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Key Points:

- This is the first dedicated study to find return paths of F region dynamo currents
- The suggested return currents are mostly confined within $\pm 20^\circ$ in MLAT at CHAMP altitudes, corresponding to $<1,300$ -km apex height
- The local time and longitude of the suggested return currents are displaced from those of the equatorial F region dynamo currents

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Closure of F Region Dynamo Currents: Revisiting CHAMP Magnetic Field Data

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Abstract In the equatorial F region exist upward/downward electric currents, which are generally attributed to dynamo action of thermospheric zonal wind. Despite the long history of their observations since the 1970s, the return path has not been thoroughly investigated. In this study, we revisit the magnetic field data of the Challenging Mini-satellite Payload (CHAMP) to address the statistical distribution of the return currents. In addition to the F region dynamo currents near the dip equator, we have identified off-equatorial bands with the reverse polarity. Both equatorial and off-equatorial bands flip signs around 1600 magnetic local time (MLT) and are the weakest during June solstice. These similarities suggest that the off-equatorial currents are tied to the equatorial F region dynamo and provide the return paths. The off-equatorial return currents have the following characteristics. First, they are mostly confined within $\pm 20^\circ$ in magnetic latitude (MLAT) at CHAMP altitudes, which corresponds to $<1,300$ -km apex height. Second, the peak locations of the equatorial dynamo and the off-equatorial return currents are zonally displaced from each other in terms of MLT and longitude. It implies that zonal currents in the topside F region participate in the current closure. Third, the return currents exhibit multiple zonal bands (beyond $|\text{MLAT}| > 20^\circ$) near dusk during combined equinoxes, whose origin is currently unknown.

1. Introduction

In the ionospheric F region, thermospheric wind collisionally transfers momentum to ionospheric plasma tied to the geomagnetic field lines. For example, wind blowing along the background magnetic field transports ionospheric plasma as a neutral entity with the help of ambipolar electric field, which binds electrons with ions together. On the other hand, winds blowing perpendicular to magnetic field directions (e.g., eastward-westward wind) can transfer different amounts of momentum to ions and electrons, resulting in net electric currents. This dynamo action (Rishbeth, 1971) generates vertical currents near the equator, which lead to latitudinally antisymmetric zonal perturbations of geomagnetic fields (e.g., eastward in one hemisphere and westward in the other). The first-ever observational evidence for their existence was given by Maeda et al. (1982), who analyzed magnetic field observations by Magsat at altitudes around 400 km. Later, Olsen (1997) confirmed the existence with the same Magsat data while additionally demonstrating that the dynamo current depends on the lunar phase. However, the Magsat data were confined to the dawn and dusk local time (LT) sectors. In the 21st century, magnetic field observations by the Challenging Mini-satellite Payload (CHAMP) revived the interest in this topic. Lühr and Maus (2006) reported LT dependence of the F region dynamo currents: downward currents near noon and upward currents near dusk, with polarity reversal in-between. Park et al. (2010) demonstrated (1) strong positive dependence of the F region dynamo currents on solar activity and (2) Wavenumber-4 structures in the longitudinal distribution of the F region currents. Since the launch of the Swarm constellation by the European Space Agency in November 2013, two more papers have been published on this subject. Lühr et al. (2015) investigated the F region dynamo currents using dual-satellite solutions of the Level-2 field-aligned current (FAC) product (https://swarm-diss.esa.int/#swarm%2FLevel2daily%2FLatest_baselines%2FFAC%2FTMS%2FSat_AC). The product gives estimates of ionospheric current density based on coordinated magnetic measurements of Swarm Alpha and Swarm Charlie, therefore with fewer assumptions than previous single-satellite estimations could. According to the paper, the latitudinal width of the vertical F region dynamo currents around the equator is $\pm 2.5^\circ$ near noon and $\pm 5^\circ$ around dusk at Swarm altitudes. Later, Lühr et al. (2019) showed that the duskside dynamo currents had bifurcated latitudinal structures, with a small dip at the magnetic

equator and two crests at off-equatorial latitudes. Those authors attributed the bifurcation to the dynamo region existing above Swarm observation points. Besides the observational studies mentioned above, a recent study by Maute and Richmond (2016) conducted extensive simulations on the dynamo currents and reproduced a large part of the previous observations.

Despite the legacy of studies on the *F* region dynamo, our knowledge on their return paths remains poor. The existence of the return currents has been briefly alluded to by previous papers, but their statistical behavior has not been extensively studied. According to Figures 2 and 3 in the seminal paper by Maeda et al. (1982), the latitudinal gradient of zonal magnetic deflection, which represents the polarity of vertical currents, changes sign at about $\pm 10^\circ$ magnetic latitude (MLAT) at the Magsat altitude; that is, the figures gave indirect evidence of return currents. The cartoon in Maeda et al. (1982, Figure 5) also suggests that the *F* region dynamo currents at the equator (e.g., upward) are closed by return currents at off-equatorial latitudes (e.g., downward) within the magnetic meridian. Similarly, Plates 2 and 3 and Figure 2 of Olsen (1997) demonstrated that upward equatorial dynamo currents at dusk are sandwiched by off-equatorial downward currents, which implies current closure between them. This sandwich structure can also be identified, albeit weakly, in the Swarm satellite data (see Figure 5 of Lühr et al., 2015, 2019). However, all the abovementioned papers just briefly alluded to or showed in passing the existence of return currents. Their dependence on latitude, LT, and season is yet to be pursued observationally.

