Ionospheric Current Variations Induced by the Solar Flares of 6 and 10 September 2017

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Abstract We examine the global ionospheric current in relation to X9.33 disk and X8.28 limb flares, which had significant differences in their solar X-ray and extreme ultraviolet (EUV) fluxes using the ground-based magnetometer data. At the peak of X9.33 flare, when X-ray and EUV radiations were significantly enhanced, the northern current vortex was situated at (40°N, 12 LT), while the southern current vortex was found at (30°S, 13LT). In comparison to the X8.28 flare, the northern current vortex was seen at (16°N, 12LT), while the southern current vortex was situated at (35°S, 14LT), which was 2 hr earlier in local time compared to those observed in the X9.33 flare. The changes in the total current intensity of the X9.33 flare is about 16% lower than that of the X8.28 flare, thus revealing that the current variations relative to both flares are due to solar flux and universal time variations. The daytime X9.33 flare northern current vortex is stronger, while the southern vortex is less intense than the corresponding vortex of X8.28 flare. Even though both flares happened in equinox, the current vortices are nearly symmetric. There were significant hemispheric changes in the focus position leading to the hemispheric asymmetry. Our results indicated that both the enhanced X-ray and EUV fluxes during flares could have impacts on the ionospheric electric field and current, but their relative contributions and the underlying physics need further investigations.

1. Introduction

In the E region ionosphere (~90 to ~150-km altitude), the solar atmospheric heating generates tidal winds and drives the ionospheric plasma against the Earth’s gravity. The relative movement of this ionospheric plasma against the Earth’s gravity induces the ionospheric electric field and current (Campbell & Schiffmacher, 1985; Yamazaki et al., 2011). Being a sunlit dependence, this ionospheric current in the order of tens of kiloamperes (kA) flows in the dayside of the E region ionosphere. During the geomagnetically quiet periods, the equivalent ionospheric current creates two opposing loops, one in the northern hemisphere and another one in the southern hemisphere on a dayside with the center of their loops (vortices) situated near local noon at the middle latitudes (Pedatella et al., 2011; Yamazaki et al., 2011). The northern hemispheric loop is anticlockwise, while the southern hemispheric loop is clockwise. At the geomagnetic equator, a large magnitude of ionospheric conductivity is created due to the orthogonality effects of the electric and geomagnetic fields, thereby creating a dayside eastward current sheet known as equatorial electrojet (EEJ) flowing in the E region of the ionosphere (Doumouya et al., 2003). On some occasions, during magnetically quiet conditions, the EEJ current that is eastward directed reversed westward (counter electrojet; CEJ) due to the flow of westward electric field created at the geomagnetic equator (Amory-Mazaudier et al., 2017).

The extreme solar forcing on the Earth’s ionosphere creates complex variations in the time-varying ionospheric current. One of the typical examples of extreme solar forcing is a solar flare event. A solar flare is a sudden heating of the solar atmosphere as a result of the violent release of the magnetic energy by magnetic reconnection, which is tightly tied to the dark spot areas on the surface of the Sun known as the sunspots. They are concomitant to an enhancement in the X-ray as well as extreme ultraviolet (EUV) irradiance in
the solar-terrestrial atmosphere (Tsurutani et al., 2005, 2009). Depending on the intensity of electromagnetic energy, solar flares are logarithmically categorized into A-, B-, C-, M-, and X-classes (Bai & Sturrock, 1989; Davies, 1990; Ishkov, 2018; Oloketyui et al., 2019), where the flux densities are in the range of $10^{-7}$ to $10^{-2}$ watts per square meter ($\text{W m}^{-2}$). The peak flux of flares is split into linear scales between 1 and 9 except for X-class flares that have no upper limit. The classifications are based on X-ray brightness with wavelength 0.1–0.8 nm as measured by the Geostationary Operational Environmental Satellites 15 (GOES-15). The X-class flares with radiation greater than $10^{-4}$ W m$^{-2}$ are the most potent flares with the extra ionization that are capable of releasing large charged particles and ions into the interplanetary space thereby causing disturbances in the upper atmosphere (Scherliess, 2016; Tsurutani et al., 2009). These disturbances, in turn, affect the Global Navigation Satellite System signals, shortwave radio communications, among many others (Berdermann et al., 2018; Liu et al., 2006; Tsurutani et al., 2005, 2009).

When a solar flare erupts, short-period changes often called the sudden ionospheric disturbances are observed in the $D$ region (Ogunmodimu et al., 2018), $E$ layer (Curto et al., 1994; Li et al., 2018; Rastogi et al., 1999; Yamazaki et al., 2009) and occasionally in the $F_2$ region (Scherliess, 2016; Thome & Wagner, 1971). These sudden ionospheric disturbances are due to the sudden increase in the X-ray and EUV irradiance (Le et al., 2007; Tsurutani et al., 2005). The X-ray flux is capable of reaching the lower part of the ionosphere ($D$ region) and enhances $D$ region ionization, while the EUV flux impacts the $E$ and $F$ regions ionosphere through increased ionization (Scherliess, 2016; Thome & Wagner, 1971). This ionization enhancement could cause perturbation in the geomagnetic fields, which often called the geomagnetic crochets or solar flare effects (Sfe) on a dayside ionosphere (Rastogi et al., 1999). Several investigations on the ionospheric current associated with Sfe found several important differences in the time-varying Sfe current and quiet ionospheric current condition (Nagata, 1966; Raja Rao & Panduranga Rao, 1963; Volland & Taubenheim, 1958). Most of these investigations revealed that the values of the ionospheric current associated with Sfe are higher compared to quiet conditions (Nagata, 1966; Van Sabben, 1961). These were attributed to extreme solar forcing (Annadurai et al., 2018; Curto et al., 2018; Gayya-Piqué et al., 2008; Richmond & Venkateswaran, 1971). In addition, the Sfe changed the focus of the ionospheric current (Annadurai et al., 2018; Gayya-Piqué et al., 2008), produced extra-ionization that reached the $D$-region ionosphere (Annadurai et al., 2018; Roy, 1977; Veldkamp & Van Sabben, 1960; Volland & Taubenheim, 1958), and significantly increased the nighttime ionospheric current (Sasti & Murthy, 1975).

