Journal of Atmospheric and Solar-Terrestrial Physics 105-106 (2013) 170–180

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Signatures of moderate (M-class) and low (C and B class) intensity solar flares on the equatorial electrojet current: Case studies

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ARTICLE INFO

Article history:
Received 16 May 2012
Received in revised form
30 August 2013
Accepted 10 October 2013
Available online 18 October 2013

Keywords:
Solar flare
X-ray flux
EUV flux
Equatorial electrojet
Equatorial ionosphere
Space weather

ABSTRACT

The present investigation brings out, in contrast to the earlier works, the changes in the equatorial electrojet (EEJ) current in response to a few moderate (M-class) and low (C and B class) intensity solar flares during 2005–2010. Special care is taken to pick these flare events in the absence of prompt electric field perturbations associated with geomagnetic storms and substorms that also affect the electrojet current. Interestingly, only the normalized (with respect to the pre-flare level) deviations of daytime EEJ (and not the deviations alone) change linearly with the increases in the EUV and X-ray fluxes. These linear relationships break down during local morning hours when the E-region electric field approaches zero before reversal of polarity. This elicits that the response of EEJ strength corresponding to less-intense flares can be appropriately gauged only when the local time variation of the quiet time E-region zonal electric field is taken into account. The flare events enhanced the EEJ strength irrespective of normal or counter electrojet (CEJ) conditions that shows that solar flares change the E-region ionization density and not the electric field. In addition, the enhancements in the X-ray and EUV fluxes, for these flares occurring during this solar minimum period, are found to be significantly correlated as opposed to the solar maximum period, indicating the differences in the solar processes in different solar epochs.

1. Introduction

The EUV and the X-rays in the solar electromagnetic spectrum contribute to the production of ionospheric plasma. While solar hard X-rays (≤ 0.1 nm) during flare events, H-Lyα (121.6 nm) absorption by NO and cosmic rays, cause the D region ionization, solar soft X-rays in the wavelength range of 0.8–20 nm and UV radiation (79.6–102.7 nm) contribute to the ionization of the E-region. The ionization in the F-region is primarily affected by the radiation in the spectral range of 14.0–79.6 nm. A detailed description on the different regions of solar spectra and their roles in the production of the ionospheric layers is available in Rishbeth and Garriot (1969). The sudden enhancements in EUV and X-ray fluxes during solar flares can cause prompt enhancements in the ionization at the ionospheric heights. The effect of the GOES (Geostationary Operational Environment Satellite) X-class flares (peak flux larger than 10^{-4} W/m^2) on the Earth's ionosphere is quite significant and as a consequence these intense flares have received maximum attention. The enhancement in the ionization at the ionospheric heights in varying degrees due to such intense flares is termed as "crochets" or Solar Flare Effects (SFE) or Sudden Ionospheric Disturbances (SID). SFEs are known to have important ramifications for radio propagations as they can lead to sudden onset of short wave fade out, phase anomaly, shift in the radio frequency, cosmic noise absorption, changes in atmospherics, etc. (e.g. Thome and Wagner, 1971; Mitra, 1974; Donnelly, 1976; Davies, 1990). Most of these effects like short wave fade outs stem from the additional ionization produced primarily in the ionospheric D region by the X-rays associated with flare. In addition, it is also shown that strong flares significantly modulate the currents flowing in the ionospheric E-region (e.g. Raja Rao and Panduranga Rao, 1963; Nagata, 1966; Oshio et al., 1967; Richmond and Venkateswaran, 1971; Rastogi et al., 1999). It is also shown that flares can have significant impact on the F-region electron content (e.g. Mendillo et al., 1974; Tsurutani et al., 2005; Liu et al., 2006; Mahajan et al., 2010), thermospheric densities (e.g. Sutton et al., 2006; Le et al., 2012) and OI 630.0 nm dayglow intensity (Das et al., 2010). Therefore, it has now become apparent that strong X-class flares do have significant impact on all the ionospheric regions.

The underlying reason behind the conspicuous impact of the GOES X-class flares on the low latitude ionosphere is the enormity of the thermal part of the total energy (hot thermal plasma emits soft X-rays) released during these flares. Although non-thermal energies can be as large as thermal energies during a flare (e.g. Saint-Hilaire and Benz, 2005, and references cited therein), it is well-accepted that as one goes from the high (X-class) to moderate (M-class) and low (C or B class) intensity solar flares based on

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1364-6826/$ - see front matter
http://dx.doi.org/10.1016/j.jastp.2013.10.005

GOES soft X-ray measurements, the total thermal energy released will be less in comparison with the high intensity X-class flares. Further, the signatures corresponding to the moderate and low intensity solar flares can get obfuscated by the possible comparable effects due to transient electric field disturbances. Such transient electric field disturbances can occur during storm sudden commencement (e.g. Sastri, 2002), prompt penetration/overshielding events (e.g. Chakrabarty et al., 2006) associated with the polarity reversal of interplanetary electric field (IEF) or substorm (e.g. Chakrabarty et al., 2010). Therefore, in order to unambiguously isolate the signatures of moderate and low intensity solar flares on the ionospheric E-region over low latitudes, it is important to choose flare events when the transient electric field disturbances are absent. It must also be mentioned here that regular ionosonde observations are often inadequate to investigate the effects of solar flare on the ionospheric E-region owing to the lack of sufficient temporal resolution as the change in solar flux associated with solar flare is ephemeral in nature. The presence of the type-II plasma irregularities over the low latitude region and more importantly, the short-wave fade-outs make the ionosonde technique poorly effective in capturing the changes in the density of the ionospheric E-region during flares.

