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Response of the equatorial and low-latitude ionosphere to an intense X-class solar flare (X7/2B) as observed on 09 August 2011

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[1] In this paper, we present response of equatorial and low-latitude ionosphere to an intense solar flare of class X7/2B that peaked at 08:05 UT on 09 August 2011 in the solar cycle 24. Global positioning system total electron content (TEC) observations in the sunlit hemisphere show enhancement of ~3 TEC units, while geomagnetic H component observations indicate sudden decrease and increase in their strength at equatorial and low-latitude stations, respectively, at several stations in the sunlit hemisphere. In addition, equatorial electrojet strength over Indian region reveals commencement of counter electrojet. Simultaneous Canadian Advanced Digital Ionosonde observations at Tirunelveli, an equatorial station in India, show the disappearance of ionogram echoes during the flare event indicating absorption of radio signals in the *D* region. Strong equatorial blanketing type E_s layer was observed in the ionogram records at Tirunelveli prior to the occurrence of the solar flare that continued for several hours though it became weak/absent during the flare event. Ionogram records on the control day show regular *F* layer movement without any blanketing type E_s layer. Very low frequency (VLF) observations at Allahabad, an Indian low-latitude station, show enhanced VLF amplitude signal during the same time revealing the sudden enhancement of *D* region ionization. Using the observations presented here, an attempt has been made to study the impact of the solar flares on the electrodynamics of the equatorial and low-latitude ionosphere.

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1. Introduction

[2] It is known for several decades that solar flares affect the Earth's ionosphere greatly in the sunlit hemisphere [e.g., *Mitra*, 1974; *Davies*, 1990 *Tsurutani et al.*, 2009]. The solar flare effect is most pronounced during noon when solar zenith angle is close to zero. Solar flares are the giant explosions on the surface of the Sun that release large amount of electromagnetic energy suddenly at a wide range of wavelengths particularly in the bands of X-ray and extreme ultraviolet (EUV) for a very short duration. These flares are often associated with solar magnetic storms known as coronal mass ejections (CMEs). They are transient in nature and last only for a few tens of minutes to a few hours. In addition to electromagnetic radiation, solar flares are also accompanied by energetic particles of the order of a few Mev though they reach the Earth later. Solar flares are classified based on their peak flux, in W/m^2 from 1 to 8 Å, as measured by the X-ray instrument on board the Geostationary Environmental Operational Satellite (GOES) and peak flux of two EUV bands, namely, 0.1–50 nm and 26–34 nm using solar EUV monitor (SEM) observations from Solar Heliospheric Observatory (SOHO). X-ray flares are classified based on magnitude of the peak intensity (I) as B-, C-, M-, and X-class flares as measured by GOES [*Davies*, 1990]. Solar flare is also classified as an optical flare based on sudden brightening of the H_α line (6563 Å) in an active region. The optical flares are classified based on an area at maximum brightness (0 to 4) and its brightness (faint "F," normal "N," and bright "B") [*Davies*, 1990]. An optical flare may be accompanied by X-ray and EUV emissions. During solar flares, the sudden increase in the X-ray and EUV bands causes extra ionization of the neutral components in the sunlit hemisphere causing a significant ionization of the *D*, *E*, and *F* regions of the Earth's ionosphere at short intervals of time. While X-rays penetrate deep into the ionosphere and could cause the enhanced *D* region ionization during solar flares, EUV flux enhances

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the ionization in the *E* and *F* regions of the ionosphere. This enhanced ionization could be seen as sudden frequency deviations, sudden increase of total electron content (SITEC), sudden radio signal fadeouts, sudden D region absorption, and geomagnetic solar flare effects (SFEs) often known as geomagnetic crochets [*Donnelley*, 1971; *Mitra*, 1974; *Rastogi et al*., 1975; *Liu et al*., 1996, 2004; *Davies*, 1990]. For more details, readers are advised to go through the review works of *Mitra* [1974] and *Davies* [1990] and references therein.

[3] The investigations on the ionospheric response to solar flares suggest that their impact on the ionosphere is different for different types of solar flares, and hence several investigations have been carried out to understand their global morphology using many solar flare events [e.g., *Thome and Wagner*, 1971, *Mendillo et al*., 1974; *Sastri*, 1975; *Rastogi et al*., 1999; *Afraimovich et al*., 2001; *Leonovich et al*., 2002; *Tsurutani et al*., 2005, 2009; *Zhang and Xiao*, 2003, 2005; *Liu et al*., 1996, 2004; 2006; *Mahajan et al*., 2010]. Further, due to open usage of existing global GPS receiver networks such as International GNSS Service (IGS) network, several scientific investigations have been carried out to study the global response of the ionospheric total electron content (TEC) to many intense solar flares in the recent years [e.g., *Afraimovich et al*., 2001; *Leonovich et al*., 2002; *Tsurutani et al*., 2005, 2009; *Zhang et al*., 2002b; *Zhang and Xiao*, 2003, 2005; *Liu et al*., 2004, 2006; *Mahajan et al*., 2010]. Using GPS receiver network, *Wan et al*. [2005] have studied the sudden increase of TEC due to intense solar flare on 14 July 2000. Further, *Tsurutani et al*. [2005] have investigated the effect of multiple October–November 2003 solar flares using GPS receiver network on an ionosphere in comparison with the 14 July 2000 event. *Tsurutani et al*. [2005] have found the enhancement of 25 TECU (total electron content unit, 1 TECU = 10^{16} el m^{-2}) during the 28 October 2003 solar flare. However, on 4 November 2003, they found TEC increase is not as high as on 28 October 2003 even though the flare event is larger than that of 28 October 2003 in the X-ray spectrum.

[4] *Sahai et al*. [2007] have studied the 28 October 2003 solar flare event over the Brazilian sector using GPS receiver and ionosonde and found increase of TEC up to 25 TECU and lack of reflected echoes in the ionograms for 1 h period during the flare onset. They suggested that the reason for complete or partial radio signal fadeout could be intense absorption. The response of Indian low to middle latitude ionosphere to a large solar flare occurred on 28 October 2003 (X17.2/4B) has been examined using geomagnetic data and GPS total electron content (TEC) by *Manju et al*. [2009]. They noticed significant enhancement in the TEC (~10 TECU) near the equatorial anomaly region. Further, their observations suggest that flare-related density enhancements in different longitude sectors in the magnetic equator can produce positive and negative variations in the electrojet due to the presence of current systems that could produce longitudinal variation. Very low frequency (VLF) radio waves in the band of 10–30 kHz have been used to study the *D* region ionization during solar flares [e.g., *Thomson and Clilverd*, 2001]. During solar flares, enhanced ionization of the *D* region could lower the reflection height of the VLF radio waveguide and advance the phase of the VLF radio wave where both of them linearly depend on intensity of X-ray flux [e.g., *Thomson et al*., 2004].

[5] As a part of Climate and Weather of the Sun-Earth System (CAWSES) India program, we are investigating the impact of the variable Sun on the Earth's ionosphere. Since each solar flare provides a unique opportunity to learn, understand, and model the response of the different regions of the ionosphere, it is important to examine their impact on the near-Earth environment. Hence, in the present paper, an attempt has been made to study the signature of recent intense X-class solar flare during 9 August 2011 on the *D*, *E*, and *F* regions of the ionosphere over the equator and low latitude using multi-instrument observations.