The electrodynamic effects of the ionospheric current associated with Sfe of different flux intensities have been extensively studied, which have explained reasonably several remarkable solar flares phenomena (Annadurai et al., 2018; Richmond & Venkateswaran, 1971; Van Sabben, 1968; Veldkamp & Van Sabben, 1960; Volland & Taubenheim, 1958). Thus, much remains to be clarified regarding the Sfe current of comparable flux intensities. This will help deepen our understanding of the solar dynamics underlying the Sfe current. Hence, we recognized the need for examining the response of Sfe current of similar flux intensities. To this end, we have selected these two most potent X-class flares, that is, the X9.33 flare of 6 September 2017 that occurred before geomagnetic storms of 7–8 September 2017 and the X8.28 flare of 10 September 2017 that occurred during the recovery phase of geomagnetic storms. From the locations of X9.33 flare (S08W33) and X8.28 flare (S08W88) in the solar meridian, the X9.33 flare is a solar disk flare, while the X8.28 flare is a solar limb flare (Ishkov, 2018; Qian et al., 2019). For both flares, the X-ray flux increased significantly while the EUV intensity of X9.33 disk flare was about 52% larger than that of X8.28 solar limb flare due to changes in the optical thickness of the soft X-rays and EUV radiations in the solar atmosphere. In addition, the EUV evolution during the late phases of these two flares showed contracting behavior. We aim at investigating the similarity as well as their differences in the Sfe current relative to disk and limb flares. The need for studying the effects of disk and limb flares on the ionospheric current will correctly lay the variability pattern of disk-limb-induced magnetic field variations on a global scale.

2. Data Sources and Method of Analysis

2.1. Data Selection

The geomagnetic data utilized in this study are 1-min resolution of 188 worldwide distributed horizontal ($H$), declination ($D$), and vertical ($Z$) geomagnetic field components obtained during 3–11 September 2017 space weather events. These geomagnetic stations are routinely available from the SuperMAG database.
In our analysis, we supplemented the SuperMAG data by $H$, $D$, and $Z$ data obtained from the Embrace Magnetometer Network (Embrace MagNet; Denardini et al., 2018), Geospatial Information Authority of Japan, Latitude Ionospheric Sensor Network, and Japan Meteorological Agency. In this study, the magnetic latitudes (MLAT) within the interval $3^\circ < |\text{MLAT}| \leq 60^\circ$ are considered to prevent potential disturbances of the equatorial and polar electrojet currents. The geographic locations of 188 magnetic stations used in this study are shown on the global map given in Figure 1. These large and high-quality amounts of magnetic field data could improve the accuracy of the spherical harmonic model by improving the overfitting effects. Thus, this leads to better precision of global equivalent ionospheric current distribution that may be compromised due to the incompleteness and inhomogeneity of magnetic observations witnessed, especially at the southern hemisphere over the last few decades.

Solar wind speed ($V_{\text{sw}}$) and the meridional interplanetary magnetic field (IMF-$B_z$) were obtained from the Advanced Composition Explorer (ACE) satellite for solar investigation. Symmetric ring current ($\text{SYM-H}$), auroral electrojet ($\text{AE}$), solar flux proxy ($F_{10,7}$ index), and 3-hourly geomagnetic activity ($Kp$) indices were obtained from OMNIWeb page to appraise the geomagnetic activities during the solar flare outbursts. Solar irradiance data in the wavelength of 0.1–0.8 nm is taken from GOES-15 spacecraft, which supplies an X-ray flux at 2-s intervals to demonstrate solar flares’ effects on the ionosphere. The 10-s resolution of EUV flux in the wavelength band of 30.4 nm is obtained from the Extreme Ultraviolet Variability Experiment onboard the Solar Dynamics Observations (SDO) satellite to study the global ionospheric current response to solar EUV flux.

### 2.2. Method of Analysis

In this section, we described the standard technique known as spherical harmonic analysis utilized to derive the global ionospheric current (Yamazaki & Maute, 2016). To begin with, we obtained the averaged values of $H$, $D$, and $Z$ at $LT \leq 2 | LT \geq 23$ local time as a baseline for ionospheric current and thereafter obtained $\Delta H$, $\Delta D$, and $\Delta Z$ by subtracting the baseline values from $H$, $D$, and $Z$ for each day and station. In this case, the geomagnetic signature of ionospheric currents, ring currents, magnetopause currents, field alight currents, among many others, are minimized (Yamazaki et al., 2011). The resulting magnetic field variations, that is, $\Delta H$, $\Delta D$, and $\Delta Z$ were further subjected to spherical harmonic functions; hence, the spherical harmonic coefficients were extracted as shown in the Equation 1 and used for further analysis.
\[ \Delta H = \sum_{m=0}^{4} \sum_{n=-m}^{m+5} (a_n^m \cos mt + b_n^m \sin mt) X_n^m (\theta) \]
\[ \Delta D = \sum_{m=0}^{4} \sum_{n=-m}^{m+5} (-b_n^m \cos mt + a_n^m \sin mt) Y_n^m (\theta) \]
\[ \Delta Z = \sum_{m=0}^{4} \sum_{n=-m}^{m+5} (c_n^m \cos mt + d_n^m \sin mt) P_n^m (\cos \theta) \]

where \( a_n^m, b_n^m, c_n^m \), and \( d_n^m \) are the spherical harmonic coefficients of order \( m \) and degree \( n \). The harmonic factors \( X_n^m (\theta) \) and \( Y_n^m (\theta) \) equal \( \partial P_n^m / n \sin \theta \) and \( m P_n^m / n \sin \theta \), respectively, \( P_n^m (\cos \theta) \) is the associated Legendre function of \( m \) and \( n \) normalized based on the Schmidt’s function, and \( \theta \) is the geomagnetic colatitude of the stations (Chapman & Bartels, 1940). We combined \( \Delta H \) and \( \Delta D \) components to obtain \( a_n^m \) and \( b_n^m \) harmonic terms since the values for \( a_n^m \) and \( b_n^m \) obtained by fitting \( \Delta H \) only into spherical harmonic functions are not the same as those obtained by fitting \( \Delta D \) alone for the singular reason that the orthogonality of the spherical harmonic functions is nearly never satisfied in practical situations. Then, the spherical harmonic coefficients, which are obtained by a least-squares method in Equation 1, are used to calculate the Gaussian coefficients for external field contribution shown in Equation 2:

