

## RESEARCH LETTER

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## Key Points:

- The IMF  $B_y$  has an impact on the high-latitude thermospheric density
- Positive/negative  $B_y$  effect in NH resembles negative/positive  $B_y$  effect in SH
- Thus, the IMF  $B_y$  is an important source for the north-south asymmetry

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North-south asymmetry of the high-latitude thermospheric density: IMF  $B_y$  effectYosuke Yamazaki<sup>1</sup>, Michael J. Kosch<sup>1,2</sup>, and Eric K. Sutton<sup>3</sup>

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**Abstract** Previous studies have established that the  $y$  component of the interplanetary magnetic field (IMF  $B_y$ ) plays a role in the north-south asymmetry of the high-latitude plasma convection and wind. The effect of the positive/negative IMF  $B_y$  in the Northern Hemisphere resembles the effect that the negative/positive IMF  $B_y$  would have in the Southern Hemisphere. In this study, we demonstrate that the IMF  $B_y$  effect can also contribute to the hemispheric asymmetry of the thermospheric density. We use high-accuracy air drag measurements from the CHALLENGING Minisatellite Payload (CHAMP) satellite and SuperMAG AE index during the period 2001–2006 to examine the response of the high-latitude thermospheric density to geomagnetic activity. Our statistical analysis reveals that the density response at 400 km is greater in the Southern Hemisphere under positive IMF  $B_y$  conditions, and greater in the Northern Hemisphere under negative IMF  $B_y$  conditions. The results suggest that the IMF  $B_y$  effect needs to be taken into account in upper atmospheric modeling for an accurate description of high-latitude densities during periods of enhanced geomagnetic activity.

