



Ionospheric F Layer Radial Current in Response to Southward and Northward IMF Turnings

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Abstract: In this work, local time variations of the response of the ionospheric F layer radial current (IRC) to southward and northward IMF turning events at low and high solar activity are investigated for the first time using Challenging Minisatellite Payload (CHAMP) observations from 2001 to 2010. The response strength of disturbed IRC to the southward and northward IMF turnings does not show any preference for low or high solar activity. At low and high solar activity, the IRC increases in the upward (downward) direction in the daytime (nighttime) within 1.5 h after a sudden southward IMF turning. Conversely, the IRC increases in the downward (upward) direction in the daytime (nighttime) within 1.5 h after a sudden northward IMF turning. The response of zonal wind is insignificant or opposite to that of the IRC. F region electron density may only contribute to the response of the IRC in certain local time sectors. This work indicates that the enhanced convection electric field induced by southward IMF turnings and the reduced convection electric field combined with the overshielding electric field during northward IMF turnings impact the prompt penetration electric field from high latitudes to low latitudes and cause local time differences in the responses of the IRC.

Keywords: ionospheric radial current; southward IMF turning; northward IMF turning; prompt penetration electric field; convection electric field; overshielding electric field



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1. Introduction

The ionospheric F layer radial current (IRC) is a vertical current near the magnetic equator and plays a pivotal role in the coupling process of ionospheric E and F layers. The IRC mainly flows downward during the day and upward at night [1] and switches directions between 15 and 16 magnetic local times (MLT) [2]. The IRC was conventionally believed to be affected by the neutral wind and plasma drift. It can be expressed as $j_z = \sigma_P(E_z - u_y B_x)$ [1,3], where j_z is the intensity of the IRC, σ_P is the local Pedersen conductivity in the F region, E_z is the radial electric field, u_y is the zonal wind, and B_x is the mean geomagnetic field at the equator. Positive B_x is northward, positive u_y is eastward, and positive E_z or j_z is downward. $\sigma_P E_z$ represents the polarization current, and $\sigma_P u_y B_x$ represents the neutral wind dynamo current. The dominant contributor of the IRC is the neutral wind dynamo current. The zonal wind is mainly westward in the daytime and eastward in the nighttime, generating a downward IRC in the daytime and an upward IRC in the nighttime. This is called the zonal wind effect [4].

However, Wang et al. (2022) [5] reported multiple changes in the polarity of the IRC within a day, which cannot be solely explained by the zonal wind effect. Using the Challenging Minisatellite Payload (CHAMP), Zhong et al. (2023) [6] found that the response of the IRC to an enhanced merging electric field was mainly attributed to the prompt penetration electric field (PPEF) rather than the neutral wind effect. The enhanced merging electric field strengthened the convection electric field, caused a daytime eastward (nighttime westward) PPEF, generated an equatorward (poleward) Hall current at equatorial latitudes,

and induced an upward (downward) increase in the IRC. Thus, the physical mechanism of the IRC needs more exploration.

The southward and northward interplanetary magnetic field (IMF) turnings have a significant impact on the equatorial ionosphere [7–10]. Based on ground magnetometer data from the Circum-Pan Pacific Magnetometer Network (CPMN) and Magnetic Data Acquisition System (MAGDAS), Ohtani et al. (2013) [7] found that the equatorial electrojet (EEJ) immediately reduced after the northward IMF turnings, while the response of the EEJ to the southward IMF turnings was far less clear. They supposed that the high ionospheric conductance during southward IMF turnings was more conducive to the penetration of the electric field. However, a sharp increase (decrease) in the EEJ index during the southward (northward) IMF turnings was observed [8–10]. Bhaskar and Vichare (2013) [8] found that the efficiency of PPEF affecting EEJ in northward turning events was almost twice that in southward turning events. They concluded that the reason for the efficiency difference between northward and southward IMF turnings was that only the increase of the convection electric field contributed to the changes in the EEJ during southward IMF turning events, whereas both the reduction of the convection electric field and the increase of the overshielding electric field worked during northward IMF turning events. Solar activity had important effects on Earth, such as thermospheric zonal winds [5], ionospheric vertical drifts [11], and ionospheric plasma density [12].

These previous studies have provided insights into the IRC and the important effects of IMF changes on the equatorial ionosphere. However, the response of the IRC to polarity changes in the IMF is still unknown and the physical mechanism involved needs exploration. In this work, IRC data derived from CHAMP are used to investigate the responses of the IRC to sudden southward and northward IMF turnings at different local times at low and high solar activity. Furthermore, by analyzing the zonal wind, electron density, and EEJ derived from CHAMP, we provide a possible physical mechanism of the variations of IRC during southward and northward IMF turning events.

