CHAPTER IV

ANALYSIS OF SOLAR FLARE EVENTS AND THE CONCOMITANT RESPONSE OF TERRESTRIAL UPPER ATMOSPHERE

4.1 Introduction

A solar flare generates the short-period electromagnetic radiation in a broad range of wavelengths from hard X-rays with a wavelength $\lambda \sim 10^{-2}$ nm (and sometimes from the gamma radiation ($\lambda \sim 10^{-4}$ nm) to kilometer radio waves ($\lambda \sim 10^{4}$ m). In powerful flares, an energy about $10^{23} - 10^{25}$ J is released in the form of radiation, (Leonovich and Tashchilin, 2007). X-rays and UV radiation emitted by solar flares can affect terrestrial ionosphere and disrupt communication and navigation systems. The frequency of occurrence of solar flares varies, from several flares per day when the Sun is particularly active to less than one every week when the Sun is quiet. Large flares are less frequent than smaller ones. Solar flares affect all layers of the solar atmosphere (photosphere, chromosphere, and corona), when the medium plasma is heated to tens of millions of kelvin and electrons, protons, and heavier ions are accelerated to near the speed of light. They produce radiation across the electromagnetic spectrum at all wavelengths, from radio waves to gamma rays, although most of the energy goes to frequencies outside the visual range and for this reason the majority of the flares are not visible to the naked eye and must be observed with special instruments. Flares occur in active regions around sunspots, where intense magnetic fields penetrate the photosphere to link the corona to the solar interior. Flares are powered by the sudden (timescales of minutes to tens of minutes) release of magnetic energy stored in the corona. The same energy releases may produce coronal mass ejections (CME), although the relation between CMEs and
flares is still not well established. X-rays and UV radiation emitted by solar flares can affect Earth's ionosphere and disrupt long-range communications.

4.1.1 Classifications of Solar flares

Solar flares are classified as A, B, C, M or X according to the peak flux (in watts per square meter, W/m²) of 0.1 to 0.8 nm X-rays near Earth, as measured on the GOES spacecraft. Each class has a peak flux ten times greater than the preceding one, with X class flares having a peak flux of order $10^{-4}$ W/m² as given in Table 4.1.

<table>
<thead>
<tr>
<th>Class</th>
<th>W/m² between 0.1 and 0.8 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>$I &lt; 10^{-6}$</td>
</tr>
<tr>
<td>C</td>
<td>$10^{-6} &lt; I &lt; 10^{-5}$</td>
</tr>
<tr>
<td>M</td>
<td>$10^{-5} &lt; I &lt; 10^{-4}$</td>
</tr>
<tr>
<td>X</td>
<td>$I &gt; 10^{-4}$</td>
</tr>
</tbody>
</table>

Within each category for X-ray flares have nine subdivisions in a linear scale ranging from, e.g., C1 to C9, M1 to M9, and X1 to X9. X2 flare is twice as powerful as an X1 flare, and is four times more powerful than an M5 flare. The more powerful M and X class flares are often associated with a variety of effects on the near-Earth space environment. Extended logarithmic classification is necessary because the total energies of flares range over many orders of magnitude, following a uniform distribution with flare frequency roughly proportional to the inverse of the total energy. The Sun shows a C3 - class solar flare (white area on upper left), a solar tsunami (wave-like structure, upper right) and multiple filaments of magnetism lifting off the stellar surface. Stellar flares and earthquakes show similar power-law distributions. Figure 4.1 depicts classification of solar flares by their X-ray flux in the 1.0 - 8.0 Angstrom band as measured by the NOAA GOES-8 satellite.
Figure 4.1: Classification of Solar Flares are classified by their x-ray flux in the 1.0 - 8.0 Angstrom band as measured by the NOAA GOES-8 satellite

Another flare classification is based on Hα spectral observations. The scheme uses both the intensity and emitting surface. The classification in intensity is qualitative, referring the flares as: (f)aunt, (n)ormal or (b)rilliant. The emitting surface is measured in terms of millionths of the hemisphere and is described below (Table 4.2) (the total hemisphere area $A_H = 6.2 \times 10^{12} \text{ km}^2$).