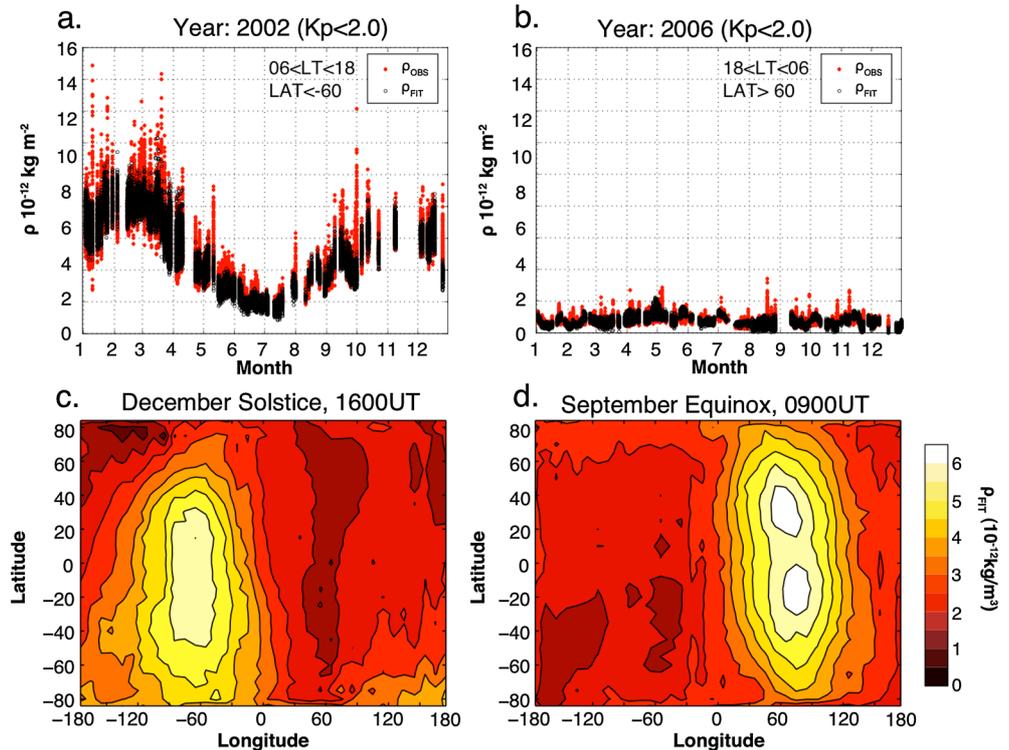
## 1. Introduction

The interaction between the solar wind and magnetosphere generates electric fields in the high-latitude ionosphere. These electric fields cause the ionospheric plasma to convect around the regions of positive and negative electric potentials. It is well known that the patterns of these convection “cells” are dependent on the strength and orientation of the IMF [e.g., *Cousins and Shepherd*, 2010]. Particularly, the role of the IMF  $B_y$  has been found to produce an asymmetry between the Northern Hemisphere and Southern Hemisphere convection patterns. For a nonzero IMF  $B_y$  condition, the cell patterns in the Northern Hemisphere resemble those in the Southern Hemisphere for the opposite sense of the IMF  $B_y$ .

The neutral gas in the high-latitude regions tends to be accelerated, or “dragged”, in the direction of the rapid motion of the ions due to collisional interactions between plasmas and neutrals. This ion drag effect brings about similarities in the patterns of high-latitude thermospheric wind and ion convection [e.g., *Richmond and Lu*, 2000]. *Förster et al.* [2008] showed that the IMF  $B_y$  effect can cause a north-south asymmetry in the high-latitude thermospheric wind in a similar manner as in the ion convection.

The IMF  $B_y$  effect on the wind may have a broad impact on the neutral atmosphere. For example, changes in the horizontal wind system can cause the vertical motion of the air, which leads to adiabatic heating or cooling of the gas. Therefore, it is possible that the temperature, composition, and mass of the upper atmosphere are altered as a result of the IMF  $B_y$  effect on the wind, although it is difficult to predict what and how much the actual variations might be.

*Crowley et al.* [2006] used a coupled thermosphere-ionosphere general circulation model to study the IMF  $B_y$  effect on the thermosphere. They ran simulations with different ion convection patterns representative of different IMF  $B_y$  conditions. Their results suggested that the density distribution in the high-latitude thermosphere systematically changes when the ion convection pattern is changed. Although efforts have also been made to provide observational evidence for the IMF  $B_y$  effect on the thermospheric density [e.g., *Immel et al.*, 1997, 2006; *Kwak et al.*, 2009], an important piece of evidence has been missing, i.e., the hemispheric asymmetry associated with the IMF  $B_y$  effect. In this paper, we will provide evidence that the north-south asymmetry of the high-latitude thermospheric density can arise from the IMF  $B_y$  effect.



**Figure 1.** (a) Quiet time thermospheric densities at 400 km in the Southern Hemisphere (poleward of  $-60^\circ$ ) for local times between 0600 and 1800 h for the year 2002. The red dots represent observations, while the black circles represent the fit to the data as expressed by equation (1). (b) The same as Figure 1a but in the Northern Hemisphere (poleward of  $60^\circ$ ) for local times between 1800 and 0600 h for the year 2006. (c) Latitude versus longitude distribution of  $\rho_{FIT}$  at 1600 UT for the December solstice and for the average solar activity condition corresponding to  $P \sim 110$  sfu. (d) The same as Figure 1c but at 0900 UT for the September equinox.

## 2. Data Analysis

We use air drag measurements by the CHAMP satellite [Reigber *et al.*, 2002] to derive the air density at 400 km for the period from July 2000 to December 2006. The density retrieval procedures and error evaluations were detailed in Sutton [2008]. We first determine quiet time densities, which will be used later as a baseline of density perturbations. For this purpose, the analysis is restricted to quiet geomagnetic conditions defined as  $Kp < 2$ . The quiet time data are divided into 1260 bins according to the geographical location of measurements in a latitude-longitude grid of  $5^\circ \times 10^\circ$ . The data in each bin are expressed as a product of functions of solar activity, season, and local time (LT). The empirical formula is given by

$$\rho_{FIT} = Re \left\{ \sum_l \sum_m \sum_n C_{lmn} (MgII)^l e^{i \left( m \frac{2\pi DoY}{365.24} \right)} e^{i \left( n \frac{2\pi LT}{24} \right)} \right\}, \quad (1)$$