Section 1 introduces the background of the IRC. Section 2 presents the methods for data processing. Section 3 describes the statistical results. Section 4 discusses previous studies concerning this study and provides possible physical mechanisms for the responses of the IRC to the southward and northward IMF turnings. Section 5 provides the conclusions of this work.

2. Materials and Methods

The CHAMP satellite was a near-polar-orbiting satellite launched on 15 July 2000, with an orbital inclination of 87.3°. It initially flew at an altitude of 456 km and continued to descend until it reached about 300 km in 2010. The orbital period of CHAMP was about 93 min and required approximately 130 days to cover all local times.

The IRC was derived from the vector magnetic field from CHAMP spanning from June 2001 to August 2010, using the single-satellite method proposed by Ritter et al. (2013) [13]. The geomagnetic main field, the core field, the crustal field, and the magnetic field from magnetospheric currents were removed by utilizing the CHAOS-7 geomagnetic field model [14].

IRC density j_r (in $\mu\text{A}/\text{m}^2$) is calculated as $j_r = -\frac{1}{2\mu_0 dt} \left(\frac{dB_y^{VSC}}{V_x^{VSC}} - \frac{dB_x^{VSC}}{V_y^{VSC}} \right) / 1000$ [13], where dB_x^{VSC} and dB_y^{VSC} (in nT) denote the horizontal gradients of the magnetic field in the spacecraft velocity frame (VSC), V_x^{VSC} and V_y^{VSC} (in m/s) denote the horizontal spacecraft velocities in VSC, μ_0 signifies the vacuum permeability, and $dt = 1$ s represents the time spacing of the magnetic field gradients and velocities. At each ascending and descending orbit, IRCs within $\pm 5^\circ$ magnetic latitude (MLat) were averaged to obtain an average IRC. Cross-track winds from CHAMP at low latitudes were approximately considered to be zonal winds [15]. F region electron density was measured by CHAMP. EEJ was derived from the scalar magnetic field from CHAMP using the method of Lühr et al. (2004) [16] and Alken et al. (2013) [17].

Criteria for identifying a southward IMF turning event: (1) The IMF maintained northward for more than 10 min before the southward turning. (2) The IMF turned southward more rapidly than 1 nT/min. (3) The IMF maintained southward for more than 10 min after the turning. Criteria for identifying a northward IMF turning event: (1) The IMF maintained southward for more than 10 min before the northward turning. (2) The IMF turned northward more rapidly than 1 nT/min. (3) The IMF maintained northward for more than 10 min after the turning.

The southward and northward IMF turning events are categorized into two types according to the solar radio flux $F_{107} < 100$ sfu (low solar activity) and $F_{107} \geq 100$ sfu (high solar activity) [18]. From June 2001 to September 2005, most solar radio fluxes are larger than 100 sfu. From October 2005 to August 2010, most solar radio fluxes are less than 100 sfu. We have excluded the events where there are both periods of $F_{107} < 100$ sfu and periods of $F_{107} \geq 100$ sfu from 1.5 h before to 6 h after the southward and northward IMF turnings. As shown in Table 1, from June 2001 to August 2010, there were 705 southward IMF turning events and 892 northward IMF turning events at low solar activity, and 941 southward IMF turning events and 1043 northward IMF turning events at high solar activity. Event numbers at high solar activity are higher than those at low solar activity.

Table 1. Event numbers of southward and northward IMF turnings at $F_{107} < 100$ sfu (low solar activity) and $F_{107} \geq 100$ sfu (high solar activity) from June 2001 to August 2010.

	Southward IMF Turning	Northward IMF Turning
$F_{107} < 100$ sfu	705	892
$F_{107} \geq 100$ sfu	941	1043

3. Results

We first examined temporal variations in IMF B_z from 1.5 h before to 6 h after the southward and northward IMF turnings at low and high solar activity with a time interval of 0.5 h as depicted in Figure 1. During southward IMF turning events at low solar activity (Figure 1a), IMF B_z decreased at -0.5 h Δ Universal Time (Δ UT), showed the sharpest decrease at 0 h, reached a minimum at 0.5 h, and then recovered to the level before IMF changes. From -0.5 h to 0.5 h Δ UT of southward IMF turnings at low solar activity, the total decrease in IMF B_z is 4.38 nT. During northward IMF turning events at low solar activity (Figure 1b), IMF B_z showed a northward turning at -0.5 h, increased most sharply at 0 h, reached a maximum at 0.5 h, and then recovered to the level it was before IMF changes. From -0.5 h to 0.5 h Δ UT of northward IMF turnings at low solar activity, the total increase of IMF B_z is 4.18 nT. Changes in IMF B_z during southward and northward IMF turnings at high solar activity have a similar trend to those at low solar activity, but the magnitude of the changes in IMF B_z is slightly larger. The total decrease of IMF B_z during southward IMF turning events at high solar activity (Figure 1c) is 4.54 nT from -0.5 h to 0.5 h Δ UT. The total increase of IMF B_z during northward IMF turning events at high solar activity (Figure 1d) is 4.24 nT from -0.5 h to 0.5 h Δ UT.