2. Experimental Data

[6] Solar flare data corresponding to 09 August 2011 are obtained from (a) X-ray (1–8 Å; 0.5–4.0 Å) measurements as measured by GOES-15 satellite and (b) EUV flux measurements in 26–34 nm and 0.1–50 nm bands from SEM on board SOHO. The 1 min variations of horizontal component H (ΔH) of the geomagnetic field from the Indian stations Tirunelveli (8.7°N, 77.8°E, dip latitude: 0.4°N) and Alibag (18.5°N, 72.9°E, dip latitude: 13.0°N) are used to study the H component variations over these stations during solar flare after taking the difference of midnight value for each station to eliminate the contribution of Earth's main field from the data. Strength of the equatorial electrojet (EEJ strength) which is given by $\Delta H = (\Delta H)_{\mathrm{Tirunelveli}} - (\Delta H)_{\mathrm{Alibag}}$ [*Rastogi and Klobuchar*, 1990] is used to study the EEJ strength variations over the Indian region during the solar flare. We have used Canadian Advanced Digital Ionosonde (CADI) data operated by us at equatorial station Tirunelveli. This ionosonde is running on a continuous basis to study the equatorial ionospheric electrodynamics. The ionosonde is a well-proven technique to study the ionosphere, and it provides useful information about various ionospheric layers and their temporal variations. CADI is widely used by many research groups across the globe [e.g., *MacDougall et al*., 1995; *Pezzopane et al*., 2013].

[7] We have also used GPS TEC observations from Scintillation Network Decision Aid (SCINDA) GPS receiver at Tirunelveli. In addition, 1 min geomagnetic H component variation data obtained from selected stations from International Real time Observatory Network (INTERMAGNET) in the sunlit hemisphere are used to study the longitudinal variation of geomagnetic field during the solar flare. To study the longitudinal variation of the GPS TEC observations during the solar flare, we have downloaded selected IGS GPS receiver stations data around the globe. See the map in Figure 1 for more details. Here it may be mentioned that there are more than 24 GPS satellites distributed in six orbital planes around the globe, which are located at an altitude of 20,200 km and shall transmit radio signals at two frequencies, namely, L1 (1575.75 MHz) and L2 (1227.25 MHz). Due to the dispersive nature of the ionosphere, the above two radio signals propagate at different velocities producing a time delay. This time delay is proportional to the TEC along the line-of-sight receiver to the satellite. Using the time delays from these two radio signals and also the more accurate phase information, the slant TEC (STEC) is obtained. The vertical TEC (VTEC) is obtained using appropriate mapping function, $S_f = \cos\chi$, i.e., VTEC = STEC × $\cos\chi$, where $\chi = \sin^{-1}[R_E \cos\alpha/(R_E + h)]$, α is the elevation angle at Ionospheric Penetration Point (IPP), $R_E = 6378$ km (Earth's

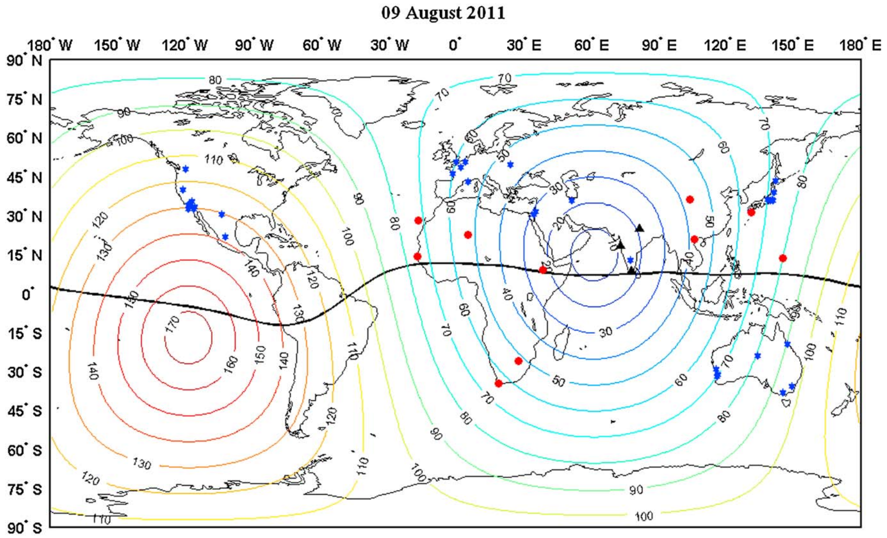
09 August 2011

Figure 1. The scatter plot of different stations in the world map which are used in the present analysis. The contour map shows the solar zenith angle on 09 August 2011 at 08:00 UT In the map, red circles represent INTERMAGNET network stations, blue hexagons represent IGS GPS network, and black triangles represent instruments operated by us. The black line in the middle of the figure shows the dip equator.

radius), and $h = 350$ km. It may be noted that from here onward, we use TEC for VTEC throughout the paper.

[8] In addition to the above, we have also studied the amplitude variation of a VLF receiver that is being operated continuously at Indian Institute of Geomagnetism (IIG) regional center called KSKGRL (Dr. K. S. Krishnan Geophysical Research Laboratory) located at Allahabad (25.28°N, 81.54°E, geomagnetic latitude 16.29°N) to monitor VLF (3–30 kHz) waves [e.g., *Singh et al.*, 2010]. The amplitude variation of the North West Coast of Australia (NWC) VLF transmitter operating at 19.8 kHz in Exmouth, Western Australia, and received at Allahabad during the 09 August 2011 solar flare is used to study the *D* region absorption or *D* region ionization. It may be mentioned that VLF signal is a powerful tool to study the *D* region electron density measurements and *D* region absorption. See Table 1 for details about the important stations in India and other countries in the sunlit hemisphere and their instruments used in the present study.

3. Results

[9] On 09 August 2011, the Sun released an X-class solar flare of magnitude X6.9 or X7/2B toward the Earth at 07:48 UT (13:13 IST (Indian Standard Time (IST) = UT + 5.5)) as recorded by the NOAA GOES and SOHO SEM satellites. This flare was erupted from the sunspot region AR#11263, and its location is 17°N, 69°W. This flare is only the third X-class flare and is the most powerful flare in the solar cycle 24 so far. This solar flare peaked at 08:05 UT (13:35 IST) before it ended at 08:08 UT (13:38 IST). National Aeronautics and Space Administration (NASA) warned that this flare might cause some radio communication blackouts. There is no geomagnetic storm on the Earth on this day.

Table 1. Important Stations and Their Instruments or Data Used in the Present Study

Station Name (Station Code)	Latitude and Longitude	Instrument/Data Source
Tirunelveli (TIR), India	8.67°N, 77.82°E	GPS SCINDA, CADI, and magnetometer
Allahabad (ALD), India	25.28°N, 81.54°E	VLF receiver
Alibag (ABG), India	18.5°N, 72.9°E	Magnetometer
Guimar Tenerife (GUI), Spain	28.317°N, 343.560°E	INTERMAGNET magnetometer
Kanoya (KNY), Japan	31.424°N, 130.880°E	INTERMAGNET magnetometer
Lanzhou (LZH), China	36.087°N, 103.845°E	INTERMAGNET magnetometer
Phu Thuy (PHU), Vietnam	21.029°N, 105.958°E	INTERMAGNET magnetometer
Addis Ababa (AAE), Ethiopia	9.035°N, 38.766°E	INTERMAGNET magnetometer
Mbour (MBO), France	14.392°N, 343.042°E	INTERMAGNET magnetometer
Tamanrasset (TAM), Algeria	22.792°N, 5.530°E	INTERMAGNET magnetometer
Hartebeesthoek (HBK), South Africa	25.900°S, 27.700°E	INTERMAGNET magnetometer
Hermanus (HER), South Africa	34.400°S, 19.200°E	INTERMAGNET magnetometer
Guam (GUA), USA	13.588°N, 144.867°E	INTERMAGNET magnetometer
Bangalore (IISC), India	13.020°N, 77.570°E	IGS GPS receiver
Addis Ababa (ADIS), Ethiopia	9.030°N, 38.760°E	IGS GPS receiver
Metzoki dragot (DRAG), Israel	31.600°N, 35.400°E	IGS GPS receiver
Mitzpe Ramon (RAMO), Israel	30.600°N, 34.760°E	IGS GPS receiver
Tehran (TEHN), Iran	35.670°N, 51.330°E	IGS GPS receiver

