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Key Points:

- Both counter electrojet and $R2 > R1$ field-aligned currents occur during the northward turning of the interplanetary magnetic field
- The counter electrojet occurrence rate more than doubles during subauroral polarization stream periods than under normal conditions
- There is an anticorrelation between $\cos^{0.5}(\text{SZA})$ (solar zenith angle) and eastward electrojet, most prominent around June solstice

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Dependence of the Equatorial Electrojet on Auroral Activity and In Situ Solar Insulation

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Abstract By using 10 years of Challenging Minisatellite Payload satellite observations, we investigate the average conditions of the interplanetary magnetic field (IMF) prevailing during the westward counter equatorial electrojet (CEJ). Equally, we compared the average IMF conditions accompanying high-latitude field-aligned currents of the Region 1 (R1) and Region 2 (R2). It shows that both CEJ and high-latitude field-aligned currents events when R2 is greater than R1 tend to happen preferably during the northward turning of the IMF Bz and the substorm recovery phase. Sunlight has an important influence on the longitudinal distribution of the equatorial electrojet (EEJ), and the effect is opposite to the tidal electric field at E region. The anticorrelation between $\cos^{0.5}(\text{SZA})$ (solar zenith angle effect) average values during CEJ events and EEJ intensity is most prominent around June solstice. By using combined measurements from Challenging Minisatellite Payload and DMSP satellites, it is found that before the occurrence and in the initial phase of a subauroral polarization stream the EEJ gets enhanced, and after about 30 min it reduces in intensity. The CEJ occurrence rate more than doubles during subauroral polarization stream periods compared to normal conditions.

1. Introduction

The equatorial electrojet (EEJ) is located in the magnetic equatorial region and at an altitude of 105–110 km. Usually, the EEJ is a relatively intense eastward current. Under certain conditions, its direction changes from eastward to westward, and the current is called the counter electrojet (CEJ). Researchers have extensively studied longitudinal, local time, seasonal, and solar cycle variations of the EEJ characteristics using measurements from rockets (e.g., Burrows & Sastry, 1976; Davis et al., 1967), geomagnetic observatories (e.g., Forbes, 1981; Onwumechilli, 1964; Rastogi, 1962), and satellites (e.g., Alken & Maus, 2007; Cain & Sweeney, 1973; Lühr et al., 2004). These studies provide valuable insights into the equatorial electrodynamics.

The EEJ intensity exhibits significant longitudinal dependence, and its generation mechanism is still a hot topic. Previous studies showed that the EEJ over Peru was stronger than that over India, and it was believed that the difference originates from the effects of the geomagnetic field on the ionospheric conductivity (e.g., Cain & Sweeney, 1973; Rastogi, 1962; Sugiura & Cain, 1966). Rabiou et al. (2011) found that along the Africa sector, the EEJ in the west is weaker than that in the east. Yizengaw et al. (2014) reported that the EEJ is stronger in the western part of the America sector, and it gradually decreases from the west to the east. The first map of the EEJ global distribution was obtained based on the observations from the Polar Orbiting Geophysical Observatory satellites (e.g., Onwumechilli & Agu, 1981). Subsequently, the longitudinal variations of the EEJ were investigated using magnetic observations from low-Earth orbit satellites, such as the Magnetic Field Satellite (Magsat), Oersted, and Challenging Minisatellite Payload (CHAMP) (e.g., Alken & Maus, 2007; Jadhav et al., 2002; Langel et al., 1993; Lühr et al., 2004).

Lühr et al. (2004) conducted a comprehensive study about the longitudinal variation of the EEJ. They found that the distances to the geomagnetic poles have the most significant influence on the EEJ variation with longitude, and the EEJ intensity increases as the distances increase. Sagawa et al. (2005) suggested that the Wavenumber-4 longitudinal structure (i.e., four peaks and troughs) cannot be explained by the declination angle, the strength of the magnetic field, or the difference between geomagnetic and geographic equators. England et al. (2006) suggested for the first time that atmospheric tides in the lower atmosphere are modulating the longitudinal variation of the EEJ. Based on the EEJ model of Alken and Maus (2007), Lühr et al. (2008)

studied the influence of nonmigrating tides in different seasons on the EEJ longitudinal variation. They discovered that during equinox and June solstice seasons, the eastward propagating diurnal tide with Zonal Wavenumber-3 (DE3) has a significant impact on the EEJ, modulating it by as much as 25%. Excluding the impact of the DE3, the EEJ over South America and Indonesia is relatively strong due to the variation of the geomagnetic field. The influence of DE3 on the December solstice EEJ is almost negligible, and the variations during this season may be related to the coincidence of the geomagnetic and geographic equators. Later, a comprehensive study of all tidal signatures in the EEJ was reported (Lühr & Manoj, 2013). In the present work, we investigate the possible influence of the solar zenith angle (SZA) on the longitudinal variations of EEJ. As far as we know, such kind of work has not been performed in the literature.

In recent years many debates have occurred about the direction of the EEJ during a substorm. On the one hand, the analysis of typical cases by Huang et al. (2004) showed that at the beginning of a substorm the eastward electric field (i.e., EEJ) dominates, which originates from the penetration of the high-latitude dawn-dusk electric field to low latitudes. On the other hand, studies showed that the CEJ often occurs during a substorm. Kikuchi et al. (2003) revealed that in two substorm events, the CEJ happened during the substorm recovery phase. Theoretical analysis shows that when compared to the rapid response of Region 1 (R1) field-aligned currents (FACs), the development of Region 2 (R2) FACs is slower, and the related shielding electric fields will build up with a delay of about 10 min. During the substorm recovery phase, R2 currents may be stronger than R1 currents, and the overshielding electric fields penetrate to low latitudes, causing the CEJ to appear in the daytime equator region (Kikuchi et al., 2000). Peymirat et al. (2000), using the Thermosphere-Ionosphere-Magnetosphere-Electrodynamics General Circulation Model, found that the sudden decrease of the polar cap potential causes R2 FACs to be greater than R1 FACs due to the fast decrease of R1 FACs. This decrease creates an overshielding effect in the inner magnetosphere and the equator region, thus forming the reversed equatorial electric field. It can be seen from the above analyses that the relative intensity of FACs plays a vital role in the formation of the EEJ and the CEJ. However, previous studies did not focus on the situation when R2 FACs are stronger than R1 FACs.