We performed a superposed epoch analysis (SEA) on the IRC from 1.5 h before to 6 h after the southward and northward IMF turnings at low and high solar activity. We divided the IRC into 4 MLT sectors: 00–06 MLT, 06–12 MLT, 12–18 MLT, and 18–24 MLT. CHAMP IRC data were almost evenly distributed in the 4 MLT sectors during southward or northward IMF turnings at low or high solar activity. Considering that the orbit period of CHAMP was about 1.5 h, we conducted the SEA with an interval of 1.5 h. Then subtract the mean IRC between -3 h and -1.5 h from the IRC in the corresponding MLT sectors to obtain disturbance IRC (Δ IRC).

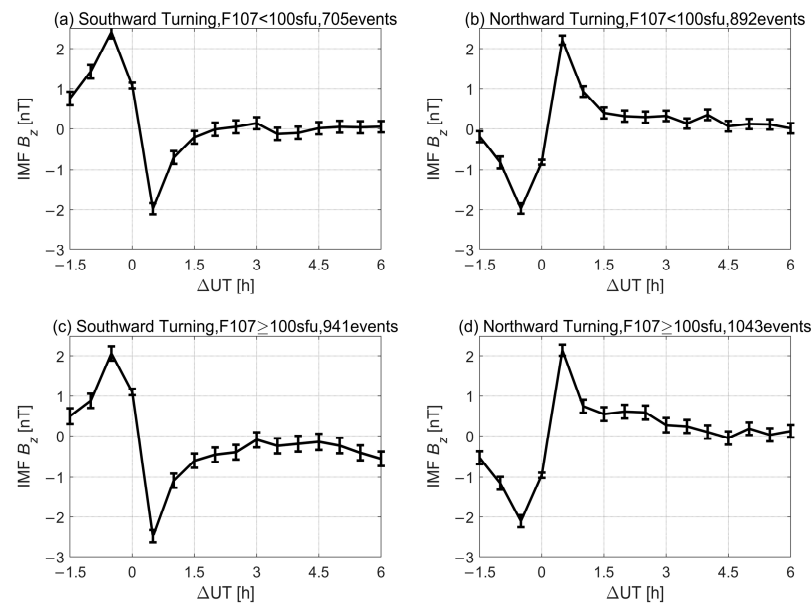


Figure 1. The superposed epoch analysis of the temporal variations in IMF B_z during southward IMF turning events at low (a) and high solar activity (c) and during northward IMF turning events at low (b) and high solar activity (d). The positive (negative) IMF B_z represents northward (southward) IMF B_z . The key time “0” Δ Universal Time (Δ UT) corresponds to the start time of IMF turning events. The error bars indicate the standard error of the mean.

Figure 2 depicts the SEA analysis on the IRC and Δ IRC during southward and northward IMF turnings at low solar activity ($F107 < 100$ sfu). In Figure 2a, the IRC is downward at 00–18 MLT and upward at 18–24 MLT during southward IMF turnings at low solar activity. When the IMF turned southward, the IRC strengthened in intensity at 00–06 MLT but weakened at other MLT sectors. The Δ IRC during southward IMF turnings at low solar activity is shown in Figure 2b. At 06–18 MLT, Δ IRC increased in the upward direction at 0–1.5 Δ UT. At 00–06 MLT and 18–24 MLT, Δ IRC increased in the downward direction at the key time. Δ IRC attained a peak after 3 h at 00–06 MLT and attained a peak after 1.5 h at other MLT sectors.

As shown in Figure 2c, the polarity of IRC during the northward IMF turnings at low solar activity was the same as that during the southward IMF turnings. However, the response of IRC to the northward IMF turnings was exactly opposite to its response to the southward IMF turnings. After the northward IMF turning, the intensity of IRC weakened at 00–06 MLT but strengthened at other MLT sectors. Figure 2d shows Δ IRC during northward IMF turnings at low solar activity. In contrast with Δ IRC responses to southward IMF turnings, Δ IRC increased in the downward direction at 06–18 MLT and increased in the upward direction at 00–06 MLT and 18–24 MLT after the northward IMF turnings. Δ IRC reached a maximum or a minimum within 1.5 h to 3 h.