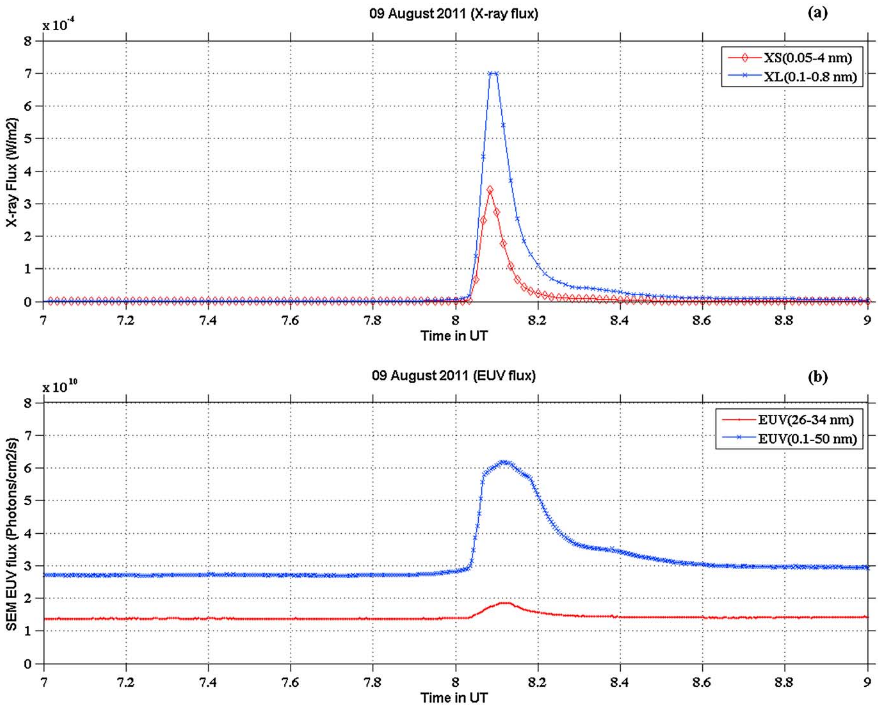

Figure 2. (a) X-ray flux (0.05–0.4 nm and 0.1–0.8 nm bands) as obtained using GOES-15 and (b) EUV flux (26–34 nm and 0.1-50 nm bands) as observed using SOHO SEM satellite on 09 August 2011 at 07:00–09:00 UT.

Solar flux at F10.7 cm on this day is 90.2 solar flux units (sfu) (1 sfu = 10^{-22} W m^{-2} Hz^{-1}) and *Ap* index is 8. To investigate the solar flux variations at different frequency bands during the solar flare event, we have plotted the variation of (a) X-ray flux as observed using GOES-15 and (b) EUV flux as observed using SOHO SEM satellite on 09 August 2011 at 07:00–09:00 UT in Figures 2a and 2b. The observations in both X-ray and EUV bands suggest that there was a solar flare at ~08:00 UT and it peaked at 08:05 UT. From the figure, one can notice that at the time of solar flare maximum, X-ray flux got saturated for a few minutes (blue color). The EUV flux in the 26–34 nm band is prolonged for a long time, and unlike the X-ray flux, EUV flux did not get saturated. When the solar flare peaked, the peak X-ray fluxes are 0.7×10^{-3} and 0.34×10^{-3} W m^{-2} (ΔX-ray: 6.45×10^{-4} W m^{-2} and 3.423×10^{-4} W m^{-2}), and peak EUV fluxes are 6.178×10^{10} and 1.854×10^{10} (ΔEUV 3.476×10^{10}; 0.481×10^{10}) photons cm^{-2}s^{-1}, respectively.

[10] GPS TEC observations at Tirunelveli using SCINDA GPS receiver and IGS GPS receiver station located at Bangalore (IISC) were examined first to study its response over the Indian region for the same solar flare. In order to study this, we have calculated simple time difference of TEC (DTEC) for each satellite being tracked with elevation >30°. It can be written as DTEC = (TEC[i + 1] − TEC[i]), where i is time in UT at a given instant of time for each satellite being tracked. It is a simple substation of each TEC from its previous TEC value. This method is often used to detect TEC variations during solar flares [e.g., *Liu et al.*, 2004; *Zhang et al.*, 2002a]. Recall that this TEC is vertical TEC calculated from slant TEC as discussed in the section 2. It may be mentioned that the GPS TEC data used here under IGS stations had 30 s resolution, while SCINDA data at Tirunelveli had 60 s resolution. In order to maintain uniform time resolution at all stations, we have interpolated TEC over Tirunelveli to 30 s resolution. Figures 3a–3d show the GPS TEC and the successive time difference of TEC (DTEC) at 30 s time interval over Tirunelveli (Figure 3a) and Bangalore (Figure 3b) with elevation angle >30°. From Figure 3, one can notice that there exists a sudden enhancement of TEC of ~2 TECU (1 TECU = 1×10^{16} elevation/m^2) in the TEC observations and DTEC of ~0.2 TECU per 30 s at both of these stations during the flare onset time. As suggested in *Liu et al*. [2006], we have also noticed that DTEC is a better parameter to identify daytime solar flare signatures in the GPS TEC than TEC itself as it takes care of background density variations.

[11] To study the longitudinal variation of TEC and DTEC in the sunlit hemisphere, we have plotted the TEC and DTEC variations on 09 August 2011 using IGS stations at (1) Addis Ababa (ADIS), Ethiopia; (2) Metzoki Dragot (DRAG), Israel; (3) Mitzpe Ramon (ROMO), Israel; and (4) Tehran (TEHN), Iran, in Figures 4a and 4b during the time of solar flare. It may be mentioned that solar zenith angle for these stations is close to 30° (see Figure 1 for details). From the observations, one can notice TEC enhancement of 2–3 TECU and its maximum DTEC variation of 0.2–0.3 TECU per 30 s during the solar flare at all these stations. In order to study the locations of GPS satellites (referred as pseudo-range numbers (PRNs)) at different longitudes during the current solar flare, the trajectories of the GPS satellites are studied. The trajectory of the GPS receivers being tracked by six GPS receiver stations during 07:30–08:30 UT (when the solar flare occurred) with elevation angles >20°

