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Key Points:

- Hemispheric asymmetry in auroral currents is largest during local winter and local autumn and smallest during local summer and local spring
- Low Kp conditions show the strongest asymmetry in local winter, with maximum NH/SH ratio of 1.21 for FAC and 1.10 for DF current
- Currents in the evening sector contribute more to the high NH/SH ratio than the morning sector

Supporting Information:

- Supporting Information S1

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Seasonal Effect on Hemispheric Asymmetry in Ionospheric Horizontal and Field-Aligned Currents

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Abstract We present a statistical investigation of the seasonal effect on hemispheric asymmetry in the auroral currents during low ($K_p < 2$) and high ($K_p \geq 2$) geomagnetic activity. Five years of magnetic data from the Swarm satellites has been analyzed by applying the spherical elementary current system (SECS) method. Bootstrap resampling has been used to remove the seasonal differences between the hemispheres in the data set. In general, the currents are larger in the Northern Hemisphere (NH) than in the Southern Hemisphere (SH). Asymmetry is larger during low than high Kp and during local winter and local autumn than local summer and local spring. For all Kp conditions together, the NH/SH ratio for FACs in winter, autumn, spring, and summer are 1.17 ± 0.05 , 1.14 ± 0.05 , 1.07 ± 0.04 , and 1.02 ± 0.04 , respectively. The largest asymmetry is observed during low Kp in local winter, when the excess in the NH currents is $21 \pm 5\%$ in FAC, $14 \pm 3\%$ in curl-free (CF) and $10 \pm 3\%$ in divergence-free (DF) current. We also find that evening sector (13–24 MLT) contributes more to the high NH/SH ratio than the morning (01–12 MLT) sector. The physical mechanisms producing the hemispheric asymmetry are not presently understood. We calculated the solar-induced ionospheric conductances during low Kp conditions from the IRI model. The model conductance NH/SH ratios are above 1 in autumn and spring, similar to the currents, but below 1 for winter, which is in contradiction with the currents. Therefore, we do not consider solar-induced conductances as the main explanation for hemispheric asymmetry.

1. Introduction

Several previous observational and model-based studies have investigated the effects of seasons on the auroral current systems (e.g., Christiansen et al., 2002; Fujii et al., 1981; Green et al., 2009; Huang et al., 2017; Juusola et al., 2009; Laundal et al., 2018; Papitashvili et al., 2002, and references therein). With the auroral current systems, we refer to both the field-aligned current (FAC) and ionospheric horizontal currents. The horizontal part of the auroral current system can further be divided into Pedersen and Hall currents which can in many situations be approximated by the curl-free (CF) and divergence-free (DF) horizontal current components, respectively.

From TRIAD satellite data in the Northern Hemisphere (NH), Fujii et al. (1981) found the seasonal effect to be confined mainly on the dayside and the intensity of FAC amplitude in summer to be about twice as large as in winter. From model calculation, Papitashvili et al. (2002) found 1.35 times stronger hemispherically integrated FAC in the local summer than in the winter season. From Ørsted satellite magnetic field measurements for the northern winter and southern summer seasons, Christiansen et al. (2002) calculated the southern summer to northern winter ratio of average FAC densities during quiet and disturbed conditions to be 1.8 and 1.6, respectively. Juusola et al. (2009) using CHAMP data and Green et al. (2009) using Iridium constellation found 1.4 and 1.3 times stronger integrated FAC in the summer than the winter season, respectively. From Swarm magnetic measurements, Huang et al. (2017) reported about 1.5 times stronger eastward electrojet current in local summer than in winter, while the westward electrojet was less dependent on seasons. Laundal et al. (2018) found that the horizontal currents connect differently to the high-latitude current system during summer and winter. During summer, CF currents can flow across the polar cap and connect to FACs, while DF currents circulate without connecting to FACs. During winter, the horizontal currents are confined only to the auroral oval and the Hall currents connect to FACs. Also, they found little seasonal variation in the westward electrojet compared to other components of the high-latitude current system. In summary, the summer to winter ratio in auroral currents has been reported to be from 1.35 to 2.

Much of the seasonal variations are attributed to the solar extreme ultraviolet (EUV) radiation contribution to the ionospheric conductivity.

Hemispheric asymmetry in currents at high latitudes has been reported in several previous studies (Coxon et al., 2016; Green et al., 2009; Huang et al., 2017; Laundal et al., 2016; Milan et al., 2017; Workayehu et al., 2019). Green et al. (2009) found larger average currents in the NH than SH using the cross-track component of magnetic field data measured by Iridium satellites. However, the authors concluded that the difference can be explained in terms of the Iridium orbit configuration. Coxon et al. (2016) and Milan et al. (2017) using the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) data showed that averaged over several years, currents in the NH were clearly larger than in the SH. Coxon et al. (2016) suggested that the NH may react more strongly to dayside reconnection than the SH, while Milan et al. (2017) stated that it is not clear if this difference is instrumental or real. Laundal et al. (2017) raised the question of the role of data analysis method with respect to this result and suggest further studies. Huang et al. (2017) studied the seasonal and interplanetary magnetic field (IMF) dependence of FAC and Hall currents within the auroral ionosphere using Swarm magnetometer data. They found larger auroral electrojets in the NH than in the SH during local summer seasons.

Recently, Workayehu et al. (2019), hereafter referred to as Paper 1, presented statistical distributions of the auroral current systems, FACs as well as the horizontal CF and DF currents, both in the NH and SH during low ($K_p < 2$) and high ($K_p \geq 2$) geomagnetic activity conditions by using Swarm satellite data. We examined Hemispheric differences of auroral currents averaged over all local seasons in terms of the north to south ratios of integrated FACs and averaged horizontal currents. We found significant hemispheric asymmetry during low activity conditions, with about 10% more intense currents in the NH than SH. The hemispheric differences were not statistically significant during high activity conditions. We speculated that the larger hemispheric asymmetry during low than high activity conditions might be due to differences in the local ionospheric conditions, such as background conductivity and differences in the magnetic field strength and configuration.

In this paper, we extend the analysis carried out in Paper 1 by studying the effect of seasons on the hemispheric asymmetry of FACs and horizontal currents during low and high geomagnetic activity conditions. We use 5 years of Swarm data, from 15 April 2014 to 14 April 2019, which is about 16 months more than in Paper 1. We utilize the spherical elementary current systems (SECSs) data analysis method (Amm et al., 2015; Juusola et al., 2016; Vanhamäki et al., 2020) like in Paper 1. In this paper, the seasonal dependence of the hemispheric asymmetry under different geomagnetic activity is studied for the first time to our knowledge. The results from Paper 1 and from this study (Paper 2) will guide us in our next paper, in which we will study the effects of the IMF on the hemispheric asymmetry.