Figure 3 depicts the SEA analysis on the IRC and Δ IRC during southward and northward IMF turnings at high solar activity ($F107 \geq 100$ sfu). Figure 3a,b show the IRC and Δ IRC during southward IMF turnings at high solar activity, respectively. Figure 3c,d show the IRC and Δ IRC during northward IMF turnings at high solar activity, respectively. The polarity of IRC at high solar activity was the same as that at low solar activity. The trend of IRC and Δ IRC changes at 0–1.5 h Δ UT during the southward or northward IMF turning events at high solar activity is the same as that at low solar activity. The amplitude of responses of Δ IRC to the southward and northward IMF turnings does not show any preference for low or high solar activity.

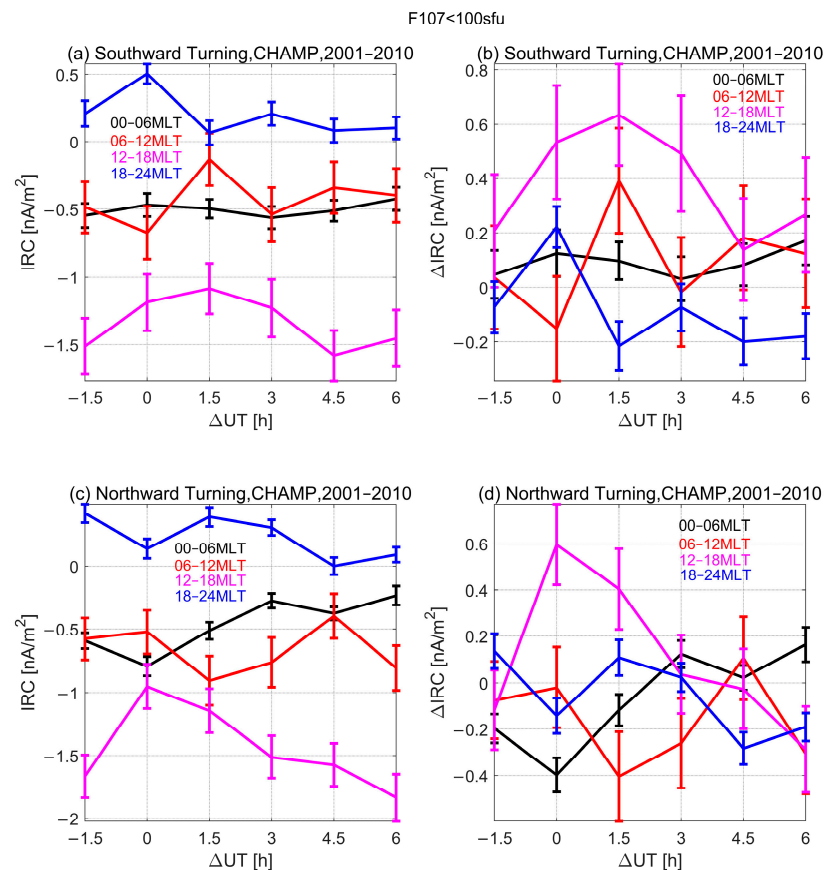


Figure 2. The SEA of the temporal variations in IRC (a,c) and Δ IRC (b,d) during southward IMF turning events (top) and northward IMF turning events (bottom) at low solar activity in different MLT sectors (represented by lines in different colors, black for 00–06 MLT, red for 06–12 MLT, magenta for 12–18 MLT, and blue for 18–24 MLT). Δ IRC represents disturbance IRC, obtained by subtracting the IRC between -3 h and -1.5 h in the corresponding MLT sectors. A positive (negative) IRC or Δ IRC represents an upward (downward) IRC or Δ IRC. The key time “0” corresponds to the start time of IMF turning events. The error bars indicate the standard error of the mean.

The IRC is almost downward at 06–12 MLT and almost upward at 18–24 MLT [19]. The amplitude of IRC at 06–12 MLT and 18–24 MLT at high solar activity is much larger than at low solar activity. The IRC switches directions during 00–06 MLT and 12–18 MLT and the local time of the IRC switching directions varies with seasons [19]. Therefore, comparing the amplitude of the mean IRC at 00–06 MLT and 12–18 MLT does not make sense.

The observational results show that whether at low or high solar activity, the responses of IRC during the daytime are opposite to those during the nighttime, and the responses of IRC to southward IMF turnings are opposite to those during northward IMF turnings. This work will explore the involved physical mechanisms in the Discussion.