Previous studies accepted that the intensity of R1 FACs is generally larger than that of R2 FACs (e.g., Christiansen et al., 2002; Fujii & Iijima, 1987; Huang et al., 2017; Iijima & Potemra, 1976; Le et al., 2010). Iijima and Potemra (1976) statistically investigated the intensity of FACs over the Northern Hemisphere using the Triad satellite. They found that the maxima of R1 FACs appear on the dayside, ranging from 1.8 to 2 $\mu\text{A}/\text{m}^2$, while the maxima of R2 FACs appear on the nightside, ranging from 1 to 1.3 $\mu\text{A}/\text{m}^2$. Wang et al. (2005) found that on both the dawnside and the duskside, the responses to reconnection electric fields of R1 FACs are stronger than those of R2 FACs. They confirmed the conclusion of Christiansen et al. (2002) that during quiet and disturbed periods the R1 current densities are stronger than those of the R2 current densities by about 40% and 50%, respectively. Le et al. (2010) found that for quiet or moderately active geomagnetic conditions, R1 FACs and R2 FACs are imbalanced on both the dawnside and the duskside, and the intensities of R1 FACs are generally stronger than those of R2 FACs. Based on 5 years of CHAMP observations, Huang et al. (2017) found that on average the amplitudes of R1 FACs dominate over the R2 FACs, and the ratio increases with magnetic activity. In this paper the interplanetary magnetic field (IMF) conditions when R2 is larger than R1 are investigated in comparison with the CEJ events, in order to provide observational evidences for the existing connection and related theories.

Ebihara et al. (2014) brought up another interesting point of view. They investigated the relationship between the occurrence of the subauroral polarization stream (SAPS) and the CEJ using a magnetohydrodynamics simulation. They found that R2 FACs flow into the low-conductive subauroral region after substorm onset, forming the relatively intensive SAPS and its polarization electric field. This poleward electric field propagates to the inner magnetosphere and then the inner magnetosphere is completely constrained by the overshielding condition. The high-latitude convection electric potential is overshielded, and a westward electric field is imposed at the magnetic equator on the dayside, which can cause the CEJ. This result indicates the important relationship between the occurrence of SAPS and the development of the CEJ. However, there is a lack of statistical observational confirmation of the connection between SAPS and the CEJ.

In this paper a statistical study is conducted based on the EEJ and FACs data measured by the CHAMP satellite. The external IMF corresponding to EEJ/CEJ and R1 and R2 FAC events are studied. The relationship between SZA and EEJ/CEJ intensities are disclosed. By using combined observations of CHAMP and DMSP satellites, the effect of SAPS on EEJ/CEJ is revealed.

2. Data and Methods

CHAMP was a German scientific minisatellite that was launched on 15 July 2000 and reentered on 19 September 2010. It had a near-circular polar orbit with 87.3° inclination and a 456-km initial altitude. The orbital period was 93 min, and the satellite circled the Earth about 15 times every day (Reigber et al., 2002). CHAMP precessed by 1 hr in local time per 11 days, so 131 days were necessary to cover all LTs. A 5-year measurement period is needed to cover uniformly all seasons and all LT. During such a period the satellite passed the equatorial region on the dayside more than 28,000 times.

In this paper we make use of latitudinal EEJ current density profiles. They were inverted from the 1-Hz scalar magnetic field data measured by the CHAMP satellite. The contributions of the main geomagnetic field, lithospheric field, and fields from large-scale magnetospheric currents are subtracted from the original field measurements by using an actual geomagnetic field model (e.g., CHAOS-6) (e.g., Finlay et al., 2016). The effect of the Sq current system is removed by fitting a function track by track to the midlatitude magnetic variations. Subsequently, the remaining clean electrojet signal around the magnetic equator is inverted to height-integrated current density profiles at 110-km altitude. Current density values at 50-km spacing are derived over a range of $\pm 20^\circ$ in latitude about the magnetic equator. For more details about the data analysis the reader is referred to Lühr et al. (2004) and Alken et al. (2013).

The EEJ is a dayside phenomenon. We thus take estimates of the EEJ current density only from the local time sector 7–17 MLT. Before 7 MLT a westward background electric field is still prevailing, and the low EEJ amplitude around sunset is often contaminated by other ionospheric disturbances.

At high latitudes we inverted the 1-Hz magnetic field vector data measured by the CHAMP satellite to FAC density. It is assumed that FACs form infinite current sheets aligned with the auroral oval, and the currents do not change significantly during the time the satellite passes through them. By considering the high velocity of the satellite (approximately 7.6 km/s), observed along-track field changes are interpreted as spatial variations. When taking the discrete variations between two measurement points (1 s apart), we can estimate the FAC density, $j_z = \frac{1}{\mu_0 v_x} \frac{\Delta B_y}{\Delta t}$, where v_x is the velocity perpendicular to the current sheet and ΔB_y is the residual magnetic field component parallel to the auroral oval. In this way we obtain FAC density values at a spacing of 7.6 km along the satellite track. These values are smoothed (filtered) to wavelength larger than 230 km. For more details about the applied FAC inversion the reader is referred to Wang et al. (2005).