where  $l = 0, 1$ ;  $m = -3, -2, \dots, 3$ ; and  $n = -4, -3, \dots, 4$ . The  $MgII$  index [Viereck *et al.*, 2001] is used as a proxy for solar EUV activity. Studies have shown that the  $MgII$  index is a good proxy for the solar activity influence on the thermospheric density [e.g., Solomon *et al.*, 2011]. The dependence on day of year (DoY) represents seasonal variations, including annual, semiannual, and terannual components. The local time variation includes 24, 12, 8, and 6 h components. The 126 coefficients  $C_{lmn}$  are determined on the basis of least squares fitting in the same way as Yamazaki *et al.* [2012]. The goodness of fit  $R^2$ , which is defined as the square of the correlation coefficient between the original data and fit, is found to be reasonably high at any geographical location. The average  $R^2$  is 0.96 at high latitudes (poleward of  $\pm 60^\circ$  latitude).

Figure 1 demonstrates spatial and temporal variabilities of  $\rho_{FIT}$ . Figures 1a and 1b compare  $\rho_{FIT}$  against the original data. Figure 1a shows quiet time densities at high latitudes in the Southern Hemisphere for the year 2002 (near-solar maximum) for local times between 0600 and 1800 h, while Figure 1b shows Northern Hemisphere densities for the year 2006 (near-solar minimum) for different local times. Density distributions are

presented in Figures 1c and 1d for different seasons and universal times, for an average solar activity condition corresponding to  $P \sim 110$  sfu. Here  $P$  represents the solar activity index by *Richards et al.* [1994], and sfu stands for solar flux unit. Examples presented in Figure 1 illustrate basic features of quiet time thermospheric density known from previous studies [see, e.g., *Qian and Solomon*, 2012, for a review].

We define density perturbations  $\Delta\rho$  as the difference between the measurements and quiet time values as expressed by (1). The density perturbations are analyzed in the Magnetic Apex coordinate system [*Richmond*, 1995] as a function of magnetic latitude (MLAT) and magnetic local time (MLT) with a grid size of  $5^\circ \times 1$  h.

We use hourly values of the SuperMAG AE index [*Newell and Gjerloev*, 2011] to characterize high-latitude geomagnetic activity. Studies have shown that the typical response time of thermospheric densities to geomagnetic activity is less than 2 h at high latitudes and about 4 h at low latitudes [*Sutton et al.*, 2009; *Ritter et al.*, 2010]. Since our study focuses on the high-latitude densities, we use AE values averaged for the present hour and 1 h prior. Our average quiet time densities correspond to an AE index of approximately 150 nT, and thus, the density perturbations are examined as a function of  $AE_d = AE - 150$  for positive values of this parameter. The density perturbations are binned in 50 nT window of  $AE_d$  up to 400 nT, and into one bin for larger values. A linear regression analysis is then performed using the median value of  $\Delta\rho$  and  $AE_d$  in each bin. This median filter effectively eliminates outliers.