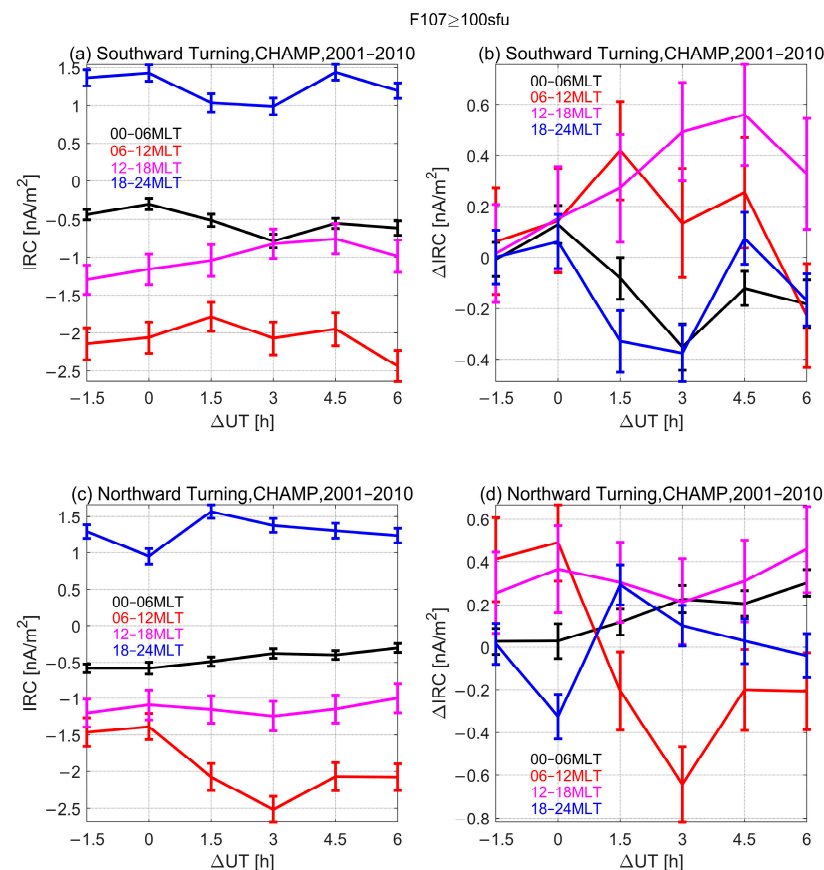


Figure 3. The superposed epoch analysis of the temporal variations in IRC (a,c) and Δ IRC (b,d) during southward IMF turning events (top) and northward IMF turning events (bottom) at high solar activity in different MLT sectors (represented by lines in different colors, black for 00–06 MLT, red for 06–12 MLT, magenta for 12–18 MLT, and blue for 18–24 MLT). Δ IRC represents disturbance IRC, obtained by subtracting the IRC between −3 h and −1.5 h in the corresponding MLT sectors. A positive (negative) IRC or Δ IRC represents an upward (downward) IRC or Δ IRC. The key time “0” corresponds to the start time of IMF turning events. The error bars indicate the standard error of the mean.

4. Discussion

According to previous studies, the IRC could be modulated by the zonal wind, ionospheric conductance, and the equatorial zonal electric field [2,4–6]. Thus, we investigated the responses of the disturbance zonal wind (Δ Uy), the disturbance electron density (Δ Ne) in the F region, and the disturbance EEJ (Δ EEJ) to southward and northward IMF turnings at low and high solar activity. Similar to Δ IRC, subtract the mean Uy/Ne/EEJ between −3 h and −1.5 h from Uy/Ne/EEJ in the corresponding MLT sectors to obtain Δ Uy/ Δ Ne/ Δ EEJ. The Uy and EEJ data derived from CHAMP are from 2001 to 2010, while the available Ne is from 2002 to 2009.

The Δ Uy, Δ Ne, and Δ EEJ during the southward IMF turnings (top panels) and northward IMF turnings (bottom panels) at low solar activity are shown in Figure 4. In Figure 4a, Δ Uy at 18–24 MLT increased in the eastward direction at 0–1.5 h Δ UT of the southward IMF turnings at low solar activity. According to the zonal wind effect, eastward (westward) Uy generated upward (downward) IRC [4]. However, Δ IRC at 18–24 MLT increased in the downward direction at 0–1.5 h Δ UT of the southward IMF turnings at low solar activity (Figure 2b), inconsistent with the zonal wind effect. Δ Uy at other MLT sectors showed insignificant changes within 1.5 h after the southward IMF turnings, while Δ IRC in the corresponding MLT sectors in Figure 2b showed clear responses at 0–1.5 h Δ UT. In Figure 4d, Δ Uy increased in the eastward direction at 0–1.5 h Δ UT at 12–18 MLT and in the westward direction at 0–3 h Δ UT at 18–06 MLT during northward IMF turnings, opposite to the responses of Δ IRC at

0–1.5 h ΔUT in the corresponding MLT sectors in Figure 2d. ΔUy at 06–12 MLT showed insignificant changes within 1.5 h after the northward IMF turnings, while ΔIRC at 06–12 MLT in Figure 2b showed a significant downward increase at 0–1.5 h ΔUT . The changes in ΔUy during the southward and northward IMF turnings at low solar activity in all MLT sectors are inconsistent with the response of ΔIRC and cannot explain the responses of ΔIRC to the southward and northward IMF turnings at low solar activity. Thus, the zonal wind effect is not the dominant contributor to the changes in the IRC during southward and northward IMF turnings at low solar activity.