3. Statistical Results

For our statistical analysis we made use of CHAMP data of the years from 20 July 2000 to 17 September 2010 (Alken et al., 2013). The peak current density is identified at the magnetic equator. When it is in eastward direction, it is defined as EEJ; otherwise, it is taken as CEJ. There are 37,524 EEJ and 18,970 CEJ events considered in the study.

3.1. Relation of IMF Conditions to the EEJ

The electrodynamics in the equatorial region is known to be influenced through the solar wind-magnetosphere-ionosphere coupling. Since there is no direct linear relationship expected between the CEJ and the IMF parameters, we want to find out more details. Figure 1 shows for four cases the temporal variations of the IMF Bz and AL index around CEJ events. The vertical lines indicate the time when CHAMP traversed the magnetic equator. The peak amplitude of the related CEJs is about -82 A/m at 18:08 UT on 28 July 2000, -47 A/m at 18:26 UT on 2 September 2000, -8 mA/m at 14:40 UT on 16 September 2000 and -4 A/m at 18:04 UT on 30 May 2002. These CEJ events occurred during a northward turning of the IMF and a decrease in AL.

A superposed epoch analysis (SEA) is performed for determining the mean IMF evolution around CEJ events. For this purpose the IMF variations ± 2 hr around the times of the CEJ observations are considered. Here we use the continuous OMNI solar wind plasma and IMF data that are time shifted, accounting for

Figure 1. Four examples of the temporal variation of IMF Bz and AL around CEJ events. The black line denotes the interplanetary magnetic field northward component (IMF Bz), and the blue line denotes the AL substorm index. The vertical line indicates the time when CHAMP traversed the magnetic equator. The magnetic local time and universal time of the peak CEJ are given in the frame.

their propagation from the location of observation to the Earth's bow shock. Figure 2 shows the mean IMF Bz (in the geocentric solar magnetic coordinate system) evolution from before to after the registration of a CEJ by CHAMP. The observation time of the CEJ peak current density defines the key time marked as 0 min on the horizontal axis, which is the moment when CHAMP traverses the magnetic equator. All the IMF Bz values of the events are binned into 10-min intervals and then averaged. The mean uncertainties

Figure 2. Mean evolution of the interplanetary magnetic field northward component (IMF Bz) before and after a CEJ detection at the key time (0 min). The zero time is defined as the moment when CHAMP traverses the magnetic equator. Vertical bars represent the mean uncertainty of the averages.

of the averages are given as vertical bars in the figure. Although the amplitude of the change in IMF Bz is not large (due to averaging over large amounts of data), the trend is apparent. Two hours before the CEJ events the mean IMF Bz is directed significantly southward and gradually becomes more northward. This confirms that a negative IMF Bz is supportive for the CEJ. CEJs are more intense and more frequent during magnetically active periods (e.g., Zhou et al., 2018). About 30 min before the CEJ observation the IMF has turned northward and returns to 0 around the key time. For CEJ current detections we find a bump in the mean IMF Bz curves deflected in opposite directions starting at epoch times of -30 min. We believe that these transient variations of Bz cause a prompt penetration electric field effect on the electorjet currents. Considering the signal propagation time from the bow shock to the equatorial region, which was reported by Manoj et al. (2008) to amount to 17 min, many of the detected CEJ events happen at the peaks of the Bz deflection bumps. A sudden northward turning enhances the CEJ probability (Zhou et al., 2018). During the 2 hr following the key time the IMF Bz curves stay close to the zero line, which is the mean value of this component. This implies there is no significant dependence between CEJ and IMF after the observation.

Figure 3. Two examples of FACs and related solar wind and magnetic activity condition. The top panels show the temporal variation of IMF Bz and AL index around the R2 > R1 FACs events. The vertical lines indicate the moment when CHAMP traverses the FAC sheet, which is the average universal time of the peak R1 and R2 FACs crossings. The bottom panels show the FACs density variation over magnetic latitude. The vertical lines mark R1 and R2 peak currents. The peak density of R1 and R2, the magnetic local time, and universal time of the event are listed in the frames.

By using FAC estimates of the CHAMP satellite during the decade 2000–2010, we searched the high-latitude data above 50° magnetic latitude (MLat) for the peaks in current density of upward and downward FACs. Cases where the two adjacent FAC peaks are separated by more than 2 hr in local time and more than 10° in MLat, or have amplitudes below $0.2 \mu\text{A}/\text{m}^2$ were rejected (Wang et al., 2005). A similar threshold of $0.25 \mu\text{A}/\text{m}^2$ was employed by Iijima and Potemra (1976) and $0.1 \mu\text{A}/\text{m}^2$ employed by Peria et al. (2000). After this processing 74% of the data remain. The MLat and magnetic local time (MLT) employed in this study were derived from the Apex coordinates described by Richmond (1995). Since the FAC configurations around the noon and midnight sectors are usually made up of complicated multisheet sequences, we focus here on FACs in the dawn (03 to 09 MLT) and dusk (15 to 21 MLT) local time sectors, where R1 FACs and R2 FACs are well recognizable. In the dawn sector the poleward currents, flowing downward into the ionosphere, are R1 FACs, while the equatorward currents, flowing upward away from the ionosphere, are R2 FACs. The direction of the currents in these two regions is opposite at dusk. Depending on the ratio of R1 to R2 peak current densities, we grouped the events into two classes. The first class of events is for R1 peak current density stronger than R2 peak current density ($R1 > R2$, 18,510 events at dawn and 17,952 events at dusk), while for the second holds $R2 > R1$ (7,023 events at dawn and 5,240 events at dusk). As expected, there are fewer R2 > R1 events than R1 > R2 events. The relative occurrence rates of $R1 < R2$ events are 28% and 23% at dawn and dusk, respectively.