### 3. Results and Discussion

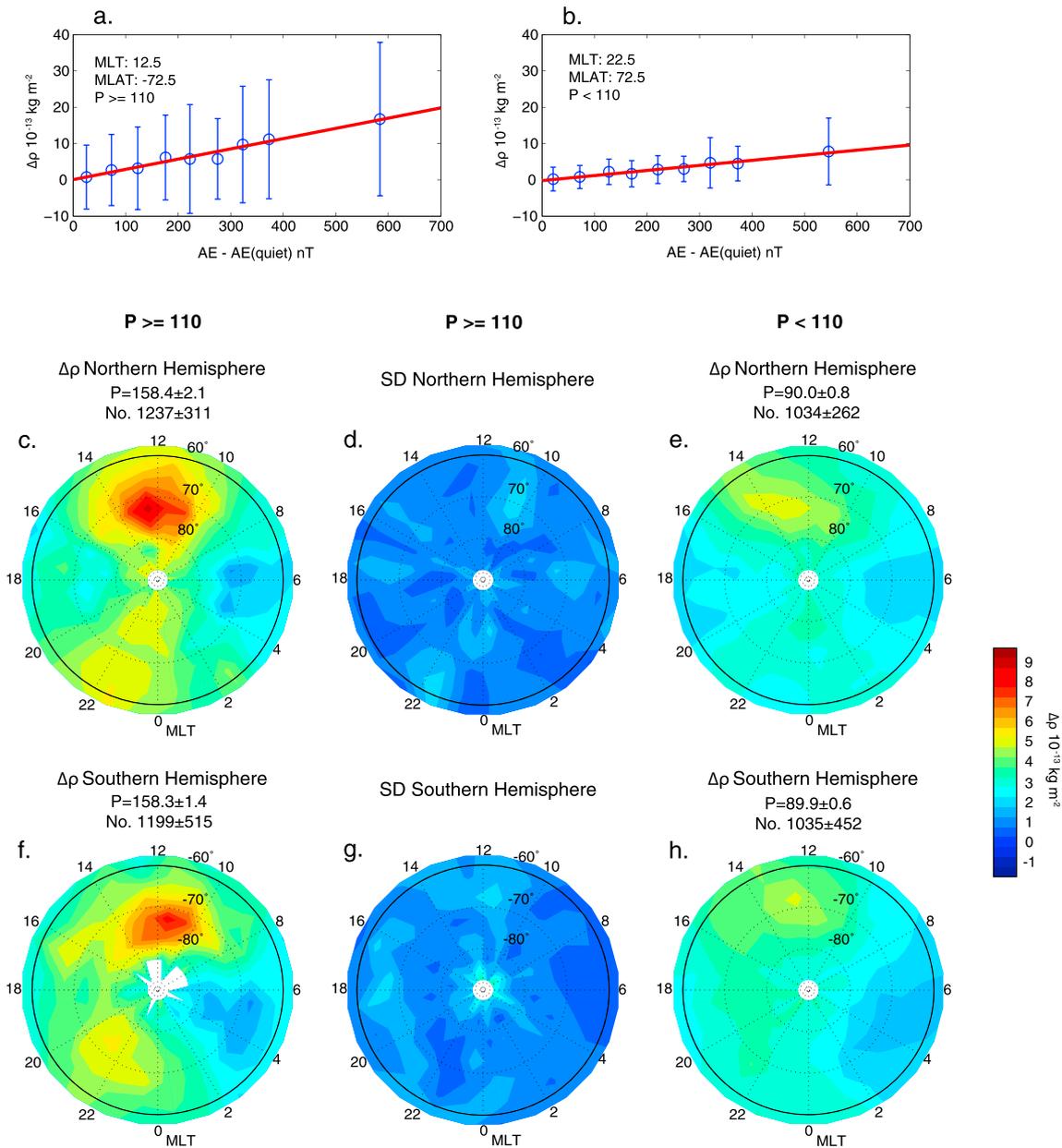
Figure 2a shows an example of results obtained from the linear regression analysis described above. The results are for a high-latitude dayside region in the Southern Hemisphere ( $12 \leq \text{MLT} < 13$  and  $-75 \leq \text{MLAT} < -70$ ) for relatively high solar activity conditions ( $P \geq 110$  sfu). The error bars have a length of twice the standard deviation of  $\Delta\rho$  in each bin. Despite the large scatter, the median density perturbations tend to linearly increase with an increase of  $AE_d$ , indicating that the day-to-day variability, unrelated to geomagnetic activity, is effectively averaged out. Figure 1b shows another example of results obtained for a high-latitude nightside region in the Northern Hemisphere ( $22 \leq \text{MLT} < 23$  and  $70 \leq \text{MLAT} < 75$ ) for  $P < 110$  sfu.

Figures 2c and 2f show the density perturbations normalized to  $AE = 400$  nT under  $P \geq 110$  sfu conditions in the Northern Hemisphere and Southern Hemisphere, respectively. The results are displayed in the MLAT and MLT coordinates. Figures 2d and 2g show the corresponding standard deviations, derived from our linear regression analysis. The standard deviations are typically about  $1 \times 10^{-13}$  kg m $^{-2}$  but occasionally large, indicating an inaccurate linear regression fit. In the rest of the paper, we do not show the standard deviations for each plot, but the density results are rejected if the standard deviation exceeds an arbitrary threshold of  $3 \times 10^{-13}$  kg m $^{-2}$ .