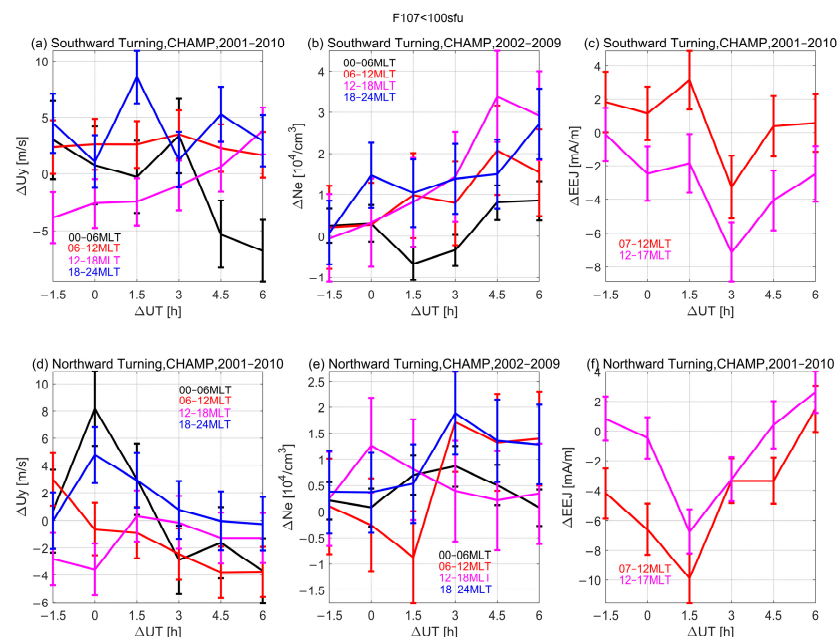


Figure 4. The SEA of the temporal variations in ΔUy (a,d), ΔNe (b,e), and ΔEEJ (c,f) during southward IMF turning events (top) and northward IMF turning events (bottom) at low solar activity in different MLT sectors. For ΔUy and ΔNe , the black line represents 00–06 MLT, the red line represents 06–12 MLT, the magenta line represents 12–18 MLT, and the blue line represents 18–24 MLT. For ΔEEJ , the red line represents 07–12 MLT and the magenta line represents 12–17 MLT. A positive (negative) ΔUy or ΔEEJ represents an eastward (westward) ΔUy or ΔEEJ . The key time “0” corresponds to the start time of IMF turning events. The error bars indicate the standard error of the mean.

As depicted in Figure 4b, ΔNe increased at 0–1.5 h ΔUT of the southward IMF turning at 06–18 MLT and decreased at 18–06 MLT. The decrease in ΔNe at 0–1.5 h ΔUT at 18–24 MLT might contribute to the weakening of IRC at 18–24 MLT during southward IMF turning events at low solar activity. But in other MLT sectors, the response of ΔNe conflicts with that of the IRC (Figure 2a). In Figure 4e, ΔNe decreased at 0–1.5 h ΔUT of the northward IMF turnings at 06–18 MLT, increased at 00–06 MLT, and showed insignificant change at 18–24 MLT. The responses of ΔNe could not explain the responses of IRC in all MLT sectors during northward IMF turning events at low solar activity (Figure 2c).

Figure 4c,f show ΔEEJ responses to southward and northward IMF turnings at low solar activity. Considering that EEJ is a dayside phenomenon, we only discussed EEJ at 07–17 MLT [20]. During southward IMF turnings in Figure 4c, ΔEEJ at 07–17 MLT increased in the eastward direction at 0–1.5 h ΔUT . After IMF turned southward, the enhanced convection electric field in high latitudes increased daytime eastward PPEF and nighttime westward PPEF in the equatorial latitudes, consequently generating an eastward disturbance of EEJ at 07–17 MLT [7–10]. Conversely, ΔEEJ at 07–17 MLT increased in the westward direction at 0–1.5 h ΔUT of the northward IMF turnings in Figure 4f. After IMF turned northward, the reduced convection electric field and the increased overshielding electric field in high latitudes induced daytime westward PPEF and nighttime eastward

PPEF in the equatorial latitudes, hence generating a westward disturbance of EEJ at 07–17 MLT [8,10]. Δ EEJ attained a peak after 1.5 h. The amplitude of the change in EEJ at 0–1.5 h Δ UT during northward IMF turnings was larger than that during southward IMF turnings, consistent with previous studies [7–9].

