Longitudinal variations of nighttime electron auroral precipitation in both the Northern and Southern hemispheres from the TIMED global ultraviolet imager

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[1] Using 6 years of Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) global ultraviolet imager auroral observations in both hemispheres, we have studied the longitudinal variations of auroral precipitation during the magnetic nighttime period of 2100–0300 magnetic local time. There was a strong seasonal dependence of the longitudinal variations of the aurora: (1) During solstices and for both hemispheres, auroral precipitation peaked between magnetic longitude (MLON) 210°E and 360°E in June and between MLON 120°E and 300°E in December. (2) In the equinoxes, the auroral longitudinal pattern was generally similar to that in local summer in each hemisphere, except that in the Northern Hemisphere the maximum precipitation was usually located in more westward longitudes in equinox than in summer. (3) The ratios between the maximum and the minimum of the precipitation energy flux along longitudes varied between 1.3 and 1.9, which were similar to those in previous studies. These features of the auroral longitudinal patterns did not change much from $Kp = 1$ to $Kp = 4$ conditions. Since the longitudinal distribution of auroral precipitation changed greatly with season in each hemisphere, the longitudinal variations of the magnetic field strength, which do not change with season, might not be the only process that caused the observed longitudinal variations of the aurora. Further data analysis shows that there was a significant negative correlation (coefficient $|r| = \sim 0.4–0.8$) between the peak auroral precipitation intensity and the solar-EUV-produced ionospheric conductivity of the same hemisphere (in summer and equinox) or of the conjugate hemisphere (in winter). These results indicate the important effects of solar-EUV-produced ionospheric conductivity, which has significant longitudinal variations, on the longitudinal patterns of the aurora at magnetic nighttime. Our results also suggest that the interhemispheric coupling during solstices might be an important factor that contributes to the longitudinal variations of the nighttime aurora. Our correlation analysis indicates that the hemispheric differences in the conjugate magnetic field strengths also contribute to the longitudinal variations of the aurora, although they appear not to be a major factor.


1. Introduction

[2] Early theoretical studies suggested that there was a marked longitudinal difference in the leakage of auroral particles from the trapped-radiation regions [Loughnan, 1961]. In the Northern Hemisphere, a consistent longitudinal variation of auroral precipitation energy flux and occurrence frequency, with a maximum to minimum ratio between 1.5 and 2, was reported in a number of studies, including those using riometer absorption [e.g., Basler, 1963; Driatisky, 1966; Berkey, 1973] and energetic precipitating particle observations [e.g., Stenbaek-Nielsen, 1974]. These studies, using observations from longitudinally separated stations, suggested that the longitudinal asymmetry of auroral precipitation appeared to be consistent with the longitudinal variation of the difference between the conjugate magnetic field strengths or magnetic mirror heights. Under this hypothesis, mirroring electrons penetrate deeper into the...
hemisphere where the magnetic field strength is weaker, and thus preferentially depletes the supply of electrons available for precipitation in the other hemisphere. Consequently, higher (lower) auroral activity takes place in the hemisphere where a weaker (stronger) magnetic field strength occurs.

[5] Therefore it was suggested that the longitudinal asymmetries in the Earth’s internal magnetic field are the primary cause of the longitudinal variations of the auroral activity, although the geometrical relation between the Earth’s rotational axis, the dipole axis, and the interplanetary magnetic field may also contribute to the hemispherical and longitudinal differences in auroral precipitation [Stenbaek-Nielsen, 1974, and references therein]. Using electron energy flux maps derived from the NO density observed by the Student Nitric Oxide Explorer (SNOE) satellite, Barth et al. [2002] reported that there was more energy deposited at western geomagnetic longitudes and less at eastern longitudes during equinox in the Northern Hemisphere. The longitudinal location of the auroral peak also had an eastward drift relative to the location of the largest differences in the conjugate magnetic field strengths. They suggested that the tilted, offset magnetic dipole field might be the controlling factor for the observed longitudinal asymmetry of the precipitating electrons.

[4] However, longitudinal variations of auroral precipitation and the mechanisms that cause them need further study. As pointed out by Stenbaek-Nielsen [1974], the longitudinal pattern of auroral activity was not certain, owing to the limited observations used in these earlier studies. Furthermore, the major mechanisms that have been proposed to explain these longitudinal variations have not yet been validated by sufficient observations from the Southern Hemisphere. In addition to the effects of the magnetic field strength, there were indications that auroral electrodynamics varies longitudinally and hemispherically owing to the influence of the nondipolar features of the geomagnetic field and the tilt of the geomagnetic dipole axis [Gasda and Richmond, 1998]. In the last two decades, many studies have shown that there is an inverse dependence of auroral precipitation on the effects of solar EUV and consequently solar-produced ionospheric conductivity [e.g., Newell et al., 1996, 1998; Liou et al., 2001; Shue et al., 2001; Ohtani et al., 2009]. These studies suggested that there might be other factors that contribute to the longitudinal pattern of auroral activity.