Table 4.2: Flare classification is based on Hα spectral observations

<table>
<thead>
<tr>
<th>Classification</th>
<th>Corrected Area (millionths of hemisphere)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>1</td>
<td>100 - 250</td>
</tr>
<tr>
<td>2</td>
<td>250 - 600</td>
</tr>
<tr>
<td>3</td>
<td>600 - 1200</td>
</tr>
<tr>
<td>4</td>
<td>&gt; 1200</td>
</tr>
</tbody>
</table>

A flare is then classified taking S or a number that represents its size and a letter that represents its peak intensity, e.g.: Sn is a normal subflare
4.2 Implication to the Upper Atmosphere

Studying about space weather has got importance since they are relevant to space-based communication/navigation systems and astronaut safety. Abrupt enhancements in solar irradiance during solar flare events can significantly changes the density, temperature, and composition in Earth’s upper atmosphere. Solar extreme ultraviolet (EUV) and X-ray photons are the primary energy source of the ionosphere and thermosphere of the Earth (Mitra, 1974; Liu et al., 2011). These will ionize the atmospheres of Earth and other planets and create planetary ionosphere.

According to Bauer (1973) and Banks and Kockarts (1977) photons in the wavelength range from about 25 nm to 91 nm create the upper part of the ionosphere (F-region); soft X-rays with wavelengths less than 15 nm create the E-region, and the Lyman-α radiation, by ionizing the minor neutral constituent nitric oxide, create the D-region. Further, UV photons with wavelengths longer than 91 nm play an important role in the creation of the E-region where Lyman-β at 102.6 nm ionizes the major thermospheric neutral constituent. Since the solar EUV irradiance is one of the most important ionization and heating sources for the ionosphere and the thermosphere, its change would directly cause variations in electron density and temperature and neutral gas density and temperature. Generally, there should be larger increase in solar EUV emission for solar flares with larger enhancements in X-ray emission; whereas for the EUV flux reaching the Earth, the situation is not always the same (Le et al., 2011). Some previous studies present that flare location on the solar disc may be an important factor to affect the variation of solar EUV flux reaching the Earth.

During solar flares, emissions in the X-rays and in some EUV lines get enhanced, with larger enhancements in wavelengths below 2.0 nm and relatively smaller enhancements in wavelengths higher than 2.0 nm. These enhanced emissions have been seen to cause sudden and intense ionization at various levels in the Earth’s ionosphere, resulting in sudden ionospheric disturbances (SIDs) and radio fadeouts. Woods and Eparvier (2006) show some interesting results, that the ratios of the flare irradiance spectrum to the pre-flare spectrum for the large X-class flares indicate an increase of more than a factor of 50 in the X-ray region and are less than a factor of 2
for the EUV. They used Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite for their study.

The upper atmosphere is controlled mainly by EUV irradiance not by X-ray irradiance even though the enhancement in X-ray region is much higher than that in EUV region. It is well known that most important source of external forcing to the ionosphere and thermosphere is solar extreme ultraviolet (EUV) irradiation which is absorbed by the upper atmosphere from roughly 90 km to 200 km and causes the large enhancement in ionization rate and heating rate in the ionosphere and thermosphere.

Solar flare EUV spectra have strong center-to-limb effects, while there is essentially none for X-rays. This aspect has been reported by Donnelly (1976). According to him solar EUV is produced in the lower solar atmosphere, thus further the flare site is away from solar disc center. the greater the EUV solar absorption. Zhang et al. (2002) analyzed the correlation of flare’s location on solar disc with the value of sudden increase of total electron content (SITEC) by using the data of the X-ray flux from GOES satellite of solar flares from 1997 to 1999 and total electron content (TEC) derived from GPS receivers, and found that for the same strength flares, the smaller the central meridian distance (CMD) of flares, the stronger the ionospheric response, which indirectly show solar EUV enhancement during flares correlate with the CMD value because the SITEC is mostly contributed to by the solar EUV enhancement. Further Zhang et al. (2011) found that the relationship between TEC enhancement and the EUV flux increases in 26 - 34 nm EUV flux during a flare is more correlative than that in 0.1 - 0.8 nm soft X-ray flux.

Geomagnetic field response to solar flare events have been examined by many workers (Rastogi et al. (1999), Manju and Viswanathan (2005), Manju et al. (2009)). VHF radar observations of backscattered power and vertical polarization electric field at equatorial electrojet location of Trivandrum are reported by Manju and Viswanathan (2005).