The rest of the paper is organized as follows. In section 2, we briefly describe the data and data analysis methods including the bootstrap resampling method. In section 3, we present the seasonal dependence of FACs and horizontal currents for the NH and SH. In section 4, we present the K_p and seasonal dependence of FACs and horizontal currents for the NH and SH. In order to compare the hemispheric differences in the ionospheric background conductivity during different seasons, we calculate conductances for geomagnetically quiet conditions from the International Reference Ionosphere (IRI) model in section 5. Finally, in section 6, we present the discussion and conclusions of the study.

2. Data Analysis

2.1. Swarm Data and SECS Analysis Method

The Swarm data set, data processing, magnetic field data analysis procedures, and coordinate systems used in the analysis were explained in Paper 1 and are briefly summarized here.

In this study, we utilize data measured by Swarm A and Swarm C satellites from 15 April 2014 to 14 April 2019. Specifically, we use the level-1b calibrated 1-Hz magnetic field data (the 0505 data set). For FAC and horizontal current estimation, we first obtain the variation magnetic field data by subtracting a background magnetic field model (CHAOS-6-x8, Finlay et al., 2016) from measured magnetic field data. During the time we were analyzing the data, the CHAOS-6-x8 was the latest extension of the CHAOS-6 model using Swarm 0505 data up to 8 February 2019 and ground observations data as available in February 2019. Note that CHAOS-6 model is a geomagnetic field model combining Earth's core, crust, and magnetospheric currents.

The SECS method (Amm et al., 2015; Juusola et al., 2016; Vanhamäki et al., 2020; Workayehu et al., 2019) is used to estimate FAC and horizontal currents. For estimating currents using the Swarm/SECS analysis method, we first discard magnetic data poleward of $\pm 80^\circ$ geographic latitude, where the longitudinal separation between Swarm A and Swarm C becomes too small for a reliable current estimation using this method. Then, the locations of the satellite's magnetic footprints and the vector data are converted to Spherical-AACGM (SPH-AACGM) coordinates (see Paper 1).

The data from each orbit are divided into four overflights between $[50^\circ, 8^\circ]$ and $[-50^\circ, -80^\circ]$ SPH-AACGM latitudes, and we discard that part of an overflight where the satellite path is nearly parallel to the SPH-AACGM latitudes, since the analysis method fails in that situation. We discard those parts of a given pass where the gradient of latitude is $< 0.015^\circ/\text{s}$. This condition is met more often in the SH and most of the rejected points take place near 80° AACGM latitude. Since we limit our analysis to SPH-AACGM latitudes lower than 80° , NH is very little affected by this rejection procedure and the effect on currents flowing within the oval is minor (see Supporting Information S1 document for SECS analysis of Swarm data with and without the rejection procedure).

For each overflight, components of the magnetic field variations are fitted with the one-dimensional (1-D) and two-dimensional (2-D) SECS (e.g., Vanhamäki & Juusola, 2020). The 1-D SECSs describe only latitudinal variations, while the 2-D SECSs describe both latitudinal and longitudinal variations. Detailed description of the fitting procedure is given in Paper 1. Finally, the AACGM coordinate system (Shepherd, 2014) is used for binning and calculating the statistical averages of the estimated results.

2.2. Division Into Seasons and Low and High Kp Conditions

To explore the effect of seasons on the hemispheric asymmetry in FACs and ionospheric horizontal currents under different geomagnetic activity levels, we divide the oval crossings into four local seasons: NH spring and SH autumn (± 45 days around March equinox), NH summer and SH winter (± 45 days around June solstice), NH autumn and SH spring (± 45 days around September equinox), and NH winter and SH summer (± 45 days around December solstice).

In section 4, we further group the oval crossings in each local season into two geomagnetic activity levels based on Kp index with $K_p < 2$ and $K_p \geq 2$. All oval crossings in each season with $K_p < 2$ are defined as the low Kp condition while the remaining data with $K_p \geq 2$ are defined as high Kp condition. With this criterion, the number of samples is roughly equal for both categories. The same criterion was used in Paper 1. For each season, the peak of the total distribution is at $K_p = 1^-$, and disturbed conditions with $K_p \geq 5$ are sparse. This is consistent with the fact that the studied time interval takes place after the sunspot maximum in the declining phase of solar cycle 24.

2.3. Bootstrapping

From Figure 1, one can easily see the hemispheric differences in the Kp distribution in each local season. For example, for local winter (summer) seasons during low Kp conditions, the number of oval crossings in the SH is larger (smaller) than that of the NH, while the difference is vice versa during high Kp conditions. Similarly, a small hemispheric difference is also seen in the local spring and autumn seasons (Figures 1b and 1d).

We correct for the hemispheric and seasonal differences in the Kp distributions by using bootstrap resampling (also known as bootstrapping). Bootstrapping is a statistical method that relies on random sampling with replacement from the original data (e.g., Chernick & LaBudde, 2011; Dekking & Meester, 2005). In this study, the original data are the Swarm oval crossings in each local season. In order to resample from the original data, we first define sampling distribution (or bootstrap distribution) according to which we randomly take samples from the original data distribution. The sampling distribution is defined in such a way that the total number of Swarm oval crossings in each Kp bin is the same for the four seasons and the two hemispheres. This is done by averaging the total oval crossings in each Kp bin during the entire study period to the four local seasons. This sampling distribution is shown by the red dashed lines in Figure 1. For each local season, a total of 1,000 bootstrap samples are randomly taken with replacement from the original data. Each bootstrap sample has 14,020 oval crossings, which is the average number of crossings in the original data set per seasons. Similar method was used in Paper 1 to remove the seasonal bias in the total Kp distribution, but in this study, our aim is to make the seasons directly comparable to each other.

Figure 1. Distribution of Swarm oval crossings as function of Kp index for the four local seasons in the Northern (NH, blue) and Southern (SH, yellow) hemispheres. The red dashed line is the resampling (bootstrap) distribution of oval crossings. Oval crossings during the low Kp ($K_p < 2$) and high Kp ($K_p \geq 2$) conditions are separated by the vertical dashed line.

The average ionospheric horizontal currents and FACs in each 1° AACGM latitude by 1-hr MLT grid cells are calculated for each of the 1,000 bootstrap samples. From this, we have 1,000 different distributions of the average values. Then, the median values of the average current densities in each grid cell are calculated from bootstrap statistics. These results, presented in sections 3 and 4, are our best estimates for the current densities in each grid cell.