\[ E_n^m = \frac{(n+1) a_n^m + n c_n^m}{n(2n+1)}, \quad e_n^m = \frac{(n+1) b_n^m + n d_n^m}{n(2n+1)} \]

where \( E_n^m \) and \( e_n^m \) are empirical constants called the external Gaussian coefficients (Yamazaki & Maute, 2016). The external magnetic potential function \( U_e \) is then given as follows:

\[ U_e (r, \theta, \lambda) = \left( \frac{r}{R} \right)^n \left\{ E_n^m \cos (m \lambda) + e_n^m \sin (m \lambda) \right\} P_n^m (\cos \theta) \]

where \( R = 6,371 \text{ km} \) denotes the radius of the earth, \( r \) is the radius vector from the center of the Earth, and \( \lambda \) is the longitude. We obtained \( U_e \) from Equation 3 and subsequently obtained the equivalent ionospheric current flowing in a thin conducting shell using Equation 4. In this study, we considered \( r = R \) since \( |r - R| \ll R \) at the Earth’s surface.

\[ J_e (\theta, \lambda) = -\frac{10 R}{4 \pi} \sum_{m=0}^{4} \sum_{n=-m}^{m+5} \frac{2n+1}{n+1} U_e (\theta, \lambda) P_n^m (\cos \theta), \quad r > R \]

To obtain the magnetic field perturbation vectors, we rotated \( \Delta H \) and \( \Delta D \) records by 90° clockwise. Since the dynamo theory describes the physical origin of the geomagnetic field, namely, the internal and external origins. The contribution of induced current accounts for about 1/3 of \( \Delta H \) variations. Considering this fact, then the \( \Delta H \) and \( \Delta D \) records can be approximated to obtain the northward and eastward current intensities using Equations 5, which were then imposed on the contour plots (Yamazaki & Maute, 2016).

\[ J_E = \frac{210}{32 \pi} \Delta H, \quad J_N = -\frac{210}{32 \pi} \Delta D \]

where \( J_E \) and \( J_N \) are eastward and northward current densities. We discuss the changes in the ionospheric current in response to X9.33 disk and X8.28 limb solar flares.

3. Observational Results

We present the dynamical processes associated with X9.33 disk and X8.28 limb solar flares from sunspots region 12,673 that occurred on the 6 and 10 September 2017, respectively (Figure 2). The black curve in Figure 2a represents the long-wavelength 0.1–0.8 nm of X-ray irradiance (W m\(^{-2}\)). The X9.33 disk solar flare, which was located at S08W33 on the solar disk, began at 11:53 UT on 6 September 2017 and reached a maximum at 12:02 UT with a magnitude of about 9.33 × 10\(^{-4}\) W m\(^{-2}\). The flare activity continues till 15:53 UT. After about 9 hr, another potent solar flare (X1.39) occurred around the commencement of the geomagnetic storm of 7 September 2017. The accompanied coronal mass ejections triggered a strong geomagnetic storm between 7 and 8 September 2017, with the peak planetary geomagnetic disturbance index (Kp) amounts to \(~8\) (Jimoh et al., 2019; Lei et al., 2018). Figures 2b–2f represent the geomagnetic and solar wind parameters during 3–11 September 2017. The quiet day shortly before the flares was on the 3 September 2017, with the average Kp index of about 2 (http://www.obsebre.es/en/rapid). Several M-class flares occurred during this
7–8 September 2017 geomagnetic storm (https://www.swpc.noaa.gov/), and Bagiya et al. (2018) have investigated their effects on the low latitude ionosphere. We will not focus our attention on these solar flares because M-class flares and X1.39 flare would have been strongly modulated by ongoing geomagnetic storm activities.

On the 10 September 2017, another brilliant limb solar flare (X8.28), which was located at S08W88 on the solar limb, exploded from the Sun at 15:35 UT and reached its maximum at 16:06 UT with a magnitude of about $8.28 \times 10^{-4}$ W m$^{-2}$ and finished at 16:31 UT. This flare occurred about 2 days after the main phase of the geomagnetic storm of 8 September 2017 coinciding with the recovery phase of the storm. In principle, the features of these solar flare events as revealed by GOES-15 and SDO satellites are a noticeable increase in intensities of the X-ray and EUV irradiance. For the X9.33 disk flare, there are two maxima in the 30.4-nm
Figure 3. Comparisons of the global ionospheric current during the X9.33 disk and X8.28 limb flares. (a and c) The solar X-ray flux ($10^{-4}\times W\ m^{-2}$) as measured by GOES-15 satellite and (b and f) the EUV flux in the 30.4-nm band ($10^{-4}\times W\ m^{-2}$) as measured by Extreme Ultraviolet Variability Experiment (EVE) onboard the SDO satellite. (c and g) The global ionospheric current during flare onset and (d and h) the ionospheric current during flare peak. The magnetic perturbations recorded at each observatory during the events are superimposed on the contour plots as red arrows with the vector scale of 50 nT. The vertical dashed lines in the top panels show the X-ray and EUV fluxes at the onset and peak of the solar flare. The 50-kA current flows within the streamlines. The red solid curve and black dashed horizontal line on the contours indicate the geomagnetic and geographic equators, respectively. The gray curves indicate the day-night terminator.
EUV spectral measured by the SDO, the first EUV flux peak was found at 11:58 UT, while the second peak was found at 12:02 UT. These enhancements registered at 11:58 UT and 12:02 UT have a significant impact on the ionosphere as well as GNSS applications (Berdermann et al., 2018). As noted earlier, all the effects begin rather suddenly at apparently the same time and end coincidentally after a time interval of about 18 min. Conditions of X8.28 limb flare persisted for several hours, even though the X-ray and EUV fluxes decreased just after the solar flare peak and remained decreased until the end of the flare. The solar perturbations of X8.28 EUV flux shown later persist for several hours, even though the X-ray flux registered lower values after the flare (Tsurutani et al., 2005, 2009). In general, during the X9.33 disk and X8.28 limb flares, the solar flux proxy ($F_{10.7}$ index) is found to be persisted at a moderate solar activity level with magnitudes of about 135 and 102 solar flux units (sfu, 1 sfu = 10$^{-22}$ W m$^{-2}$ Hz$^{-1}$), respectively. In addition, the $V_{sw}$, IMF-$B_z$, SYM-$H$, and $AE$ dropped to a minimum value (Figure 2b–2f). Further details of the observations revealed in Figure 2 will be discussed in the subsequent sections.