In this study, we investigate the LT/longitude/season dependence of the *F* region dynamo return currents. We revisit CHAMP magnetic field observations rather than contemporary data such as from Swarm satellites because of the following reasons. Off-equatorial return currents have generally weaker density than the equatorial *F* region dynamo currents (Maute & Richmond, 2016, Figure 7; Olsen, 1997, Figure 2). In case of low-current density of the equatorial *F* region dynamo, an even lower-current density of the off-equatorial return paths might be compromised by the instrumental/statistical noise of the data. CHAMP has several advantages in this respect. First, solar activity during the CHAMP mission was much higher than in the current solar cycle: Higher solar activity leads to stronger dynamo current (Maute & Richmond, 2016, Figure 7; Park et al., 2010, Figure 6) and expectedly stronger return currents. Second, CHAMP was at lower altitudes than the currently operating Swarm constellation: Dynamo current density (and possibly their return current density) is expected to decrease as heights increase above ~ 120 km (Maute & Richmond, 2016, Figure 9).

In the following, section 2 is devoted to descriptions of the satellite, instrument, and data processing methods. The bin-averaged vertical currents at equatorial and off-equatorial latitudes, which are, respectively, deemed the dynamo and return currents, are presented in section 3. In section 4, the statistical results of the *F* region dynamo and the return currents are discussed in detail. In the final section, the main findings of this study are summarized, and conclusions are drawn.

2. Data Sets and Processing Methods

The CHAMP satellite was launched on 15 July 2000 into a polar circular orbit at an altitude of about 450 km. The orbit inclination angle is 87.27° , and the orbital period was about 94 min (https://www.dlr.de/eoc/en/desktopdefault.aspx/tabid-5517/9225_read-17762/). The primary payloads are a suite of precision magnetometers that can measure geomagnetic field vectors with absolute calibration at a data rate of 1 Hz. In this study, we make use of the CHAMP/FGM Level-3 magnetic field data with a 1-s cadence (Rother & Michaelis, 2019), which are available at the following website (<ftp://isdctf.gfz-potsdam.de/champ/ME/Level3/MAG/>), from 2000 to 2010. To attenuate possible effects of the solar activity (e.g., Park et al., 2010), we separate CHAMP data into two parts: the earlier period (26 July 2000 to 25 July 2003; with higher solar activity) and the later (5 September 2003 to 4 September 2010; with lower solar activity). For the earlier period, we obtain mean activity values, $F_{10.7} = 169.5 \pm 36.3$ and $A_p = 14.6 \pm 20.3$ ($A_p = 15$ corresponds to $K_p = 3.0$), and for the later period, we get $F_{10.7} = 84.5 \pm 32.9$ and $A_p = 9.4 \pm 16.8$ ($A_p = 9$ corresponds to $K_p = 2.3$). Note that CHAMP was above the altitudes of *F* region peak density for a dominant part of its mission lifetime (Yue et al., 2011). That is, we consider that the CHAMP data used in this study generally represent the topside ionosphere.

We extract vertical current density from the magnetic field data by the following procedure. First, we subtract from the CHAMP data the geomagnetic field components generated by the Earth interior (outer core and crust) and the external currents, based on the CHAOS model (<https://www.space.dtu.dk/english/>

Figure 1. Upward current density as a function of MLAT (ordinate) and MLT (abscissa), which is the mean value in each bin of 1° MLAT by 0.2 hr MLT. Panels from the top represent (a) combined equinoxes, (b) June solstice, and (c) December solstice. Thin black curves are added to emphasize zero-current contours. Note that only the hemispherically symmetrical components are shown here.

research/scientific_data_and_models/magnetic_field_models; Version 6-x9 downloaded on 11 May 2019). The result is called magnetic residual hereafter. Because CHAMP provides observations only along the one-dimensional satellite track, additional assumptions on the current sheet morphology are necessary for calculating current density. We assume that both the dynamo and return currents form homogeneous infinite sheets of vertical currents and that the sheets are normal to the satellite velocity vector. According to Ampère's induction law, the vertical current density in the ionosphere can be estimated from the along-track gradient of the eastward component (nearly cross-track component for CHAMP) of the magnetic residual.

For checking data quality, we neglect daily files where the maximum difference between adjacent current density data points exceeds $500 \mu\text{A}/\text{m}^2$ or where the daily mean of vertical currents is beyond $\pm 10 \text{ nA}/\text{m}^2$. The remaining vertical currents are bin averaged according to the MLAT at CHAMP altitudes, magnetic local time (MLT), magnetic longitude (MLON), and season. The magnetic coordinates are calculated by the quasi-dipole equations according to Richmond (1995) and Laundal and Richmond (2017). In the following sections, we present and discuss the statistics of the bin-averaged vertical currents. Throughout this paper, positive (negative) current densities represent vertically upward (downward) currents.