3. Seasonal Dependence

In this section, we present the seasonal variation of the median FACs and horizontal currents calculated from the bootstrap statistics for all Kp values ($K_p \leq 6^+$). In order to quantify the seasonal and hemispheric differences in FACs and horizontal CF and DF currents, we calculate the total integrated FAC values, and the average horizontal CF and DF currents for the four local seasons using the same formula as in Paper 1, summarized below.

For each local season in each hemisphere, the total FAC value flowing between $[60^\circ, 80^\circ]$ AACGM latitudes and all MLTs is obtained by

$$I = \sum_{m=1}^M |\text{FAC}_m| S_m, \quad (1)$$

where FAC_m is the FAC density in grid cell m , S_m is the physical grid cell area calculated by converting the AACGM grid cell (MLT versus AACGM latitude) to geographical coordinate system, and M is the total number of grid cells. The integrated FAC values contain contributions both from the upward and downward FACs.

For the CF and DF currents, we first calculate the magnitude of the current densities in each grid cell as the square root of the sum of the squares of meridional (positive southward) and zonal (positive eastward) current density components. The average CF and DF current values between $[60^\circ, 80^\circ]$ are then calculated between $[60^\circ, 80^\circ]$ AACGM latitudes over all MLTs using the formula

$$I = \frac{1}{M} \sum_{m=1}^M \Delta_{m,\phi} \sqrt{J_{m,\phi}^2 + J_{m,\theta}^2}, \quad (2)$$

Figure 2. Bootstrapped data point distribution for the four local seasons in the NH and SH for the time period from 15 April 2014 to 14 April 2019. The plots are given in AACGM latitude by MLT.

where $J_{m,\theta}$ and $J_{m,\phi}$ are the meridional and zonal current density components in grid cell m , respectively, M is the total number of grid cells between $[60^\circ, 80^\circ]$ AACGM latitudes and over all MLTs, while $\Delta_{m,\phi}$ is the zonal dimension of the grid cell calculated by using the AACGM coordinates.

Figure 2 shows the bootstrapped distributions of data points in the two hemispheres for the four local seasons for the whole time period. In all local seasons, the NH has more data points than the SH poleward of $\pm 66^\circ$ AACGM latitude, while the SH has more samples between 60° and 65° AACGM latitudes. This is due to the difference in the locations of AACGM poles relative to the GEO poles in the two hemispheres and the Swarm A and Swarm C satellites' near polar orbits (see Figure 1 in Paper 1).

Figures 3a and 3d show distributions of median FAC densities obtained with bootstrapping in both hemispheres for all four local seasons. The well-known R1 and R2 current systems are clearly seen in all seasons. In both hemispheres, the dawnside FACs seem to be stronger in summer than in winter. The duskside FAC is stronger on the dayside in summer than in winter, but on the premidnight sector FACs in winter are stronger than in summer between 19 and 24 MLT. This is in line with previous report by Ohtani et al. (2005) who showed more intense FACs flowing in the dark (winter) than sunlit (summer) ionosphere between 20 and 02 MLTs. In order to see the seasonal variations more clearly, we compare the total integrated FACs in the local spring, autumn, and summer seasons with the integrated value in the local winter for both hemispheres. The local spring, autumn, and summer-to-local winter ratios and 90% confidence intervals of integrated FACs in the NH (SH) are 1.15 ± 0.04 (1.26 ± 0.06), 1.23 ± 0.04 (1.27 ± 0.06), and 1.33 ± 0.05 (1.53 ± 0.08), respectively. The summer-to-winter ratios in both hemispheres are in agreement with previous studies (e.g., Christiansen et al., 2002; Juusola et al., 2009; Papitashvili et al., 2002). Overall, the seasonal ratios in the NH and SH are not equal indicating the existence of hemispheric differences on the seasonal variations of FACs. The amplitude of the seasonal variation is larger in SH than in NH. The seasonal variation of the integrated FAC values and the median NH/SH ratios are shown in Figures 4a and 4b, respectively.

Figures 3e–3h show distributions of median CF currents (both magnitude and vectors) in both hemispheres for all four local seasons. The CF currents flow poleward (equatorward) in the evening (morning) sector and part of the CF current is also flowing across the polar cap from morning to evening connecting the downward R1 (morning sector) current to the upward R1 (evening sector) current. Around midnight and noon MLT sectors the CF currents flow westward and eastward, respectively. The magnitudes of the CF currents in the dusk and dawn sectors are more prominent during local summer than winter season. The only exception is winter 19–23 MLT, when CF current is stronger in winter than in summer in NH. This is in accordance with

Figure 3. Distributions of (a–d) median FAC density, (e–h) median CF current density, and (i–l) median DF current density for the four local seasons during all ($K_p \leq 6^+$) activity conditions in the NH and SH. Downward FAC is defined positive (red color). The magnitudes and flow directions of median CF and DF currents are shown in color and arrows, respectively. The plots are given in AACGM latitude by MLT. For both hemispheres, the noon (12 MLT) is at the top and evening (18 MLT) is at the left and the lowest latitude is 60° .

Figure 4. Median values of (a) integrated FAC, (c) average CF, and (e) average DF current intensities as function of seasons for all Kp conditions together in the NH and SH. The bottom panels are the median NH/SH ratios of (b) FAC, (d) CF current, and (f) DF current. The error bars are the 90% confidence intervals.

Juusola et al. (2009), who however combined data from both hemispheres. The local spring, autumn, and summer to local winter ratios of average CF currents in the NH (SH) are 1.13 ± 0.03 (1.28 ± 0.03), 1.28 ± 0.03 (1.28 ± 0.03), and 1.45 ± 0.03 (1.58 ± 0.04), respectively. In the SH, the average CF current in the local autumn and spring seasons are equal, while the average CF current in the NH during autumn is larger than the current in the local spring. Visually, the hemispheric differences are more evident in the local winter and autumn seasons than local spring and summer seasons, with larger CF current intensities in the NH than SH. The seasonal variation of the average CF current values and the median NH/SH ratios are shown in Figures 4c and 4d, respectively.