Mahajan et al. (2010) found a poor correlation between X-ray fluxes and EUV fluxes by using the X-ray data from GOES-10 and EUV data from SEM/SOHO during X-class flares in solar cycle 23. However, if X-ray fluxes are adjusted for the
CMD factor, they would have a higher correlation with the EUV fluxes. Thus they can be a good proxy for the EUV flux. These results show again that the variation in EUV flux is much related to the flare site on the solar disc. Updates there are a few case studies like mentioned above, which mostly studied some large X-class flares. But there are few statistical studies, especially for more flares including M-class and C-class flares. Actually, there are, on average, one X-class flare per month, one M-class solar flare every three days and much more C-class solar flares during a solar cycle. For example, the number of C-class, M-class, and X-class flares during solar cycle 23 are about 13049, 1428, and 126, respectively (Le et al., 2011). The investigation of variation in X-ray flux and EUV flux and their relationship during solar flares would be helpful for the estimation and prediction of variation in the ionosphere and thermosphere during solar flares. Le et al. (2011) have shown using statistical analysis that limb effect decreases as the flare class decreases. Le et al. (2012) have shown in their recent analysis of thermospheric density response to solar flares that the thermospheric density enhancement has significant limb effect: which is also attributed to the limb effect of the EUV flux. During a solar flare sudden enhancement of the solar radiation in the X-ray and extreme ultra-violet (EUV) band will happen and these can produce great changes in the ionospheric electron density on the dayside of the Earth (Thome and Wagner, 1971; Mendillo et al., 1974).

Earlier, ground-based measurements were used to get evidence of solar flare effects in the upper ionosphere. Deminger and Geisweld (1949) and Knecht and Davies (1961) observed an increase in the critical frequency of the F2 region during solar flare events by using ionosonde. Thome and Wagner (1971) reported an increase in electron density in the E and F1 regions with incoherent scatter radar. Sudden change in frequency of the carrier of an ionospherically propagated HF wave, called sudden frequency deviation (SFDs) is studied by Davies (1962), Baker and Davies (1966) and Davies and Donnelly (1966). Unfortunately, the first two techniques could not provide the desired high time resolution, while the third technique had a limitation on the spatial and altitude location of the effect. However, with the advent of space-based techniques, especially the radio beacons, it became possible to examine the solar flare effects in the upper ionosphere, not only with high time but spatial resolution also.
Garriott et al. (1967) derived electron content values from continuous measurements of the plane of polarization of VHF telemetry signals received from the geostationary satellite ATS-1 at 137.35 MHz. They were the first to identify solar flare effects in the upper ionosphere from the sudden increase in the total electron content (SITEC) for the flares of 21 and 23 May 1967. They could see enhancements between 1 and 2 TEC units (1 TEC unit = 1016 electron/cm²) at four stations for one flare and at five stations for the other flare. Finally the authors concluded from their analysis that the electron density increased throughout the upper ionosphere during these flares, and the major contributions came from the F2 region and the topside ionosphere. Mendillo et al. (1974) examined ionospheric effects of the large solar flare of 7 August 1972 by using TEC measurements at 17 stations and presented the first global morphology of effect in the upper ionosphere. They could see SITEC values varying between 1.8 to 8.6 TEC units, with the larger increase at lower latitudes. But they did not find any significant relationship between SITEC and solar zenith angle at the various sub-ionospheric points.

To study the ionospheric total electron content variations, Global positioning system (GPS) is used now-a-days. The details of GPS are described in chapter 2. The ionosphere introduces a time delay in the 1.57542 GHz (L1) and 1.22760 GHz (L2) simultaneous transmissions from GPS satellites orbiting at ~ 20,000 km. The relative ionospheric delay of the two signals is proportional to the total number of electrons along the ray path or the total electron content (TEC). Therefore, time delay measurements of L1 and L2 frequencies can be converted to TEC along the ray path from the receiver to the satellite. Since GPS is a dual-frequency satellite navigation system, it has been widely used for ionospheric studies. Early reports of TEC enhancements during flare events were given by Garriott et al. (1967), Mendillo et al. (1974) and Sato (1975). Ho et al. (1996) studied the global distribution of TEC variations during magnetically disturbed periods using worldwide GPS receivers. The ionospheric response to the solar flare of 14 July 2000 has been analyzed by Liu et al. (2004) and they have shown that TEC is suitable to monitor the overall variations of flare radiations.
4.3 Data and Method of Analysis

In this chapter, following data's are incorporated.