Note that latitudinally antisymmetric components (e.g., upward in one hemisphere and downward in the other), so-called interhemispheric field-aligned currents (IHFACs; see Yamashita & Iyemori, 2002), have already been removed from the following figures (Figures 1–6) based on the method of Yamashita and Iyemori (2002) and Park et al. (2020). IHFACs represent a different kind of current circuit, which connects two hemispherically conjugate current sources in the *E* region (e.g., Lühr et al., 2015; Olsen, 1997; Yamazaki & Maute, 2017). As the vertical currents observed by a low-Earth-orbit satellite include both IHFACs and *F* region dynamo/return currents, properly removing the former can improve the visibility of the latter. However, there is no straightforward way to decompose vertical currents observed by CHAMP into *F* region dynamo/return currents and IHFACs: We need simplifying assumptions. In this study we follow the assumption of “hemispheric symmetry” adopted by some existing papers (e.g., Park et al., 2010; Yamashita & Iyemori, 2002) to facilitate discussions in the context of previous studies. According to this

Figure 2. Global distribution of the hemispherically symmetric component of vertical current density. Each column represents an MLT sector: (a–c) dayside and (d–f) duskside. Each row from top to bottom corresponds to a season, as in Figure 1.

method, the observed current density profiles are first decomposed into (1) IHFACs, of which the values at the conjugate points oppose with each other, and (2) the remaining net current density. The latter cannot be explained by IHFACs but are conventionally attributed to *F* region dynamo circuits. We equally attribute half of the net current density to the northern and southern conjugate points. As a result of the decomposition, only the symmetrical components with respect to the dip equator (e.g., upward at conjugate points in both hemispheres) are shown in each MLT sector or MLON sector in Figures 1–6. We admit that hemispherically asymmetric ionospheric conductance in the real-world ionosphere can result in asymmetric *F* region dynamo/return current distributions. That is, the “net current density” may be divided unequally between conjugate points while the total sum of the two values stays the same. It is one limitation of this study that such asymmetries cannot be resolved.

With only CHAMP data, from which we estimate “vertical” current density, we have no general way to distinguish currents perpendicular to the magnetic field from FACs. Just at the dip equator we can safely state that the vertical currents are perpendicular to the background magnetic field. At off-equatorial regions, we assume in the following discussions that the vertical currents represent FACs, following results and suggestions in previous studies (e.g., Lühr et al., 2019; Maeda et al., 1982; Maute & Richmond, 2016), as well as the fact that field-aligned conductivity is much higher than perpendicular ones.

3. Results

Figure 1 shows bin-averaged upward current density as a function of quasi-dipole MLAT (*y* axis) and MLT (*x* axis). The bin widths are 1° by 0.2 hr in quasi-dipole MLAT and MLT, respectively. The resultant two-dimensional array has been filtered by a 7-by-7 median filter (i.e., ~ 800 km in MLAT and 1.4 hr in MLT) to improve visibility. Thin black curves are added to emphasize zero-current contours. The period

Figure 3. Similar to Figure 1 but for the period from 5 September 2003 to the end of the CHAMP mission.

of interest in Figure 1 is from the Years 2000 to 2003, where solar activity was much higher than for the remaining period of the CHAMP mission. Only the data obtained during geomagnetically quiet periods ($K_p \leq 3.0$) are used. Each panel represents a season, from top to bottom: combined equinox, June solstice, and December solstice. The June and December solstice seasons are defined as ± 65 days around Days of Year 172 (near the northern summer solstice) and 355 (near the northern winter solstice), respectively. The combined equinox is composed of ± 32 days around Days of Year 80 (March equinox) and 264 (September equinox). The white rectangles are given to guide readers' eyes, and each one represents dayside and duskside F region dynamo currents. The average altitude during the period of interest is given in the title. Note that the standard error of the mean (or uncertainty) in each bin of Figure 1 (and later for Figure 3) is around 1.5 nA/m^2 .

3.1. Identifying Return Currents of the F Region Dynamo

We start with verifying that our results are consistent with earlier reports on the F region dynamo. First, currents at the magnetic equator (i.e., F region dynamo currents) flow downward around noon (see the left white rectangle) and upward near dusk (see the right white rectangle), in agreement with Lühr and Maus (2006) and Lühr et al. (2015, 2019). Second, the dynamo currents are generally weak between midnight and sunrise, as seen in Park et al. (2010, Figure 2). Third, the dynamo currents are weaker during June solstice than in the other seasons, as reported by Park et al. (2010, Figure 3).

With increasing $|\text{MLAT}|$ from the equator, the sign of the current changes between 5° and $10^\circ |\text{MLAT}|$ so that another regime of the opposite current polarity appears between 10° and $20^\circ |\text{MLAT}|$. As the equatorial currents change polarity from 1500 to 1800 MLT, so do the off-equatorial currents. Besides, both the equatorial and off-equatorial currents are weaker during June solstice than in the other seasons. Hence, the current system at off-equatorial MLATs is the putative return current of the F region dynamo, as reported

Figure 4. Similar to Figure 2 but for the period from 5 September 2003 to the end of the CHAMP mission.

previously by Olsen (1997, Figure 2 and Plates 2 and 3) and Maute and Richmond (2016, Figure 9). Hereafter, we will call the equatorial vertical currents the “*F* region dynamo currents” or “dynamo currents” and the off-equatorial vertical currents with the opposite polarity the “return currents.”