Figures 3i–3l show distributions of median DF currents (both magnitude and vectors) in both hemispheres for all four local seasons. The DF currents flow eastward in the evening and westward in the morning sectors, which displays the eastward and westward electrojets, EEJ and WEJ, respectively. In the local winter seasons, an extension of the WEJ flows poleward of the EEJ current around the premidnight MLT sector. A reverse EEJ (sunward flowing) in the dawn MLT sector is also seen poleward of the WEJ in the local summer seasons. In both hemispheres, the seasonal variation of median DF current is clearly seen in the evening MLT sector EEJ with the smallest and largest currents in the local winter and summer season, respectively. The local spring, autumn, and summer to local winter ratios of average DF currents in the NH (SH) are 1.14 ± 0.03 (1.25 ± 0.03), 1.26 ± 0.03 (1.25 ± 0.03), and 1.50 ± 0.03 (1.58 ± 0.03), respectively. We further separate the DF current into EEJ and WEJ based on the direction of its east-west (zonal) component. Comparison of the average EEJ and WEJ currents indicate that the seasonal dependence is stronger in EEJ than in WEJ. The local summer-to-winter ratios of EEJ (WEJ) are 1.94 ± 0.06 (1.39 ± 0.06) and 2.07 ± 0.08 (1.51 ± 0.08) in the NH and SH, respectively. The EEJ ratios are slightly larger than reported by Huang et al. (2017), who noticed that the value of EEJ during local summer is larger by a factor of 1.5 than during the local winter. Like FACs, the ratios for DF currents in local autumn and spring indicate that stronger average current flows in the local autumn than in the local spring in the NH, while in the SH, the DF current in the local spring and autumn is equal. The seasonal variation of the average DF current values and the median NH/SH ratios are shown in Figures 4e and 4f, respectively.

To show the seasonal variation in the hemispheric asymmetry in currents more clearly, we calculate the integrated FAC, average CF, and DF currents, and the corresponding NH/SH ratios for the four local seasons

separately for each of the bootstrap samples discussed in section 2.3. After that, we calculate the median NH/SH ratios and the corresponding 90% confidence intervals.

Figures 4a and 4b show the seasonal variation of integrated FACs and median NH/SH ratios. The seasonal variation pattern of FACs is clearly different in the NH and SH. In the NH, integrated FACs in the local autumn and spring seasons are asymmetric, while they are symmetric in the SH. Comparison of values in each local season shows that larger currents are flowing in NH than in SH for winter, spring, and autumn seasons, while in summer, the currents in the two hemispheres are equal within the confidence level. The median NH/SH ratios in winter, spring, autumn, and summer are 1.17 ± 0.05 , 1.07 ± 0.04 , 1.14 ± 0.05 , and 1.02 ± 0.04 , respectively, which indicate the hemispheric asymmetry is statistically significant in the local winter, spring, and autumn seasons. The largest hemispheric asymmetry occur in winter and autumn seasons.

Figures 4c and 4d show the seasonal variation of average CF currents and median NH/SH ratios. Similar to the integrated FAC values, the average CF currents show seasonal dependence with the largest and smallest currents in the local summer and winter seasons, respectively, with the values in the local spring and autumn seasons in between. In the local spring, the value in SH is slightly larger than in NH, while in local autumn, the current in the NH is significantly larger than SH. In the SH, the local autumn and spring seasons are symmetric, but in the NH, local autumn and spring seasons are asymmetric. The median NH/SH ratios of CF currents are 1.10 ± 0.02 , 0.97 ± 0.02 , 1.09 ± 0.02 , and 1.01 ± 0.02 in winter, spring, autumn, and summer, respectively. Like FACs, the largest hemispheric asymmetry occurs in winter and autumn, while the hemispheres are largely symmetric in spring and summer.

Figures 4e and 4f show the seasonal variations of average DF currents and median NH/SH ratios. The seasonal variation of the average DF current has similar pattern as in the average CF current, with the largest and smallest currents in the local summer and winter seasons, respectively. In the SH, the local autumn and spring seasons the DF currents are symmetric, but in the NH, the average DF currents in the local autumn and spring seasons are asymmetric. The median NH/SH ratios are 1.08 ± 0.03 , 0.98 ± 0.02 , 1.09 , and 1.03 ± 0.02 in winter, spring, autumn, and summer seasons, respectively. Like for FACs and horizontal CF currents, the largest hemispheric asymmetry in the horizontal DF currents occurs in winter and autumn.

4. Kp and Seasonal Dependence

In Paper 1, we showed that the hemispheres are asymmetric for low ($K_p < 2$) activity conditions, while the hemispheres are largely symmetric during geomagnetically active conditions ($K_p \geq 2$). Now, we study how the geomagnetic activity effects are seen during different seasons. Section 3 showed that the largest NH/SH asymmetry occurs in winter and autumn and the smallest in summer and spring within the studied 5-year period. The current values are most intense in summer and weakest in winter. Therefore, we have selected winter and summer seasons for plots showing the full magnetic latitude—MLT distributions of currents during low ($K_p < 2$) and high ($K_p \geq 2$) geomagnetic activity conditions in Figure 5.

Figures 5a–5d show the distributions of median FACs in the local winter and summer seasons during low (Figures 5a and 5b) and high (Figures 5c and 5d) geomagnetic activity conditions in the NH and SH. As expected, FAC densities become stronger and the oval expands equatorward as the activity changes from low to high, during both local winter and summer seasons. Visually, the FAC densities seem to be significantly stronger in the NH than in the SH during local winter under low activity conditions, while in the local summer, the FAC densities in the two hemispheres seem to be quite similar under both low and high activity conditions.

Figure 6 quantifies the magnitudes of currents and NH/SH ratios. Figures 6a and 6b show the seasonal variations of integrated FACs in the NH and SH during low (Figure 6a) and high (Figure 6b) activity conditions for all the four seasons. Here, the seasonal variation of FAC is clearly seen with the largest and smallest currents in the local summer and winter, respectively. The error bars are the 90% confidence ranges. During low activity conditions, the error bars for the local winter, spring, and autumn are not overlapping. This indicates statistically significant hemispheric difference in these seasons, with larger FAC flowing in the NH than SH. The hemispheric difference is larger during low K_p conditions. In the NH, FACs tend to be stronger in autumn than in spring for both activity levels, while in the SH such an effect is not visible.

Figure 5. Distributions of (a–d) median FAC density, (e–h) median CF current density, and (i–l) median DF current density for the local winter and summer seasons during low ($K_p < 2$, left panels) and high ($K_p \geq 2$, right panels) activity conditions in the NH and SH. The magnitudes and flow directions of median CF and DF currents are shown in color and arrows, respectively. Note that the color scales for low and high activity levels are different.

Figure 6. Median values of (a, b) integrated FAC, (d, e) average CF, and (g, h) average DF currents with 90% confidence limits as function of season during low ($K_p < 2$, upper panels) and high ($K_p \geq 2$, middle panels) activity levels. The bottom panels show the median NH/SH ratios of (c) FAC, (f) CF current, and (i) DF current for the four local seasons during low K_p (solid lines) and high K_p (dashed lines) conditions.