[5] In this paper, we use a large number of auroral energy flux images (>55,000) observed by the global ultraviolet imager (GUVI) instrument on board the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite during 2002–2007 to investigate the longitudinal variations of auroral activity during magnetic nighttime (2100–0300 magnetic local time (MLT)) in both hemispheres and in different seasons. A correlation analysis between the auroral intensity and the magnetic field strength and ionospheric conductivity has been carried out to discuss the possible processes that contribute to the observed longitudinal variations of the aurora.

2. Data Sets and Analysis Method

[6] The GUVI images of auroral precipitation energy flux (http://guvi.jhuapl.edu) from February 2002 to October 2007 were used in our study. Each image covered about one third to one half of the auroral region. Most of the images included ~300,000–400,000 pixels with a resolution of about 40 × 40 km or 0.44° × 0.44° in magnetic latitude (MLAT) and magnetic longitude (MLON). These raw images were produced by the GUVI instrument performing cross-track scanning while the TIMED satellite passed over the auroral region. The auroral precipitation energy flux was derived from simultaneous observations of Lyman-Birge-Hopfield short (LBHs; 140.0–150.0 nm) and Lyman-Birge-Hopfield long (LBHl; 165.0–180.0 nm) emissions. These FUV radiances were used to estimate mean energy and energy flux of auroral electrons through an auroral model (Boltzman Three Constituent-B3C [see Danieli, 1993]) and an airglow model (Atmospheric Ultraviolet Radiance Integrated Code-AURIC [see Strickland et al., 1983]) [Strickland et al., 1999; Zhang and Paxton, 2008]. A detailed description and the validation of the method used to convert the observed auroral emission rates into precipitation energy flux and to remove the dayglow contamination are given by Zhang and Paxton [2008] and Luan et al. [2010]. The energy flux data of each orbit/image are organized by MLAT and MLT in the Altitude Adjusted Corrected Geomagnetic Coordinate (AACGM) as well as by UT for each pixel in the online database.

[7] In this study we obtained the associated magnetic longitude (MLON) for each image pixel by using the MLT and UT information of that pixel and considering the equation of time, which was calculated from the AACGM routine. The equation of time is the difference between the yearly mean solar time and the true solar time for a given place at the same real instant of time. Thus each pixel was associated with a set of MLAT, MLT, and MLON. These GUVI pixels were then binned into 12 magnetic longitudinal sectors that were 30° wide. There were more pixels at lower latitudes and fewer at higher latitudes owing to the difference in geographic areas at different latitudes. However, the peak auroral precipitation mostly occurred within a narrow magnetic zonal band just several degrees wide in magnetic latitude. Thus the effects of the unevenly distributed pixels with latitude on auroral longitudinal patterns were minor. The data were also binned for different Kp levels (1–4) in order to study the possible geomagnetic activity effect on the longitudinal variations of the aurora, since the precipitation energy flux increases greatly with geomagnetic activity [Luan et al., 2010]. Furthermore, our analysis focuses on the longitudinal patterns at magnetic nighttime between 2100 and 0300 MLT, since auroral precipitation is the strongest during this period, when ~50% of the contribution to the total hemispheric power occurs [Luan et al., 2010].

[8] The GUVI precipitation data in the magnetic night (2100–0300 MLT) were divided into three seasons in each hemisphere: summer, winter, and equinoxional seasons. The data in local summer and winter represented predominantly sunlit and dark conditions, respectively, whereas the results in the equinoxional seasons corresponded to mixed conditions of both sunlight and darkness. Data in each solstice season were binned for 90 days centered on the solstice day, whereas the data in the equinoxional seasons were binned in two groups of 45 days centered at the spring and fall equinoxional days, respectively. This data selection in the
The equinoctial seasons was applied to choose data under dark to weak sunlit conditions in both hemispheres between 2100 and 0300 MLT.

Figure 1 shows orbit or image counts (i.e., the total number of TIMED/GUVI orbits that passed over a particular location from 2002 to 2007) for $K_p = 2$ condition in three different longitudinal sectors (magnetic longitude (MLON) 60°E, 180°E, and 300°E) in the June solstice (Figure 1a) and equinoctial (Figure 1b) seasons for both hemispheres. In each magnetic longitudinal sector, data were binned using a grid of 1° × 0.5 h in MLAT and MLT. Between 2100 and 0300 MLT, the orbit counts in the June solstice of both hemispheres were mostly larger than 40 for each MLAT and MLT grid. Also, orbit counts were generally larger in the Southern Hemisphere than in the Northern Hemisphere in the June solstice. This was a result of the 74° inclination of the TIMED satellite. Opposite conditions occurred in the December solstice (not shown), when the magnetic nighttime auroral regions of the Northern Hemisphere had more TIMED passes. The orbit counts at the equinox for both hemispheres were mostly larger than 60 between 2100 and 0300 MLT. For each season/hemisphere, the observational counts in magnetic local nighttime were generally similar in different longitude sectors and also between magnetically premidnight and postmidnight hours, except that there were relatively fewer data samples around 180°E sector. In each season/hemisphere, the observational samples were about the same for $K_p = 1–3$ conditions. However, only about half as many samples occurred when $K_p$ was 4.