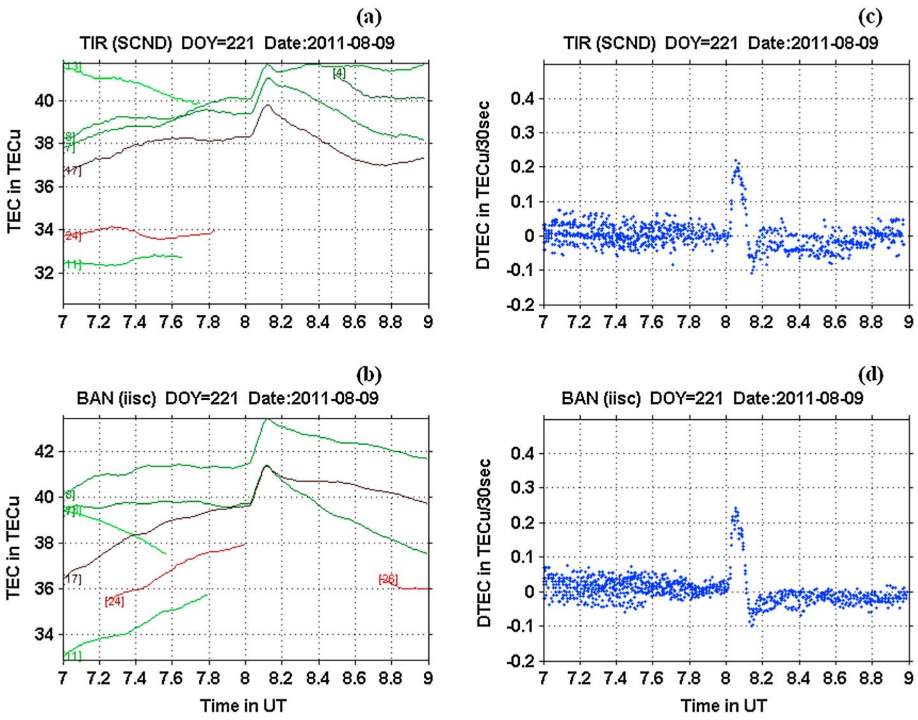

Figure 3. (a and b) The GPS TEC and (c and d) their time derivative (DTEC) during 07:00–09:00 UT over Tirunelveli and Bangalore. Elevation threshold >30° is used to obtain this figure. Each satellite is shown with different color, and the satellite numbers are given in the bracket.

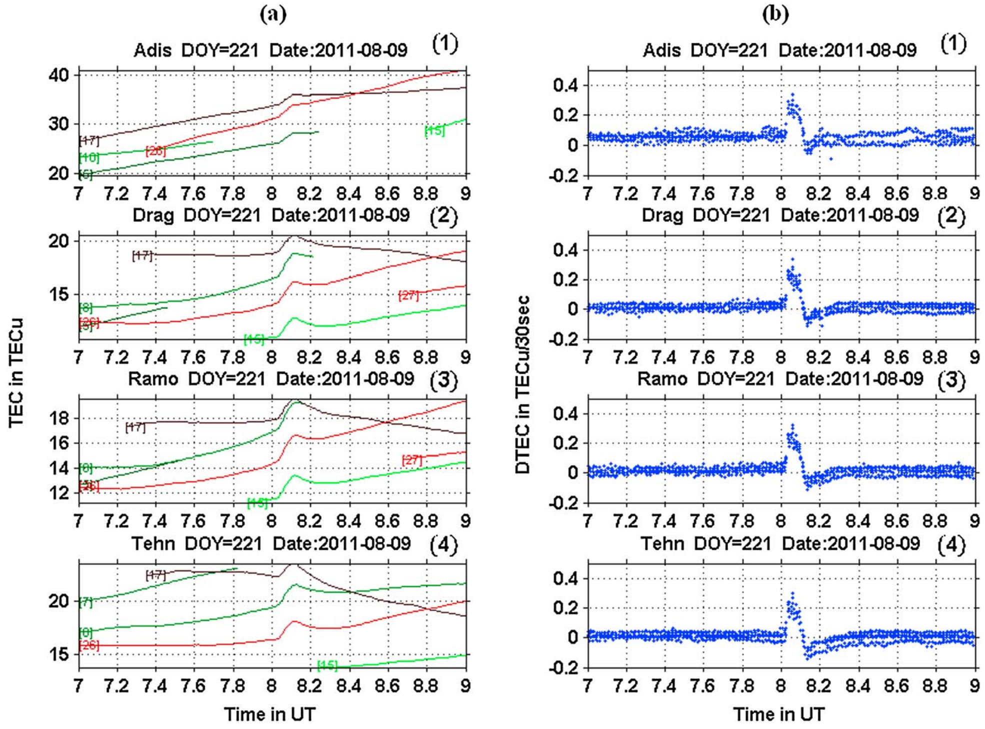

Figure 4. (a) The GPS TEC from IGS stations at (1) Addis Ababa (ADIS), Ethiopia; (2) Metzoki Dragot (DRAG), Israel; (3) Mitzpe Ramon (ROMO), Israel: and (4) Tehran (TEHN), Iran; and (b) their derivatives, respectively, during 07:00–09:00 UT, quite similar to that of Figure 3. Elevation threshold >30° is used to obtain this figure. Each satellite is shown with different color, and the satellite numbers are given in the bracket.

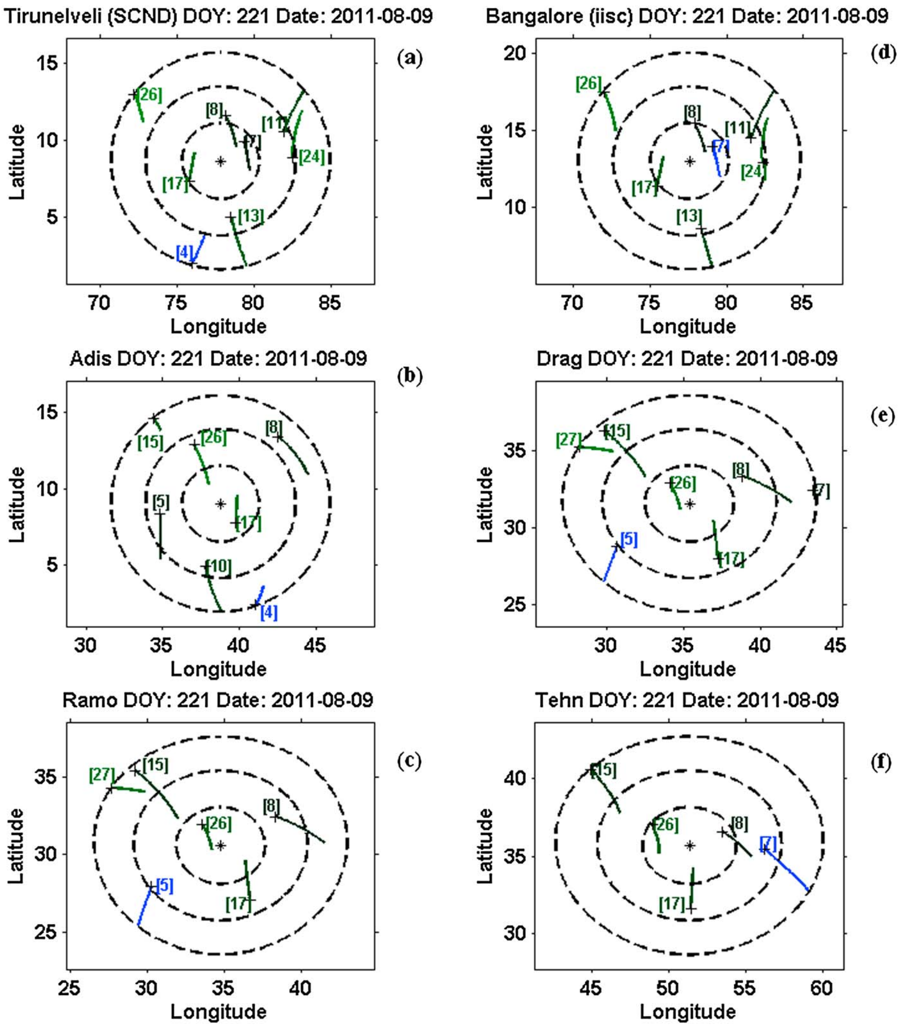

Figure 5. (a–f) The trajectory of GPS satellite locations at elevation angles >20° at six GPS receiver stations during 07:30–08:30 UT at different longitudes. Small to large dotted circles at each station represent elevation angles of 50°, 30°, and 20°, respectively. Each satellite is shown with different color, and the satellite numbers are given in the bracket. Crosses indicate start time of each satellite, and asterisks indicate the GPS receiver station.