Figures 2c and 2f reveal a strong density response in the dayside region. The dayside high-latitude thermosphere is where the cusp region density enhancement is often observed [e.g., *Lühr et al.*, 2004]. It should be noted, however, that the cusp region density enhancement generally occurs in a much narrower region with a half width of a few hundred kilometers. Thus, the enhanced dayside response shown in Figures 2c and 2f could be due to other processes. The density response is also relatively large in the premidnight sector (20–24 MLT), where the substorm onset often occurs. The density response is least significant around the dawn sector (4–7 MLT) in both hemispheres.

*Crowley et al.* [1996], using a thermosphere-ionosphere general circulation model, predicted the existence of organized density structures, or “density cells”, in the high-latitude thermosphere. Those cells are the regions where the density is locally increased or decreased from the background level. Their model showed two to four high- and low-density cells with a size of 1000–2000 km in diameter at 140 and 200 km altitudes. Our results in Figures 2c and 2f seem to indicate such organized structures mainly with a high-density cell in the noon sector and a low-density cell in the dawn sector. It should be pointed out, however, that in the simulations by *Crowley et al.* [1996], the density cells decayed with height and no structure was evident above 350 km.

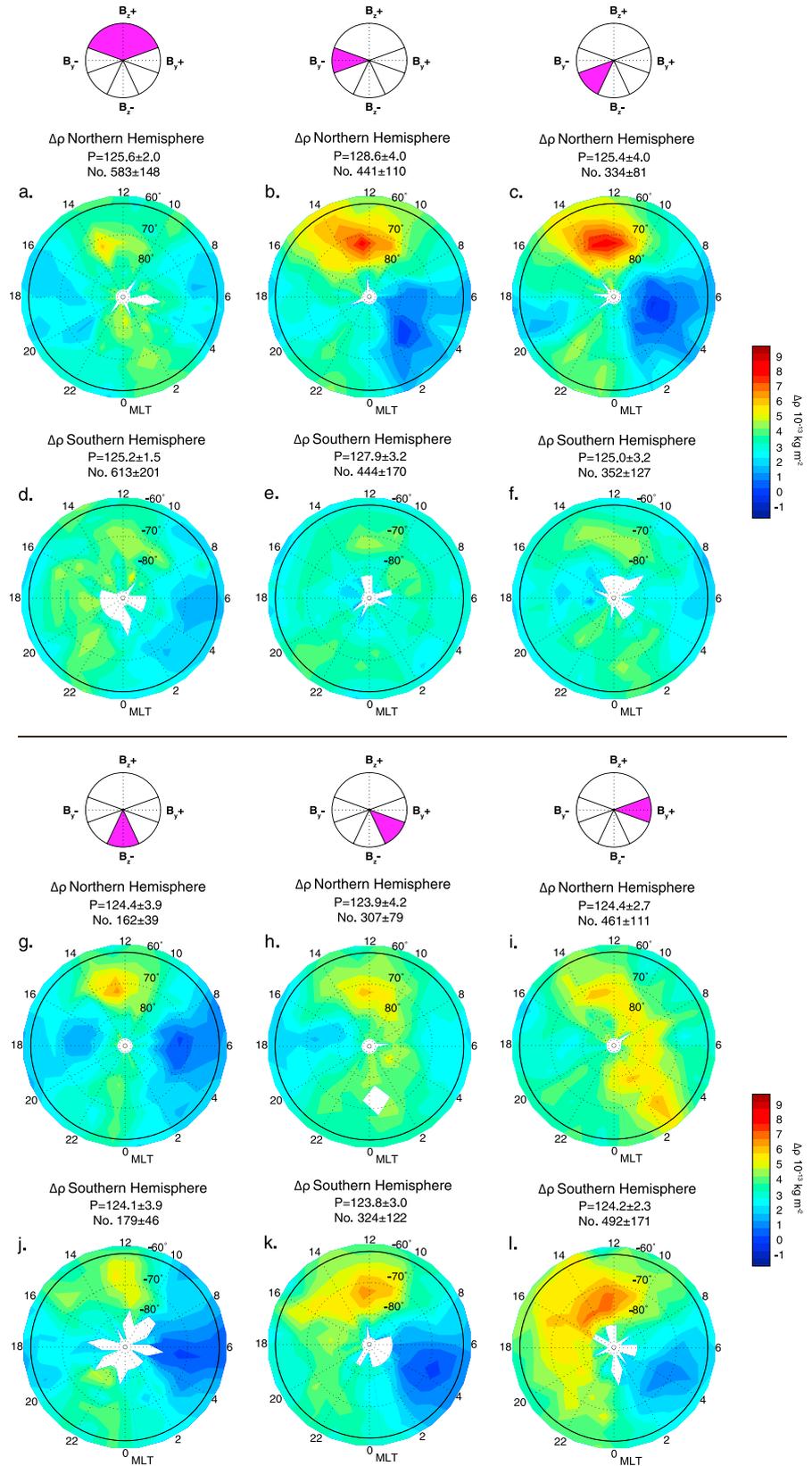
Figures 2e and 2h are the same as Figures 2c and 2f except for  $P < 110$ . A comparison between the results for  $P \geq 110$  and  $P < 110$  indicate that high-latitude density perturbations are larger during higher solar flux periods, for the same level of geomagnetic activity. This is owing to the fact that the magnitude