The connection between X9.33 solar disk flare and the ionospheric current is presented in Figures 3c and 3d, where the top panel shows the variation of X-ray and EUV fluxes during the X9.33 disk flare (Figures 3a and 3b). At the flare onset, the X-ray and EUV fluxes increased sharply, peaked at 12:02 UT, as discussed later (Figures 3a and 3b). By observing the solar-terrestrial environment during the period, none of the time-varying geomagnetic parameters shows any significant changes, indicating an extended quiet condition (Figures 2b–2f). Superimposed magnetic perturbations with red arrows on the contour plots represent the direction of the ionospheric current, while the black dashed horizontal line and the red curve indicate the geomagnetic and geographic equators, respectively (Figures 3c and 3d). The gray curves on the contour plot indicate the day-night terminator. It is obvious that when the X9.33 disk flare begins around 11:53 UT, only the European-African ionospheric current (Figure 3c) recorded a current of about 150 and $-143$ kA in the northern and southern hemispheres, respectively. In the northern and southern hemispheres, focus positions were seen around ($-35^\circ$N, $-12$ LT) and ($-30^\circ$S, $-12$ LT), respectively. The first peak of the X9.33 disk flare ionospheric current at 11:58 UT recorded a larger magnitude of about 222 and $-208$ kA in the northern and southern hemispheres, respectively. During this period, their centers of the northern and southern day circulations correspond to ($-38^\circ$N, $-12$LT) and ($-30^\circ$S, $-13$LT), respectively (not shown). When the X9.33 flare reaches its peak around 12:02 UT, the whole hemispheric ionospheric current increases (Figure 3d). Specifically, the northern ionospheric current across the European-African sector increases up to about 292 kA, and in the southern hemisphere, it becomes about $-267$ kA. During this period, the foci positions are seen at ($-40^\circ$N, $-12$ LT) and ($-30^\circ$S, $-13$ LT). These scenarios indicate a higher northern ionospheric current compared to the southern ionospheric current during X9.33 flare peak (Figure 3d). In addition, the magnetic perturbation vectors show high and low current densities in opposite directions at the northern and southern hemispheres (Figures 3c and 3d). During the flare peak, the magnetic perturbation vectors at the African sector are larger compared to other sectors at the middle to low latitudes. We also observed a directional change at the southern hemisphere around 50$^\circ$W and 80$^\circ$E due to a small drift of an electric field (Figures 3c and 3d). Compared to magnetic perturbations during the flare onset, similar features are also seen but with less intensities.

It is of interest to examine the changes in the ionospheric current during the X9.33 disk flare. These effects are estimated by subtracting the ionospheric current values without the flare from those during the flare, that is, flare peak at 12:02 UT and preflare at 11:40 UT (Figure 4a). However, we considered the ionospheric current during the same time evolutions on the 3 September 2017 as the reference values for comparison (Figure 4c). We observed that the total background ionospheric current intensity during the quiet day is by far less (Figure 4c), accounting for only about 20% of the total background ionospheric current produced at the peak of the flare (Figure 4a). The ionospheric current foci positions also varied significantly and registered at ($-38^\circ$N, $-12$LT) in the northern hemisphere, while that of the southern ionospheric current vortex is recorded at ($-30^\circ$S, $-13$ LT) over the European-African sector (Figure 4a). Earlier studies found that the daytime ionospheric current had a sudden increment at the peak of a solar flare, and the enhancement increased with the increasing X-ray and EUV radiations (Annadurai et al., 2018; Curto et al., 2018). Hence, the significant enhancements in the background ionospheric current on the sunlit ionosphere were due to X9.33 disk flare, whereas the enhanced background ionospheric current observed at nighttime is
unlikely to be caused by the sudden radiation of the X9.33 solar flare but was most likely attributed to the sparse data distribution, albeit there have been several observational reports of significant nighttime ionospheric current due to solar flares (Sastri & Murthy, 1975). The UT or longitudinal variations observed in the ionospheric current during the quiet period followed the variations during the flare peak (Figure 4a). The background ionospheric current obtained demonstrated similar ionospheric current variations, indicating no specific solar flare effect of ionospheric current (Figure 4c).

The variations of the X-ray and EUV fluxes during the X8.28 limb solar flare are illustrated in Figures 3e and 3f. During the X8.28 flare, the X-ray increased and reached its peak at 16:06 UT (Figure 3e), while the EUV flux started increasing at around 15:54 UT and reached the maximum at about 16:08 UT (Figure 3f). The magnitude of EUV flux variation during the peak of X8.28 limb flare recorded about $8.28 \times 10^{-4}$ W m$^{-2}$, which increased by 24% with respect to that of the flare onset. Thereafter, the EUV flux enhancement continues increasing until shortly after the flare had faded away. The solar and geomagnetic conditions during X8.28 limb flare were moderately quiet, supporting the certainty of magnetic effects due to solar flares (Figures 2b–2f). At around 90°W longitude, the ionospheric current increase was stronger during the flare peak. An exception seen in southern central Asia was a strong decrease in ionospheric current at the flare peak. The northern American focus, which was observed during the flare onset was located at

Figure 4. Differences in the global ionospheric current between (a) flare peak and preflare for X9.33 disk solar flare and (b) flare peak and preflare for X8.28 limb solar flare. (c and d) The global ionospheric currents are the same except for the quiet reference day 3 September 2017. The red solid curve and black dashed horizontal line on the contours indicate the geomagnetic and geographic equators, respectively. The 50-kA current flows within the streamlines. The gray curves indicate the day-night terminator centered at 12:02 and 16:06 UT.
(~25°N ~ 75°W), changes its position to ~28°N and ~80°W during the flare peak. During the peak flare, the magnetic perturbation vectors are eastward with a magnitude of 50 nT at the American geomagnetic equator (Figures 3g and 3h). The direction of magnetic perturbation vectors shows no clear variations over the Asian African sectors.