The current study will focus on the interhemispheric comparison of the nighttime precipitation intensity during the same MLT period (2100–0300). To reduce the possible uncertainty due to the uneven distribution of observational samples, the average energy flux in each MLAT × MLT grid was further averaged for the entire 2100–0300 MLT period for each longitudinal sector. Longitudinal variations of the precipitation energy flux for all $K_p$ conditions (1–4) have been examined. However, we will show only the results for $K_p = 2$ and $K_p = 4$ conditions since auroral longitudinal
variations were very similar for all $Kp$ conditions from $Kp = 1$ to $Kp = 4$.

3. Results and Discussion

3.1. Auroral Longitudinal Variations

[13] Figure 2 shows longitudinal variations of the averaged auroral precipitation energy flux of both hemispheres during nighttime (2100–0300 MLT) under $Kp = 2$ (Figures 2a–2c) and $Kp = 4$ (Figures 2d–2f) conditions. From top to bottom, the images are the results for the June solstice (Jun.), December solstice (Dec.), and equinoctial seasons (Eqx.) in each hemisphere, respectively. Figures 2a and 2b show that the longitudinal variations of auroral precipitation were mostly symmetric between the two hemispheres for both the June and December solstice periods for $Kp = 2$. In the June solstice, higher precipitation mostly occurred from about 180° to 30°E (counted in the direction from MLON 0°E to 360°E; the same convention is used in the remainder of the paper if not otherwise specified) in both hemispheres with peaks centered around 270°–300°E, whereas in the December solstice period, stronger precipitation mostly occurred from 120° to 300°E in both hemispheres with peaks centered around 210°E. In addition, the maximum to minimum ratios were 1.6 for the June solstice and 1.4 for the December solstice in both hemispheres at 68° MLAT. There were, however, slight differences in the longitudinal variations of the auroral precipitation between the Northern and Southern hemispheres in the solstices. For example, during both solstice periods there were apparent longitudinal variations of the latitude of the peak auroral precipitation in the local winter hemispheres, whereas there were no such variations in the local summer hemispheres.

[12] Figure 2c shows the results in the equinoctial seasons in the two hemispheres. In the Northern Hemisphere, stronger precipitation occurred mostly in the western longitudes (~180°–30°E). The maximum precipitation centered around 240°–270°E MLON. At 68°N MLAT, the maximum to minimum ratio was 1.5. In the Southern Hemisphere, stronger precipitation occurred at latitudes between 120° and 300°E with a broad peak of precipitation centered near the 210°E longitude. At 68°S MLAT, the maximum to minimum ratio was 1.6. In each hemisphere, the longitudinal structure of the auroral energy flux was roughly the same in local summer and in the equinoxion, except that the maximum precipitation in the Northern Hemisphere was located at more westward longitudes in equinoxion than in summer. The longitudinal patterns for summer and equinoxion in the Northern Hemisphere in this study are similar to previous results derived from NO density observations [Barth et al., 2002] in equinoxion and observations from an all sky camera near the spring equinox [Stenbaek-Nielsen, 1974], as well as other early observations for all seasons [Berkey, 1973].

[13] Figures 2d–2f show the results for $Kp = 4$ conditions. Although the observational samples for $Kp = 4$ were only about half of those for each of $Kp = 1–3$ conditions, longitudinal and latitudinal variations of auroral precipitation between $Kp = 2$ and $Kp = 4$ were generally similar. In fact, similar longitudinal variations of the precipitation energy flux occurred for all $Kp$ used ($Kp = 1–4$). The latitude of the maximum auroral precipitation, of course, moved to lower latitudes with increasing $Kp$. During solstice periods, the maximum to minimum ratios of auroral precipitation varied between 1.3 and 1.9 for all $Kp = 1–4$. During equinoctial seasons, the maximum to minimum ratios varied between 1.3 and 1.6 for all $Kp = 1–4$ conditions.

[14] The longitudinal structure of auroral precipitation was more interhemispherically symmetric during the solstice periods than during the equinoctial periods (Figure 2). As we will discuss later, the local summer hemisphere is predominantly sunlit during solstice periods, whereas the local winter hemisphere is completely dark from 2100 to 0300 MLT. During the equinoctial period, both hemispheres vary from darkness to weakly sunlit conditions. Therefore, during the solstice seasons, the generally similar longitudinal features of precipitation between the Northern and Southern hemispheres could not be caused merely by charged particles following the Earth’s magnetic field lines, since no such hemispheric symmetry in auroral precipitation occurred in the equinoxions, when the geophysical conditions between the two hemispheres were more symmetric than they were in the solstices. These results suggest that there might be strong interhemispheric coupling during the solstice period that would lead to similar longitudinal structures in auroral activity.

[15] The center UT is different for different longitudinal sectors during 2100–0300 MLT. Therefore the significant auroral longitudinal patterns also indicate there are significant UT variations in the total auroral precipitation energy deposited in the polar ionosphere in each season and in each hemisphere.