Figure 5 shows the Δ Uy, Δ Ne, and Δ EEJ during the southward and northward IMF turnings at high solar activity. Similar to Δ Uy at low solar activity, Δ Uy at high solar activity in Figure 5a,d show opposite or insignificant responses at 0–1.5 h Δ UT during the southward and northward IMF turnings, which cannot explain responses of the IRC. Note that 1.5 h after the southward IMF turnings, a sharp decrease in Δ Uy occurs at 00–06 MLT, consistent with Xiong et al. (2016) [21]. The physical mechanisms involved are currently unclear. In Figure 5b, the decrease in Δ Ne during 0–1.5 h Δ UT at 12–24 MLT might contribute to the weakening of IRC. However, the responses of Δ Ne at 0–1.5 h Δ UT in other MLT sectors were opposite to the changes in IRC. In Figure 5e, the increase in Δ Ne during 0–1.5 h Δ UT at 06–12 MLT and 18–24 MLT might contribute to the strengthening of IRC in the corresponding MLT sectors during southward IMF turnings at high solar activity, but the response of Δ Ne at 0–1.5 h Δ UT was insignificant or opposite to the change in IRC at 12–18 MLT and 00–06 MLT. Δ EEJ at 07–17 MLT increases in the eastward direction at 0–1.5 h Δ UT of the southward IMF turnings at high solar activity (Figure 5c). In contrast, Δ EEJ at 07–17 MLT increases in the westward direction at 0–1.5 h Δ UT of the northward IMF turnings at high solar activity (Figure 5f).

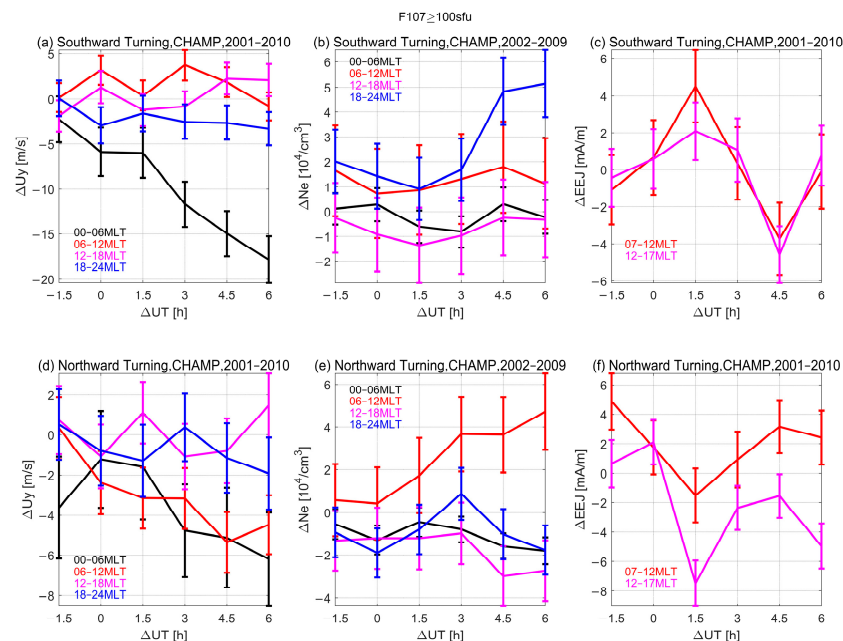


Figure 5. The superposed epoch analysis of the temporal variations in Δ Uy (a,d), Δ Ne (b,e), and Δ EEJ (c,f) during southward IMF turning events (top) and northward IMF turning events (bottom) at high solar activity in different MLT sectors. For Δ Uy and Δ Ne, a black line represents 00–06 MLT, a red line represents 06–12 MLT, a magenta line represents 12–18 MLT, and a blue line represents 18–24 MLT. For Δ EEJ, a red line represents 07–12 MLT and a magenta line represents 12–17 MLT. A positive (negative) Δ Uy or Δ EEJ represents an eastward (westward) Δ Uy or Δ EEJ. The key time “0” corresponds to the start time of IMF turning events. The error bars indicate the standard error of the mean.

At low and high solar activity, the responses of Δ Uy are insignificant or opposite to those of Δ IRC after southward and northward IMF turnings. The Δ Ne may contribute to the responses of IRC in part of the MLT sectors. Δ EEJ shows eastward increases in the daytime at 0–1.5 h Δ UT during southward IMF turnings at low and high solar activity and westward increases in the daytime at 0–1.5 h Δ UT during northward IMF turnings at low and high solar activity.