in the sunlit hemisphere is shown as polar diagrams in Figures 5a–5f. From the observations, it is evident that PRNs 8, 7, 10, 13, 15, 17, and 26 with elevation angle >30° are noticed simultaneously in the solar flare-related TEC enhancements. To study the latitudinal and longitudinal variations of flare-related TEC enhancement, we have investigated the pre-flare and flare time TEC variations during 09 August 2011 using the GPS receiver network shown in Figure 1. The latitudinal and longitudinal variations of TEC enhancement (ΔTEC) to the 09 August 2011 flare at IPP are shown in Figure 6 as a scatter diagram using all the GPS stations. The color code represents the TEC enhancement due to solar flare. Also, the superimposed contour plot is the solar zenith angle at the time of the solar flare (08:00 UT). Here while x axis represents geographic longitude, y axis represents geographic latitude. The ΔTEC shown in Figure 6 is obtained using the following method. To study the flare-related TEC enhancement at each GPS station, first, we identified the satellites that are available for a period between 07:30 and 08:30 UT with elevation threshold >30°. Next, we took the mean TEC during 07:54–08:00 UT for each PRN that is continuously available during 07:30–08:30 UT and is considered as a pre-flare mean TEC response for that PRN. Then, maximum TEC during 08:02–08:07 UT for the same PRNs is considered as a flare period TEC response. Now, the difference of flare TEC to pre-flare TEC for each PRN is considered as a flare-related TEC enhancement (ΔTEC) for that PRN. There could be some errors involved in estimation of ΔTEC using this method. We assumed here that there is no variation in TEC during 07:54–08:00 UT (i.e., 6 min) to obtain pre-flare TEC which may not be true and may lead to some errors in ΔTEC estimation. Apart from this, we also assumed that satellite position relative to receiver is fixed during this period which is not true. These assumptions may lead to some errors in ΔTEC estimation. The overall error in this method could be approximately 0.1–0.2 TECU, which is quite small as compared to the flare time TEC enhancement (ΔTEC) as noticed in the present observations. From the figure, it can be

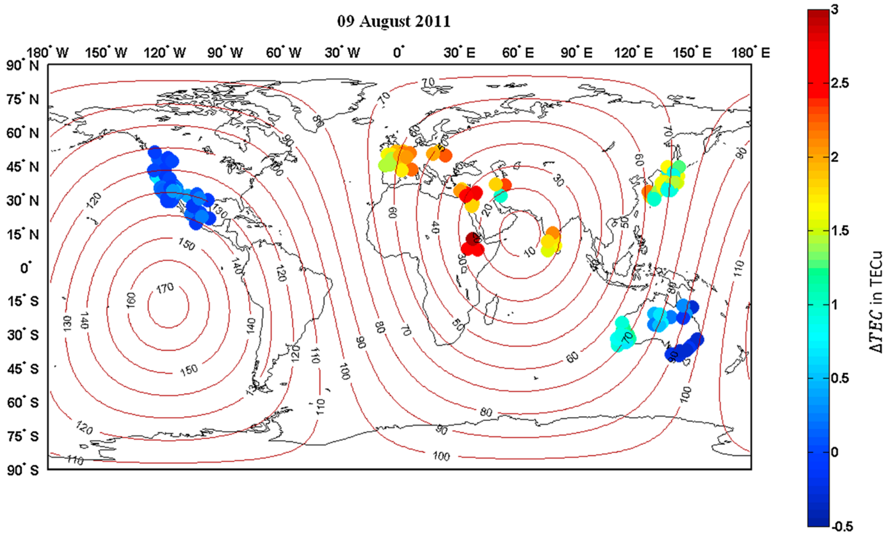

Figure 6. The latitudinal and longitudinal variations of flare time TEC enhancement (ΔTEC) during solar flare on 09 August 2011 using GPS observations around the globe. Also, the superimposed contour plot is the solar zenith angle at the time of solar flare (08:00 UT).

seen that there is ΔTEC enhancement of 2–3 TECU during solar flare. Further, it may be noted that ΔTEC is more pronounced in the sunlit hemisphere where solar zenith angles are smaller than 70°. The ΔTEC values are diminished when solar zenith angles are above 70°. Since the Sun was overhead when the solar flare occurred in the Indian sector and other European and Asian countries, ΔTEC values are also quite high over these longitudes than at other regions. We have studied the ΔTEC enhancement due to solar flare with reference to solar zenith angle to understand their dependence as earlier studies have shown that ΔTEC varies with solar zenith angle [e.g., *Zhang and Xiao*, 2005]. To study the correlation between ΔTEC and solar zenith angle on 09 August 2011, we have plotted their relation in scatter diagram in Figure 7. Here while x axis shows the solar zenith angle, y axis shows the ΔTEC. The figure suggests that there exists a good correlation between them.

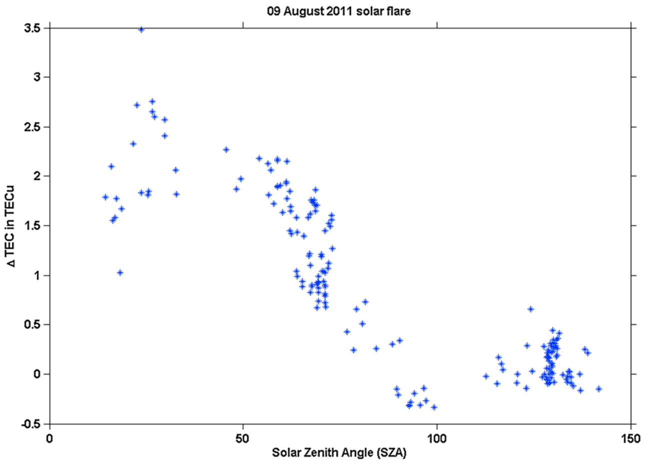

Figure 7. The scatter plot of the correlation between ΔTEC and solar zenith angle at 08:00 UT on 09 August 2011.

[12] In order to study the geomagnetic field variations during the solar flare, we have plotted the temporal variation of EEJ strength (nT; Figure 8a) and geomagnetic H component (ΔH; Figure 8b) over Tirunelveli (red stars) and Alibag (blue hexagons) during 00:30–12:30 UT (06:00–12:00 IST) on 09 August 2011 in Figures 8a and 8b. The observations of ΔH variations at both stations suggest that H component variations before 02:00 UT (early morning hours in Indian stations) are close to zero. But, as time progresses, the H component variation slowly increases in the prenoon sector, and it reaches 80 nT over Tirunelveli. This increase could be understood through variation of E region electron density due to daytime photo-ionization and ionospheric conductivity due to strong ionospheric currents. However, after reaching its maximum of 70–80 nT at 04:00–05:30 UT, it starts slowly decreasing its strength and becomes 20–25 nT after ~05:30 UT. In addition to slow decrease of H component, abrupt decrease in the H component is also noticed during the time of onset of solar flare over Tirunelveli. On the other hand, the H component variation over Alibag rises to as high as 40 nT in the prenoon hours. After that, its strength goes down to as low as 20 nT for a while before it again rises to 45 nT at 07:30 UT. But when solar flare occurred, the ΔH variations over Alibag rapidly shoot up to ~80 nT temporarily for 10 min but reach back to normal within few minutes. Similarly, temporal variability of EEJ strength shows that EEJ strength is zero during early morning but slowly increases in the prenoon hours and reaches ~50 nT before it slowly goes below zero at 07:00 UT and becomes negative after that, indicating that counter electrojet (CEJ) starts developing. But when solar flare occurred, sudden depression in the EEJ strength can be noticed. In order to study the longitudinal variation of geomagnetic H over equatorial and low-latitude stations in the sunlit hemisphere, we have investigated the longitudinal variation of geomagnetic H component using INTERMAGNET observations. Figures 9a–9j show the temporal variation of geomagnetic H component at equatorial (red circles) and low-latitude stations (blue stars) at different locations in