(1) EUV photon fluxes measured by the Solar EUV Monitor (SEM) experiment onboard the Solar Heliospheric Observatory (SOHO).

(2) X-ray flux measured by sensors onboard Geosynchronous Operational Environmental Satellite, GOES.

(3) GPSTEC data over Indian longitudes.

(4) Geomagnetic field data over Indian longitudes.

(a) UV and X-ray flux data

15-second average SEM/SOHO fluxes downloaded from the web site http://www.usc.edu/dept/space_science/semdatafolder/ is used. The SEM-SOHO experiment has been described by Ogawa et al. (1993). The solar X-ray fluxes used are obtained GOES series of satellites. In this study, we have mostly used the 1-minute averaged X-ray data observed by GOES-8/GOES-10 in the wavelength band 0.1 to 0.8 nm available at the NOAA’s Space Environment Center (NOAA-SEC) web site http://www.ngdc.noaa.gov/stp/GOES/.

(b) GPSTEC data

GPSTEC data from the stations of Trivandrum (TRV) (8.5°N, 77°E), Hyderabad (HYD) (18°N and 78°E), Raipur (RAI) (21°N 81°E) and Delhi (DEL) (28°N, 77°E) are used in this study. Carrier phase delays and pseudo ranges of the GPS signals at L1 and L2 frequencies are used to obtain the Absolute Slant GPSTEC (STEC). The STEC are then converted to Absolute Vertical TEC (VTEC) using the mapping function given below.

\[ VTEC = STEC \cos (\chi), \quad \text{...............} \quad (4.1) \]

Where, \( \chi \) is the zenith angle at ionospheric pierce point (IPP) which is estimated from the satellite elevation angle. The shell height is taken as 350 km. Ramarao et al. (2006) have shown that an elevation angle cut off of \( > 50^\circ \) is ideally suited to represent the TEC over the Indian sector and hence the present analysis is based on this criterion.
(e) **Magnetic field data**

The horizontal component of geomagnetic field (H) data is acquired from the magnetometer at the Alibag (8° 39' N, 72° 55' E).

### 4.4 Observations

#### 4.4.1 Variability of solar EUV and X-ray flux enhancements during Flare events originating from different locations of solar disk

Figure 4.2 represents the variations of EUV ratio (EUV flux at peak/EUV flux just before flare start) with position on the solar disc for X class flares. We have included all the flares in this class for which we had both flux and CMD information. It is clear from the figure that the EUV flux is higher for flares occurring in the CMD region (\(< 40^\circ\)) while it is lower for flares occurring in the limb region (\(> 40^\circ\)). In this figure points are available in all regions of solar disk. Of course if we are considering only location as factor controlling the UV enhancement then this figure can be misleading as some cases with large CMD are showing relatively high increase compared to cases with low CMD due to the flare being of higher class. Never the less an examination of several flares occurring in the limb and central meridian reveals that it is the combined effect of location and rank that determines the enhancement. For example the flare of 4 November is a limb flare (rank X 28) but relatively higher enhancement of 1.77 is seen. At the same time the X 17 flare on 28 October near central meridian shows much higher enhancement of 2.3 although the rank is lower. Hence we are concluding that net effect of the location and rank of the flare will determine the enhancement thus pointing out that limb effect is also very important in controlling the flare increase. Mahajan et al. (2010) have reported a limb effect for UV flux emissions for X class flares. This is confirmed by Le et al. (2011). Our observation shown in Figure 4.2 is also on similar lines and brings out limb effect for UV emissions in the case of X class flares. Le et al. (2011) further examined the presence of CMD effect for M and C class flares also and noted that the effect is progressively reduced as the class of the flare decreases. They have further shown that for these weaker flares the CMD effect is weak because of active regions spread all over the solar disk also contribute to the EUV flux for such flares.
The variation of X ratio (X ray flux at peak/X ray flux just before flare start) with CMD is examined for several X (left panel), M (middle panel) and C (right panel) class flares and these are depicted in Figure 4.3. No limb effect is discernible in X ray flux for any of the three classes of flares. Similar result is already reported by Mahajan et al. (2010) and Le et al. (2011) for X class flares. In this study we are reporting the absence of limb effect even in the case of M and C class flares thus clearly showing that the intensity of a flare is the only factor that determines the X ratio for all class of flares.