3.2. MLT Displacement Between the Peaks of the Dynamo and Return Currents

In Figure 1, the return currents generally appear equatorward of 20° MLAT. We can also see that the strength of the return currents changes with MLAT, MLT, and season. Dayside return currents (reddish regions within the left white rectangle) are the strongest and reach the highest MLAT before noon (between 09 and 12 MLT). Duskside return currents (bluish regions within the right white rectangle) during the combined equinoxes (Figure 1a) and December solstice (Figure 1c) are the strongest at 17–18 MLT but reach the highest MLAT later around 20 MLT. On the other hand, duskside return currents during June solstice (Figure 1b) are generally weak albeit identifiable, and the dependence of their MLAT range with MLT is unclear.

Notably, the dependence of off-equatorial return current strength on MLAT, MLT, and season is different from that of the equatorial dynamo currents. For example, the dayside dynamo currents in Figure 1 (deep blue regions within the left white rectangle) are the strongest around/past noon. In contrast, the return currents (reddish regions within the left white rectangle) maximize before noon. Duskside dynamo currents (reddish regions within the right white rectangle) have maximum intensity near or past 18 MLT, but the return currents are the strongest before that. In summary, peaks of the return currents seem to be offset toward earlier MLTs from the peak dynamo currents.

3.3. MLON Displacement Between the Peaks of the Dynamo and Return Currents

Figure 2 is similar to Figure 1, but the horizontal axis is changed from MLT to MLON. As a result, the panels present global distribution of the hemispherically symmetric vertical current density at some selected MLT ranges. The left and right columns represent dayside and duskside, respectively, as annotated by white rectangles in Figure 1. Rows from top to bottom, respectively, correspond to combined equinoxes, June solstice, and December solstices. The bin size is 5° in MLON and 1° in MLAT, and the final bin averages are smoothed by a 7-by-7 median filter to enhance visual clarity. Note that each global map in Figure 2 is not

Figure 5. (a) Vertical current density of CHAMP upleg (northbound) passes as a function of time (horizontal axis) and MLAT (vertical axis) and (b) that of CHAMP downleg (southbound) passes. Black contours represent current density levels of +2 and +4 nA/m² and white contours of −10 and −3 nA/m². (c) $P_{10.7}$ index, (d) K_p index, and (e) sampled MLT during CHAMP upleg passes from December 2001 to February 2002.

a snapshot at a fixed Universal Time (UT), but rather a patchwork image for a fixed MLT sector. Solid white curves near South America represent the background geomagnetic field intensity of 23,000 and 26,000 nT. These contours mark the location of the South Atlantic Anomaly (SAA) and will be referred to in later discussions.

In Figure 2, it is manifest that peaks of equatorial currents (i.e., F region dynamo currents) appear at different MLON sectors from those of off-equatorial currents (return currents). For example, equatorial currents near the SAA (near the white contours) exhibit a local maximum in Figures 2a and 2b, while the corresponding off-equatorial currents are negligibly small. Also, equatorial currents during December solstice (Figure 2c) exhibit Wavenumber-3 signatures in the MLON dependence, while the off-equatorial currents seem to have a Wavenumber-4 structure. Even on the duskside (right column), this difference between equatorial and off-equatorial currents can be seen. In Figure 2d, equatorial currents have a maximum intensity across South America, but such structure is not evident in the off-equatorial currents. In Figure 2e, the global maximum of equatorial currents above the Pacific is not accompanied by a corresponding peak of off-equatorial currents. In summary, equatorial currents (i.e., F region dynamo currents) have maxima at different MLT and MLON from those of off-equatorial currents (i.e., return currents).

3.4. Multiband Structure Near Sunset and Solar Minimum Data

During the combined equinoxes (Figure 1a), the return currents between 15 and 18 MLT (refer to the region between the two white rectangles) appear to be composed of multiple stripes. Specifically, a band-like structure appears poleward of 20° |MLAT|. The wavelength in the MLAT direction is approximately 10–15°, which amounts to 1,100–1,600 km. For solstices (Figures 1b and 1c), this multiband structure is not

Figure 6. The same as Figure 5 but for the period from October 2005 to January 2006.

conspicuously seen. The origin of this feature is currently unknown. Thermospheric terminator waves in neutral mass density (Forbes et al., 2008) and zonal wind (Liu et al., 2009) may exist between 15 and 18 MLT, but they have wavelength was about 3,000 km, which is much longer than that seen in our Figure 1a (about 1,100–1,600 km).

Figures 3 and 4 are similar to Figures 1 and 2 but for a later period (from 5 September 2003 to the end of the CHAMP mission). Current density is in general lower than in Figures 1 and 2 (note the different color bars), which reflects lower solar activity during the later part (5 September 2003 to 4 September 2010: mean $F_{10.7} = 84.5$) of the CHAMP mission than in the earlier part (26 July 2000 to 25 July 2003: mean $F_{10.7} = 169.5$). Also, the overall distribution of off-equatorial return currents in Figures 3 and 4 looks more complex than for the solar maximum results in Figures 1 and 2. Nevertheless, all the key points addressed in preceding paragraphs are manifest: (1) displaced peak locations between the dynamo and return current densities and (2) multiband structures between 15 and 18 MLT during combined equinoxes. One peculiarity in Figure 3 may be the afternoon (near 14 MLT) hot spot of return currents during December solstice (Figure 3c), which cannot be identified in Figure 1. Another notable feature is the emergence of equatorial upward current at 08–09 MLT. Still, all these peculiarities do not compromise the above-mentioned key point that equatorial and off-equatorial current peaks are displaced in MLT.