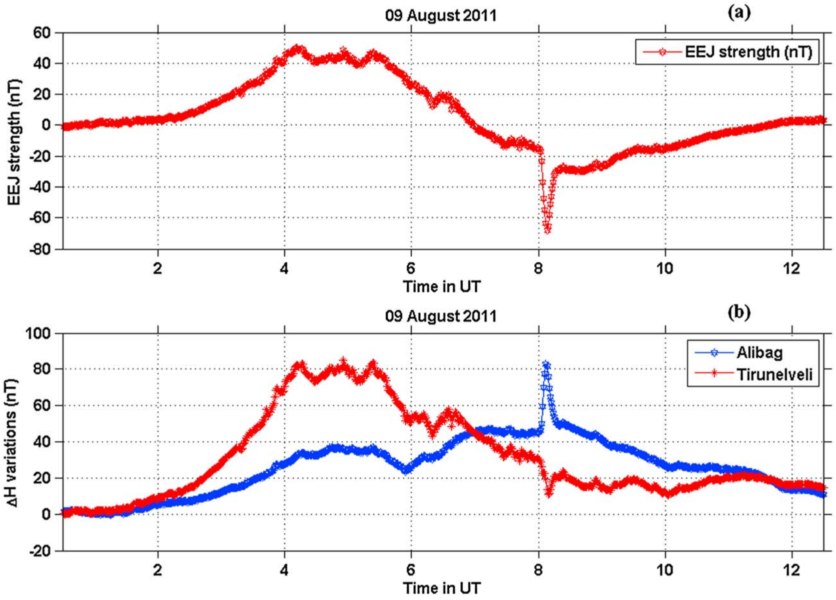

Figure 8. The temporal variation of (a) EEJ strength (nT) and (b) geomagnetic H component variation over Tirunelveli and Alibag during 0:30–12:30 UT on 09 August 2011.

the sunlit hemisphere during 07:00–09:00 UT on 09 August 2011 solar flare. These observations also showed sudden increase of H component in the low latitudes and sudden decrease of H component near the equatorial stations which are having almost similar features as that of Indian stations. Apart from this, change in delta *H* due to this solar flare at low latitudes shows some correlation with solar zenith angle (not shown here). These observations indicate that signature of solar flare on the variations in the geomagnetic H component is remarkable and may be used to infer some more details about the ionospheric current variations in the equatorial and low-latitude ionosphere.

[13] We have analyzed CADI data at Tirunelveli on 08 and 09 August 2011 to investigate the ionospheric variability due to the solar flare on 09 August 2011. Here it may be noted that we have chosen ionogram records on 08 August 2011 as control day. The CADI observations were collected continuously at an interval of 10 min on both these days. The ionogram records at Tirunelveli at every 10 min interval during 06:30–09:20 UT (12:00–15:00 IST) on 09 August

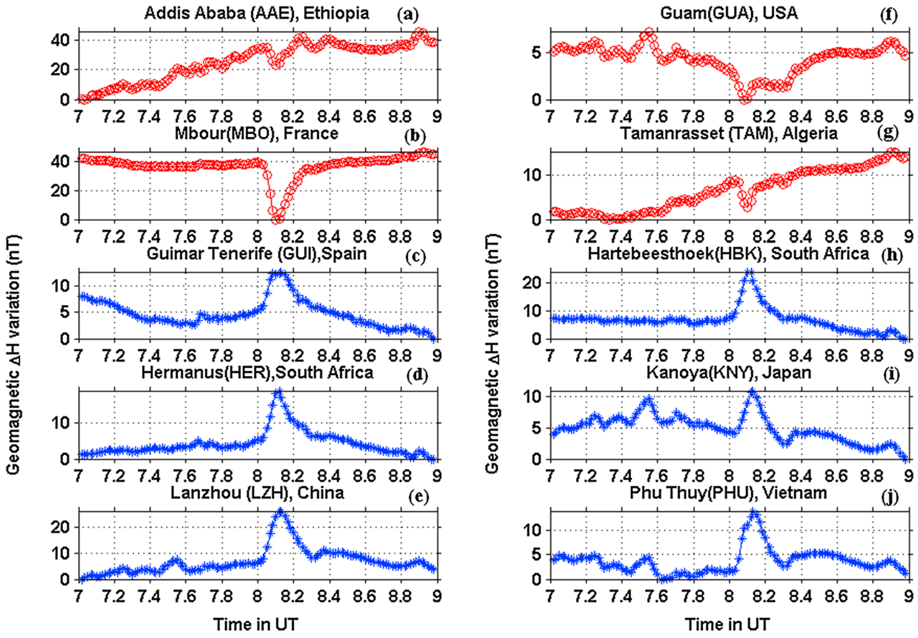

Figure 9. (a–j) The temporal variation of geomagnetic H component at different locations in the sunlit hemisphere during 07:00–09:00 UT on 09 August 2011. Here equatorial stations are shown in red hexagons, while low-latitude stations are shown in blue stars.

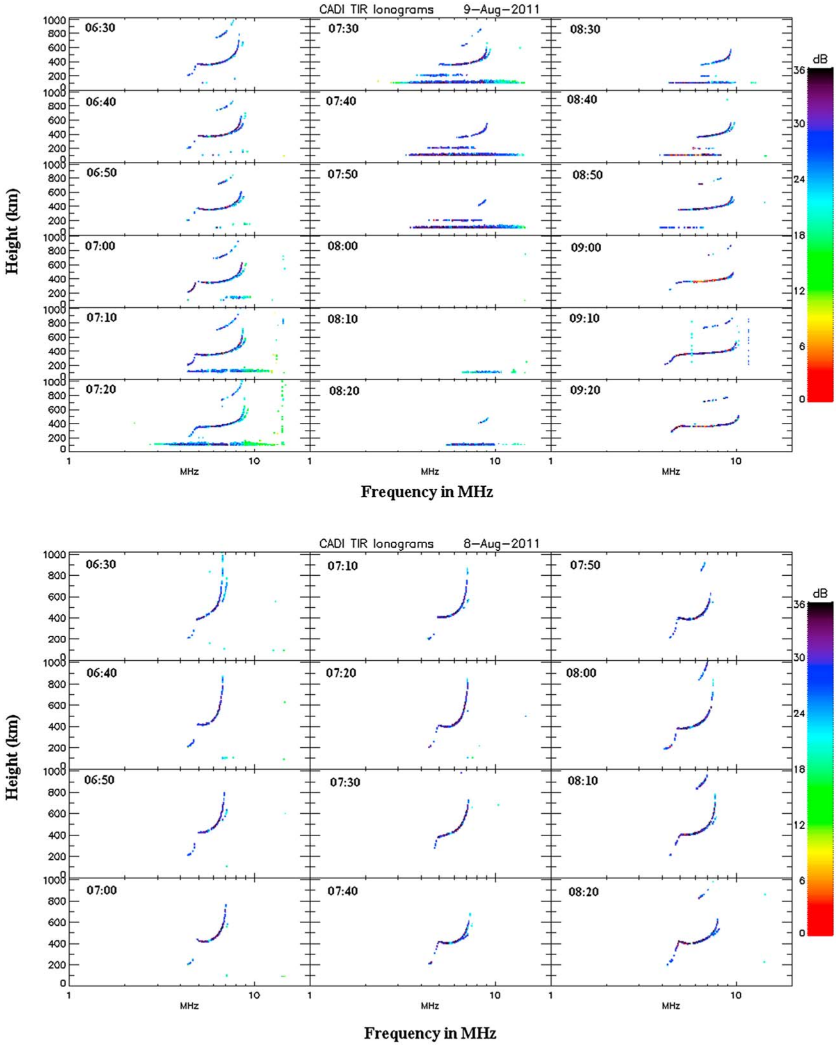

Figure 10. The ionogram records on (a) 09 August 2011 during 06:30–09:20 UT and (b) 08 August 2011 during 06:30–08:20 UT. Here subplots represent ionogram records at every 10 min interval. Time in UT is given on each subplot.