3.2. Auroral Longitudinal Pattern Comparison Between Premidnight and Postmidnight

[16] Figure 3 shows longitudinal variations of the averaged auroral precipitation energy flux under $Kp = 2$ conditions during the premidnight (2100–0000 MLT, Figures 3a–3c) and postmidnight (0000–0300 MLT, Figures 3d–3f) periods. The averaged energy flux was calculated in the same way as it was during the 2100–0300 MLT period. Auroral longitudinal patterns were generally similar between the premidnight and postmidnight sectors. This similarity occurred for all $Kp = 1–4$ (not shown). The major difference in the longitudinal patterns between these two periods was the obvious eastward shifts of the location of the maximum and minimum precipitation intensities from the premidnight to postmidnight periods by ~30°. This difference may be related to variations in solar illumination between these two periods, as will be discussed later (section 3.3.3). In addition, the precipitation energy flux occurred in a wider latitudinal range and at higher latitudes during the premidnight period than during the postmidnight period. The wider latitudinal range of precipitation before midnight could result from discrete auroral precipitation on the poleward side during the premidnight period, when these discrete aurora are mostly seen in DMSP observations [Newell et al., 1996] and are the most intense, as seen by POLAR UVI [Liou et al., 2001]. The differences in the latitudes of peak precipitation energy flux appeared to be caused by the different location of the upward field-aligned
currents between premidnight and postmidnight [Green et al., 2009]. Discrete aurorae are only a minor part of the total auroral precipitation energy flux [Newell et al., 2009], and thus the auroral longitudinal pattern is largely determined by the variations of the diffuse aura on the equatorward side of the auroral oval.

[17] In both hemispheres, there were clear longitudinal variations of the peak precipitation latitudes in the winter
and equinoctial seasons, whereas there were no such significant variations in summer (e.g., NH-Jun. and SH-Dec.). In the equinoctial seasons of both hemispheres, the latitudes of the peak auroral intensity were generally higher around those longitudes where there was strong precipitation (i.e., within \(\sim 270^\circ - 60^\circ\)E in the Northern Hemisphere and within \(\sim 60^\circ - 240^\circ\)E in the Southern Hemisphere). In the winter seasons of both hemispheres, the latitudes of the peak intensity were higher around the longitudes where there was relatively weak precipitation, that is, at \(\sim 330^\circ - 60^\circ\)E in the Northern Hemisphere and \(\sim 60^\circ - 240^\circ\)E in the Southern Hemisphere. These longitudinal variations of the peak precipitation latitudes were stronger during the premidnight period than they were during the postmidnight period.

Figure 3. Longitudinal variations of the averaged auroral precipitation energy flux under \(K_p = 2\) conditions during (a–c) premidnight (2100–0000 MLT) and (d–f) postmidnight (0000–0300 MLT) periods.
3.3. Relative Contributions From the Magnetic Field Strength and Solar Illumination

3.3.1. Comparison With the Magnetic Field Strength

Figures 4a–4d show maps from the International Geomagnetic Reference Field (IGRF) at 120 km altitude for the magnetic field strength in the Northern Hemisphere, the magnetic field strength in the Southern Hemisphere, the difference of the magnetic field strengths (dB) between the Southern and Northern hemispheres, and an eastward shift (50°) of dB in Figure 4c, respectively. The dotted lines indicate the locations of the minimum and maximum dB. The possible shifting effect, which might be caused by eastward $E \times B$ drift of plasma sheet particles, of the difference of the magnetic field strengths on the longitudinal variations of auroral precipitation was suggested by Barth et al. [2002]. Here we shifted the difference of the magnetic field strengths eastward by 50° to examine this effect. In the Northern Hemisphere, it appears that the longitudinal variations of the aurora corresponded well with the longitudinal asymmetry of the eastward shifted hemispheric differences in the geomagnetic field strengths during both summer and equinox. For instance, the longitudes of the minimum and maximum precipitation intensities were, in general, aligned with the locations of the minimum (~120°E) and maximum (~280°E) of the shifted differences of the magnetic field strengths, respectively. However, there was little or no such alignment in local winter in the Northern Hemisphere.

Figure 4. Maps from the International Geomagnetic Reference Field for (a) magnetic field strength in the Northern Hemisphere, (b) magnetic field strength in the Southern Hemisphere, (c) magnetic field strength difference (dB) between the Southern and Northern hemispheres, and (d) an east shift of dB in Figure 4c. The dotted lines indicate the locations of the minimum and maximum dB in Figures 4c and 4d.

[18] The magnetic field does not have any seasonal variations, and thus the seasonal variations of the auroral longitudinal pattern suggest that other physical processes should also contribute to the observed auroral longitudinal pattern. This is even more evident when the Southern Hemisphere case is considered. If the magnetic field configuration was the major determining factor of longitudinal variations of the aurora as previously suggested [Stenbaek-Nielsen, 1974; Barth et al., 2002], then the longitude of the peak of auroral precipitation would occur around 60°E and 110°E in the Southern Hemisphere for the unshifted (Figure 4c) and shifted (Figure 4d) cases of the deference of the interhemispheric magnetic field strengths, respectively. Also, it would not be dependent on seasonal conditions. In addition, the longitudes of the minimal auroral activity would be at ∼230°E and 290°E in the Southern Hemisphere for these two cases.