**Figure 2.** (a, b) Examples of the relationship between  $AE_d$  and density perturbations  $\Delta\rho$  at 400 km. (c, f) Distributions of the high-latitude density perturbations  $\Delta\rho$  at 400 km for  $AE = 400$  nT and  $P \geq 110$  sfu. The average value of  $P$  and its standard deviation (in sfu) are also indicated, along with the average number of the data points and its standard deviation. (d, g) Distributions of the standard deviation (SD) for the high-latitude density perturbations  $\Delta\rho$  at 400 km for  $AE = 400$  nT and  $P \geq 110$  sfu. (e, h) The same as Figures 2c and 2f but for  $P < 110$  sfu.

of density perturbations tends to increase with the background density. It is interesting to note that the density response in the dawn sector shows the opposite solar activity dependence. That is, the normalized density perturbation is slightly lower for the higher solar activity condition.

Figure 3 illustrates the dependence of the high-latitude thermospheric density perturbations on the IMF clock angle for  $AE = 400$  nT. The IMF clock angle was derived from hourly values of OMNI solar wind data at the Earth's bow shock nose. We define  $\theta$  as the IMF clock angle averaged for the present hour and 1 h prior. (As mentioned, the  $AE$  index is also averaged for the same interval.) Binning ranges for  $\theta$  are as follows: (a, d)  $-70^\circ \leq \theta < 70^\circ$ , (b, e)  $250^\circ \leq \theta < 290^\circ$ , (c, f)  $205^\circ \leq \theta < 250^\circ$ , (g, j)  $155^\circ \leq \theta < 205^\circ$ , (h, k)  $110^\circ \leq \theta < 155^\circ$ , (i, l)  $70^\circ \leq \theta < 110^\circ$ . We initially attempted to separate the  $B_z > 0$  data into smaller bins, but it proved difficult to obtain the normalized densities because  $B_z > 0$  leads  $AE_d$  to be negative, and thus, our linear regression analysis tends to be unsuccessful.



**Figure 3.** The high-latitude density perturbations  $\Delta\rho$  at 400 km for  $AE = 400$  nT for (a, d)  $-70^\circ \leq \theta < 70^\circ$ , (b, e)  $250^\circ \leq \theta < 290^\circ$ , (c, f)  $205^\circ \leq \theta < 250^\circ$ , (g, j)  $155^\circ \leq \theta < 205^\circ$ , (h, k)  $110^\circ \leq \theta < 155^\circ$ , and (i, l)  $70^\circ \leq \theta < 110^\circ$ . Binning ranges for  $\theta$  are indicated in the  $B_y$ - $B_z$  plane on the top of Northern Hemisphere results.

