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Key Points:
- Solar flares induce a westward disturbance in dayside equatorial electric field
- Negative correlation between the equatorial electric field and electrojet during solar flares
- The weakened eastward electric field depresses low-latitude ionospheric electron density during solar flares

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Equatorial ionospheric electrodynamics during solar flares

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Abstract Previous investigations on ionospheric responses to solar flares focused mainly on the photoionization caused by the increased X-rays and extreme ultraviolet irradiance. However, little attention was paid to the related electrodynamics. In this letter, we explored the equatorial electric field (EEF) and electrojet (EEJ) in the ionosphere at Jicamarca during flares from 1998 to 2008. It is verified that solar flares increase dayside eastward EEJ but decrease dayside eastward EEF, revealing a negative correlation between EEJ and EEF. The decreased EEF weakens the equatorial fountain effect and depresses the low-latitude electron density. During flares, the enhancement in the Cowling conductivity may modulate ionospheric dynamo and decrease the EEF. Besides, the decreased EEF is closely related to the enhanced ASY-H index that qualitatively reflects Region 2 field-aligned current (R2 FAC). We speculated that solar flares may also decrease EEF through enhancing R2 FAC that leads to an overshielding-like effect.

1. Introduction

The solar flare is an extreme space weather event that induces sudden increase in solar X-ray and extreme ultraviolet (EUV) irradiance. The increased irradiance produces the extra ionization at Earth's ionospheric heights and results in various disturbances, disrupting navigation, and communication systems.

Extensive studies have been carried out to investigate the solar flare effects on the ionosphere [e.g., *Afraimovich et al.*, 2001; *Le et al.* 2007, 2013, 2016; *Leonovich et al.*, 2002; *Liu et al.*, 2004; *Mendillo and Evans*, 1974; *Nogueira et al.*, 2015; *Tsurutani et al.*, 2005; *Wan et al.*, 2005; *Xiong et al.*, 2011; *Zhang and Xiao*, 2005; *Zhang et al.*, 2011]. These studies showed that the ionospheric responses to solar flares can be interpreted by the photochemical processes resulted from the increased solar X-rays and EUV [*Liu et al.*, 2011].

Some researchers also investigated the equatorial electrojet (EEJ) responses to solar flares and showed various complexities as observed by magnetometers. During solar flares, the dayside eastward EEJ often presents an impulsive increase [*Rastogi et al.*, 1997]. Whereas *Rastogi et al.* [1999, 2013] and *Sripathi et al.* [2013] found that solar flares can produce a westward increase in the EEJ under a counter electrojet (CEJ) and a partial CEJ. *Manju et al.* [2009] reported diverse variations in EEJ at African and Indian sectors in the same flare event. *Abdu et al.* [2017] investigated the EEJ responses to intense solar flares under a superstorm and revealed that the EEJ can flow spectacularly westward under disturbance dynamoelectric fields near sunrise.

The equatorial electric field (EEF) is a key factor in determining the dynamics and structure of the low-latitude ionosphere [*Fejer*, 2011]. However, its behavior is rarely mentioned during solar flares. Both the observation [*Liu et al.*, 2007] and simulation [*Qian et al.*, 2012] showed the weakened equatorial ionization anomaly (EIA) during the 28 October 2003 flare, which implies the potential electric field effects. However, there were no direct electric field observations during this flare. Subsequently, *Xiong et al.* [2014] uniquely reported the EEF variations during a solar flare.

Up to now, it is still ambiguous whether there is a common feature for the EEF response to solar flares. Thus, it is necessary to further identify the behavior of the EEF during solar flares. If solar flares do cause changes in the EEF, how does the EEF affect the ionosphere? Furthermore, what are responsible for the changes of the EEF during solar flares?

The major motivation of this paper is to observationally identify the behavior of the EEF during solar flares. The EEF is detected by the Jicamarca (11.95°S, 76.87°W) incoherent scatter radar (ISR) and the Jicamarca Unattended Long-Term studies of the Ionosphere and Atmosphere (JULIA) system during the period from 1998 to 2008. Meanwhile, we investigate the correlation between the EEF and EEJ, present the EEF effects on low-latitude ionosphere, and try to seek the possible involved physics of the EEF variations during solar flares. The results provide a new perspective for the study of the ionospheric responses to solar flares, focusing on the related electrodynamics.