An eastward (westward) zonal electric field generated a poleward (equatorward) Hall current at low altitudes, expressed as: $j_x = -\frac{\sigma_1}{\sin I} E_z - \frac{\sigma_2}{\sin I} E_y$ [22], where positive j_x is the poleward Hall current, positive E_y represents the eastward electric field, positive E_z represents the downward electric field, σ_1 and σ_2 are Pederson and Hall conductance, and I is the inclination of the geomagnetic field. Zhong et al. (2023) [6] reported that after the enhanced solar wind input, a daytime eastward (nighttime westward) PPEF occurred around the equator, generating a daytime poleward (nighttime equatorward) Hall current at low altitudes. The IRC constitutes a current loop with meridional currents and E-region Hall currents [1]. Thus, an increase in the poleward (equatorward) Hall currents could induce an upward (downward) IRC in the daytime (nighttime) [6].

As shown in Figures 4c and 5c, a daytime eastward PPEF in the equatorial latitudes occurred after the southward IMF turnings, due to the enhanced convection electric field [8,10]. The daytime eastward PPEF caused an equatorward Hall current at low latitudes [22] and generated an upward perturbation of the IRC through the current loop composed of the IRC, meridional currents, and E-region Hall currents [6]. In the nighttime, a westward PPEF induced a poleward Hall current at low latitudes, generating a downward perturbation of the IRC.

In contrast, during northward IMF turning events (Figures 4f and 5f), a daytime westward PPEF in the equatorial latitudes occurred, due to the reduction of the convection electric field and the enhancement of the overshielding electric field [8]. The daytime westward PPEF generated a poleward Hall current in the equatorial latitudes and induced a downward perturbation of the IRC. In the nighttime, an eastward PPEF generated an equatorward Hall current at low latitudes, generating an upward increase in the IRC.

The amplitude of IRC at 06–12 MLT and 18–24 MLT at high solar activity is much larger than at low solar activity, due to higher equatorial ionospheric conductance [12] and stronger zonal wind [5] at high solar activity. However, the amplitude of responses of Δ IRC to the southward and northward IMF turnings does not show any preference for low or high solar activity.

5. Conclusions

Based on the observations of CHAMP from 2001 to 2010, we have investigated the response of the ionospheric F layer radial current (IRC) to southward and northward IMF turning events in different MLT sectors at low and high solar activity for the first time. The new findings are summarized as follows:

1. The amplitude of the IRC at 06–12 MLT and 18–24 MLT at high solar activity is much larger than at low solar activity due to higher equatorial ionospheric conductance and stronger zonal wind at high solar activity. However, the response strength of Δ IRC to the southward and northward IMF turnings does not show any preference for low or high solar activity.
2. At low and high solar activity, the IRC increases in the upward (downward) direction in the daytime (nighttime) within 1.5 h after a sudden southward IMF turning. Conversely, the IRC increases in the downward (upward) direction in the daytime (nighttime) within 1.5 h after a sudden northward IMF turning.
3. After southward and northward IMF turnings, the disturbances of F layer zonal wind are insignificant or opposite to the responses of IRC, thus it cannot explain the local time variations of disturbance IRC. The changes in electron density can only explain the responses of IRC in part of MLT sectors.
4. During southward IMF turning events, the enhanced convection electric field increases daytime eastward (nighttime westward) prompt penetration electric field (PPEF), generates an equatorward (poleward) Hall current around the equator, and induces an upward (downward) IRC disturbance in the magnetic equatorial F layer.
5. During northward IMF turning events, the reduced convection electric field combined with the enhanced overshielding electric field causes daytime westward (nighttime eastward) PPEF, generates a poleward (equatorward) Hall current around the equator,

and induces a downward (upward) IRC disturbance in the magnetic equatorial F layer.

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Data Availability Statement: The CHAMP thermospheric zonal wind data are from the website (<http://thermosphere.tudelft.nl/>), accessed on 5 December 2023), which has a “Download data” button that provides a file transfer protocol server for downloading data. The magnetic field data and electron density data of CHAMP are available at the Information System and Data Center of German Research Centre for Geosciences (GFZ) (<https://isdc.gfz-potsdam.de/champ-isdc/access-to-the-champ-data/>), accessed on 10 December 2023). The solar wind and interplanetary magnetic field data are from National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center (GSFC) Space Physics Data Facility’s OMNIWeb (https://spdf.gsfc.nasa.gov/pub/data/omni/high_res_omni/), accessed on 2 April 2024).

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Conflicts of Interest: The authors declare no conflicts of interest.

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