4. Discussion

4.1. Multiday Variability of the Dynamo and Return Currents: A Robustness Check

In previous sections, we have investigated the distribution of the equatorial (F region dynamo) and off-equatorial (return) currents as a function of MLT (Figures 1 and 3) or MLON (Figures 2 and 4) for each season. It would be interesting to check whether multiday variations of the two systems exhibit correlation.

In Figure 5, the horizontal axis represents the time period from 12 December 2001 to 21 February 2002 and the vertical axis the MLAT. The bin sizes are 1° in MLAT and 1 day in time. The values shown in color represent daily averages (covering all longitudes) of upward current density for each bin. On a given day, the upleg and downleg equator crossings of CHAMP are approximately 12 hr apart in MLT. Hence, the two legs are separately shown in Figures 5a and 5b. Note that a 5-by-5 median filter has been applied to enhance visual clarity. The bottom three panels (panels c–e) in Figure 5 present the solar $P_{10.7}$ index (e.g., Zhou, Lühr, Xu, & Alken, 2018), K_p index, and the representative MLT of the upleg (corresponding to the data in the top panel), respectively. MLTs of the downleg arcs can be estimated simply by adding or subtracting 12 hr to/from that given in Figure 5e. Occasional gaps in the bottom panel curve signify the absence of valid data on that day, but the corresponding data gaps in the top two panels (Figures 5a and 5b) are filled by the 5-by-5 median filtering process.

Due to the orbit precession of CHAMP, the LT sampled by the spacecraft decreases slowly with a speed of about -0.09 hr/day (i.e., -12 hr in MLT during about 131 days). Therefore, Figures 5a and 5b can be interpreted as left-to-right flipped images of parts of Figures 1 and 3. In order to avoid the aliasing of temporal variation with MLT dependence, in this section we focus on variations with periods clearly shorter than ~ 131 days. White and black contours in the top two panels (Figures 5a and 5b) are given to aid readers' visual inspection and correspond to certain negative (-10 and -3 nA/m²) and positive ($+2$ and $+4$ nA/m²) values of vertical current density, respectively.

In fact, Figure 5 covers the time of a sudden stratospheric warming (SSW) event already addressed by Park and Lühr (2012). According to that paper, equatorial F region dynamo currents exhibit a 13.26-day periodicity, which is the Doppler-shifted lunar tide as seen by the precessing CHAMP platform. This quasi-13-day oscillation of the dynamo currents can be confirmed in Figure 5a (deep blue regions at the equator) without similar periodicities in solar and geomagnetic activities: Note that the vertical grid lines are given every 13 days. Besides, we can see that the return currents (off-equatorial reddish regions) are modulated nearly in phase with the equatorial dynamo currents. The considerable agreement between the ~ 13 -day temporal variations of equatorial downward and off-equatorial upward currents suggests that the two are connected, possibly forming a closed circuit.

On a longer time scale, the equatorial dynamo currents are generally stronger in the left half of Figure 5a than in the right, while the off-equatorial currents are more intense in the right half than in the left. This difference can be attributed to the slowly decreasing MLT of the CHAMP orbit over ~ 131 days. It conforms to the fact that equatorial and off-equatorial currents in Figure 1 are biased toward postnoon (corresponding to the left half of Figure 5a) and prenoon (corresponding to the right half of Figure 5a) sectors, respectively. Hence, we can get credence that the MLT displacement between the dynamo and return currents, as seen in Figure 1, is a robust feature. Figure 5b (downleg) represents nightside MLTs during the SSW period and only exhibits weak and insignificant vertical currents.

Figure 6 is the same as Figure 5 but for a different period from 26 October 2005 to 11 January 2006. A large part of Figure 6a represents nightside data with only faint signatures of vertical currents. On the other hand, in Figure 6b (downleg), multiday oscillations are conspicuous for the equatorial dynamo currents, and the off-equatorial return currents oscillate nearly in phase with them.

Temporally repeated polarity changes of the equatorial dynamo currents from 26 October to 4 December (i.e., within the left half of Figure 6b) reflect the fact that this MLT sector (around 1600 MLT) is where the F region dynamo inherently becomes very weak (e.g., Lühr & Maus, 2006) and thermospheric zonal winds change direction. As a result, slight temporal modulations by external drivers, for example, planetary wave effects, may easily lead to temporally changing signs of the equatorial (or off-equatorial) currents.