2. Observations

Figure 1 gives an overview of the solar flare on 7 September 2005. Figure 1a depicts the X-ray fluxes in the wavelength bands from 0.1 to 0.8 nm observed by the Geostationary Operational Environmental Satellites (GOES) at the interval 1400–2000 UT. As illustrated by the vertical black lines, the solar flare starts at 1717 UT, peaks at 1747 UT, and ends at 1803 UT. The increase of the X-ray flux reaches 1.81×10^{-3} W/m^2 during this extreme solar flare.

Figure 1b shows the scaled *H* components at Jicamarca (blue line) and Piura (red line) in this solar flare. The scaled *H* components at each station are obtained from the *H* values after subtracting the averaged value around midnight. The *H* components at both stations show a rapid increase after the solar flare onset. The increased magnitude can attain 283 nT over Jicamarca and 137 nT at Piura. From the difference in the scaled *H* values between Jicamarca and Piura [e.g., *Rastogi and Klobuchar*, 1990; *Anderson et al*., 2002], we can deduce the EEJ strength over Jicamarca, which is shown in Figure 1c. It can be seen that the EEJ increases dramatically from 74 to 225 nT after the solar flare onset.

Figure 1d depicts the 150 km echoes vertical drift measured by JULIA system with a resolution of 5 min. *Woodman and Villanueva* [1995] and *Chau and Woodman* [2004] verified that the 150 km echoes vertical drifts are in good agreement with the ISR *F* region vertical drifts, and the measured errors are smaller than 1 m/s. As shown in Figure 1d, the vertical drift decreases from 24.5 to 10.2 m/s between 1717 UT (1217 LT) and 1803 UT (1303 LT) during this solar flare. The decreased vertical drift is induced by a westward electric field in the dayside equatorial ionosphere. As a result, a westward disturbance electric field is observed during the solar flare.

The abrupt westward disturbance in dayside EEF can occur under the control of the overshielding penetration process [*Kelley et al*. 1979]. The physics of penetration process can be described by a current source, the imbalance between the Region 1 field-aligned current (R1 FAC) and Region 2 field-aligned current (R2 FAC) [e.g., *Wolf et al*., 2007; *Wei et al*., 2015]. The northward turning or decrease of southward interplanetary magnetic field (IMF) B_z will decrease the R1 FAC rapidly, while the R2 FAC takes longer to decay. As a result, the R2 FAC is stronger than R1 FAC temporarily and can cause a westward disturbance electric field in the dayside equatorial ionosphere. This is the so-called overshielding penetration electric field. Besides, *Wei et al*. [2008] proposed that the abrupt decreased solar wind dynamic pressure may change the magnetospheric configuration and also cause an overshielding effect.

We examine the IMF B_z, solar wind pressure, and *AE* index in Figures 1e–1g. The solar wind parameters are obtained from the OMNI database and have been shifted to account for the time propagation from the L1 point to the magnetosphere. It is found that the IMF B_z is northward, and the solar wind dynamic pressure and *AE* index do not depict any abrupt disturbances before and during the solar flare. Thereby, the westward disturbance in EEF is unambiguously related to the solar flare in Figure 1.

In order to avoid the aforementioned possible disturbances, we select only the cases where the solar flares occur without obviously abrupt disturbances in IMF B_z, solar wind pressure, and *AE* index. Due to the rare observations of the EEF, we find only another seven cases from 1998 to 2008 without interplanetary disturbances.