To investigate the changes in the ionospheric current, we obtained the differences between the flare peak at 16:06 UT and pref flare at 15:32 UT (Figure 4b). For comparison, the reference ionospheric current values are estimated as stated above, except for day 3 September 2017 reference day (Figure 4d). The differences in the ionospheric current changes during quiet periods are almost zero, confirming that no significant SFE ionospheric current change during the X8.28 limb flare onset (Figure 4d). However, the differences during the peak flare increased significantly to about 100 kA in the northern hemisphere and an increase of about −150 kA in the southern hemisphere with the total absolute change in ionospheric current intensity of around 250 kA registered at flare peak (Figure 4b). These values were about 36% larger than the current

Figure 5. Ionospheric current intensity during the (a–d) X9.33 disk and (e–f) X8.28 limb flares. (a and e) The solar X-ray flux ($10^{-4} \times \text{W m}^{-2}$) as measured by GOES-15 satellite and (b and f) the EUV flux in the 30.4-nm band ($10^{-4} \times \text{W m}^{-2}$) as measured by EVE onboard the SDO satellite. (c and g) The global ionospheric current intensity during flare and during 3 September 2017 quiet reference day (blue dashed lines). (d and h) The differences in the current intensity between flare day and quiet reference day. The vertical dashed lines on the panels show the start and peak times of X-ray.
intensity observed during the quiet period at the start of the flare (Figure 4d). In addition, the X8.28 background current shows a remarkable change in the foci positions, and most of the enhancements occurred around 90°W longitude. The background ionospheric current response to X8.28 flare was reduced in the northern hemisphere, and in the dark region ionosphere, there was slightly enhanced ionospheric currents at (~20°S, ~170°W). The enhancement observed around 100°E longitude in the southern hemisphere during the quiet day 3 September 2017 might not be real ionospheric current, as there are no magnetic stations in this location to account for such ionospheric current enhancement. The diurnal and semidiurnal variations in the ionospheric current variation at the time of flare maximum could be influenced by the neutral winds or background electric fields as earlier stated (Figure 4b). We can see that the daytime ionospheric current was enhanced around 90°W longitude, and the enhanced magnitude is related to the strong solar X-ray and EUV radiations.

To further understand the solar flare influences on the ionospheric electrodynamics, we obtained the ionospheric current intensity (i.e., the maximum northern current value minus minimum southern current value) during the X9.33 disk (Figure 5c) and X8.28 limb flares (Figure 5g). The change in the current intensity (ΔI), which accounts for the local time effects is also obtained by finding the difference in the current intensity between the flare and reference day (Figures 5d and 5h). Evident from the plot is the enhancement in the current intensity during both flares, which is more intense due to X8.28 flare in comparison with the X9.33 flare. The values of the current intensity show a similar variation with X-ray and EUV fluxes, with a total current intensity of 564 kA flowing during the course of the X9.33 flare, whereas that of X8.28 limb flare is 511 kA with a similar pattern as EUV flux. Thus, the absolute change in the current intensity due to X8.28 flare is approximately registered at 314 kA, while that of the X9.33 flare is 271 kA with respect to the current at the flare onset (Figures 5d and 5h). Compared the ionospheric current variations with the X-ray and EUV fluxes shown in Figures 5a and 5b, the ionospheric current intensity and changes in the current intensity approximately reflect the X-ray and EUV fluxes variations observed due to X9.33 flare effects. As the X-ray and EUV fluxes increase, the value of current intensity increases, which further confirmed the dependence of ionospheric current on the X-ray and EUV fluxes (Curto et al., 2018; Richmond & Venkateswaran, 1971). For the X8.28 flare, the variation of the EUV did not show such in-phase behavior with X-ray as that of the X9.33 flare. The variations in the current intensity during X8.28 limb flare could be modulated by the EUV flux. Thus, it appears that the ionospheric electric fields associated with the F region conductivity changes could play an important role in altering the current intensity. However, the interplay of the F region conductivity is unknown, and numerical simulations are needed in this regard to understand the solar flare effects on the ionospheric electrodynamics and to further address the E and F regions coupling studies.

4. Discussion

We have examined the global ionospheric current during the X9.33 disk and X8.28 limb solar flares using the global geomagnetic field perturbations. We found that a significant enhancement in the time-varying ionospheric current when the solar flare is maximum due to enhancement in the X-ray and EUV fluxes (Annadurai et al., 2018; Curto et al., 2018; Gaya-Piqué et al., 2008; Nagata, 1966; Raja Rao & Panduranga Rao, 1963; Richmond & Venkateswaran, 1971; Van Sabben, 1961; Volland & Taubenheim, 1958). Ionospheric current effects due to the X9.33 disk flare have been investigated by Curto et al. (2018) and found that the northern daytime ionospheric current is more intense than the corresponding southern current during the solar flare peak. These results are in good agreement with the results obtained in this investigation. However, an opposite effect is found in the ionospheric current due to X8.28 limb flare, that is, the southern daytime hemispheric current is more intense than the corresponding northern hemispheric one. A similar situation occurs during the solar flare, where there is a significant change in the current vortices positions at the solar flare peak leading to the enhanced southern current vortex and hemispheric asymmetry (Annadurai et al., 2018). In this study, both the X9.33 disk and X8.28 limb flares professed asymmetrical pattern of the ionospheric current despite the fact that they occurred during the equinox, where the ionospheric current vortices nearly symmetric, because of the configuration of the solar terminator and the geomagnetic meridian.