After 17 December 2005 in Figure 6b, the vertical currents exhibit simple latitude profiles composed of one equatorial minimum (blue) sandwiched by two off-equatorial maxima (yellow-red; one peak per hemisphere), which is as expected from Figure 1. Before 17 December 2005, on the contrary, the latitudinal structures appear complicated, consisting of multiple peaks. For example, the vertical current polarity on 23 November is upward (yellow) at the equator, downward (blue) at $\sim 7^\circ$ MLAT, and this structure is repeated with increasing MLAT. The wavelength is approximately 10° in MLAT. This structure resembles the multi-band features before dusk during combined equinoxes (Figures 1 and 3), as briefly alluded to in section 3. In

retrospect, this latitudinally periodic multiband structure can also be seen in Figure 5a, near 14 December 2001 when CHAMP was around 1600 MLT. The wavelength is again $\sim 10^\circ$ in MLAT. Note that the season of this example is not the equinox, but December solstice.

In summary, the time series of daily averaged (over all longitudes) vertical currents given in Figures 5 and 6 confirm robustness of the features identified in Figures 1 and 3: (1) MLT offset between equatorial and off-equatorial currents and (2) latitudinally multiband structures before sunset during equinoxes. Furthermore, the similar, though not identical, temporal variations of the equatorial and off-equatorial currents in Figures 5 and 6 give us credence to the connection of the two currents.

4.2. Balance of Upward and Downward Currents

To get further confidence that the equatorial and off-equatorial vertical currents form a unified circuit, we have estimated the integral current balance. Within each white square in Figures 1 and 3 (one for noon and one for dusk), we calculate the sum of positive current densities and that of negative current densities. Then, the absolute ratio between the two (ratio of the smaller to the larger) is calculated: hereafter called “current balance ratio.” Ideally, the ratio should be 100%. For Figure 1 (high solar activity), the current balance ratios for noon MLT (left white rectangle) are 90%, 77%, and 91% for the combined equinoxes, June solstice, and December solstice, respectively. Considering that our estimates are based on a simple assumption of a one-dimensional current sheet, the current balance ratios for noon MLT and high solar activity can be deemed close to the ideal value. This result provides additional support that the equatorial and off-equatorial currents in Figure 1 are actually tied together.

The ratios become lower for dusk MLT or low solar activity. For Figure 1 (high solar activity), the duskside ratios are only 72%, 50%, and 67% for the combined equinoxes, June solstice, and December solstice, respectively. For Figure 3 (low solar activity), the ratios in the three seasons are only 59%, 57%, and 61% for the noon MLT, while those of dusk MLT are 65%, 55%, and 93%.

In summary, the overall current balance is best for noontime solar maximum years (left white rectangle in Figure 1), where the mean vertical currents are the strongest (i.e., signal-to-noise ratio is the highest). The relatively large current imbalance for the other conditions (e.g., dusk MLT or solar minimum years) implies that low-current density and concomitantly low signal-to-noise ratio may have prevented us from estimating the true current balance. This conjecture is further supported by the fact that the current balance ratio is the lowest during June solstice irrespective of MLTs and solar activities and that the overall current densities are also the lowest in that season.

4.3. Displaced Peaks Between the Dynamo and Return Currents

If the equatorial and off-equatorial vertical currents really form one unified electric circuit, how can we understand their displaced peak locations in MLT or MLON? In this subsection we address this topic.

If the F region dynamo currents at the equator are entirely closed within a meridional plane (i.e., without zonal currents), variations of off-equatorial return current density should exactly follow that of the dynamo currents. In other words, the peaks of the former should emerge at the same MLT and MLON as those of the latter. However, we have demonstrated in section 3 that peaks of dynamo currents and return currents are displaced in both MLT and MLON. This result suggests that the current closure is not restricted to the same meridian, but zonal currents are involved in the process.

Previous studies reported the existence of various zonal currents in the topside ionosphere (e.g., Alken et al., 2016; Lühr et al., 2016, Figure 5; Maus & Lühr, 2006; Maute & Richmond, 2016, Figure 7). First, the Earth's gravity drives eastward currents irrespective of altitude ranges and LT. This current density is proportional to local plasma density and is affected by magnetic field inclination. Second, the vertical gradient in ionospheric plasma density results in zonal currents: so-called “pressure-gradient-driven currents.” Plasma density decreases with height in the topside ionosphere, where CHAMP made most observations. Hence, the pressure-gradient-driven currents are in the westward direction irrespective of MLT, although the magnitude may change according to the vertical-scale height of the gradient. Third, the zonal electric field, combined with ionospheric Pedersen conductance in the ionosphere, can drive zonal currents. This current is not directly proportional to the local electron density but Pedersen conductivity which is a function of both plasma and neutral concentrations. As the E field is generally eastward during daytime and

westward at night (e.g., Fejer et al., 2008), the resultant currents are expected to flow eastward during the daytime and westward in the middle of the night. Because Pedersen currents driven by the E field are controlled by ion-neutral collisions, we expect for CHAMP altitudes (i.e., topside ionosphere) that they can be weaker than from other drivers such as gravity- and pressure-gradient-driven currents.

In summary, zonal currents at CHAMP altitudes are composed of contributions from multiple drivers, whose relative magnitudes may change depending on locations and time. According to the simulation results in Maute and Richmond (2016, Figure 7), the magnitude of the zonal currents is nonzero and smaller than 200 nA/m^2 . Lühr et al. (2016) measured the magnitude of the net zonal currents using multispacecraft observations by Swarm during a limited period of orbit coplanarity. According to their Figure 5, the magnitude at about 500-km altitude (1) is occasionally larger than 10 nA/m^2 at low latitudes and (2) varies significantly with MLAT and MLT. Considering that the vertical current density in our study is only several nA/m^2 , the magnitude of the zonal currents mentioned above can contribute to the closure of meridional (F region dynamo and return) currents.