Figure 6c shows the seasonal variation of the median NH/SH ratios and the corresponding 90% confidence range of FACs obtained from bootstrapping for both low (solid line) and high (dashed line) magnetic activity conditions. Figure 6c confirms the visual inspection of Figure 5 that during winter the NH/SH ratio is higher for low than for high K_p conditions. The values of the median NH/SH ratios during low (high) activity conditions are 1.21 ± 0.06 (1.06 ± 0.05) in winter, 1.12 ± 0.05 (1.02 ± 0.05) in spring, 1.17 ± 0.06 (1.08 ± 0.06) in autumn, and 1.01 ± 0.05 (1.00 ± 0.04) in summer. The hemispheric asymmetry is statistically significant in winter, spring, and autumn for low K_p conditions and in winter and autumn for high K_p conditions. As shown in Table 1, much of the hemispheric asymmetry during low K_p conditions is from the evening MLT sector. For example, in winter, the FAC in the NH is stronger than in the SH by a factor of 1.13 in the MLT range between 1 and 12, while in the MLT, range between 13 and 24 the NH is 1.28 times stronger than the SH. In summary, the values of the NH/SH ratios confirm that the hemispheric asymmetry is larger during low than high activity conditions, which is in accordance of the results reported in Paper 1 for all seasons together.

Figures 5e–5h show the distributions of median CF currents during low (Figures 5e and 5f) and high (Figures 5g and 5h) activity conditions in the NH and SH during winter and summer. In both hemispheres, the median CF current densities both in the dusk and dawn MLT sectors intensify and expand to lower latitudes as the geomagnetic activity changes from low to high conditions. Like for FACs, large hemispheric difference occurs in winter during low activity conditions with larger median CF current density in the NH than in the SH.

Table 1
Integrated FACs, Average Horizontal CF and DF Currents, and Median NH/SH Ratios for Different MLT Sectors During Low Kp Conditions

NH/SH ratios of currents during Kp < 2 for different MLT sectors									
Seasons	FAC			I_{CF}			I_{DF}		
	1–24 MLT	1–12 MLT	13–24 MLT	1–24 MLT	1–12 MLT	13–24 MLT	1–24 MLT	1–12 MLT	13–24 MLT
Winter	1.21	1.13	1.28	1.14	1.15	1.12	1.10	1.06	1.14
Spring	1.12	1.09	1.15	1.04	1.02	1.05	0.98	0.96	1.01
Summer	1.01	1.01	1.01	1.06	1.03	1.08	1.01	0.92	1.09
Autumn	1.17	1.09	1.26	1.10	1.04	1.15	1.03	0.92	1.15

Figures 6d and 6e show the seasonal variations of the average CF currents in the NH and SH during low (Figure 6d) and high (Figure 6e) geomagnetic activity conditions for all seasons. During low activity conditions, larger average CF currents are flowing in the NH than in the SH for all local seasons. During high activity conditions, the average CF currents are larger in the NH for local winter and autumn, while the currents are larger in the SH in the local spring and summer seasons.

Figure 6f shows the median NH/SH ratios of the horizontal CF currents as a function of local seasons during low and high activity conditions. During low activity conditions, the values of the median ratios are 1.14 ± 0.03 in winter, 1.04 ± 0.05 in spring, 1.10 ± 0.05 in autumn, and 1.06 ± 0.05 in summer. Table 1 shows that much of the hemispheric differences come from the evening MLT sector. Like for FACs, the largest asymmetry occurs in winter and autumn seasons. During high activity conditions, the NH/SH ratios are 1.06 ± 0.03 , 0.94 ± 0.02 , 1.09 ± 0.03 , and 0.98 ± 0.02 in winter, spring, autumn, and summer, respectively. In this case, the largest hemispheric asymmetry is observed in autumn, and the average CF current in spring is larger in the SH than in the NH.

Figures 5i–5l show the distributions of the median DF currents during low (Figures 5i and 5j) and high (Figures 5k and 5l) activity conditions in the NH and SH during winter and summer. In both hemispheres, the WEJ intensifies more than the EEJ as the activity changes from low to high conditions. Like FACs and CF currents, clear hemispheric difference in the median DF currents occur in winter under low activity conditions, with larger current density in the NH than SH. Apart from the hemispheric differences in the magnitudes of DF currents, an interesting winter-summer difference is observed in both hemispheres between 19 and 23 MLTs, which is the Harang discontinuity region. In the local winter, an overlap between EEJ and WEJ with sharp latitudinal separation occurs during both low and high activity conditions and in both hemispheres, with the WEJ extending to the premidnight sector poleward of the EEJ. In contrast, during summer the EEJ and WEJ are separated longitudinally, and there is no clear overlap between EEJ and WEJ around the Harang discontinuity region. These two configurations may correspond to the expansion-type and rotation-type Harang discontinuities discussed by Amm et al. (2000).

Figures 6g and 6h show the seasonal variations of the average DF currents in the NH and SH during low (Figure 6g) and high (Figure 6h) activity conditions for all seasons. During low activity conditions, larger average DF currents are flowing in the NH than SH for local winter, while in the other local seasons, the average DF currents are largely symmetric between the hemispheres. During high activity conditions, the average DF current is larger in the SH for local spring, while larger DF currents are flowing in the NH than in the SH for local winter and autumn. In the local summer, the average DF currents from the two hemispheres are equal.

Figure 6i shows the median NH/SH ratios of the horizontal DF currents as a function of local seasons during low and high activity conditions. In the low activity conditions, the NH/SH ratios are 1.10 ± 0.04 in winter, 0.98 ± 0.03 in spring, 1.03 ± 0.03 in autumn, and 1.01 ± 0.02 in summer. These values indicate that the largest hemispheric asymmetry occurs in winter, while the hemispheres are symmetric in the other seasons within uncertainty limits. As shown in Table 1, most of the hemispheric asymmetry in the median DF current in winter comes from the EEJ, with only little hemispheric difference in the WEJ. In the evening sector, the EEJ in the NH is larger than in the SH by a factor of 1.14. Also in autumn, a significant hemispheric asymmetry exists in the evening sector with the EEJ in the NH is larger than in the SH by a factor of 1.15. During the high activity case, the NH/SH ratios of DF currents are 1.05 ± 0.03 in winter, 0.95 ± 0.02 in spring, 1.08 ± 0.03 in autumn, and 1.00 ± 0.02 in summer. The NH/SH values indicate that the largest hemispheric asymmetry

Figure 7. Distribution of height integrated Pedersen conductivities in Siemens (S) during local autumn in the NH and SH in AACGM latitude and MLT coordinates averaged over 00–24 UT.

occurs in autumn with larger DF current in the NH than in the SH. Like for CF currents, the median NH/SH is <1 indicating that the DF currents are larger in the SH than in the NH in spring.