2011 are shown in Figure 10a. The time displayed on the top left corner in each subplot is in UT. The color bar shows the signal strength of the received echo. From the figure, it can be noted that at 06:30 UT (12:00 IST) noon, *F* region trace was quite noticeable, and equatorial blanketing type *E*s layer was quite weak/absent. However, as time progresses, *F* region trace becomes quite weak, and blanketing E_s layer becomes stronger. At 07:30 UT, the blanketing E_s layer becomes very strong, which weakens the *F* layer trace further. At 08:00 UT (13:30 IST), when the solar flare peaks its intensity, ionogram completely becomes blank, and no echo can be traced in the ionogram. But after 08:30 UT (14:00 IST), again ionogram becomes normal ionogram, and blanketing E_s layer becomes visible again. The blanketing E_s layer disappears at about 08:50 UT, but *F* layer trace is visible. In order to study the ionospheric condition on 08 August 2011 (control day), we have plotted the ionogram records on 08 August 2011 during 06:30–08:20 UT in Figure 10b quite similar to that

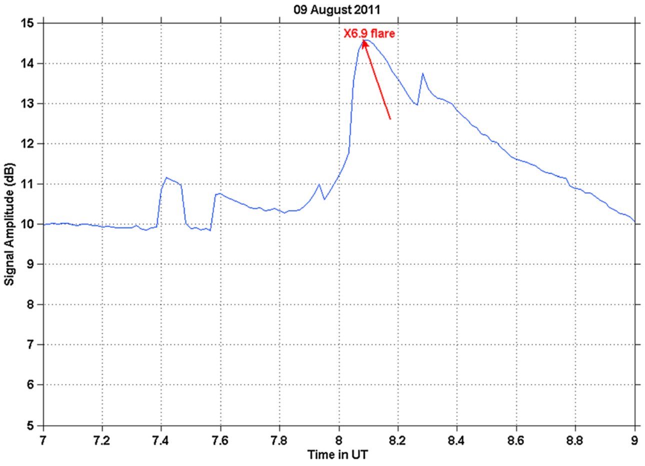

Figure 11. The amplitude variation of VLF signal at Allahabad during 07:00–09:00 UT on 09 August 2011.

of Figure 10a. From the figure, it can be noticed that no such blanketing type E_s layer is present on this day, which is in contrast to 09 August 2011 where strong blanketing E_s layer was present.

[14] To investigate whether absorption in the *D* region is enhanced or not during solar flare, we have looked into amplitude signal of VLF transmitter NWC operating at 19.8 kHz from Australia and received at Allahabad. The temporal variation of amplitude signal of VLF observations during 07:00–09:00 UT on 09 August 2011 over Allahabad is shown in Figure 11. From the figure, it can be noticed that during the X-class solar flares, VLF signal amplitude gets enhanced by ~4 dB indicating enhanced *D* region absorption.

4. Discussion

[15] The response of equatorial and low-latitude ionosphere presented above using multi-instrument observations during the 09 August 2011 solar flare suggests the following points: (a) observation of maximum TEC enhancement of 2–3 TECU in the sunlit hemisphere, (b) good correlation of ΔTEC with respect to solar zenith angle where lower solar zenith angle has larger TEC values, (c) commencement of CEJ prior to solar flare event, (d) sudden increase of H component in the low latitudes and sudden decrease of H component near equatorial locations, respectively, over Indian longitudes, (e) occurrence of blanketing type E_s layer as compared to the control day, (f) disappearance of ionogram echoes at the time of peak solar flare, (g) enhanced signal amplitude of VLF radio signal due to enhanced *D* region ionization, and (h) sudden increase of H component in the low latitudes and sudden decrease of H component near equatorial locations at wide longitudes in the sunlit hemisphere which are quite similar to that of Indian stations.

[16] In order to understand these observations, we have investigated ionospheric response of the 09 August 2011 flare with reference to some of the previous solar flares such as the 28 October 2003 (X17.2/4B), 04 November 2003 (X28/3B), and 09 September 2005 (X3.6) flares using GPS TEC. While the 04 November 2003 flare was more intense than any other flares in the recent times, the TEC enhancement during this flare is quite low as compared to the 28 October 2003 flare. *Tsurutani et al.* [2005] have studied the reason for this contrasting behavior in TEC during 28 October 2003 and 04 November 2003. They suggested that it could be due to the fact that the 28 October 2003 flare was an intense flare as seen in the EUV spectrum which ionizes *E* and *F* region ionosphere and hence contributes to TEC enhancement. However, the solar flare on 4 November 2003 was largest in the X-ray spectrum that contributes mostly to *D* region ionization that has faster recombination. Hence, it is suggested that it did not reflect in TEC observations.

[17] On the other hand, it has been suggested that maximum TEC enhancement occurs when solar flares are close to central meridian distance (CMD) [*Zhang et al.*, 2002a; *Afraimovich et al.*, 2002; *Mahajan et al.*, 2010]. *Zhang et al.* [2002a] have examined the relation of solar disk to location of solar flares for several solar flares and suggested that flares occurring close to solar meridian result in stronger ionospheric response. *Mahajan et al.* [2010] have examined the TEC response to peak X-ray and peak EUV flux with reference to their CMD to some of the intense solar flares such as 28 October 2003 and 04 November 2003 and suggested that change in TEC (ΔTEC) highly correlates with peak EUV flux but not with X-ray flux. But they suggested that correlation improves between peak X-ray flux and ΔTEC when X-ray flux is multiplied by cos(CMD). Hence, they suggested that not only the flare intensity but also the CMD location of the flare is an important parameter that has to be taken into account while studying the effect of solar flares on the ionosphere/upper atmosphere during X-class flares. Recently, *Manju et al.* [2009] have examined the response of low-latitude ionosphere to the 28 October 2003 flare over Indian region using geomagnetic and GPS TEC observations. They noticed sudden enhancement of TEC of ~10 TECU close to anomaly region over Indian longitude. When we analyzed TEC data on these events, our observations also indicated that the TEC enhancement on 28 October 2003 was as high as 18 TECU at locations close to solar zenith angles <30°. But on 04 November 2003, the TEC enhancement was found to be ~5 TECU even though solar zenith angle was close to zero. On 09 September 2005, the TEC enhancement is found to be ~2–3 TECU. When we looked at their CMD locations, it is found that the flare on 28 October 2003 was very close to solar meridian than the 04 November 2003 solar flare. Hence, our observations also support the argument that CMD location does contribute to the enhancement of TEC on this flare up to 18 TECU. However, when we noticed the flare location on 09 August 2011, it is found that its location is close to 69° westside limb of the Sun, and hence its impact on the TEC is restricted to a few TECU. Also, since this flare occurred at a time when solar cycle 24 was in ascending phase, its TEC response could be weak unlike the October 2003 event which occurred at the peak of the solar cycle 23.