Figure 3 shows for two examples the temporal variation of the IMF Bz and AL index around R2 > R1 FACs events (top panels). The bottom panels present the related latitudinal profiles of FACs obtained by CHAMP. The vertical lines in the top panels indicate the time (about 07:57 UT on 1 February 2001 and 11:01 UT on 24 June 2001) when CHAMP traversed the FAC sheets in the dusk sector. The peak amplitude of the R1 FAC was about $0.4 \mu\text{A}/\text{m}^2$ ($0.5 \mu\text{A}/\text{m}^2$), and for the R2 FAC it was $-1 \mu\text{A}/\text{m}^2$ ($-0.7 \mu\text{A}/\text{m}^2$). These R2 > R1 events occurred during the course of an IMF northward turning and a decreasing AL amplitude.

Figure 4. Superposed epoch analyses applied to the IMF Bz and the AL index with respect to FAC observations at the key time (epoch 0 min). The zero time is defined as the moment when CHAMP traverses the FAC sheets $R1 < R2$. The black curves represent mean IMF Bz evolution and the blue that of AL. The top frames represent observations from the dawnside, and the bottom frames from the duskside.

For investigating the IMF characteristics accompanying these cases we performed a SEA with respect to $R2 > R1$ detections. Similar to Figure 2, Figure 4 shows the mean evolution of IMF Bz at the bow shock from 2 hr before to 2 hr after the FAC detections. The time, at which a current event is observed by CHAMP, is represented by 0 min, and, as before, the related IMF and substorm parameter (AL) are binned into 10-min intervals from 2 hr before to after the key time. The mean uncertainty of the averages for the bin averages is also added as vertical bar in the figure.

Here we find a northward turning of the IMF Bz before the key time. When taking into account the propagation delay of about 20 min from the bow shock to the auroral region, as quoted, for example, by Vennerström et al. (2002), the positive peak of Bz coincides well with the key time. Interestingly, the shape of the mean AL index curve matches well the evolution of the IMF Bz, just somewhat delayed. The AL signature implies that $R2 > R1$ events occur during the monotonic decrease in AL. These conclusions are valid for both dawn and dusk sectors.

By comparing Figure 2 and Figure 4, it is tempting to suggest that CEJ and $R2 > R1$ events tend to be related. Both happen after a northward turning of IMF Bz and during the substorm recovery phase. It is worth to mention that the exact time when the CEJ or $R2 > R1$ FACs begins to show up cannot be determined by a single satellite. Such discrete observation of CEJ or $R2 > R1$ FACs by CHAMP is just used as key time for synchronizing the continuous IMF and AL data set of the corresponding signal. There may just be a certain time shift of the actual evolution because we do not know whether CHAMP passed the CEJ or $R2 > R1$ FACs, at the beginning, middle, or end of the event. However, since we have a large number of events, the uncertainty becomes small, and the average curve represents mainly the situation at the middle of the event. In addition, since both CEJ and $R2 > R1$ FACs are transient phenomena, in contrast to the EEJ and $> R1 > R2$ FACs that are normal phenomena, the presented SEA method of determining favorable conditions for the occurrence of these transient phenomena can be regarded as a valid approach.

To further test the validity of the SEA analysis, we have used a different statistical method. We compared each event of CEJ and $R2 > R1$ FACs with the AL index, in order to find out their relationship with the substorm phase. It turns out that 63% of CEJ events, and 70% (73%) of $R2 > R1$ events at dawn (dusk) occur during a substorm. During these substorm events, about 65% of CEJ events, and 60% (64%) of $R2 > R1$ events at dawn (dusk) were detected during the recovery phase. This confirms the conclusion that the substorm recovery phase favors the occurrence of CEJ and $R2 > R1$ FACs events.

Our statistical results are consistent with the event study of Kikuchi et al. (2003). The two CEJ events they investigated occurred during the substorm recovery phase, and they claimed that the CEJ is related to the northward turning of the IMF and the resulting decay of the polar cap potential. During the substorm recovery phase the $R2$ FACs are still well developed, while $R1$ FACs have already decreased. Therefore, an overshielding electric field in the auroral oval can penetrate to the low-latitude equatorial region and favor the formation of a CEJ. However, Kikuchi et al. (2003) did not consider IMF data and the high-latitude FACs in their study. They thus could not see the IMF northward turning nor the relative strengths of the $R1/R2$ FACs. Our results are also consistent with those of Yamazaki and Kosch (2015). By using measurements from geomagnetic observatories in Peru and India, they found that at substorm onset the low-latitude eastward electric field on the dayside dominates for a certain time, which is caused by the penetration of the high-latitude dawn-to-dusk electric field to low latitudes. This is consistent with the result of Huang et al. (2004). The eastward electric field decreases about 1 hr after substorm onset and a westward electric field appears at low latitudes. The theoretical explanation they proposed for the weakening of the eastward electrojet is that the dusk-to-dawn shielding E field responses slower to the reducing dawn-to-dusk electric field in the polar cap.

3.2. Influence of SAPS on the Electrojet

Based on magnetohydrodynamics simulations, Ebihara et al. (2014) found that after a substorm enhanced $R2$ FACs are generated due to the increase of the plasma pressure in the inner magnetosphere on the nightside. As a consequence, $R2$ FACs flow into the low-conductive subauroral region, resulting in an increase of the poleward electric field and positive potential, which drives the SAPS. The SAPS signal propagates upward along a field line to the inner magnetosphere as shear Alfvén waves, resulting after a certain time in an overshielding in the inner magnetosphere. This overshielding process can explain the generation of the CEJ in the simulation result.