It has been observed that brilliant solar flare events depend on its time evolution, for example, the growth and decay times and its positions on the solar disk as shown by Qian et al. (2010, 2011). Recent studies carried out
Various electrodynamic effects of the $F$ region during the solar flares due to changes in the electric field, which causes its density to decrease, have been reported (Tsurutani et al., 2009). Since the ionospheric conductivity strongly depends on the plasma density due to changes in the X-ray and EUV radiations, the changes in the conductivity will dominate the $E$ region, thereby decreasing the role of the electric field in coupling the conductivity of the ionosphere (Tsurutani et al., 2005, 2009). By considering the effect of EUV flux contribution, the changes in the electric field will alter the ionospheric plasma density due to the ionization and recombination of electrons and ions, affecting the electron density distribution, which may affect the direction of zonal winds, and $F$ region dynamo currents. Several other mechanisms such as varying meteorological influences, diurnal and semidiurnal tidal winds become the dominant drivers of ionospheric current (Rishbeth, 1997; Scherliess, 2016; Thome & Wagner, 1971; Yamazaki et al., 2011). When the X-ray and EUV irradiance that controls solar flare increase significantly at ~12:02 UT on 6 September 2017, the ionospheric current vortices in both hemispheres were significantly increased (Curto et al., 2018). The northern and southern currents foci positions were registered at (~40°N, ~12LT) and (~30°S, ~13LT), respectively (Figure 3d). During this period, the northern ionospheric currents vortices due to X9.33 flare are weaker on the dayside region. In fact, sunlit background ionospheric currents in the northern hemisphere are stronger during the X9.33 flare, and its center is not at the same local time as in the northern hemisphere (Figure 4b). The currents foci appeared earlier in local time and greater in latitude in the northern sunlit hemisphere than in the southern sunlit hemisphere, with a time difference of about 3 hr. We also found that a diurnal background variation is responsible for these larger current vortices during the peak phase of an X9.33 flare (Figure 4b). This diurnal signature seen in the background ionospheric variation has been reported in the day-to-day variation of ionospheric current on the sunlit side given that they are caused by irregular variations in the neutral winds (Stening, 1969; Tarpley, 1970). Richmond et al. (1976) confirmed that both diurnal winds and semidiurnal tides variation affect the ionospheric current generation.

In the case of X8.28 flare, a significant increase in the ionospheric current that changes from around 197 to 511 kA simultaneously changed the focus position from (~25°N, ~90°W) to (~35°N, ~95°W) in the northern American sector (Figure 5d). This observation confirms our earlier understanding that enhancement in ionospheric current due to solar flare is the reason for the changes in the focus position (Annadurai et al., 2018; Curto et al., 2018; Gaya-Piqué et al., 2008). It is also the reason for more enhanced ionospheric current in the southern hemisphere compared to the northern hemisphere. However, there is a strong background ionospheric current vortex in the southern hemisphere for the X8.28 limb flare. It is observed that the foci of the current appeared almost at the same local time and lower in latitude in the northern sunlit hemisphere than in the southern sunlit hemisphere. The time difference between the northern and southern background ionospheric current vortices due to X8.28 flare is about 0.8 hr. An additional typical dominating component that could change the ionospheric current morphology is the storm effects, indicative of the fact that the spherical harmonic analysis method lacks the capacity to separate the storm effects from Sfe. Since the X8.28 limb flare is far from the main phase of the geomagnetic storm, the solar and geomagnetic conditions, to some extent, are not the major contributors to the significant changes in the background ionospheric current. By comparing the background ionospheric current charts during both flares and reference day, we can see that there is significant variation in the ionospheric current due to both flares. Effect of the X9.33 flare is more pronounced in the northern hemisphere than that in the southern hemisphere.
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On the average, the ionospheric current variations due to X9.33 disk and X8.28 limb flare were twice as strong as the ionospheric currents of the daily variations. The total current intensity increased from around 293 kA at the start flare to 564 kA during the X9.33 flare peak, and it increased from 197 to 511 kA during the peak of the X8.28 flare. The percentage change of the total current intensity of the X9.33 flare is about 16% lower than that of the X8.28 flare. This indicates that the differences in solar flux or the associated ionospheric conductance, the ionospheric current changes in response to these two solar flares also depend on universal times of the solar flare occurrence, that is, the corresponding geographic longitudes, where the subsolar point is located. The longitudinal effect causing by universal time variations of the magnetic field as well as the seasonal effect could also play a major role.

Moreover, apart from the storm conditions, X-ray and EUV fluxes effects probably be the underlying electro-dynamics and coupling processes driving them and might be connected with the lower atmospheric forcing, which has been reported (Lei et al., 2018; Pedatella, 2016). More observations and numerical studies are needed to study the influence of different sources of forcing on ionospheric current. It is important to note that the changes in the current intensities relative to both flares have improved our understanding that the solar flare intensity is of paramount importance when studying the solar flare mechanism producing these effects. Although much remains yet to be found out regarding the connection between the location on the solar surface and the ionospheric responses (Qian et al., 2010, 2019; Zhang et al., 2002). The magnetic field variations of X9.33 disk and X8.28 limb flares have given hints about the dynamics of electromagnetic radiation being controlled by the solar flare mechanisms. The two events are only thin hints and do not allow conclusions about different dynamics of electromagnetic radiation at Earth’s surface due to the two different flair types. Future studies will be needed to investigate the statistics of several disk and limb flares.

5. Conclusions

We have presented a detailed study on the global ionospheric current during the solar disk and limb flares using the global magnetic field records observed during 6 and 10 September 2017. At the peak of the X9.33 disk flare, X-ray and EUV radiations are significantly enhanced, which had led to two enhanced current vortices appearance at (~40°N, ~12 LT) and (~30°S, ~13LT) in the northern and southern hemispheres, respectively. At the peak of X8.28 limb flare, two enhanced current vortices appear at (~16°N, ~10:10 LT) and (~35°S, ~10:30 LT) in the northern and southern hemispheres. The total current intensity increased from 293 kA at the start flare to 564 kA at the peak of X9.33 flare, and it increased from 197 to 511 kA at the peak of X8.28 flare. In other words, the change of the total current intensity of the X9.33 flare is about 16% less than that of the X8.28 flare, although the changes of X-ray and EUV for the X9.33 flare were much stronger. Moreover, the typical ionospheric current response to X9.33 disk flare is more in the northern hemisphere than that of the southern hemisphere, whereas ionospheric current due to X8.28 limb flare registered opposite variability. Overall, the enhanced ionospheric conductance along with the associated electric field changes could result in the observed ionospheric current variations during the solar flare. In addition, the longitudinal variations of the magnetic field as well as the seasonal effect could also play an important role. Further investigations are required to explore the involved physical processes.