Figure 4.2: The variations of EUV ratio (EUV flux at peak/EUV flux just before flare start) with position on the solar disc for X class flares.
Figure 4.3: The variation of X ratio ((X-ray flux at peak/X-ray flux just before flare start) with CMD for several X (left panel), M (middle panel) and C (right panel) class flares

4.4.2 E region response

The seasonal variation of the response of the E region to X and M class flare events is examined using magnetometer data at the station of Alibag in the Indian longitude sector. The geomagnetic field variation is taken as a proxy for the E region response to solar flares.

(a) Dependence of H ratio on UV ratio for X and M Class flares

The scatter plot of H ratio and UV ratio for X and M class flares during the period 1998-2003 is shown in Figure 4.4. There is no significant correlation between the two parameters. This shows that increased enhancement in UV flux is not proportionately reflected in the enhancement in geomagnetic field represented by H ratio. It therefore seems that the E region response is not dominated by UV flux enhancements during flare events.
Figure 4.4: The scatter plot of $H$ ratio and UV ratio for X and M class flares during the period 1998-2003.

(b) Dependence of $H$ ratio on X ratio for X and M Class flares

The variation of $H$ ratio as a function of X ratio is examined for X and M class flares during the period 1998-2003 (Figure 4.5). It is evident from the figure that as X ratio increases $H$ ratio also increases. The correlation coefficient ($R$) between the two parameters is 0.67, which is more than 95% significant. Thus the E region geomagnetic field variations are significantly controlled by the X-ray flux enhancements during flares.

Figure 4.5: The variation of $H$ ratio as a function of X ratio for X and M class flares during the period 1998-2003.
Variability of geomagnetic field response to flare events located at different locations on solar disk

The variation of H ratio as a function of CMD is examined and depicted in Figure 4.6. It is obvious from the figure that there is no significant limb effect for the geomagnetic field response to flare events. It seems that only the intensity of the flare controls the geomagnetic field response.

**Figure 4.6:** The variation of H ratio as a function of CMD for X and M class flares during the period 1998-2003

4.4.3 F region response

The seasonal variation of the response of the F region to X rank flare events is examined using GPSTEC data at different stations in the Indian longitude sector.

(a) Variability of TEC response as seen by different stations in the Indian longitudes sector to two X rank flare events located at different locations on solar disk

The ionospheric response to two X rank flare events (January 17 and 20, 2005) is examined using GPSTEC data. The flare of January 17, had a Central Meridian Distance (CMD) of 25°, while that on January 20, has a CMD of 61°. The ranks of the
two flares are X3.8 (January 17) and X7.1 (January 20). The TEC response at stations, TRV, HYD, RAI and DEL covering the Northern Indian EIA region is investigated. The variation of TEC increment as a function of CMD is shown in Figure 4.7. The large enhancement for the flare close to Central Meridian compared to the limb flare is evident for all the stations examined. The fact that the rank of the flare close to central meridian is lower than that at the limb reveals the relatively greater importance of the location of the flare in controlling the TEC response.

![Graph showing TEC increment vs CMD](image.png)

**Figure 4.7:** The variation of flare induced TEC increment at 4 stations as a function of CMD

(b) *Latitudinal variation of TEC response in the Northern EIA region to X rank flare events during different seasons*

Figure 4.8 (left panel) shows the latitudinal variation of TEC increment during summer season in the Indian region considering data from 4 stations. It is evident that the flare related increase in TEC is higher at higher latitudes in the EIA region for summer. The correlation coefficient of 0.53 is more than 95% significant. Figure 4.8 (right panel) depicts the same as the left panel but for equinox and winter seasons. These two seasons are clubbed together as the Sun is away from the northern EIA
region during both these seasons. From Figure 4.8 (right panel) it is clear that as the latitude increases the flare related TEC increment is smaller. The correlation coefficient (R) of 0.73 is more than 95% significant.

![Figure 4.8: Latitudinal variation of flare induced TEC increment during summer (left panel) and winter & equinox (right panel) seasons in the Indian region.]