Specifically, according to Lühr et al. (2016, Figure 5), (1) the zonal currents at the equator are generally weaker than off-equatorial zonal currents (at least between 09 and 21 MLT) and (2) the off-equatorial zonal currents are eastward on the dayside (before 18 MLT) and westward on the duskside (between 18 and 21 MLT). Note that the reference altitude of Lühr et al. (2016, Figure 5) was about 500 km, which is above CHAMP altitudes. Lately, Zhou et al. (2020) estimated F region zonal height-integrated current intensities using CHAMP observations. Though their results focus on nighttime and the altitudes of the current centers are found to be below CHAMP, Figure 6 of Zhou et al. (2020) supports Lühr et al. (2016, Figure 5) in that duskside (morningside) off-equatorial currents are more westward (eastward) with respect to the corresponding equatorial currents.

This distribution of zonal currents can help interpret the MLT offset of vertical currents in our Figures 1 and 3. Let us refer to the cartoon in Figure 7a. This cartoon presents excessive off-equatorial upward currents (“return currents” in Figure 7a) before noon and excessive equatorial downward currents (“dynamo currents” in Figure 7a) past noon, which is consistent with Figure 1. Zonal currents above CHAMP (yellow arrows) are expected to be much weaker than those below CHAMP (green arrow) because of the decreasing conductance and plasma density with height in the topside ionosphere. Nevertheless, the zonal currents “above” CHAMP still play a key role in current closure because they act as “the only bridge over the stream” for the excessive upward and downward currents. If zonal currents above CHAMP (yellow arrows) are absent or in the wrong direction, no circuit can be formed at all in Figure 7a, and we cannot explain the observed MLT offset between the equatorial and off-equatorial currents. Fortunately, daytime off-equatorial zonal currents flow more eastward than the equatorial zonal currents above CHAMP (Lühr et al., 2016, Figure 5). They can connect the excessive upward currents at the off-equatorial prenoon sector and the excessive downward currents at the postnoon equatorial region at CHAMP altitudes. Similar arguments can be made for the duskside (Figure 7b). Overall, Figure 7 suggests that the observed MLT offset between equatorial and off-equatorial vertical currents is a consequence of the existence of F region zonal currents and their variations with MLAT and MLT. In the cartoons, note that we use strictly vertical arrows (with no zonal tilt) to represent equatorial dynamo currents. This arrow direction is adopted just to emphasize the difference between equatorial and off-equatorial regions in terms of zonal current strengths and does not necessarily mean that zonal current at the equator is 0.

The MLON offsets between the dynamo and return current peaks, as shown in Figures 2 and 4, suggest that nonmigrating tides (or equivalently, longitude dependence for a fixed MLT range) also play a role in the three-dimensional current closure. In Figures 2 and 4, the equatorial dynamo currents themselves clearly exhibit longitude dependence (or nonmigrating tidal effects) and so do the return current systems. According to Zhou et al. (2020, Figure 7), F region zonal currents also exhibit signatures of nonmigrating tides. Though that study refers to currents flowing mainly at altitudes below CHAMP and focuses on nighttime, we may theoretically expect the nonmigrating tidal signatures even at other altitudes and MLT sectors. For example, topside plasma density and E field, both of which participate in generating zonal currents, are known to be modulated by nonmigrating tides (e.g., Lühr et al., 2007; Ren et al., 2010; Zhou et al., 2016). Also, the Earth’s geomagnetic main field should create a longitudinal variation of the ionospheric currents. E region currents, which are expected to play an important role in closing the F region dynamo currents, are

Figure 7. Cartoons of the combined circuit of the *F* region dynamo, return, and zonal currents: (a) on the dayside and (b) on the duskside.

also modulated by nonmigrating tides (e.g., Zhou, Lüher, & Alken, 2018). In summary, we suggest that (1) the zonal currents play an active role in connecting the equatorial and off-equatorial vertical currents and that (2) the current closure is also influenced by nonmigrating tides and thus exhibits a longitude dependence.

Our results can complement the following aspects of previous studies on *F* region zonal currents (Alken et al., 2016, Figure 8; Maute & Richmond, 2017, Figure 1). First, vertical *F* region dynamo currents and their closure paths, as investigated in this study, participate in the three-dimensional current system of gravity- and pressure-gradient-driven currents. Second, one may expect from the two cartoons (Alken et al., 2016, Figure 8; Maute & Richmond, 2017, Figure 1) that the gravity- and pressure-gradient-driven zonal currents in the topside ionosphere may be fully canceled out. However, Lüher et al. (2016) demonstrated the existence

Figure 8. Cartoons of fake vertical currents that might be induced by horizontal solar quiet currents flowing in the *E* layer (~110-km altitude).

of net zonal currents around an altitude of 500 km, and our results suggest that the nonzero topside zonal currents are indispensable for completing the current circuits of the *F* region dynamo. Third, the return currents in Figure 7 are, strictly speaking, “net” return currents resulting from a superposition of respective return paths of the *F* region dynamo currents, gravity-driven currents, and pressure-gradient-driven currents. Possibly because the latter two tend to oppose each other (Alken et al., 2016, Figure 8; Maute & Richmond, 2017, Figure 1), MLT dependence of the “net” return currents as observed by CHAMP (e.g., polarity flip around 16 MLT) largely follows that of equatorial *F* region dynamo currents.