[19] The concept that magnetic field configuration determines the longitude of the maxima and minima of precipitation requires the minimum (maximum) auroral activity in the Southern Hemisphere to occur at the longitudes of the maximum (minimum) auroral activity in the Northern Hemisphere. However, it is apparent that during both the equinoxes and the solstices, the maximum (minimum) auroral precipitation in the Southern Hemisphere did not occur at longitudes where there was minimum (maximum) auroral precipitation in the Northern Hemisphere. Instead, both Figures 2 and 3 demonstrate that the longitudinal
patterns of the two hemispheres were more or less symmetric in the solstices, with the auroral maxima and minima occurring at roughly the same longitudes, for both $Kp = 2$ and $Kp = 4$ and for the premidnight and postmidnight periods. Therefore our results are not consistent with the previously suggested, hemispheric asymmetry pattern of the auroral precipitation intensity that would occur mainly owing to the hemispheric asymmetry of the magnetic field strength or the magnetic mirror height [Stenbaek-Nielsen, 1974; Barth et al., 2002].

[21] The magnetic field strength effect involving mirror height depends on the type of aurora [Stenbaek-Nielsen et al., 1973]. For diffuse aurora, which is produced by particles slowly scattered into the loss cone, the relative differences of the conjugate magnetic field strength would have important effects on the auroral longitudinal pattern. These effects would mostly change the equatorward side of the auroral precipitation. On the other hand, for discrete aurora, which is mostly accelerated by field-aligned electric fields, its pitch angle distribution will become highly field-aligned in both hemispheres. Thus discrete aurora would not be affected much by the magnetic field strength. Discrete aurorae occur mostly on the poleward side in the premidnight sector [Newell et al., 2009]. Besides the variations in the mirror height, another possible effect of the magnetic field strength is that the precipitating particles are spread out over a larger geographic area in the hemisphere where the magnetic field is weak. This will have the opposite effect on auroral intensity in comparison with that from the mirror height; that is, higher averaged auroral precipitation intensity occurs where the magnetic field is stronger.

[22] Our results from GUVI (Figures 2 and 3) showed that longitudinal variations of the precipitation intensity changed significantly with season in each hemisphere, whereas the longitudinal variation of the magnetic field strength does not. These observations, therefore, do not support the hypothesis that the magnetic field strength is the most important factor in producing auroral longitudinal variations. There must be other factors that determine both the longitudinal variations of the aurora and their seasonal dependence. These observations, however, do not rule out the possibility that the magnetic configuration still contributes, to some extent, to the longitudinal variations of auroral precipitation. A detailed correlation analysis between the auroral precipitation intensity from TIMED/GUVI and the magnetic field strength has been carried out in this paper. The results will be discussed later in section 3.3.3 to obtain more physical insight on this subject.

3.3.2. Comparison With Longitudinal Variations of Solar-Produced Ionospheric Conductivity

[23] Given an inverse dependence of the auroral precipitation energy flux/occurrence frequency on the solar-EUV-radiation-produced ionospheric conductivity [e.g., Newell et al., 1996, 1998; Liou et al., 2001; Shue et al., 2001; Ohtani et al., 2009], the longitudinal variations of auroral precipitation might be related to longitudinal variations of the solar-EUV-produced ionospheric conductivity. Figure 5 shows the averaged longitudinal variations of the solar-EUV-produced Pedersen conductivity and the percentage of sunlit hours (solar zenith angle $\chi < 97.6^\circ$) as a function of MLAT and MLON between 2100 and 0300 MLT for all seasons and both hemispheres. Note that in local winter seasons, both hemispheres are dark during this MLT period. The height-integrated Pedersen conductivity ($\Sigma_P$) was calculated using an empirical formula [Rasmussen et al., 1988; Newell et al., 2002].

$$\Sigma_P(\chi) = (4.5/B)(1 - 0.85u^2)(1 + 0.15u + 0.05u^2),$$  \hspace{1cm} (1)

where $B$ is the magnetic field strength in gauss and the parameter $u = F_{10.7}^{\gamma}/90$, in which $F_{10.7}$ is a proxy for solar-EUV flux. The zenith angle $\chi$ defines $u$, namely, $u = \chi/90$. We set $\Sigma_P = 0$ when $\chi > 97.6^\circ$. In our analysis, we set a constant $F_{10.7} = 110$ to match the mean solar activity conditions for GUVI observations between 2002 and 2007. The magnetic field strength $B$ was obtained from the IGRF model. According to equation (1), the magnitude of the ionospheric conductivity changes nonlinearly with $F_{10.7}$. The magnetic field strength can also affect the magnitude of the conductivity.