5. Conductances From IRI and NRLMSISE Models

Ionospheric conductivity affects the electromagnetic coupling between the ionosphere and magnetosphere (Newell et al., 1996). In Paper 1, we speculated that background conductivity during low Kp conditions may play a role in hemispheric asymmetry of currents. The high-latitude ionospheric conductivities are produced by the solar extreme ultraviolet (EUV) radiation and precipitating energetic particles. Ionization due to solar EUV radiation depends smoothly on the solar zenith angle, while particle precipitation varies rapidly both in space and time depending on the geomagnetic activity level (e.g., Sheng et al., 2014). The electric conductivity due to these ionization processes depends also on the atmospheric composition and magnetic field strength.

Under quiet geomagnetic conditions, ionospheric conductivity due to precipitating particles is relatively small, so in the dayside, the ionospheric conductivity variations are dominated by solar illumination. During nighttime, the solar-induced ionization in the E-region decays rapidly, and the conductance variations are dominated by precipitation.

We calculate the height integrated Pedersen (Σ_p) and Hall (Σ_H) conductivities for each local season in the NH and SH under similar geomagnetic and solar activity conditions. We take one representative day per local season: solstices for the local summer and winter and equinoxes for the local spring and autumn. We use the results to assess the degree of asymmetry in the ionospheric conductivities between the NH and SH. The electron and ion density profiles are taken from the IRI (IRI-2016) model (Bilitza et al., 2017), and the neutral density profiles are calculated from the Naval Research Laboratory Mass Spectrometer Incoherent Scatter Radar (NRLMSISE-00) model (Picone et al., 2002). The input parameters to the IRI-2016 and NRLMSISE-00 models are location, date, and time, as well as the F10.7, F10.7a, Ap indices, and the sunspot number (Rz). We run the two models for geomagnetically quiet conditions using the following values: F10.7 = 40 sfu, F10.7a = 40 sfu, Ap = 3 (which is equal to Kp = 1[−]), and Rz = 30. We use the IRI model option “E-peak auroral storm model on” to capture auroral precipitation effects. The resulting Hall and Pedersen conductivities are height integrated in the altitude range 90–200 km. Detailed description of the conductivity calculation and height integration are given in the Appendix A1.

Figure 7 shows an example of model calculations for the distributions of Pedersen conductances in the NH and SH during local autumn averaged over 00–24 UT. In both hemispheres, the conductivities due to solar EUV are highest at low latitudes on the day MLT sector (06–18 MLT) and lowest on the night MLT sector (18–06 MLT) at all latitudes. Comparison of the two hemispheres indicates hemispheric differences in the magnitude as well as latitudinal distributions of Pedersen conductances. Crucially, the auroral oval is not visible in either hemisphere. This is true for both Hall and Pedersen conductances in all local seasons.

Conductances are highest near 60° latitude on the dayside (Figure 7), while auroral currents flow mainly at higher latitudes during low Kp conditions. To select the grid cells for conductance calculation, we use

Figure 8. Distributions of height integrated (a–d) Pedersen and Hall conductivities for all local seasons. The grid cells with conductivities shown correspond to locations where strong median (a–d) CF and (e–h) DF currents are flowing during low Kp conditions. Note that the color scales for Pedersen and Hall conductances as well as for different seasons are different.

CF currents for Pedersen and DF currents for Hall conductance (see Figure 5). For local winter, the median CF and DF current densities larger than 20 mA/m and for local spring, autumn, and summer seasons, the median CF and DF current densities larger than 30 mA/m are used to select grid cells for conductances. The result is shown in Figure 8.

As expected, the magnitudes of conductances are smallest in local winter and largest in local summer while the magnitudes in spring and autumn are somewhere in between. In the local winter solstices, the conductances are very small, and in the night sector, both Pedersen and Hall conductances are ≤ 0.1 S. Also, there is no indication of an auroral oval in the night sector. However, the magnitude as well as MLT distributions of conductances are different in different hemispheres. In the day MLT sector, both Pedersen and Hall conductances are larger in the NH than in the SH during all seasons. On the night MLT sector, during local summer, conductances are slightly larger in the SH than in the NH.

The hemispheric difference in the solar EUV produced conductances, which seem to dominate the IRI results, can be attributed to several factors. One of the factor is that the Earth receives more sunlight in December solstice (NH winter/SH summer) than in June solstice (NH summer/SH winter) due to the change in the Sun–Earth distance. The Earth receives about 7% more solar radiation flux in December solstice than in June solstice, which leads to about 3% difference in the E-region electron density (assuming α -type recombination), and would result in the NH/SH ratio of 1.03 for winter and 0.97 for summer. The SH magnetic

Table 2

Average Pedersen and Hall Conductances in Siemens (S) and the Corresponding NH/SH Ratios for the Four Local Seasons During Low Activity Condition

Average conductances within 60° to 80° AACGM latitude for Kp = 1 ⁺ , F10.7 = 40								
	Winter		Spring		Autumn		Summer	
	$\langle \Sigma_P \rangle$	$\langle \Sigma_H \rangle$	$\langle \Sigma_P \rangle$	$\langle \Sigma_H \rangle$	$\langle \Sigma_P \rangle$	$\langle \Sigma_H \rangle$	$\langle \Sigma_P \rangle$	$\langle \Sigma_H \rangle$
NH	0.063	0.15	1.00	1.53	1.10	2.02	2.51	4.42
SH	0.068	0.16	0.87	1.35	0.73	1.27	2.61	4.67
NH/SH	0.93	0.96	1.15	1.13	1.51	1.59	0.96	0.95

pole lies at a lower geographic latitude than NH magnetic pole, which results in different daily and yearly variations in the solar illumination. The weaker magnetic field strength in the SH high-latitude region (60° to 80°) also results in larger conductance in the SH than in the NH for similar solar zenith angles (see Equations A1 and A2).

The seasonal variations as well as the hemispheric asymmetry of conductances are more clearly seen from the average values and the corresponding NH/SH ratios. Table 2 shows the area-weighted average Pedersen and Hall conductances for all local seasons from regions, where auroral currents flow (Figure 8). They are calculated as

$$\langle \Sigma \rangle = \frac{1}{S} \sum_{m=1}^M \Sigma_m S_m, \quad (3)$$

where Σ_m is conductance in grid cell m , S_m is area of grid cell, and $S = \sum_{m=1}^M S_m$. Both the Pedersen and Hall conductances are larger in the SH than in the NH during local winter and summer seasons, while in the local spring and autumn season the values are larger in the NH than in the SH. The average values of Pedersen and Hall conductances in winter given by the model seem to be too small (<0.1 S) to support realistic ionospheric currents. This may be related to the fact that the auroral oval caused by particle precipitation is not reproduced in the model. In each hemisphere, the average conductances in the local spring and autumn are not identical. In the NH, the conductances in the local autumn are larger than in spring, while in the SH, the conductances are larger in the local spring than in autumn.