References

Amory-Mazaudier, C., Bolaji, O. S., & Doupnia, V. (2017). On the historical origins of the CEJ, DP2, and Ddyn current systems and their roles in the predictions of ionospheric responses to geomagnetic storms at equatorial latitudes. Journal of Geophysical Research: Space Physics, 122, 7827–7833. https://doi.org/10.1002/2017JA024152
Annadurai, N. M. N., Hamid, N. S. A., Yamazaki, Y., & Yoshikawa, A. (2018). Investigation of unusual solar flare effect on the global ionospheric current system. Journal of Geophysical Research: Space Physics, 123, 8599–8609. https://doi.org/10.1029/2018JA025601
Bagiya, M. S., Thampi, S. V., Hui, D., Sunil, A. S., Chakraborty, D., & Choudhary, R. K. (2018). Signatures of the solar transient disturbances over the low latitude ionosphere during 6 to 8 September 2017. Journal of Geophysical Research: Space Physics, 123, 7598–7608. https://doi.org/10.1002/2018JA025496

Banerjee, K., & Sturrock, P. A. (1989). Classification of solar flares. Annual Review of Astronomy and Astrophysics, 27(1), 421–467. https://doi.org/10.1146/annurev.aa.27.091889.002225

Berdermann, J., Krieger, M., Banay, D., Heymann, F., Hoque, M. M., Wilken, V., et al. (2018). Ionospheric response to the X9.3 flare on 6 September 2017 and its implication for navigation services over Europe. Space Weather, 16, 1604–1613. https://doi.org/10.1029/2018SW001913

Campbell, W. H., & Schiffmacher, E. R. (1985). Quiet ionospheric currents of the northern hemisphere derived from geomagnetic field records. Journal of Geophysical Research: Space Physics, 90(A7), 6475. https://doi.org/10.1029/JA090iA07p06475

Chapman, S., & Bertels, J. (1940). Geomagnetism. (1st ed., Vol. 1). London: Oxford University Press.

Curto, J. J., Amory‐Mazaudier, C., Torta, J. M., & Menivielle, M. (1994). Solar flare effects at Ebre: Regular and reversed solar flare effects, statistical analysis (1953 to 1985), a global case study and a model of elliptical ionospheric currents. Journal of Geophysical Research: Space Physics, 99(A3), 3945. https://doi.org/10.1029/93JA02270

Curto, J. J., Marsal, S., Blanch, E., & Aladill, D. (2018). Analysis of the solar flare effects of 6 September 2017 in the ionosphere and in the Earth's magnetic field using spherical elementary current systems. Space Weather, 16, 1709–1720. https://doi.org/10.1029/2018SW001927

Davies, K. (1990). Ionospheric Radio. London: Peter Peregrinus Limited. https://doi.org/10.1049/PBEW031E

Denardini, C. M., Chen, S. S., Resende, L. C. A., Moro, J., Bilibio, A. V., Fagundes, P. R., et al. (2018). The embrace magnetometer network for South America: Network description and its qualification. Radio Science, 53, 288–302. https://doi.org/10.1002/2017RS006477

Doumossoy, V., Cohen, Y., Arora, B., & Yamamoto, K. (2003). Local time and longitude dependence of the equatorial electrojet magnetic effects. Journal of Atmospheric and Solar‐Terrestrial Physics, 65(14–15), 1265–1282. https://doi.org/10.1016/j.jastp.2003.08.014

Gaya‐Piqué, L. R., Curto, J. J., Torta, J. M., & Chulliat, A. (2008). Equivalent ionospheric currents for the 5 December 2006 solar flare event determined from spherical harmonic cap analysis. Journal of Geophysical Research, 113, A07304. https://doi.org/10.1029/2007JA012934

Gjerloev, J. F. (2009). A global ground‐based magnetometer initiative. Eos, Transactions American Geophysical Union, 90(27), 230–231. https://doi.org/10.1029/2009EO270002

Ishkov, V. (2018). Catalog of Solar Flare Events With X‐ray Class MI–Xc=17.5.XXXIII Cycle of Solar Activity (1996–2008) ESDB repository, GC RAS, Moscow, https://doi.org/10.2205/ESDB‐SAD‐FE‐02 (smore database). National Geophysical Data Center (NGDC).

Jemal, O., Chen, S. S., Mendillo, M. S., & Titheridge, A. (1995). High‐latitude magnetic anomalies associated with solar flare events. Journal of Geophysical Research: Space Physics, 100(A1), 61–67. https://doi.org/10.1029/94JA02005

Liu, J., Lu, N., Tian, C., Yin, H., Ge, W., & Fassold, R. (2016). Magnetic signatures of the solar flare of 6 September 2017 in the low latitude ionosphere. Journal of Geophysical Research: Space Physics, 121, 5958–5967. https://doi.org/10.1002/2016JA023706

Liu, S., Liu, Z., & Sun, X. (2015). Global signature of geoelectricity following the solar flare on 2015 May 16. Geophysical Research Letters, 42, 8213–8219. https://doi.org/10.1002/2015GL065219

Liu, J., Liu, C., Chen, Y., Liu, X., Fang, T., & Chen, H. (2007). Study on the ionospheric electric field effect on the geomagnetic field. Journal of Geophysical Research: Space Physics, 112, A08S11. https://doi.org/10.1029/2006JA011306

Oguz, H., Cakir, M., & Cakir, E. (2016). Geomagnetic activity and its relation to solar activity during solar cycle 24. Space Weather, 14(9), 1615–1620. https://doi.org/10.1002/2015SW001615

Oguz, H., Özdemir, F., & Cakir, E. (2017). The relation of geomagnetic activity with solar cycle 24. Journal of Atmospheric and Solar‐Terrestrial Physics, 161, 99–105. https://doi.org/10.1016/j.jastp.2017.04.005

Ozmen, S. (2019). Ionospheric storms and geomagnetic storms caused by solar flares. Journal of Geophysical Research: Space Physics, 124, 9381–9404. https://doi.org/10.1029/2019JA026590

Piqué, L. R., Curto, J. J., Torta, J. M., & Ministrero, A. (2008). Equivalent ionospheric currents for the 5 December 2006 solar flare event determined from spherical harmonic cap analysis. Journal of Geophysical Research, 113, A07304. https://doi.org/10.1029/2007JA012934