[24] The ionospheric conductivity calculation was done on a grid of $1^\circ \times 1$ h in MLAT and MLT during 2100–0300 MLT for 48 magnetic longitudinal (MLON) sectors that were $7.5^\circ$ wide. Here we used more longitudinal sectors than the 12 longitudinal bins used for TIMED/GUVI data to obtain smoother contours of conductivity in Figure 5. In each longitudinal sector, the calculation was carried out from day 1 to day 365 between MLAT 50$^\circ$ and 90$^\circ$ for both hemispheres. The solar zenith angle and magnetic field strength were calculated using a geographic latitude, longitude, and UT that corresponded to a particular MLAT and MLT grid point in a particular MLON sector. We first obtained the daily averaged conductivity during 2100–0300 MLT. These daily values were then binned into three different seasons for both hemispheres in the same way as the seasonal binning was done for the auroral precipitation from GUVI observations. The center of the maximum solar illumination/solar-EUV-produced conductivity moves westward for 2100–0000 MLT and eastward for 0000–0300 MLT relative to the position shown in Figure 5 in each summer and equinoctial seasons (not shown here).

[25] Figure 5 shows that while the local winters (NH-Dec. and SH-Jun.) are all in darkness during the night during solstice periods, there are also longitudes under dark or weak sunlit conditions in local summers (270$^\circ$ to 60$^\circ$E in NH-Jun. and 90$^\circ$ to 300$^\circ$E in SH-Dec.). Comparing the longitudinal variations between the solar-produced ionospheric conductivity (Figure 5) and the aurora (Figure 2), we can see that at the longitudes of low ionospheric conductivity in local summer, there was generally higher precipitation intensity in both the local summer and the conjugate winter hemispheres. Accordingly, during solstices, higher precipitation intensity generally occurred around longitudes where both hemispheres were in darkness or under weak sunlit conditions, when the solar-produced conductivity was relatively low. In addition, it is important and interesting to note that in local winters, auroral precipitation was relatively weaker at longitudes where the conjugate summer hemisphere was under strong sunlight conditions, despite the fact that all longitudes were dark during nighttime and there was no solar-radiation-produced ionospheric conductivity.

[26] The anticorrelation between the solar-produced conductivity and the precipitation intensity shown here
(Figures 2, 4, and 5) suggests the important role that solar illumination plays on the overall longitudinal variations of auroral activity. This anticorrelation is consistent with previous studies, which used DMSP [Newell et al., 2010] and Freja satellite [Hamrin et al., 2005] observations, to show that all types of aurora (both the discrete and diffuse) varied with sunlight. It has also been reported that during 2000–0200 MLT, both region 1 (R1) and region 2 (R2)
field-aligned currents tend to be larger when the ionosphere is in darkness than when it is sunlit [Ohtani et al., 2005]. For both R1 and R2 current regions, the electron energy flux is larger in darkness than in sunlight [Ohtani et al., 2009]. An anticorrelation between the solar-EUV-produced conductivity and auroral brightness was also reported from Polar UV observations in the premidnight sector (MLT 2300, MLAT 65°) [Shue et al., 2001]. This change of auroral intensity with conductivity should not only be caused by the suppression of discrete auroral occurrence by sunlight, but also be largely due to the suppression of diffuse auroral intensity by sunlight, since the majority of precipitation intensity comes from diffuse aurora [Newell et al., 2009]. Newell et al. [1998] used 12 years of DMSP particle precipitation observations to find that there was a strong anticorrelation (r = -0.96) between the F10.7 index and the mean frequency of electron acceleration events. These previous studies binned aurora activity explicitly by solar-produced conductivity or by the F10.7 index and revealed that there were precipitation differences not only between sunlit (summer) and dark (winter) conditions, but also between different levels of solar illumination. This may largely explain the observed longitudinal variations of nighttime auroral precipitation and their seasonal variations, not just in local summers and equinoxes, but also in local winters provided that there is an interhemispheric coupling process occurring that enables the summer ionospheric conductivity to affect the auroral activity in the winter hemisphere.

[27] In the local winter (i.e., December solstice season in the Northern Hemisphere or June solstice season in the Southern Hemisphere), when there was no solar illumination at nighttime, the auroral precipitation energy flux (Figure 2) was generally anticorrelated with solar-produced conductivity in the conjugate summer hemisphere (Figure 5), indicating a possible ionospheric control of the longitudinal pattern of auroral precipitation by the conjugate summer ionospheric conductivity. A possible coupling between the two hemispheres may be through interhemispheric field-aligned currents [e.g., Richmond and Roble, 1987; Benkevich et al., 2000; Laundal and Østgaard, 2009]. Benkevich et al. [2000] suggested that there were more significant interhemispheric field-aligned currents for summer/winter conditions than for equinoctial conditions. Both the work of Richmond and Roble [1987] and Benkevich et al. [2000] suggested that the magnitude of the total interhemispheric current was large and comparable to that of the total field-aligned currents. Laundal and Østgaard [2009] reported a case that interhemispheric currents were observed simultaneously from both hemispheres. However, regular and significant interhemispheric currents have not been reported from other observations, and their roles in the interhemispheric coupling and auroral longitudinal patterns require further study.