Figure 9 shows the NH to SH ratios of average Pedersen and Hall conductances from the bottom row of Table 2. The NH/SH ratio for conductances is larger than 1 in autumn and spring, which is in agreement with the NH/SH ratio for FACs and CF currents during low Kp conditions (see Figure 6). However, the peak NH/SH ratio for currents takes place during winter (Figure 6), while the ratio is below 1 for conductances in winter (Figure 9). Figure 9 shows a clear spring-autumn asymmetry in the hemispheric ratios of conductances. However, the conductance values in spring and autumn are not very much different, but they seem

Figure 9. The NH/SH ratios of average conductances for the four local seasons.

to behave in an opposite manner for NH and SH, making the NH/SH ratio very asymmetric between the equinoxes (see Table 2). In NH, conductances in local autumn are a bit higher than in local spring, while in SH local autumn has a bit smaller conductances than local spring.

The conductances estimated from the IRI model in winter are too small to support realistic ionospheric currents. In addition, the auroral oval is not reproduced by the model during any local season, and hence, nighttime conductances are always very small. Certainly, these things limit the reliability of the results. However, the calculations still indicate that there are some hemispheric differences in the average conductances, but they do not seem to explain the hemispheric asymmetry in currents. Possibly, they may play a role in the spring/fall asymmetry discussed in Section 4.

6. Discussion and Conclusions

In this paper, we have investigated the effect of seasons on the hemispheric asymmetry of FACs and ionospheric horizontal currents during low and high magnetic activity conditions using 5 years of Swarm vector magnetic field measurements. We find that both the seasons and geomagnetic activity level affect the hemispheric asymmetry in currents.

The most important findings of this paper are the following:

- Considering all data with $K_p < 6^+$, hemispheric asymmetry in auroral currents is largest in winter and autumn and smallest in summer and spring. The NH/SH ratio for FACs in winter, autumn, spring, and summer are 1.17 ± 0.05 , 1.14 ± 0.05 , 1.07 ± 0.04 , and 1.02 ± 0.04 , respectively.
- NH/SH ratios during all seasons for FACs and in most cases for horizontal currents are higher for low K_p (< 2) than high K_p (≥ 2) conditions. This is in accordance with Paper 1.
- In Paper 1, we found that for high K_p conditions and all seasons together, the NH/SH ratio for currents was about 1, when the uncertainty limits were taken into account. However, now, we find that also for high K_p , the NH/SH ratio is above 1 in winter and autumn with statistical significance.
- Evening sector contributes more to the high NH/SH ratio than the morning sector. For example, for low K_p conditions and for FACs, the NH/SH ratio for 13–24 MLT is 1.28 (1.26) in winter (autumn) and for 01–12 MLT 1.13 (1.09) in winter (autumn).
- Summer-to-winter ratio of FACs is 1.33 in NH and 1.53 in SH. For horizontal CF and DF currents, summer-to-winter ratio values range from 1.45 to 1.58. All values are in accordance with earlier studies of summer-to-winter ratios. However, it is worth noticing that the amplitude of the seasonal variations in auroral currents is larger in the SH than in the NH.
- In the NH, the currents are stronger in autumn than spring, with autumn-to-spring ratios 1.06 for FAC, 1.12 for CF, and 1.10 for DF currents. In the SH, auroral currents in spring and autumn are equal.
- Seasonal dependence is stronger in the EEJ than in the WEJ: The summer-to-winter ratios of EEJ (WEJ) are 1.94 (1.39) and 2.07 (1.51) in the NH and SH, respectively. This may be related to the fact that the EEJ is dominated by convection electric field, and hence, the role of the background conductivity can be expected to play a larger role than for WEJ, which is dominated by conductivity produced by electron precipitation (Kamide & Kokubun, 1996).

The physical mechanisms producing the hemispheric asymmetry are not presently understood. However, the fact that the observed hemispheric asymmetry depends both on local seasons and geomagnetic activity conditions suggest that both the local ionospheric conditions, such as magnetic field strength or daily variations in insolation, as well as external forcing from the magnetosphere associated with orientations of the IMF components may play a role.

The statistical results show a clearly smaller hemispheric asymmetry in currents during high activity conditions compared to the asymmetry during low activity conditions. During high geomagnetic activity conditions, particle precipitation from the magnetosphere and consequently also the ionospheric conductances are strongly enhanced and thus dominates the background conductivity caused by solar EUV. Also, the magnetospheric convection and the related ionospheric electric field are greatly enhanced during active conditions. If the hemispheric asymmetry would be caused by some persistent background effect, for example, in conductivity, the enhancements during active conditions would overwhelm these intrinsic differences, resulting in progressively smaller hemispheric asymmetry with increasing activity.

We calculated the ionospheric conductances during low magnetic activity conditions from the IRI, NRLM-SISE, and CHAOS models in section 5 in order to understand the role of local background ionospheric conditions on the hemispheric asymmetry. The results show seasonal variations of conductances in both hemispheres, which produce NH/SH ratios values above 1 in autumn (peak value) and spring, and values slightly below 1 in winter and summer within the region where majority of the currents flow. The results are in contradiction with FAC and CF current NH/SH ratios in winter, where the NH/SH ratio has a peak value above 1. In autumn and spring, the FAC and CF current NH/SH ratios are above 1 for low Kp conditions like the conductance ratios. However, the IRI model results are limited in reliability, because they don't seem to reproduce the auroral oval in conductivities.

Recent statistical studies (e.g., Laundal & Østgaard, 2009; Østgaard & Laundal, 2013; Østgaard et al., 2015, and references therein) have shown hemispheric asymmetries in auroral intensities. These are obviously related to particle precipitation and associated conductance enhancements. The asymmetric auroral intensities are also attributed to hemispheric differences in the solar wind dynamo efficiency when the IMF has a significant B_x component. In their review paper, Østgaard et al. (2015) reported that the auroral intensity is stronger in the NH (SH) with $B_x < 0$ ($B_x > 0$).