Figure 2 gives three cases on 17 September 2001, 13 December 2001, and 13 September 2005, respectively. The corresponding vertical drifts are detected by Jicamarca ISR with a resolution of 5 min. The vertical drifts from ISR are averaged at altitudes between 200 and 600 km, and the measured errors are smaller than 1 m/s [e.g., *Kudeki et al*., 1999; *Zhang et al*., 2016]. Figure 3 gives another three cases on 16 July 2004, 14 August 2004, and 22 August 2005, respectively. The corresponding vertical drifts are from JULIA. The EEJ data are absent on 16 July to 14 August 2004. The cases in Figures 2 and 3 are under the northward IMF B_z and are not influenced by the solar wind origins and magnetospheric reconfiguration. Figure 4 shows a case on 27 April 2006. This flare occurs under the stable southward IMF B_z with a magnitude smaller than −4 nT, solar wind pressure of 2 nPa, and *AE* index smaller than 180 nT. Under these conditions, the EEF should not be

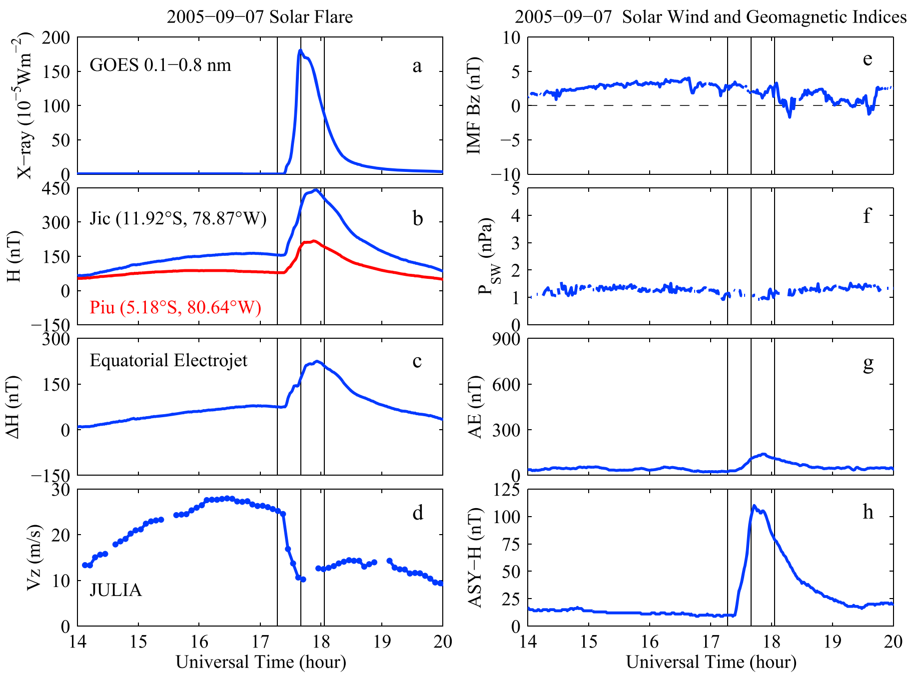

Figure 1. The (a) X-ray fluxes (0.1–0.8 nm) observed by GOES, (b) scaled geomagnetic *H* component at Jicamarca (11.92°S, 78.87°W) and Piura (5.18°S, 80.64°W), (c) equatorial electrojet (EEJ), (d) averaged 150 km vertical drift observed by JULIA, (e) interplanetary magnetic field (IMF) B_z, (f) solar wind dynamic pressure, (g) *AE* index, and (h) asymmetric ring current (ASY-H) index during the solar flare on 7 September 2005. The vertical black lines in each panel from left to right show the start, peak, and end time of the flare, respectively.