4.5 Discussion

4.5.1 X-ray and UV flux enhancements during flare events

Donnelly (1976) reported significant reduction in intensity of EUV flux for flares occurring near the solar limb in relation to those at central meridian location. The limb effect is also seen in total electron content as reported by Afraimovich et al. (2002), Liu et al. (2006), Leonovich et al. (2010) and Mahajan et al. (2010). This effect is attributed to the fact that X-rays originate from a coronal active region, the EUV originates from a transition region to a corona (Bauer, 1973) while the EUV emissions come from low-lying regions and hence suffer absorption in the solar atmosphere. Le et al. (2011) have shown that the limb effect on EUV flux decreases with the rank of the flare. They further showed that there is larger percentage contribution from other region for the weaker flares, which would reduce the loss of
EUV radiation due to limb location of flare and then weaken the CMD effect for weaker flares like M and C class.

In this analysis of UV flux enhancements for X class flares, we found significant limb effect in agreement with the previous results. Here we are concluding that the net effect of the location and rank of the flare will determine the enhancement thus pointing out that limb effect is also very important in controlling the flare increase even when the entire X class range flares are considered. The X-ray flux enhancements as a function of CMD for X, M and C class flare events have also been examined. It is seen that for all three classes of flares, there is no limb effect. This demonstrates that the enhancement in X-ray flux is controlled only by the intensity of the flare event and not by the location.

4.5.2 E region response to flares

The flare time enhancement in the geomagnetic field is a representative of the changes in the overhead currents in the E region. Several workers have examined the enhancement in geomagnetic field during flare events and reported the changes in E region currents during such times (Richmond and Venkateswaran, 1971; Rastogi et al., 1999; Manju and Viswanathan, 2005; Manju et al., 2009). The relative roles of flare time UV and X-ray flux enhancements, in modulating the E region currents, have been rather less explored. Similarly the limb effect if any on the geomagnetic signatures of flares is also not well investigated.

Our analysis reveals that the enhancement in geomagnetic field represented by H ratio does not show any dependence on UV ratio. On the other hand, H ratio is directly related to X ratio indicating that the X-ray flux enhancement is predominantly responsible for the increased ionization in the E region. This reveals that the UV flux enhancement is not so significant in producing enhanced ionization during flare times at lower altitudes in the E region.

The study further demonstrates that H ratio does not show any significant limb effect. That is, H ratio depends only on the intensity of the flare and not on the position. This is further confirmation of the fact that H ratio and thereby the E region
response is controlled by X-Ray flux (which has no limb effect) increase rather than by UV flux (which has limb effect).

4.5.3. The F region response to flares

The flare time TEC variation is predominantly representative of the F region response to flares. The investigation of TEC enhancement over Indian longitudes is carried out for two X rank flare events which occurred at different locations on the solar disk in January 2005. It is seen that for the event which occurred near the central meridian the TEC enhancement is much higher than for the event which occurred near the limb. That is, clear limb effect is manifested in all the 4 stations spread over the northern EIA region. This is in agreement with the results of Afraimovich et al. (2002), Liu et al. (2006), Leonovich et al. (2010) and Mahajan et al. (2010). This limb effect in TEC is indicative of the UV flux control on the ionization in the F region.

The seasonal pattern of TEC increase due to flare events has been examined for summer, equinox and winter seasons with data availability in the Indian EIA region. It is seen that the TEC enhancement is higher in summer near the northern most station with lower values closer to equator. In summer (northern hemisphere), solar zenith angle is larger at equator than the northern EIA region, which causes smaller production rate at equator and hence the smaller TEC increase. On the contrary, in winter and equinox, solar zenith angle is smaller at equator than the northern EIA region, which causes larger production rate at equator and hence the larger TEC increase. Le et al. (2007) have modeled the ionospheric response to solar flares and their results showed significant solar zenith angle effect on the TEC response to flares.

4.6. Summary

1. UV flux enhancement depends on both intensity of flare and its position on the solar disk while X-ray flux enhancement depends only on the intensity of the flare irrespective of its position on the solar disk.

2. The E region response to flare events for X and M class flares as seen in geomagnetic field is directly related to the X-ray flux enhancement and it does not show any relationship with UV flux.
3. The geomagnetic field response does not show any limb effect confirming that it is being controlled by the X-ray flux which does not exhibit limb effect.

4. F-region response to flares as seen in TEC shows limb effect indicating the UV flux control on the same.

5. The TEC response to flares is greater at equatorial regions during winter and equinox than at low latitude stations towards the north, whereas during summer it is greater at northern low latitude regions compared to equatorial regions. This is an effect of the variation of solar zenith angle and consequent modulation of production rate.