In addition to ionospheric conductances, the FACs and horizontal currents are related to the electric field imposed on the ionosphere by the ionosphere-magnetosphere coupling as well as IMF B_y polarity. Pettigrew et al. (2010) have conducted a statistical study on the dipole tilt angle dependency, which is related to seasonal variations, and hemispheric symmetry of the high-latitude convection pattern and cross polar cap potential using Super Dual Auroral Radar Network (SuperDARN) measurements. Their results show that when the hemispheres are compared under opposite signs of IMF B_y during positive tilt (summer like) and neutral tilt (equinox like), the cross polar cap potential of the hemisphere with IMF $B_y < 0$ is larger. Using data from POGO, Magsat, CHAMP, and Swarm, Smith et al. (2017) have found a seasonal dependent hemispherical asymmetry response of auroral electrojet to the polarity of IMF B_y . They found stronger (weaker) auroral electrojet currents in the NH than in the SH during $B_y > 0$ ($B_y < 0$) around the local winter. However, they didn't find a significant B_y effect on the auroral electrojet in the local summer season. Using Average Magnetic field and Polar current System (AMPS) model, Laundal et al. (2018) investigated the ionospheric horizontal and field-aligned currents in the NH polar region for different seasons and orientations of the IMF. They found that the horizontal current is generally stronger when $B_y > 0$ than when $B_y < 0$. Also, they pointed out the capability of AMPS model for investigating the hemispheric asymmetry in the ionospheric current system like what we did in this study.

Hence, external forcing related to hemispherically asymmetric particle precipitations and magnetospheric convection electric field is likely to contribute to the hemispheric asymmetry in the FACs and ionospheric horizontal currents. In our next paper, we will investigate the effect of the IMF on the hemispheric asymmetry of auroral current systems in order to further gauge the conditions where significant asymmetries appear.

Appendix A: Formulae for Conductance Calculation

The altitude profiles of Pedersen and Hall conductivities are calculated using the following formulae:

$$\sigma_P = \frac{eN_e}{B} \left[\frac{\nu_{en}\Omega_e}{\nu_{en}^2 + \Omega_e^2} + r_{i1} \frac{\nu_{in1}\Omega_{i1}}{\nu_{in1}^2 + \Omega_{i1}^2} + r_{i2} \frac{\nu_{in2}\Omega_{i2}}{\nu_{in2}^2 + \Omega_{i2}^2} + r_{i3} \frac{\nu_{in3}\Omega_{i3}}{\nu_{in3}^2 + \Omega_{i3}^2} \right], \quad (A1)$$

and

$$\sigma_H = \frac{eN_e}{B} \left[\frac{\Omega_e^2}{\nu_{en}^2 + \Omega_e^2} - r_{i1} \frac{\Omega_{i1}^2}{\nu_{in1}^2 + \Omega_{i1}^2} - r_{i2} \frac{\Omega_{i2}^2}{\nu_{in2}^2 + \Omega_{i2}^2} - r_{i3} \frac{\Omega_{i3}^2}{\nu_{in3}^2 + \Omega_{i3}^2} \right], \quad (A2)$$

where e is the electron charge, B is the magnetic field, N_e is the electron density, Ω_e is the electron gyro frequency, Ω_i is the ion gyro frequency, ν_{en} is the electron-neutral collision frequency, and ν_{inj} are the ion-neutral collision frequencies for three ion species $j = 1, 2, 3$, which are NO^+ , O_2^+ , and O^+ , respectively. The altitude-dependent relative abundances of ions are $r_{i1} = [\text{NO}^+]/N_e$, $r_{i2} = [\text{O}_2^+]/N_e$, and $r_{i3} = [\text{O}^+]/N_e$, where the square brackets indicate number densities of corresponding ions. The CHAOS-6 model is used to calculate the magnetic field.

The electron-neutral and ion-neutral collision frequencies are calculated using the formula given by Schunk and Nagy (2009) as follows, where the three most important neutral species O₂, N₂, and O are included.

$$\begin{aligned} \nu_{en} = & 2.33 \times 10^{-17} \times n(\text{N}_2) \times [1 - 1.21 \times 10^{-4} \times T_e] \times T_e \\ & + 1.82 \times 10^{-16} \times n(\text{O}_2) \times [1 + 3.6 \times 10^{-2} \times \sqrt{T_e}] \times \sqrt{T_e} \\ & + 8.9 \times 10^{-17} \times n(\text{O}) \times [1 + 5.7 \times 10^{-4} \times T_e] \times \sqrt{T_e}, \end{aligned} \quad (\text{A3})$$

$$\begin{aligned} \nu_{in1} = & 4.34 \times 10^{-16} \times n(\text{N}_2) + 4.27 \times 10^{-16} \times n(\text{O}_2) \\ & + 2.44 \times 10^{-16} \times n(\text{O}), \end{aligned} \quad (\text{A4})$$

$$\begin{aligned} \nu_{in2} = & 4.13 \times 10^{-16} \times n(\text{N}_2) + 2.31 \times 10^{-16} \times n(\text{O}) \\ & + 2.59 \times 10^{-17} \times n(\text{O}_2) \times \sqrt{T_r} \times (1 - 0.073 \times \log_{10}(T_r))^2 \end{aligned} \quad (\text{A5})$$

$$\begin{aligned} \nu_{in3} = & 6.82 \times 10^{-16} \times n(\text{N}_2) + 6.66 \times 10^{-16} \times n(\text{O}_2) \\ & + 3.67 \times 10^{-17} \times n(\text{O}) \times \sqrt{T_r} \times (1 - 0.064 \times \log_{10}(T_r))^2, \end{aligned} \quad (\text{A6})$$

where $n(\text{N}_2)$, $n(\text{O}_2)$, and $n(\text{O})$ are number densities of N₂, O₂, and O, respectively, T_e , T_i , and T_n are electron, ion, and neutral temperatures, respectively, and $T_r = (T_i + T_n)/2$.

The Pedersen and Hall conductances are height integrated as

$$\Sigma_P = \sum_{k=1}^N \sigma_P(z_k) \delta z, \quad (\text{A7})$$

and

$$\Sigma_H = \sum_{k=1}^N \sigma_H(z_k) \delta z, \quad (\text{A8})$$

where N is the number of altitudes between 90 and 200 km and δz is the altitude resolution. In our calculation, δz was 2 km.

Data Availability Statement

The calibrated 1-Hz Swarm magnetic field data are available at <https://swarm-diss.eo.esa.int>. The Kp index data used in this study are available at <https://isgi.unistra.fr>. These data are calculated and made available by the GFZ German Research Centre for Geosciences from data collected at magnetic observatories. We thank the involved national institutes, the INTERMAGNET network, and the International Service of Geomagnetic Indices. The CHAOS-6-x8 model is available at <http://www.spacecenter.dk/files/magnetic-models/CHAOS-6>. The Altitude adjusted corrected geomagnetic (AACGM) coordinate transformation software is available at <https://superdarn.thayer.dartmouth.edu/aacgm.html>. The authors greatly appreciate the availability of the software from these websites.

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