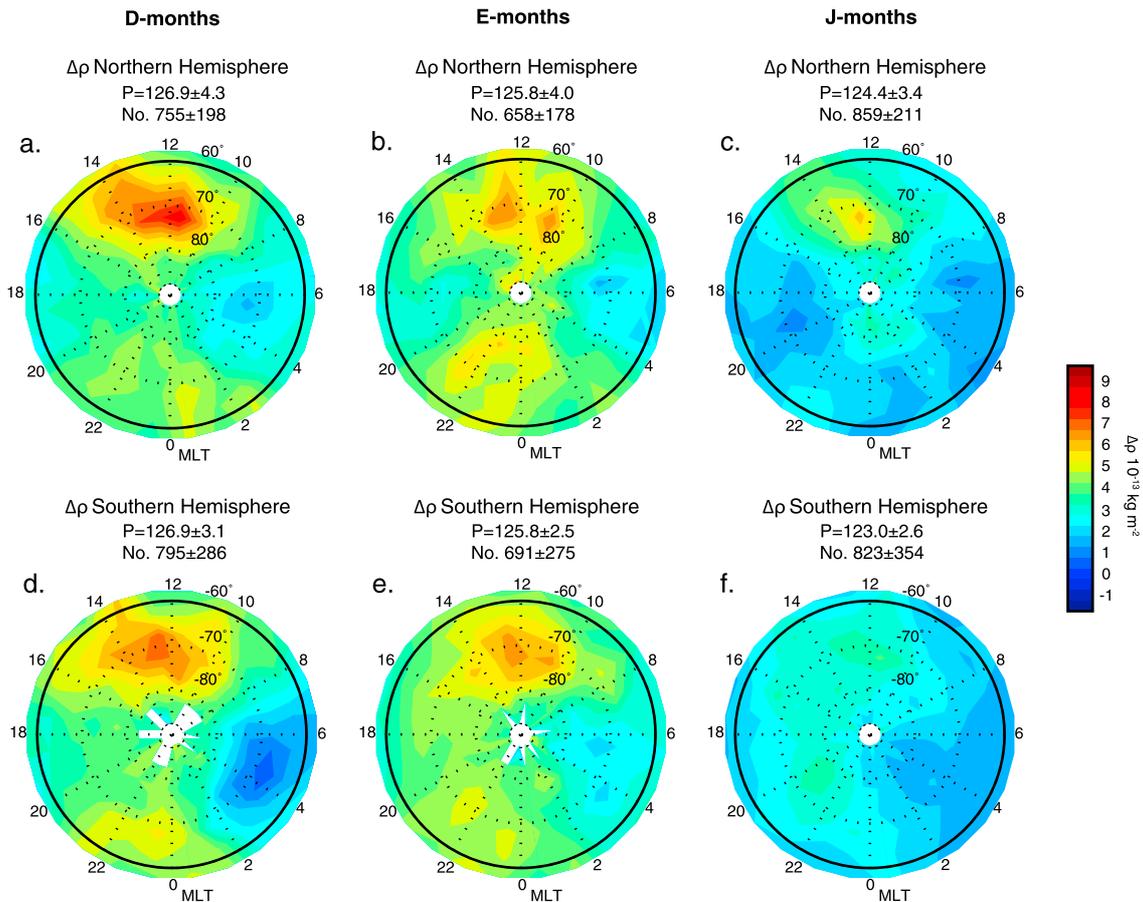


Figure 4. The dependence of the high-latitude density perturbations  $\Delta\rho$  at 400 km on the season for  $AE = 400$  nT.

The results in Figure 3 indicate that the IMF  $B_y$  direction is an important factor for the north-south asymmetry of the high-latitude density response to geomagnetic activity. It can be seen that negative and positive  $B_y$  conditions are preferred for the Northern Hemisphere and Southern Hemisphere density cells to develop. Previously, Crowley *et al.* [2006] numerically predicted that a polarity change of the IMF from  $B_y < 0$  to  $B_y > 0$  causes a reduction in the magnitude of the density cells in the Northern Hemisphere. The sense of the effect is consistent with our results. However, their study was limited only up to 200 km, and thus, the direct comparison with our results is not possible.

In Figure 3, the dayside density response to the IMF  $B_y$  is greater than the response to the negative IMF  $B_z$ . The interpretation for this needs to be made carefully, as the IMF  $B_z$  correlates with the  $AE$  index. For example, when the IMF clock angle is  $180^\circ$ , the  $AE$  index is likely to be higher than when the IMF clock angle is  $90^\circ$ . Thus, the actual dayside density perturbations for  $\theta = 180^\circ$  are, on average, greater than those for  $\theta = 90^\circ$ .