[18] The response of ionosphere and thermosphere system is studied using theoretical model to understand the effect of location of the flare on the solar disk by assuming two identical X17 flares where one occurs close to the CMD location and the other is near the limb [*Qian et al.*, 2010]. Their model results showed that while flare location does not affect the *E* region ionosphere where soft X-ray dominates, flare location does affect the *F* region ionosphere and neutral density in the upper thermosphere where soft X-ray dominates. Further, their model results indicated that while flare location did not affect the timings for the ionospheric response, the thermospheric response was ~20 min faster for the flares that are close to CMD location. Since the flare location in the present case is quite far from CMD, flare time increase of ~2–3 TECU only in the present case can be understood. Though TEC enhancement in the present solar flare is very small, its impact on *D* region was quite high as seen in the ionogram records as well as amplitude variation of VLF observations.

[19] Now we shall examine the causes for geomagnetic variations during the present solar flare. It may be mentioned that unlike other flares, current solar flare occurred at a time when it was local noon over India (13:30 IST). So this provided us an opportunity to investigate the noontime geomagnetic variations of ionosphere over Indian region. *Sastri* [1975] has studied the geomagnetic solar flares effect using a chain of Indian geomagnetic observatories that spread over several latitudes and suggested that SFEs can be characterized by a decrease in the H component at

electrojet stations and an increase in the H component at stations outside the electrojet. The response of low-latitude ionosphere to the 28 October 2003 flare is investigated using geomagnetic observations and GPS TEC data [*Manju et al.*, 2009]. They noticed sudden depression in ΔH over Trivandrum and sudden enhancement of TEC of ~10 TECU close to anomaly region over Indian longitude. Further, they have shown that ΔH at other longitudes also varies quite similarly to that of EUV flux variation and suggested that flare-related density enhancements in different longitude sectors in the magnetic equator can produce positive and negative variations in the electrojet due to the presence of varying current systems at different longitudes. *Rastogi et al.* [1999] have studied the SFEs on geomagnetic components for different electrojet strengths over Indo-Russian latitudes along Indian longitude zone. They suggested that during normal electrojet event, SFEs consist of positive impulse in H component at all stations. However, during counter electrojet, SFE consists of positive impulse in H component at low latitude, negative impulse at equatorial stations, and again negative impulse at stations north of *Sq* focus. As ionospheric current system over equatorial stations reverses during strong CEJ period from eastward to westward, strong depression in H component may be noticed at equatorial stations. However, since equatorial current system does not extend to low-latitude stations, the ionospheric current system remains in the eastward direction due to prevailing *Sq* current system, and the solar flare produces positive impulse in H component over low latitudes [*Rastogi et al.*, 1999]. Changes in the H component at Tirunelveli and Alibag during the present solar flare when CEJ was active also suggest that there could be positive impulse at low latitudes and negative impulse at equatorial stations. The longitudinal variation of geomagnetic H component here also suggests that CEJ is active at other longitudes as well. These changes in the geomagnetic field could be due to prevailing ionospheric current systems at that time.

[20] Observation of blanketing type E_s layer over Tirunelveli during CEJ event prior to solar flare in the present case can be understood through the transport of long-lived metallic ions from low to equatorial latitudes by equatorward winds which could produce large horizontal shears. Earlier studies have shown that it is possible to have blanketing type E_s layers over the equator during CEJ events [*Reddy and Devasia*, 1973; *Chandra and Rastogi*, 1975]. Since efficiency of vertical shears at equator decreases, it is shown that horizontal shears of horizontal winds are the most likely sources for such blanketing type E_s layers over the equator which is contrary to midlatitude sporadic *E* layers, where they are generated due to vertical convergence of ionization due to vertical shears of horizontal winds [*Reddy and Devasia*, 1973]. Absence of E_s layers during the time of solar flare could be understood due to absorption of radio signals by enhanced *D* region ionization. It may be mentioned that VLF observations can be used to study the *D* region electron density [e.g., *Thomson and Clilverd*, 2001]. Previous reports suggest that whenever *D* region ionization is enhanced, VLF amplitude signal gets amplified [e.g., *Thomson and Clilverd*, 2001]. During solar flares, enhanced ionization in the *D* region could lower the reflection height of the VLF radio waveguide and advance the phase of the VLF radio wave where both of them linearly depend on intensity of X-ray flux [e.g., *Thomson et al.*, 2004]. So present observations of *D* region absorption in the ionogram at the time when amplitude signal of the VLF waves was amplified (Figure 11) suggest that there could be enhanced *D* region ionization due to solar flare which caused absorption of radio signal in the ionogram records.

[21] The response of equatorial *E* region electric fields and *E* region currents during solar flares has been studied at Trivandrum using multi-instrument observations by *Manju and Viswanathan* [2005]. They have shown that radar backscattered power is substantially reduced during peak of the solar flare, and also electric field direction is changed from eastward to westward. They have also shown the occurrence of sporadic *E* layer just prior to solar flare, weakening/disappearance of ionogram traces during flare, and again appearance of sporadic *E* layer. They suggested that weakening of sporadic *E* layer could be due to weakening/reversal of electric field direction. They also indicated that the weakening of electric field also could reduce the geomagnetic H component variation. The observations of ionogram traces of the 09 August 2011 flare here also suggest that there could be weakening of electric field resulting in depression in geomagnetic H component as well as weakening of blanketing E_s layer. These observations are quite similar to the ones that were presented by *Manju et al.* [2009]. While we have presented here some preliminary results, this needs further investigation. Some of the recent studies have shown that response of ionized and neutral densities to solar flares could be different depending upon the location of flare and strength of the flare [e.g., *Liu et al.*, 2007; *Le et al.*, 2012; *Qian et al.*, 2010, 2012]. This suggests that solar flares can produce a wide range of physical, chemical, and electrodynamic processes over equatorial and low-latitude ionosphere that needs in-depth investigation, and we will focus more attention on these aspects in future work.

5. Summary

[22] In the present paper, an attempt has been made to study the response of equatorial and low-latitude ionosphere to an X-class solar flare (X7/2B) on 09 August 2011. Particular attention is being made to Indian longitudes since midday solar flare is observed at these longitudes. The results presented above suggest the following points:

[23] 1. Sudden increase in GPS TEC values of ~2–3 TECU for ~5 min was observed over Indian region during the time of solar flare. This increase was noticed at wide longitudes where solar zenith angles are $<70°$.

[24] 2. Sudden disappearance of ionogram echoes in Turunelveli at the time of solar flare coincided with sudden increase in amplitude measurement of VLF signal. This feature is in accordance with earlier reports where they attributed this increase to enhanced *D* region ionization.

[25] 3. Commencement of CEJ prior to solar flare was noticed. However, sudden increase in CEJ current at the time of solar flare could be due to sudden increase in delta *H* at the low-latitude station of Alibag.

[26] 4. In addition, sudden decrease and increase in the geomagnetic delta *H* observations are noticed at equatorial and low-latitude stations, respectively. These types of observations are noticed at several longitudes over Asian, European, and African longitudes in the sunlit hemisphere.

The increase and decrease in delta *H* over low latitudes and equator, respectively, could be due to flare-related ionospheric currents prevailing at that time.

[27] 5. Observations of strong blanketing type E_s layer at Tirunelveli that occurred just prior to the solar flare and continued until 14:20 IST (though it disappeared during the time of solar flare period) suggest that horizontal wind shears might have existed in the *E* region altitude that could have caused commencement of CEJ event prior to solar flare occurrence.

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