We conducted an analysis of the EEJ evolution during SAPS events using data from the Defense Meteorological Satellite Program (DMSP) together with those from CHAMP. The SAPS events are detected by the DMSP satellites. The DMSP satellites operate in Sun-synchronous orbits at an altitude of 835 km with a period of 100 min. The F13 satellite covers the dawn/dusk local time sectors, while the F15 satellite covers the day/night local time sector (09–21 MLT). DMSP is equipped with the ion drift meter and the Special Sensor for Precipitating Particles, Version 4 (SSJ/4). The ion drift meter measures the 3-D drift velocity of ions, while the SSJ/4 measures the flux of electrons and ions in the range of 30 eV to 30 keV. Data from the SSJ/4 can be used to calculate the distribution of the ionospheric conductivity due to auroral precipitation and find the equatorward boundary of the auroral oval. In the present work, the SAPS is defined as rapid sunward plasma flows in the subauroral region, which intensifies in the sector before midnight. A threshold of SAPS velocity greater than 100 m/s is used for selection. We identified more than 6,000 SAPS events in the Northern Hemisphere in 2002 and 2003, with 2,509 events from the F13 satellite and 3,757 events from the F15 satellite. Previous works have studied the spatial and temporal variation of the SAPS and the impact of the SAPS on thermosphere winds (e.g., Wang et al., 2008, 2011).

Figure 5 presents two examples of SAPS and CEJ events. The top panels show the latitudinal profile of the ionospheric Pedersen conductivity induced by the particle precipitation, and the bottom panels show the plasma convection velocity. The large conductivity regions represent the auroral oval. The enhanced westward plasma drift equatorward of the aurora oval is the SAPS. The peak SAPS at a velocity of -479 m/s (-781 m/s) occurred around 09:18 UT (08:58 UT) on 12 May 2000 (30 September 2002), which was located at 16.2 MLT (16.6 MLT) and 69.6° (67.3°) MLat. After about 18 (15) min, around 09:36 UT (09:13 UT), CHAMP passed the magnetic equator in the 13.9 MLT (13.0 MLT) sector, and detected a CEJ event with a peak amplitude of -31 mA/m (-21 mA/m). In the previous orbit of CHAMP, around 08:04 UT (07:40 UT), an EEJ event with a peak amplitude of 106 mA/m (41 mA/m) was observed. The CEJ event occurred after the appearance of SAPS, which indicates that the SAPS has an effect on the occurrence of the CEJ. Ebihara

Figure 5. Latitudinal profiles of ionospheric conductivity and convection velocity obtained by DMSP F13 on 12 May and 30 September 2002. The locations of peak westward SAPS are indicated by vertical dashed lines. The UT, MLat, and MLT of the SAPS peaks are listed in the frames.

et al. (2014) explained that the SAPS-related positive potential generates a southward electric field at middle latitude, which was related to CEJ. In these two events, the southward electric field (i.e., eastward plasma velocity) equatorward of SAPS was not detected by DMSP, which cannot be regarded as the cause of CEJ.

Figure 6. Superposed epoch analyses applied to the EEJ amplitude with respect to SAPS observations at the key time.

For evaluating the typical response of the EEJ to a SAPS we perform a SEA. The key time is defined by the appearance of a SAPS detected by the DMSP F13 or F15 satellites. CHAMP EEJ samples recorded within 7 and 17 LT are dropped into the related 15-min time bins of the study period. Averages of all the EEJ peak amplitudes within the bins are formed. The typical number of EEJ samples within a bin is 324 for F13 and 486 for F15. Here we focus on the results from F13 because SAPS can be detected most reliably around 18 MLT.

Figure 6 shows the mean response of the EEJ amplitude to the occurrence of a SAPS. We find a peak in EEJ amplitude coinciding with the key time. Thereafter, reduced EEJ amplitudes appear reaching minimum values between 30 and 60 min. Ebihara et al. (2014) showed that the peak of SAPS took place about a few tens of minutes before the peak of CEJ. EEJ amplitude peaks are also found in Figure 6 about 100 min before and after the key time. These are just one DMSP orbit period apart. SAPS signatures are sometimes detected on subsequent orbits. From the rather discrete sampling by DMSP it is challenging to identify the initial SAPS after a substorm. Still, the analysis infers that a SAPS initially enhances the EEJ intensity and about 30 min later suppresses the eastward current, favoring the occurrence of CEJ. When considering the 45-min interval centered on the 45-min SAPS epoch time we obtain a CEJ occurrence rate of 54% compared to 23% of the average CEJ rate. We also analyzed F15

Figure 7. (top frame) Longitudinal variation of the EEJ and collocated solar insolation effect, $\cos^{0.5}(\text{SZA})$. SZA stands for the solar zenith angle. The blue line represents the mean current density, and the red line the $\cos^{0.5}(\text{SZA})$ variation. (bottom frame) The same as above but for the CEJ. The correlation coefficients between the electrojets and $\cos^{0.5}(\text{SZA})$ are listed in the plots. Note that in the top frame the scale for $\cos^{0.5}(\text{SZA})$ is reversed. The vertical bars indicate the uncertainty of the bin averages.

SAPS events occurring in the 23 MLT local time sector (not shown here). They provide a very similar EEJ evolution pattern, although the features do not come out so clear. Furthermore, all the features appear at about 30 min earlier epoch times. This suggests that the SAPS propagate from their initiation in the evening sector at a certain speed toward midnight.