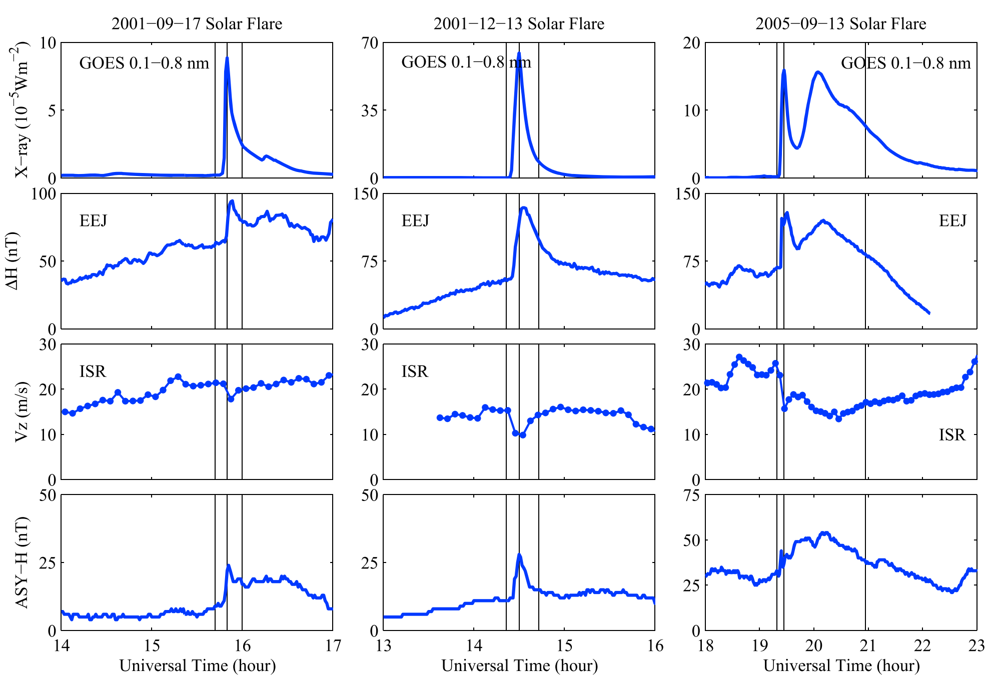

Figure 2. The panels from top to bottom present the X-ray fluxes (0.1–0.8 nm), EEJ over Jicamarca, averaged *F* region vertical drift observed by Jicamarca ISR, and ASY-H index during solar flares on (left column) 17 September 2001, (middle column) 13 December 2001, and (right column) 13 September 2005. The vertical black lines in each panel from left to right show the start, peak, and end time of the flare, respectively.

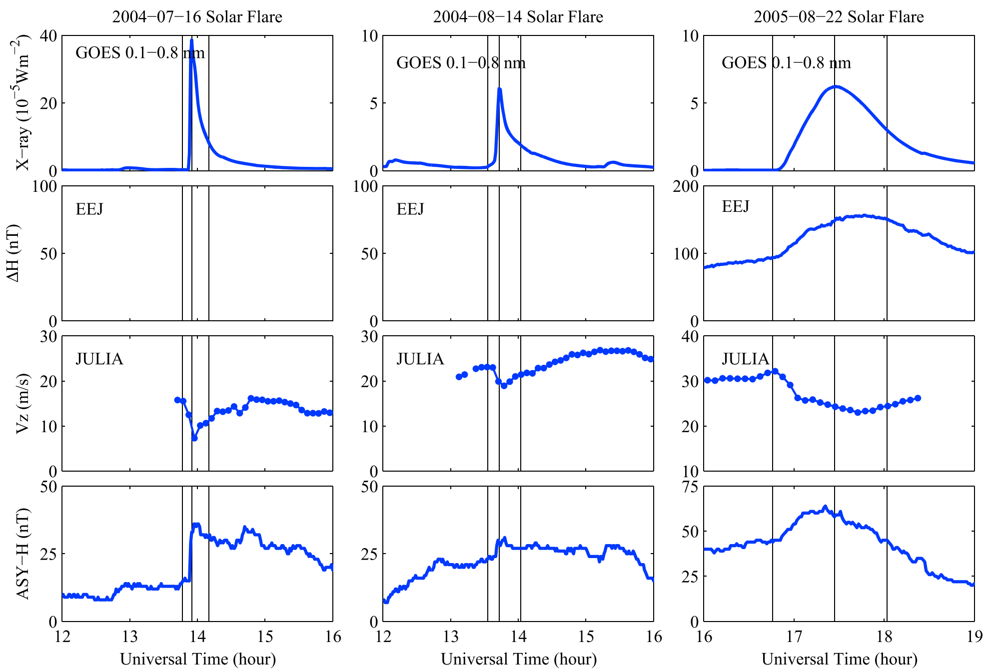

Figure 3. Same as Figure 2 but for the cases on (left column) 16 July 2004, (middle column) 14 August 2004, and (right column) 22 August 2005. Besides, the vertical drifts are observed by JULIA. The EEJ data are absent on 16 July to 14 August 2004.

affected by the solar wind and magnetospheric origins. Hence, the observed changes in the EEF should be induced by the solar flare.