4.4. Possible Effects of Other Current Systems: Are We Really Talking About the *F* Region Dynamo Currents?

As mentioned in section 2, we have estimated vertical current density from magnetic observations along CHAMP tracks. Current estimation from the one-dimensional data may suffer from cross contamination by remote current systems. For example, solar quiet (Sq) horizontal currents in the *E* layer (e.g., Yamazaki & Maute, 2017) include north-south currents diverging from the dip equator around dusk.

These currents generate hemispherically antisymmetric magnetic field residuals at CHAMP altitude (i.e., eastward in the Northern Hemisphere and westward in the Southern Hemisphere). Even if no vertical current is actually flowing at the CHAMP altitude, our method might get “fake” vertical currents out of the magnetic residual profiles.

However, the expected fake vertical currents, if any, would have an MLT dependence distinctly different from that of the vertical currents in Figure 1. As shown in the cartoon in Figure 8, the fake vertical currents should be the weakest at noon, and the current directions should be upward before noon and downward after noon. Furthermore, the fake vertical currents resulting from Sq currents should keep the same sign within one hemisphere from the equator up to 35° |MLAT|, which is the nominal focus latitude of Sq vortices. None of these features conform to Figures 1 and 3, which supports that our statistics are not severely affected by fake vertical currents resulting from Sq currents.

As a cross-check, we have generated figures similar to Figures 1 and 3 but with the dual-satellite solutions of the Swarm Level-2 FAC product (i.e., the “SW_OPER_FAC_TMS_2F” product available at <https://swarm-diss.eo.esa.int/#swarm%2FLevel2daily>). The data set gives vertical current density based on 4-point measurements by twin satellites (Ritter et al., 2013). Hence, it is more immune to contamination by remote currents, such as Sq currents, than single-satellite solutions can be. A short period between April and December 2014 is analyzed because (1) Swarm Charlie’s absolute magnetometer was alive during most of the time and (2) solar activity was the highest among all the years of Swarm formation flight (see also Lühr et al., 2015). The results (not shown here) also support (1) the existence of bands of return currents equatorward of 20° |MLAT| and (2) the MLT/MLON offsets between the equatorial *F* region dynamo currents and off-equatorial return currents. In other words, the Swarm data give further confidence that contamination by Sq currents does not have deleterious effects on this study.

We have also pondered on whether vertical currents other than *F* region dynamo currents may have affected our results. According to the simulations of Alken et al. (2016, Figure 7a), gravity-driven vertical currents exist in the equatorial plane, but they are mostly downward from sunrise to sunset, which is different from the sign flip near 16 MLT in our Figure 1. Alken et al. (2016, Figure 7b) also suggested that pressure-gradient-driven vertical currents in the equatorial plane flip signs before 14 LT, which again differs from the sign flip near 16 MLT in our Figure 1. Hence, we can conclude that equatorial vertical currents in Figure 1 are dominated by neither the gravity- nor pressure-gradient-driven “vertical” currents flowing within the equatorial plane. This supports our interpretation that Figures 1 and 3 largely represent the *F* region dynamo/return current system.

5. Summary and Conclusion

In this paper, we have investigated return currents of the *F* region dynamo using geomagnetic field observations by CHAMP over 10 years. The main conclusions of our statistical data analyses can be summarized by the following points.

1. From the distribution of vertical current density in the MLAT versus MLT space, we identify a group of off-equatorial currents, which exhibits the opposite polarity to those of the equatorial *F* region dynamo currents. Both the equatorial and off-equatorial currents flip signs around 1600 MLT and are weaker during June solstice than in the other seasons. Based on these similarities, we deem the off-equatorial currents a provider of return paths for the equatorial *F* region dynamo. The return currents are generally confined within $\pm 20^\circ$ MLAT at CHAMP altitudes (i.e., $<1,300$ -km apex height).
2. Peaks of the off-equatorial return currents emerge at MLT and MLON sectors displaced from those of the *F* region dynamo currents. It suggests that “zonal” currents flowing in the *F* region participate in the current closure.
3. Right before dusk (15–18 MLT) during combined equinoxes, the return currents exhibit multiband structures with wavelengths of about 1,100–1,600 km. Their origin is currently unknown.

Data Availability Statement

The CHAMP data product is available via the GFZ website (<https://isdc.gfz-potsdam.de/champ-isdc/access-to-the-champ-data/> or <ftp://isdcftp.gfz-potsdam.de/champ/ME/Level3/>). Swarm data can be downloaded

from the official data repository (<https://swarm-diss.esa.int/#swarm>). Kp indices are derived and disseminated by GFZ, and the Ap , Kp , and $F_{10.7}$ indices used in this study were downloaded from the NASA OMNIWeb (<https://omniweb.gsfc.nasa.gov/>).

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