The influence of other forcing, for example, high-latitude convection expansion, on the occurrence of CEJ is not involved in the present work, which is an interesting topic for future investigation. The relative contribution from SAPS and other forcing can be distinguished in future model studies.

3.3. Longitudinal Variation of the Electrojet

It is known that the EEJ intensity shows pronounced longitudinal patterns, which change significantly with season. Main drivers for that are atmospheric tides (e.g., Lühr et al., 2008; Lühr & Manoj, 2013). When averaging the EEJ intensity over full years and over all local time hours the tidal effect is largely suppressed. Then the effect of other influences, like ambient magnetic field or ionospheric conductivity, becomes apparent. Here we investigate the effect of photoionization by sunlight on the EEJ intensity. To our knowledge this has never been studied before.

For this purpose we sort the EEJ and CEJ peak current densities separately into bins of 15° in geographical longitude. CHAMP data from all the years and the local time hours 07–17 MLT are considered. The derived distributions of the EEJ and the CEJ over geographic longitude are shown as blue lines in Figure 7 top and bottom, respectively. It can be seen that the EEJ is on average strongest over South America (75°W) and exhibits a secondary maximum over East Asia (110°E). This longitudinal distribution is consistent with previous result. For example, Sugiura and Cain (1966) found that EEJ at Peru is larger than that at India. Their

Figure 8. Seasonal and UT variation of EEJ amplitude (left) and $\cos^{0.5}(\text{SZA})$ (right). The top frames are for eastward EEJ, and the bottom frames are for westward EEJ. Note that in the CEJ plot, the blue color represents intense current.

theoretical study revealed that the longitudinal variation of the EEJ was due to the longitudinal structure of the geomagnetic field. The average CEJ amplitude also shows some peaks. These appear approximately at the minima of EEJ intensity, as earlier reported by Zhou et al. (2018).

Accordingly, we calculated the SZA corresponding to time and location of each peak current sample over the equator. The local solar influence on the ionospheric conductivity can be represented, according to Chapman's theory, by $\cos^{0.5}(\text{SZA})$. When SZA is larger than 100° , the ionospheric E region is in darkness (Schlegel, 1988). The above function does not work for $\text{SZA} > 90^\circ$. Therefore, we replace SZA in the range 80° – 100° by $\text{SZA} = -0.025 \times (\text{SZA} - 80)^2 + \text{SZA}$. By using this approximation $\cos^{0.5}(\text{SZA})$ varies smoothly with the SZA from 0° to 100° (see Wang et al., 2005).

Figure 7 presents also the distribution of $\cos^{0.5}(\text{SZA})$ (red curves) over geographic longitude for the two types of currents. Note that the right-side y axis in the top panel is inverted for the SZA curve. It can be seen that the average solar irradiance also exhibits significant longitudinal variations. Interestingly, in the case of EEJ the small values of $\cos^{0.5}(\text{SZA})$ are collocated with the peaks of EEJ intensity. The correlation coefficient between $\cos^{0.5}(\text{SZA})$ and the EEJ is -0.77 , indicating that there is a linear anticorrelation between the two parameters. In the case of CEJ the maximum values of $\cos^{0.5}(\text{SZA})$ coincide with the peaks of CEJ amplitude. The correlation coefficient between $\cos^{0.5}(\text{SZA})$ and the CEJ amplitude is somewhat smaller and amounts to 0.64 , indicating a positive correlation between them. Our study reveals that in situ solar radiation plays an important but unexpected role for the EEJ longitudinal current variations. Results of Figure 7 suggest that enhanced solar insulation may add a westward electric field component.

We wanted to find out more about the relation between EEJ and solar insulation. For that reason we plotted in Figure 8 the monthly variation of the EEJ and CEJ intensity for each UT hour, which has not been presented before. Such presentation is useful for modelers since they work in the UT space. The averages are performed from all longitudes at a certain UT. It is known that CEJs occur more frequently during morning

and late afternoon hours. To eliminate the CEJ effect on the mean EEJ, we calculate the average value for each UT hour and month, from the local time sectors of 08–16 LT for EEJ, and 07–08 and 16–17 LT for CEJ.

A number of well-known features can be recognized. The EEJ is weakest around June solstice months (see Figure 8, top left). This is consistent with the result of Lühr et al. (2004). They also reported that the mean amplitude of maximum values varied with season, and during northern summer months the EEJ was weakest. Large amplitudes are observed around 16–18 UT, noontime in South America and 2 UT, noontime in East Asia. Relatively small EEJ amplitudes are found around 8 UT, noontime near the Indian sector. These results are consistent with previous reports that EEJ over Peru was stronger than that over India (e.g., Cain & Sweeney, 1973).

In the case of CEJ (Figure 8, bottom left) one has to note that red colors represent small negative amplitudes. Weakest CEJs are found during all seasons around 14–16 UT. Largest amplitudes are observed at 04–10 UT around June solstice and fall. Apart from that the CEJ is generally more active during northern summer months. Similar seasonal variations of CEJ have been reported previously (e.g., Stening et al., 1996; Vineeth et al., 2016; Zhou et al., 2018). Stening et al. (1996) revealed that the winter CEJ is closely related to sudden stratospheric warming. The summer CEJ is related to meteor trails (Vineeth et al., 2016). Vineeth et al. (2016) argued that the meteoric dust produces a layer in the E layer that attract electrons and sets up a downward electric field that favors CEJ.