The seven cases in Figures 2–4 show a common feature that the vertical plasma drifts are decreased in the dayside equatorial ionosphere during solar flares, similar to the results in Figure 1. Besides, the EEJ is enhanced in all five cases with ΔH observations.

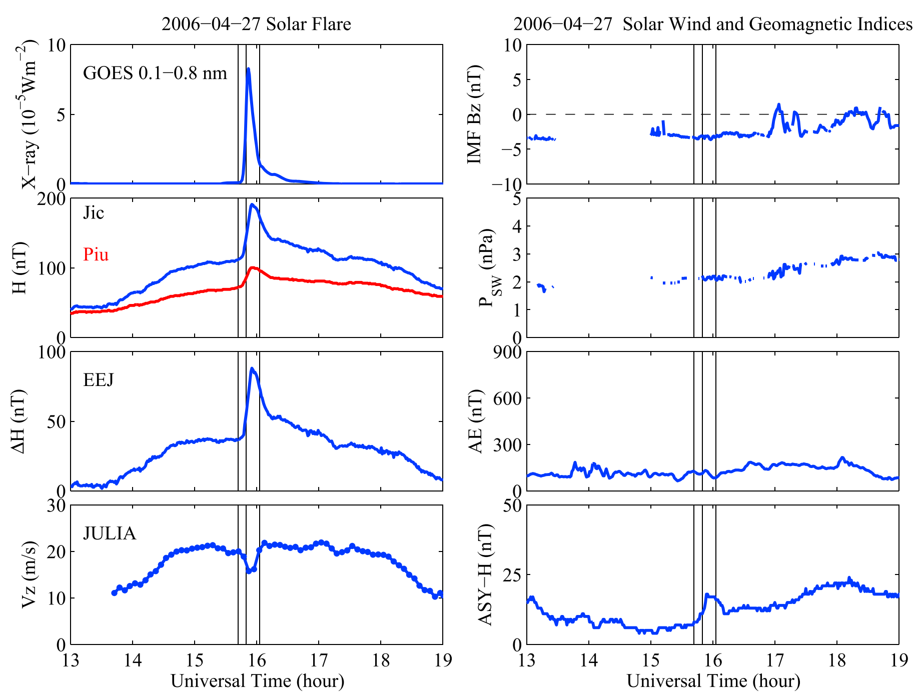

Figure 4. Same as Figure 1 but for the case on 27 April 2006.

3. Discussion

3.1. Correlation Between EEF and EEJ During Solar Flares

We explored the vertical plasma drifts observed by the Jicamarca ISR and JULIA system from 1998 to 2008 and found eight cases during solar flares without interplanetary disturbances. The results verified that the dayside upward vertical drifts have significant decreases during all solar flares; that is, the solar flares induce a westward disturbance electric field.

Meanwhile, the observations of EEJ presented the concurrent increases during six solar flares. The EEJ is eastward at preflare stages, and the increases in ΔH indicate the enhanced eastward EEJ, confirming the earlier results of *Rastogi et al*. [1997] that solar flare effects are primarily the augmentation of the preflare current system. *Anderson et al*. [2002] used the ΔH deduced from magnetometers and vertical plasma drifts observed by Jicamarca ISR to identify a positive and linear relationship between the EEJ and EEF. Since then, the ΔH is widely known as a substitution for the EEF. However, the current observations suggested an opposite correlation between EEF and EEJ during flares, which is contrary to that built by *Anderson et al*. [2002]. So it is inaccurate to use ΔH as a substitution for EEF during solar flares.