Qian, L., Burns, A. G., Chamberlin, P. C., & Solomon, S. C. (2010). Flare location on the solar disk: Modeling the thermosphere and ionosphere response. Journal of Geophysical Research, 115, A09S31. https://doi.org/10.1029/2009JA015225

Qian, L., Burns, A. G., Chamberlin, P. C., & Solomon, S. C. (2011). Variability of thermosphere and ionosphere responses to solar flares. Journal of Geophysical Research, 116, A10309. https://doi.org/10.1029/2011JA016777

Qian, L., Wang, W., Burns, A. G., Chamberlin, P. C., Coster, A., Zhang, S.-R., & Solomon, S. C. (2011). Solar flare and geomagnetic storm effects on the ionosphere during 6–11 September 2017. Journal of Geophysical Research: Space Physics, 122, 2288–2311. https://doi.org/10.1002/2018JA026175

Raja Rao, K. S., & Panduranga Rao, M. (1963). On the location of ionospheric current system causing geomagnetic solar effects. Journal of Atmospheric Sciences, 20, 498–501. https://doi.org/10.1175/1520-0469(1963)20<498:OTLOCIS>2.0.CO;2

Rastogi, R. G., Pathan, B. M., Rao, D. R. K., Sastry, T. S., & Sastri, J. H. (1999). Solar flare effects on the geomagnetic elements during normal and counter electrojet periods. Earth, Planets and Space, 51(9), 947–957. https://doi.org/10.1186/BF03351565

Richmond, A. D., Matsushita, S., & Tarpley, J. D. (1976). On the production mechanism of electric currents and fields in the ionosphere. Journal of Geophysical Research, 81(4), 547–555. https://doi.org/10.1029/JA081i004p00547

Richmond, A. D., & Venkateswaran, S. V. (1971). Geomagnetic crochets and associated ionospheric current systems. Radio Science, 6(2), 136–139. https://doi.org/10.1029/RS006i002p00139

Rishbeth, H. (1997). The ionospheric E‐layer and F‐layer dynamics—A tutorial review. Journal of Atmospheric and Solar‐Terrestrial Physics, 59(15), 1873–1880. https://doi.org/10.1016/S0303-9040(97)00070-X

Roy, M. (1977). Mutual induction between the E‐ and D‐layers of the ionosphere during a solar flare. Journal of Atmospheric and Solar‐Terrestrial Physics, 39(2), 221–227. https://doi.org/10.1016/0021-9169(77)90115-5

Sastri, J. H., & Murthy, B. S. (1975). Geomagnetic effects in the dark hemisphere associated with solar flares. Journal of Geophysical Research: Space Physics, 27(1), 67–73. https://doi.org/10.1029/JG027i001p00067

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Scherliess, L. (2016). Ionospheric response to X-ray and EUV flux changes during solar flares. Geophysical Monograph Series, 225–242. https://doi.org/10.1029/9781118929216.ch18

Sterling, R. J. (1969). An assessment of the contributions of various tidal winds to the Sq current system. Planetary and Space Science, 17(5), 889–908. https://doi.org/10.1016/0032-0633(69)90095-6

Tapeley, J. D. (1970). The ionospheric wind dynamo—II. Solar tides, planet. Space Science, 18(7), 1091–1103. https://doi.org/10.1016/0032-0633(70)90110-8

Thome, G. D., & Wagner, L. S. (1971). Electron density enhancements in the E and F1 regions of the ionosphere during solar flares. Journal of Geophysical Research, 76(28), 6883–6895. https://doi.org/10.1029/JA076i028p06883

Tarpley, J. D. (1970). The ionospheric wind dynamo—I. Solar tides, planet. Space Science, 18(7), 1091–1103. https://doi.org/10.1016/0032-0633(70)90110-8

Van Sabben, D. (1961). Ionospheric current system of ten IGY-solar flare effects. Atmospheric and Terrestrial Physics, 22(1), 32–42. https://doi.org/10.1016/0021-9169(61)90175-1

Van Sabben, D. (1968). Solar flare effects and simultaneous magnetic daily variation, 1959–1961. Journal of Atmospheric and Terrestrial Physics, 30(9), 1641–1648. https://doi.org/10.1016/0021-9169(68)90012-3

Veldkamp, J., & van Sabben, D. (1969). On the current system of solar-flare effects. Journal of Atmospheric and Terrestrial Physics, 18(2–3), 192–202. https://doi.org/10.1016/0021-9169(69)90092-1

Volland, H., & Taubenheim, J. (1958). On the ionospheric current system of the geomagnetic solar flare effect (s.f.e.). Journal of Atmospheric and Terrestrial Physics, 12(4), 258–265. https://doi.org/10.1016/0021-9169(58)90056-4

Yamazaki, Y., & Maute, A. (2016). Sq and EEJ—A review on the daily variation of the geomagnetic field caused by ionospheric dynamo currents. Space Science Reviews, 206(1–4), 299–405. https://doi.org/10.1007/s11214-016-0282-z

Yamazaki, Y., Yumoto, K., Cardinal, M. G., Fraser, B. J., Hattori, P., Kakinnami, Y., & Yoshikawa, A. (2011). An empirical model of the quiet daily geomagnetic field variation. Journal of Geophysical Research, 116, A10312. https://doi.org/10.1029/2011JA016487

Yamazaki, Y., Yumoto, K., Yoshikawa, A., Watari, S., & Uita, H. (2009). Characteristics of counter-Sq SFe (SFE*) at the dip equator CPMN stations. Journal of Geophysical Research, 114, A05306. https://doi.org/10.1029/2009JA014124

Zhang, D. H., Mo, X. H., Cai, L., Zhang, W., Feng, M., Hao, Y. Q., & Xiao, Z. (2011). Impact factor for the ionospheric total electron content response to solar flare irradiation. Journal of Geophysical Research, 116, A04311. https://doi.org/10.1029/2010JA016089

Zhang, D. H., Xiao, Z., & Zhang, Q. (2002). The correlation of flare’s location on solar disc and the sudden increase of total electron content. Chinese Science Bulletin, 47(1), 82–85. https://doi.org/10.1360/02hb9017