[28] At the equinoxes, the ionosphere was under mixed conditions from darkness to weak sunlight, as shown in Figures 5c and 5f. As a result, the auroral precipitation intensity shows some mixed features from both the summer and winter seasons, although the overall longitudinal pattern was generally similar to the summer pattern in each hemisphere (Figures 2 and 3). In the northern equinox, the maximum precipitation, which was centered around 240°E, appeared to be the combination of the longitudinal precipitation patterns of summer (Figure 2, plots for NH-Jun.) and winter (Figure 2, plots for NH-Dec.) conditions. Similarly, the wide precipitation peak around MLON 180°E at the southern equinox also represented mixed features of summer and winter conditions of the same hemisphere.

[29] These results lead us to a conjecture that solar illumination and the consequent solar-produced conductivity might have important effects on auroral longitudinal patterns. In addition, as we mentioned earlier, the center of the maximum solar illumination and the consequent ionospheric conductivity shifted eastward from premidnight to postmidnight. This shift was also consistent with the eastward shift of the maximum and minimum auroral precipitation intensity from the premidnight period to the postmidnight period (Figure 3). Other factors, such as the dipole tilt, the magnetic field strength, and the spatial structure might also have made additional contributions. It is obvious that in the summer and equinoctial seasons, the longitudinal variations of the solar zenith angle and solar-produced conductivity also depend on the dipole tilt variations, since there is more solar illumination when the tilt is more toward the Sun.

3.3.3. Correlation Coefficients Comparison

[30] Figure 6 presents comparisons of the 2-D correlation coefficients between the auroral precipitation intensity and several parameters that might be the cause of the longitudinal variations of auroral precipitation. These parameters include the magnetic field strength (B) in the same hemisphere (case a), the differences between the conjugate magnetic field strengths (dB, case b), dB shifted eastward by 50° (case c), and the solar-produced ionospheric conductivity (case d). All these cases are calculated in a magnetic latitudinal range defined within the equatorward and poleward edges of the auroral oval, where auroral precipitation energy flux is equal to 50% of the peak energy flux at a particular magnetic longitude. We also defined the latitudinal range by e-folding, instead of 50% of the peak energy flux, and obtained a similar result. In addition, Figure 6 gives the 2-D correlation coefficient between auroral energy flux and the ionospheric conductivity for the case in which the magnetic latitude range is defined as 6° wide (i.e., 3° from the latitude of peak precipitation energy flux in both the equatorward and poleward directions) for each magnetic longitude (case e). The coefficients are for Kp = 1–4 and for all seasons in both the Northern Hemisphere (Figure 6, left-hand charts) and the Southern Hemisphere (Figure 6, right-hand charts), respectively. The correlation with the solar-EUV-produced conductivity was obtained by using the conductivity from the same hemisphere in summer and equinox, and from the conjugate hemisphere for local winter. The correlation between the auroral precipitation intensity and the solar-EUV-produced conductivity is negative. The absolute correlation coefficients are presented in Figure 6 for better visualization. The current correlation analysis only provides some indication of the relative roles that the magnetic field strength and solar illumination might play in the longitudinal variations of the aurora. To further understand the causal relationship, more observations are needed as well as physics-based modeling effects.

[31] Figure 6 shows that for all seasons, and in both hemispheres, the correlation between the auroral precipita-
tion intensity and the magnetic field strength in the same hemisphere was relatively weak. The correlation coefficients were mostly around 0.1–0.3. There were persistent positive correlations between the auroral precipitation intensity and the hemispheric difference of the magnetic field strength (dB) during the December solstice and equinox in both hemispheres, with correlation coefficients mostly between 0.2 and 0.4. However, there were much weaker correlations, and possibly no correlations, between the two during the June solstice. The correlation between the auroral intensity and the shifted dB, on the other hand, appeared to be obvious during the June solstice for both hemispheres and for the northern equinox case. This indicates that there might be contributions from the differences in the conjugate magnetic field strengths to the auroral longitudinal patterns. However, the dB and shifted dB are not expected to have seasonal variations, whereas the longitudinal variations of the aurora changed with season. It is expected that at lower latitudes, when the longitudinal asymmetry of the geomagnetic field strength becomes more severe, especially in the Southern Hemisphere, the effect of the conjugate magnetic field strength difference can become stronger. This could happen under high \( Kp \) conditions when the aurorae expand to lower latitudes. In the present study, however, there is no indication of the change of correlation coefficients from \( Kp = 1 \) to \( Kp = 4 \).

There were significant negative correlations (mostly \( -0.3 \) to \( -0.6 \)) between the auroral precipitation intensity and the solar-EUV-produced ionospheric conductivity in the same hemisphere for local summer and equinox and in

![Figure 6](image-url)
the conjugate hemisphere for local winter. The correlation coefficients were even more negative (mostly \(\sim -0.4\) to \(-0.8\)) for case e. These results suggest the significant effects of the solar illumination on the auroral longitudinal pattern, in addition to the contribution from the hemispheric difference of the conjugate magnetic field strengths. This result is consistent with the general anticorrelation between the auroral precipitation intensity and the solar-EUV-produced conductivity, as shown in Figures 2 and 5. Figure 6 also shows that the absolute correlation coefficients between the auroral precipitation intensity and the solar-EUV-produced conductivity were generally larger than those between the auroral precipitation intensity and the differences of the conjugate magnetic field strengths. This result indicates that the effect of the solar illumination is probably more important than that of the difference of the magnetic field strengths in controlling the longitudinal variation of the aurora.