3.2. Effects of the EEF on the Ionosphere During a Solar Flare

The observations indicated a westward disturbance electric field in the dayside ionosphere during solar flares. Now we present its effects to the ionospheric responses during a solar flare. Figure 5 displays the electron density at 360 km at 1035 LT observed by the planar Langmuir probe onboard the Challenging Minisatellite Payload (CHAMP) satellite. The red lines denote the results from 1742 to 1812 UT on 7 September 2005. This period was around the peak of the solar flare, and the EEF decreased to a minimum. As a reference, we plot the results from 1715 to 1746 UT on 6 September 2005 with the blue lines.

Under the action of the enhanced photoionization during a solar flare, electron density should be increased in the equatorial to middle latitude ionosphere. As shown in Figure 5, the electron density is indeed increased significantly at equatorial and middle latitudes during a solar flare, whereas the low-latitude ionospheric electron density outside the EIA crests is depressed shown by the red line with dots. In addition, the red dotted line shows that the double crests of EIA move to lower latitudes compared to the blue dotted line, illustrating a weakened equatorial fountain effect during solar flares. The results suggest the effects of the decreased eastward EEF in the ionospheric responses to solar flares. Besides, in the results of *Wan et al*. [2005] the variation rate of the total electron content at low latitudes becomes negative at the later stage of a solar flare, maybe hinting the effects of decreased EEF.

3.3. Possible Mechanisms for the Westward Disturbance in EEF During Solar Flares

The ionospheric electric field is mainly produced by the *E* region dynamo in the dayside, which can be influenced by the changes in the conductivity. As discussed by *Manju and Viswanathan* [2005] and *Manju* [2016], during solar flares the vertical polarization electric field can be influenced by the ratio of the Hall-to-Pedersen conductivity. *Qian et al*. [2012] proposed that the zonal electric field (current EEF) can be also modulated by the variations in ionospheric conductivity during the solar flare. Solar flares can enhance the electron density in the *E* region and thus increase the Hall, Pedersen, and Hall-to-Pedersen conductivities, which can in turn decrease the dayside eastward EEF [*Qian et al*., 2012]. The present observations showed an enhancement in the EEJ and a decrease in the EEF. Associated with the Ohm's law $\vec{J} = \sigma \cdot \vec{E}$ ($\vec{J}$ is EEJ, σ is Cowling conductivity, and $\vec{E}$ is EEF), it can determine an enhanced Cowling conductivity during solar flares. The enhancement in the Cowling conductivity may modulate the ionospheric dynamo and decrease the EEF similar to the simulation conducted by *Qian et al*. [2012].

Besides, we note that the EEF may be influenced by other sources during solar flares. It is interesting that the ASY-H index has an increase in all solar flare events. The striking characteristic is the one-to-one correspondence between the decreased vertical plasma drift and the enhanced ASY-H index. When the ASY-H index shows an enhancement associated with the enhanced solar X-ray, the vertical plasma drift responds as a decrease trend. The ASY-H index is interpreted as a good indicator of asymmetric (partial) ring current, which is known as connecting to R2 FAC [e.g., *Iyemori and Rao*, 1996; *Wei et al*., 2008]. Therefore, we can estimate the development of R2 FAC associated with the ASY-H variations, at least qualitatively. The R2 (R1) FAC is connected with the auroral oval near its equatorward (poleward) edge and is intimately related to spatial