On the right side of Figure 8 the SZA effects corresponding to the EEJ/CEJ observations are plotted. By comparing the EEJ amplitude with the collocated SZA effect (Figure 8, top row), it is not obvious to identify the anticorrelation between the two quantities, as deduced from the average curves in Figure 7. We find regions where the amplitudes are anticorrelated, for example, from 05 to 11 UT at June solstice months. But there are also times of in-phase variation, for example, around 15–21 UT. In the case of CEJ the correlation of the oppositely colored patches is slightly more convincing. High $\cos^{0.5}(\text{SZA})$ values correspond more often to larger CEJ amplitudes (blue patches) and also that is not perfect. Surprisingly, the best anticorrelation is found between the EEJ amplitude (top left) and SZA effect during CEJ events (bottom right). This implies that EEJs tend to be weak in regions where CEJs occur closer to solar zenith.

The general effect of an enhanced solar insulation is a reduction of the EEJ amplitude and an enhancement of the CEJ intensity. In the next section we try to explain the apparent anticorrelation between the solar insulation intensity and the distribution of EEJ average amplitude.

4. Discussion

4.1. CEJ and FACs

Previous studies revealed that the intensity of R1 FACs is generally larger than that of R2 FACs (e.g., Christiansen et al., 2002; Fujii & Iijima, 1987; Huang et al., 2017; Iijima & Potemra, 1976; Le et al., 2010). However, these studies did not focus on the situation when R2 FACs are stronger than R1 FACs. As disclosed in the present work, although the cases of $R1 > R2$ FACs are dominant, the cases of $R1 < R2$ FACs are not rare. Based on CHAMP observations at auroral and equatorial region in relation to the external IMF condition, it is found that both $R2 > R1$ FACs and CEJ occur during a northward turning of IMF Bz and in the substorm recovery phase. Thus, it is concluded that CEJ and $R2 > R1$ FACs events seem to be related to each other. The substorm recovery phase occurs after a northward turning of the IMF. At this time the polar cap potential and R1 currents have rapidly decreased as they are directly related to the IMF. Since the response of R2 current to the solar wind input is slower by tens of minutes than R1 FACs (Kikuchi et al., 2000), R2 current can be in the full development stage during the substorm recovery phase. Thus, $R1 < R2$ events tend to occur. The R2 FACs can shield the high-latitude convection electric field from middle and low latitudes. Under the condition of $R2 > R1$, the overshielding electric field can propagate to the equator and reverse the electric field at the daytime from eastward to westward. These results are consistent with previous works (e.g., Kikuchi et al., 2000, 2003). Kikuchi et al. (2000) showed that the enhanced negative bay at the equator was associated with the shielding electric field related to the R2 FACs. Kikuchi et al. (2003) suggested that DP1 current dominate during the northward turning of IMF, which is composed of Hall current surrounding R2 FACs at midlatitudes and the CEJ at the dayside equator. Here we note that Kikuchi et al. (2003) discussed the net intensity of FACs, while in the present work the peak current density is used as a proxy for the net

intensity of FACs. Through analyzing the effects of the IMF on both $R2 > R1$ and CEJ events, the present work provides observational evidences for the existing theories.

4.2. EEJ and SAPS

The SEA shows that before the occurrence of SAPS, the EEJ gets initially enhanced in intensity. This enhancement in the eastward direction might be related to the penetration of the high-latitude dawn-dusk convection electric field, which plays an important role in the trigger of SAPS. According to the theory of SAPS generation mechanism (Anderson et al., 2001), the enhanced convection electric field injects more ions into the inner magnetosphere, forming a larger azimuthal pressure gradient. Then the enhanced misalignment between the large azimuthal pressure gradient and the orientation of the magnetic field flux tube generates R2 FACs, which flow into the ionospheric region of low conductivity in the dusk sector. To maintain current continuity, the poleward electric field will get enhanced. Such an enhanced poleward electric field generates the fast westward plasma flow, that is, SAPS. By using DMSP satellite observations, Wang et al. (2008) disclosed that there is a good correlation between SAPS velocity and the high-latitude cross polar cap potential when averaged over a time of 15–30 min prior to SAPS, representing the integrated effects of the cross polar cap potential on plasma drifts. This convection electric field prior to SAPS can penetrate to the equator and increase the EEJ intensity.

After a SAPS occurred, the related poleward electric field can form an overshielding effect in the inner magnetosphere and generate the westward electric field at the dayside equator. The EEJ intensity is depressed and the CEJ occurrence is favored. Anderson et al. (2001) found that SAPS can last from 30 min to 3 hr. The long persistence of SAPS may explain the decrease in the EEJ that lasts on average about 1 hr after SAPS occurrence. When considering the 45-min interval centered on the 45 min after SAPS epoch time, we found that the occurrence probability of the CEJ is more than doubled, compared to that during regular periods. These observational evidences indicate that SAPS contribute to the occurrence of CEJ.

In addition to the overshielding electric field effect, it is known that SAPS have significant effects on the ionosphere and thermosphere. SAPS can cause storm enhanced densities and plasmaspheric plumes (Foster & Vo, 2002), lead to large field-aligned vertical plasma flow (Anderson et al., 1991; Wang & Lühr, 2013), and produce a density trough in the middle-latitude ionosphere (Spiro et al., 1978; Wang et al., 2012). SAPS can drive westward winds and cause air density bulges at subauroral regions (Wang et al., 2011). The plasma temperature can be enhanced at middle latitudes due to the SAPS ion-neutral frictional heating (Wang et al., 2012). This can drive equatorward wind, which turns westward at low latitudes owing to the Coriolis force. The disturbance wind will generate a westward electric field at the daytime equator, which contributes to the development of CEJ (Blanc & Richmond, 1980; Zheng et al., 2018). It takes on average several hours for the equatorward wind to propagate from the subauroral region to the low latitudes due to the inertia of the neutrals, which is much slower than the prompt effect of the penetration electric field (Xiong et al., 2016). Further model studies will be required to understand the relative contribution from the penetration and wind dynamo electric field during SAPS periods.

