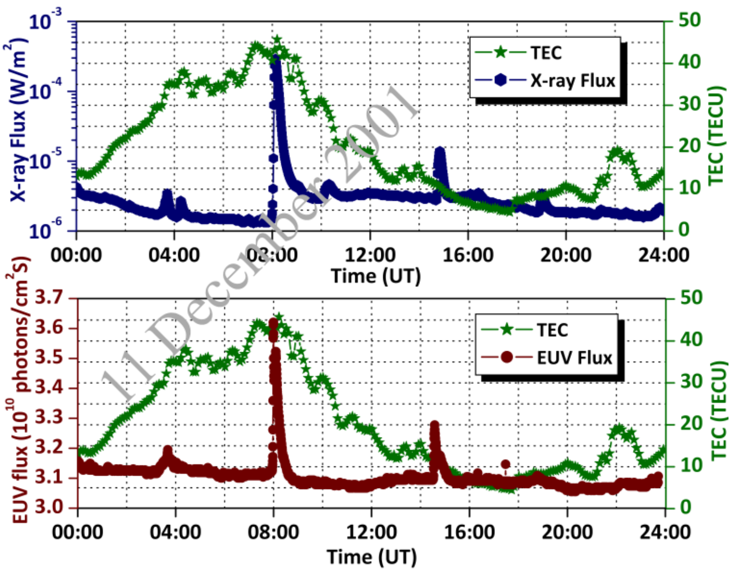

Fig. 1. Variation of TEC along with the changes in the X-ray and EUV flux.

Fig. 2 shows the correlation between the peak values and peak enhancements of TEC with the peak values and peak enhancements of X-ray flux and EUV flux for all selected 20 events. The correlation coefficient between peak TEC and peak X-ray flux is 0.52 while that between peak TEC and peak EUV flux is 0.65. The correlation between the peak enhancements in TEC (ΔTEC) and peak flux enhancements ΔX-ray and ΔEUV is represented in the bottom panels of Fig. 2. The correlation of ΔTEC with ΔX-ray and ΔEUV is 0.64 and 0.79, respectively. Fig. 2 therefore clearly shows that the correlation of peak enhancements in TEC with peak enhancements in fluxes is better than those between peak values themselves.

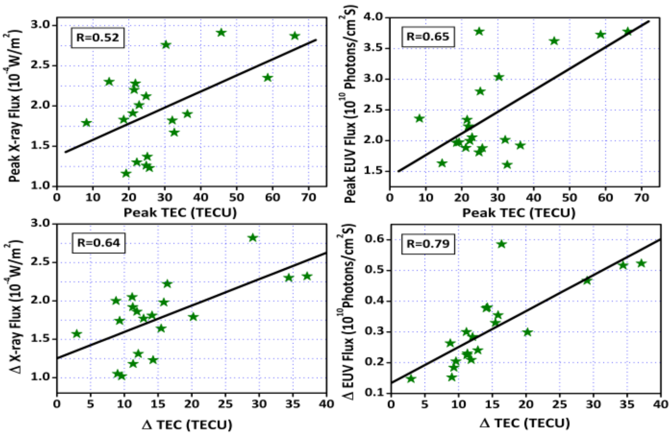

Fig. 2. Correlation of peak values and peak enhancements of TEC with peak and peak enhancements of fluxes.

We then adjusted the peak fluxes to CMD to bring the flare location into picture. When the peak X-ray and peak EUV flux were multiplied by Cos(CMD) and then their correlation is examined with ΔTEC, we find the correlation is increased considerably. Fig. 3 represents the correlation of ΔTEC with peak X-ray and peak EUV fluxes and CMD adjusted peak fluxes i.e peak fluxes multiplied by Cos(CMD). From this figure we find that correlation is highly improved when CMD is taken into account. Thus it is necessary to consider the location of flares on the solar disc while investigating the effect of solar flares on the ionosphere as shown by Tsurutani *et al.* [2] and Mahajan *et al.* [10].

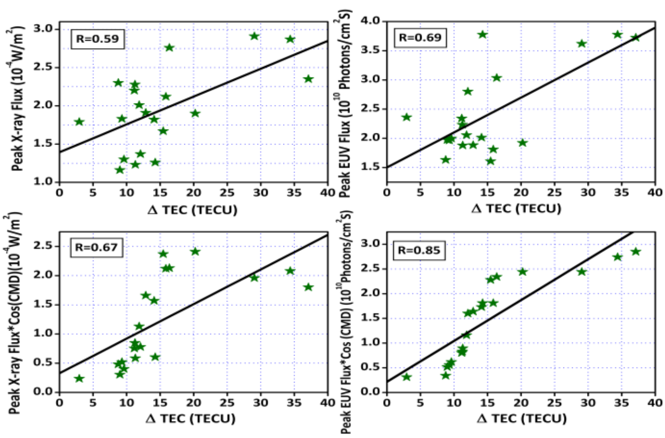

Fig. 3. Correlation of ΔTEC with peak fluxes and CMD adjusted fluxes.

4. Discussion

Various techniques have been used in past to study the ionospheric effects of solar flares. In our study we have used the GPS to monitor the ionospheric effects of solar flares. The GPS has higher time resolution (~seconds) as compared to that of Ionosonde (~minutes), hence is much suitable for monitoring the ionospheric influences of solar flares. We found the similar results as obtained by GPS in some earlier studies. Another important result of the study which we would like to discuss is that solar flares of almost same class do not produce same impact on the ionosphere; while some produce very intense ionization others are less effective although these belong to same GOES class. This seems to be due to two reasons: first, the different location of the flares on the solar disc and the second is spectral variability in flares. We have shown in our study that the location effect can be taken care of by modifying the flux with CMD as also shown in earlier studies using GPS observations [2, 10].

Also from our analysis we found that the impact of flare time radiation flux on the ionosphere is immediate as reported by Mitra [3]. The impact depends on the spectrum and content of radiation.

5. Conclusion

By using X-ray and EUV radiation flux data observed during twenty X-class solar flares by GOES and SEM/SOHO satellites that occurred during 1998-2011, we summarize our results as follows:

- The radiation flux enhancements follow a good association with changes in ionospheric parameters during extreme solar events.
- The correlation between the radiation flux and ionospheric parameters get largely improved as the radiation flux is adjusted to CMD. This can take care of the error that occurs due to flare location.

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