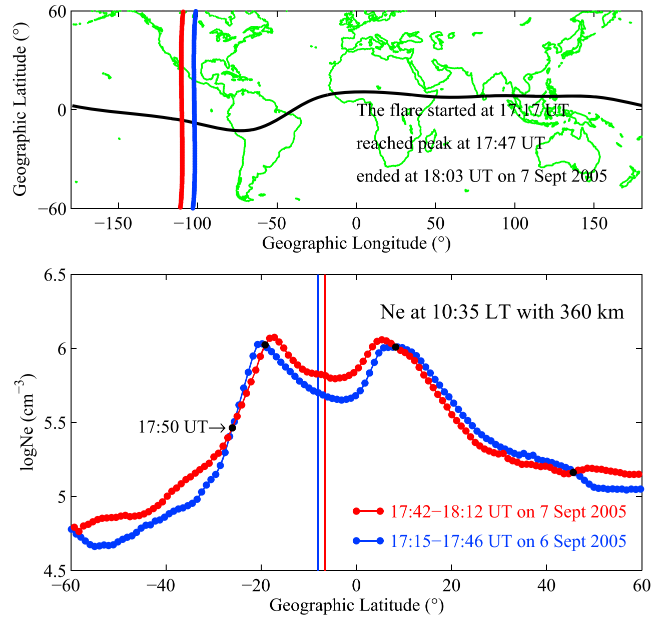

Figure 5. (bottom row) The comparison of the electron density at 360 km between the geographic latitudes of 60°S and 60°N observed by CHAMP satellite from 1715 to 1746 UT on 6 September 2005 (blue line with dots, quiet time) and from 1742 to 1812 UT on 7 September 2005 (red line with dots, solar flare), in which the vertical lines represent geographic latitude of the magnetic equator. (top) The corresponding ascending orbits. The equatorial crossing local time is at 1035 LT for these two orbits.

variations in the ionospheric electric field and conductivity. It may reasonably speculate that during solar flares the increased conductivity may modify the R2 FAC larger than R1 FAC due to the lower latitude of R2 FAC. A larger enhancement in R2 FAC may lead the R2 being greater than R1 and imbalance between R2 and R1 FAC, which may induce a westward disturbance in dayside EEF, like an overshielding effect.

Recently, *Abdu et al*. [2017] investigated the EEJ responses to intense solar flares under a superstorm. The results showed that a rapid recovery in the storm time *AE* index can delay the EEJ responses to the solar flare because of the overshielding electric field of westward polarity. The overshielding effect in *Abdu et al*. [2017] is under the rapid recovery *AE* activity and should be induced by the slowly decreased R2 FAC compared to R1 FAC that is controlled by the interplanetary electric field [*Kelley et al*., 1979]. However, it should be noted that the current supposed overshielding-like effect is not the same as theirs. The overshielding-like effect here is controlled by the enhanced R2 FAC due to the changed conductivity in the ionosphere induced by solar flares. Further, the change of R2 FAC during the solar flare is a possible speculation according to the ASY-H index. The mechanisms of the decreased EEF induced by solar flares still need to be further identified in the future work.

4. Conclusions

In this study, we investigated the behavior of the equatorial electric field (EEF) during solar flares from 1998 to 2008 without interplanetary disturbances. The EEF was measured by the Jicamarca ISR and JULIA system. The most important result is to verify that the decreased EEF is a common feature during solar flares. Another important finding is that there is a negative correlation between the EEF and ΔH; that is, the equatorial electrojet (EEJ) deduced from ΔH is enhanced during solar flares. It implies that ΔH is not an accurate substitution for EEF during solar flares.

During solar flares, the electron density is increased significantly at equatorial and middle latitudes. In contrast, the low-latitude ionospheric electron density is depressed. Further, the double crests of EIA shift to lower latitudes during solar flares, presenting the effects and importance of the decreased EEF in the ionospheric responses to solar flares. Thus, in the future flare study, it is worthy to focus on the related electrodynamics, not only the photochemical process.

The possible involved physics of the westward disturbance electric field during solar flares is also to try to study. The enhancement in the Cowling conductivity may modulate the ionospheric dynamo and decrease the EEF. Besides, the developments of the EEF are closely related to the enhanced ASY-H index that qualitatively reflects Region 2 field-aligned current (R2 FAC). We speculated that solar flares may also decrease EEF through enhancing R2 FAC that leads to an overshielding-like effect.

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The X-ray data observed by GOES 10 were obtained from the NOAA ftp site (ftp://ftp.ngdc.noaa.gov). The vertical plasma drift and equatorial electrojet data at Jicamarca can be downloaded from the Web (jro.igp.gob.pe/madrigal/). The solar wind and geomagnetic data are from the OMNI data set (http://omniweb.gsfc.nasa.gov). This research is supported by National Natural Science Foundation of China (41231065 and 41621063), Chinese Academy of Sciences (KZZD- EW-01-3), and the National Important Basic Research Project of China (2012CB825604).

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