We also noticed that there is no one to one correspondence between SAPS and CEJ. One possible reason for this is that, although the SAPS polarization electric field can penetrate into the equatorial region and superimposes onto the original eastward electric field, it might only reduce the eastward electric field, and it is not always sufficient to flip the sign of the eastward electric field. When a SAPS occurs, the intensity and the direction of the EEJ also depend on the ionospheric conductivity where the R2 FACs occur (Ebihara et al., 2014). The simulation results show that for higher conductivity, the EEJ is weakened or even reversed, becoming a CEJ (see their Figure 11). Both the superposition of the electric field and the subauroral conductivity may explain why the EEJ stays eastward in 46% of the cases during the occurrence of a SAPS.

4.3. SZA Effect

The solar radiation exhibits obvious longitudinal variations, which can affect the ionospheric electron density (Ne) at both *E* and *F* regions. Xiong et al. (2014) investigated the longitudinal variations of the Ne at different latitudes in the top ionosphere based on CHAMP observations. They found that the equatorial ionization anomaly (EIA) trough over the magnetic equator shows prominent Wave-4 structure, which is in antiphase with the EIA crest. By comparison, it can be found that the Wave-4 variation of the EIA trough is in phase with that of $\cos^{0.5}(\text{SZA})$, as shown in Figure 7. This indicates that the local solar irradiation can develop longitudinal structure of the EIA trough, a similar structure as that caused by the *E* region tidal winds. Accordingly, one can expect the solar illumination effect on the *E* region Ne over the magnetic

equator in a similar way. Previous work revealed that the longitudinal variation of EEJ is mainly caused by the electric field modulated by the tide winds. The present work shows that the ionospheric conductivity induced by the solar illumination can play a role in the longitude change of the EEJ, which is opposite to the dynamo electric field.

In addition to the influence on the conductivity of the ionosphere, a relation with the SZA can be related to the location of the magnetic equator either in the Northern Hemisphere or Southern Hemisphere. In the latter case we have only an indirect relation with the Sun. In search for an explanation of the anticorrelation relationship between $\cos^{0.5}(\text{SZA})$ during CEJ and the EEJ amplitude, as shown in Figure 7, we looked into different upper atmospheric quantities.

Häusler et al. (2007) presented the first comprehensive study of the longitudinal variation of the equatorial zonal winds by using CHAMP observations. They found that around June solstice there is during morning hours a small additional westward wind component at longitudes where the magnetic equator is in the Northern Hemisphere and an eastward component where currents flow in southern regions. The zero crossing of the longitude dependent zonal wind component is close to the crossing between the dip and geographic equator. The westward component contributes surely to the many morning CEJs occurring over African and India during summer. The effect of the opposite directed wind component around December months is not obviously related to the EEJ intensity.

Another explanation comes from the asymmetry of the EIA. Xiong and Lüher (2013) examined the longitudinal variation of the interhemispheric asymmetry of the EIA by using 9 years of CHAMP observations. They disclosed the obvious longitudinal dependence of the displacement of the EIA crests in latitude with respect to the magnetic equator. Around June solstice the crest is displaced southward by several degrees in latitude in the Eastern Hemisphere from 45°W to 180°E, which coincide with longitudes where the magnetic equator is in the Northern Hemisphere. To the west of that there was a northward displacement.

The displacement of the EIA can be interpreted as a combined effect of solar irradiance and meridional wind. The summer Sun is expected to amplify the EIA crest in the north. In the eastern sector 45°W to 180°E GLon the northern crest is right under the Sun. But the summer-to-winter meridional wind pushes ions up the field lines and moves the crest southward. In the western sector the crests are quite far from the Sun that only their northern parts are well developed, in spite of the summer-to-winter wind.

The meridional wind obviously also depletes the *E* region over the magnetic equator in the eastern sector, which causes a weaker EEJ right under the Sun. In the western sector the meridional wind obviously transports plasma from the latitudes closer to the Sun to the magnetic equator and thus strengthens the EEJ. In this way no connection between conductivity and *E* field is required, as could be suggested from Figure 7. For the months around December, we do not find such a clear correlation between EIA displacement and EEJ intensity. Then other processes seem to compensate the described effects.

5. Conclusions

By using 10 years of CHAMP satellite observations during the period of 2000–2010, the average conditions of the IMF during westward CEJ events are investigated. For comparison, the IMF and auroral activity conditions for $R2 > R1$ FACs are studied. In addition, the effect of the solar insolation and SAPS on the EEJ and CEJ are disclosed. The main conclusions are summarized as follows:

1. Both CEJ and the condition $R2 > R1$ FACs tend to occur during the northward turning of the IMF B_z and during the substorm recovery phase. Thus, it is concluded that $R2 > R1$ events tend to support the occurrence of CEJ.
2. Before the occurrence and during the initial phase of a SAPS the EEJ gets enhanced in intensity. After about 30 min the EEJ amplitude is depressed and the CEJ occurrence is favored for another 30 min. The CEJ occurrence rate more than doubles during SAPS periods compared to normal conditions.
3. Solar irradiation intensity over the magnetic equator exhibits significant longitudinal and seasonal variations. The minimum values of $\cos^{0.5}(\text{SZA})$ coincide on average with the peaks in EEJ intensity and with weak CEJs. The anticorrelation relationship between $\cos^{0.5}(\text{SZA})$ and EEJ is most prominent when considering the $\cos^{0.5}(\text{SZA})$ values during CEJ events especially around June solstice. Our favored explanation for that is the effect of the meridional summer-to-winter wind.

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