In order to gauge the flare-related changes in the equatorial electrojet current flowing in the dip-equatorial E-region, it is necessary to understand the factors that determine the amplitude of the changes in the EEJ strength. It is known that the ionospheric E-region is characterized by the generation of the solar quiet (S_q) time electric fields (E_{sq}) due to the global scale dynamo action. These electric fields are mapped to the F-region of the ionosphere through the geomagnetic field lines. In the E-region, the motion of the electrons is governed by the strength of the geomagnetic field and thus electrons respond to the $E_{sq} \times B$ drift while the ions move with the neutrals under the influence of collisions resulting in a vertical polarization field. This polarization field forces the electrons to move usually in the westward direction during daytime causing the intense eastward jet of current known as the equatorial electrojet (EEJ). Due to the mutually perpendicular geometry of E_{sq} and B, this effect is most pronounced in a narrow latitudinal belt ($\pm 3^{\circ}$) and at a narrow height region (10 km) centered around 105 km where the Cowling conductivity maximizes. On many occasions, for reasons still being debated, the direction of the EEJ current reverses giving rise to the counter-electrojet (CEJ). As the EEJ strength depends on the available ionization (n) and the plasma drift velocity ($\mathbf{v}$), significant and prompt changes in EEJ are caused by the additional ionization generated during the transient events like solar flares and/or by the perturbation electric field (that can change plasma drift velocity) associated with the space weather events. It is shown that these transient electric field disturbances can alter EEJ significantly (e.g. Kikuchi et al., 2003; Chakrabarty et al., 2010; Simi et al., 2012).

The strength of EEJ is conventionally derived based on ground-based magnetic measurements. Further, the changes in EEJ corresponding to the transient events like moderate and low intensity solar flares can only be captured by magnetic measurements with high precision and cadence. The ground-based measurements of the magnetic field respond to both the solar flare and transient electric field perturbations. Therefore, unambiguous identification of the effects of moderate and low intensity solar flares on the EEJ strength requires careful delineation of the contribution due to the flares from that due to the electric field disturbances. Manju and Viswanathan (2005) investigated a number of flare events and its impact on the E-region current and electric field in the 95–110 km altitude region using VHF (54.95 MHz) coherent backscatter radar observations during daytime from Thumba, a dip equatorial station in India. Although they identified significant changes in the ionospheric E-region over low latitudes corresponding to the X-class solar flares, similar effects could not be identified during M and C class flares. It is to be noted that the magnetometer measurements used by them had lesser cadence and precision. As the strength of the flares is determined based on the X-ray flux and the ionization in the ionospheric E-region depends considerably on the EUV flux, it is important to also understand the relationship between the X-ray and EUV fluxes during these moderate and low intensity solar flares.

There are a number of studies (e.g. Donnelly, 1976; Tsurutani et al., 2005; Leonovich et al., 2010; Mahajan et al., 2010; Le et al., 2011; Zhang et al., 2011) that highlight the discrepancy in the relationship between the solar X-ray and EUV fluxes during flare events. The underlying factor for this discrepancy is pointed out to be associated with the center-to-limb distance (CMD) of the flare location. As the solar EUV radiation originates in the lower solar atmosphere, the absorption of EUV radiation increases as the flare site is located increasingly away from the central meridian. This center-to-limb effect is nominal for the X-ray flux as they originate from the coronal region. This leads to the reduced correlation coefficient between solar X-ray and EUV fluxes during flares. Keeping this in mind, the X-ray fluxes are often adjusted for the CMD factor (multiplied by cos(CMD)) that leads to better correlation. Le et al. (2011) have recently pointed out that the CMD effects for the EUV enhancements are smaller for M and C class flares. However, most of the above-mentioned investigations including the investigation by Le et al. (2011) belong to the solar maximum period.

The solar cycle 23 is characterized by an unusually deep minimum (e.g. Nandi et al., 2011; Broomhall et al., 2009; Bisoi et al., in press) and it is important to investigate how the moderate and low intensity flares affect the equatorial ionosphere during this solar minimum period. In addition, many of the flare events investigated in the earlier reports occurred when geomagnetic storms or substorms were in progress. In order to find the tell-tale ionospheric signatures for the moderate and low intensity flares, it is important to identify and isolate the transient and simultaneously occurring electric field disturbances associated with the storm or substorm events. In the present investigation, a three-pronged approach is adopted to investigate the effects of the moderate and low intensity X-class flares on the equatorial E-region. First, the active regions on the solar disk responsible for these flares are identified so that the relationship between the X-ray and EUV fluxes during these flares occurring during the minimum of the solar cycle 23, is better understood. Second, the interplanetary as well as storm–substorm parameters are carefully analyzed to identify the background geomagnetic conditions so that the possible transient electric field effects on the equatorial E-region can be isolated. Third and the most important one, the relationship between the deviations in the EUV flux during these flares and the associated response in the strength of EEJ is addressed.

2. Data

For the present investigation, the active region maps of the Sun provided by the Mees Solar observatory (http://www.solar.ifa.hawaii.edu/) are used. These maps provide the number of the active region, its location on the visible disk and the area of spots in millionths of the visible hemisphere. The X-ray (0.1–0.8 nm) fluxes (in W m^{-2}) are obtained from the X-ray detectors on-board the Geostationary Operational Environment Satellite (GOES, http://spidr.ngdc.noaa.gov/spidr/) with 1 min cadence. Excess of X-ray flux (ΔX-ray) associated with a flare is taken as the difference between the peak X-ray flux and the pre-flare flux (taken here as the background flux) just prior to the onset of the