3.4. On the Summer-Winter Difference

[33] Discrete auroral precipitation is more often suppressed in sunlit/summer than in darkness/winter conditions [Newell et al., 1996; Liou et al., 2001] as a result of the feedback effect of the ionospheric conductivity or other similar mechanisms [Newell et al., 2001, and references therein]. This present work also indicates a significant solar illumination/ionospheric conductivity effect on the peak precipitation, which is mostly due to diffuse aurora. However, in the present work, local summer had roughly similar peak precipitation intensity to that of local winter during 2100–0300 MLT for both hemispheres (Figures 2 and 3). This appears to be mainly caused by the occurrence of darkness or weak solar illumination conditions at certain longitudes in the summer hemisphere. As we showed in Figure 5, the summer hemisphere is not necessarily sunlit for all longitudes during 2100–0300 MLT. For example, it is dark during these local times at longitudes from 270° to 60°E in the northern summer and from 90° to 300°E in the southern summer. At those locations the averaged solar-EUV-produced ionospheric conductivity is very small in the auroral oval. Thus it is not a surprise that the maximum precipitation energy flux intensities between the summer and winter hemispheres are comparable. We have tested different binning methods and found that the size of the bin does not change our conclusions about the fact that there are longitudes in which solar illumination and ionospheric conductivity are low in local summer. In addition, the effects of the solar-produced ionospheric conductivity on the precipitation energy flux may not be linear, thus the auroral precipitation intensity and auroral longitudinal pattern may depend on the relative longitudinal variations of the conductivity of each season/hemisphere. It is also interesting to note that precipitation intensity in local winter on the equatorial side of the auroral oval is suppressed like the intensity in local summer sunlit conditions (Figures 2 and 3).

[34] During each solstice period, when the auroral longitudinal pattern of peak precipitation were similar in the equatorward part of the auroral oval, there were significant summer-winter or hemispheric differences from TIMED/GUVI that occurred in the poleward part of the auroral region, for instance, around 70° MLAT during the premidnight period and around 68° MLAT during the postmidnight period (Figure 3). During 2100–0000 MLT, in the June solstice, the precipitation intensity above 70° MLAT was obviously larger in the southern winter hemisphere (SH-Jun.) than in the northern summer hemisphere (NH-Jun.) for all longitudes (Figure 3a). In particular, between \(\sim 60°\)E and 210°E, the high-latitude precipitation intensity seemed to be greatly suppressed in the summer hemisphere under sunlit conditions (Figure 5a), but the aurora extended to even higher latitudes in the conjugate winter hemisphere. Around the same longitudes, the equatorward diffuse aurora in both hemispheres was suppressed. Similar summer-winter difference patterns also occurred during the December solstice period. Those differences at higher latitudes might be related to the suppression effects of the sunlit conditions on discrete aurora in the summer hemisphere (compare Figures 3 and 5), as has been reported previously [e.g., Newell et al., 1996; Liou et al., 2001]. In addition, these differences in the poleward part of the auroral oval may also lead to the different longitudinal patterns in the latitudes of maximum precipitation intensity between summer and winter. Similar explanations for the longitudinal patterns of the latitudes of peak intensity can be also applied to the equinoctial seasons of both hemispheres. The longitudinal variations in the latitudes of the maximum precipitation intensity appeared to be weaker during the postmidnight hours than during the premidnight hours. This is consistent with the higher occurrence frequency of the discrete aurora during the premidnight period than during the postmidnight period [Newell et al., 1996].

[35] During the solstice period, the longitudinal pattern of auroral activity appears to be anticorrelated with the total solar-EUV inputs from both hemispheres. This result is, in general, consistent with the anticorrelation between geomagnetic activity indices (Am and AL) and the total ionospheric conductivity in the nightside auroral oval of both hemispheres [Newell et al., 2002]. Furthermore, it has been shown that auroral activity has evident semiannual variations with equinoctial peaks in previous solar cycles. However, during the declining phase of the solar cycle 23 when GUVI measurements were made, the overall auroral precipitation intensity at equinox was not much stronger than that at solstice [Luan et al., 2009, and references therein]. The lack of seasonal variations in GUVI observations might be related to the very low magnitudes of solar wind/IMF during the declining phase of solar cycle 23. In addition, in the present study, the longitudinal patterns of auroral activity were binned under the same geomagnetic activity (\(Kp\)) conditions in each season/hemisphere, which probably masked any possible seasonal differences (including summer-winter differences) in the auroral precipitation intensity.

4. Summary

[36] The auroral precipitation energy flux from TIMED/GUVI showed strong longitudinal variations during magnetic nighttime (MLT 2100–0300) in all seasons and both hemispheres for \(Kp = 1–4\). The ratios between the maximum and minimum of the precipitation energy flux along longitudes varied between 1.3 and 1.9. During solstices
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