It is noted that the density perturbation in the dawn sector is sometimes negative. This means that the densities in those regions tend to decrease with increasing geomagnetic activity and therefore indicates a strong cooling effect against heating due to auroral processes. The effect may be explained by enhanced production of nitric oxide during periods of increased geomagnetic activity. Nitric oxide acts to increase the radiative cooling of the thermosphere and thus causes a reduction of local densities [e.g., Lei *et al.*, 2012; Knipp *et al.*, 2013]. The dawn sector is where pulsating auroras often appear [Omholt, 1971]. The pulsating aurora is caused by precipitation of hard electrons, which penetrate into the upper mesosphere and thus add to production of nitric oxide.

Figure 4 shows the seasonal dependence of the high-latitude density perturbations. The data were grouped into three seasonal bins: D months (November–February), J months (May–August), and E months (March,

April, September, and October). The results do not show a strong north-south asymmetry unlike the case for nonzero IMF  $B_y$  conditions.

There is an apparent annual modulation in the density response to geomagnetic activity. That is, the overall density perturbations are smaller during the J months than D months for the same level of geomagnetic activity. The background thermospheric density tends to be globally low during the J months [e.g., Qian *et al.*, 2009], which may be a reason for the weak response during the J months. Also, the AE index, which is based on the Northern Hemisphere magnetometer data, undergoes an annual variation [e.g., Singh *et al.*, 2013], and it may affect our results.

#### 4. Summary and Conclusions

Earlier studies have established the role of the IMF  $B_y$  in producing a hemispheric asymmetry of the high-latitude ion convection and wind. The effect of positive/negative  $B_y$  in the Northern Hemisphere has been found to be similar to the effect of negative/positive  $B_y$  in the Southern Hemisphere. We have investigated the possible contribution of the IMF  $B_y$  to the north-south asymmetry of the high-latitude thermospheric density response to geomagnetic activity by using air drag measurements from the CHAMP satellite. The results of our statistical analysis revealed that such an effect does exist.

We have shown that the high-latitude disturbance density structure is often characterized by a high-density region around the noon sector and a low-density region in the dawn sector. They have the features of the density cells, which has been theoretically predicted but only below 350 km [Crowley *et al.*, 1996, 2006]. It was found that the cell structures in the Northern Hemisphere and Southern Hemisphere become more evident under negative and positive  $B_y$  conditions, respectively. This is qualitatively consistent with simulation results by Crowley *et al.* [2006], although their simulations were limited up to 200 km. Their model used different patterns of the high-latitude ion convection according to the  $B_y$  input, and thus, changes in the density were mainly due to the ion drag effect on the neutral wind. The model used by Crowley *et al.* [2006] was, however, unable to examine the possibility that the IMF  $B_y$  might cause a hemispheric asymmetry in the energy input from the magnetosphere. For example, magnetohydrodynamic simulations of the coupled solar wind-magnetosphere-ionosphere system by Tanaka [2001] predicted a hemispheric asymmetry in the distribution of high-latitude field-aligned currents under nonzero IMF  $B_y$  conditions. Further numerical investigations will be necessary to clarify the mechanism for the IMF  $B_y$  effect on the thermospheric density.

The IMF  $B_y$  effect is not considered in most empirical models of the thermosphere. Our results suggest that the IMF  $B_y$  effect needs to be taken into account for an accurate description of the density response to geomagnetic activity, especially at high latitudes.

The seasonal effect was another possible source for the hemispheric asymmetry. However, we did not find evidence of the seasonal effect on the north-south asymmetry of the high-latitude density perturbations. A more comprehensive study is planned to examine the combined effect of the seasons and IMF  $B_y$ , e.g., the seasonal effect on the north-south asymmetry due to the IMF  $B_y$  effect.

Finally, the results in this paper represent only the average state and do not necessarily agree with individual cases. The large scatter of the data, which was found in the binning process (see Figures 2a and 2b), indicates that there are many data points that deviate from the average results. Therefore, it is important to be aware of other sources of variability as well, when interpreting case study results.

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