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RESEARCH ARTICLE

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Key Points:

- A reduced geomagnetic field causes an increase in the longitudinal difference in the thermospheric mass density
- The zonal differences in electron density decreases at auroral latitudes, but shows a mixed local time response at midlatitudes
- Larger effects of the magnetic field are observed during equinox seasons in comparison to those during solstice seasons

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Longitudinal modulation of electron and mass densities at middle and auroral latitudes: Effect of geomagnetic field strength

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Abstract In this study, the effect of a reduction in magnetic field strength on the longitudinal modulation of electron density (ΔN_e) and mass density ($\Delta \rho$) is investigated. We study conditions during the September equinox and June and December solstices at middle and auroral latitudes in both Northern and Southern Hemispheres. The Global Ionosphere-Thermosphere Model was employed for the theoretical study. Simulations were performed with a realistic International Geomagnetic Reference Field (IGRF) model and an IGRF model reduced in strength by 50%. The reduction in field strength increased the longitudinal variations in ΔN_e by 2–34% in the nighttime sector but reduced the variation by 7–20% in the daytime sector at midlatitudes in both hemispheres. Conversely, at auroral latitudes ΔN_e was reduced by 2–32% at all local times. The changes during equinoxes are larger than those for the solstices. The differences with local time in the response of ΔN_e to a reduction in magnetic field strength were mainly due to changes in the oxygen/molecular nitrogen (O/N_2) ratio in the Northern Hemisphere, whereas the differences were due to the combined effects of vertical winds and changes in the O/N_2 ratio in the Southern Hemisphere. Both vertical winds and horizontal $\vec{E} \times \vec{B}$ convection eliminated ΔN_e at high latitudes. $\Delta \rho$ got enhanced at both middle and auroral latitudes, which was related to the enhanced Joule heating effect when the magnetic field was reduced.

1. Introduction

It is important to understand the spatial distribution of the thermospheric neutral mass density (ρ) and ionospheric electron density (N_e), because of the increasing amount of satellite-based technology (navigation, radio wave propagation, etc.) operating within the upper atmosphere.

There are distinct longitudinal (zonal) differences in the ionospheric electron density and thermospheric mass density. The midlatitudinal electron density exhibits obvious wave-2 and wave-1 variations along geographic longitudes (GLon) in the Northern and Southern Hemispheres, as revealed by observations from both ground-based Global Positioning Satellite (GPS) receivers and the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) and Challenging Minisatellite Payload (CHAMP) satellites, as well as by global simulations [Zhang *et al.*, 2011, 2012, 2013; Xu *et al.*, 2013; Luan and Dou, 2013; Xiong and Lühr, 2014; Wang *et al.*, 2015, 2016a; Wang and Zhang, 2016]. As its thermospheric counterpart, the mass density exhibits a wave-1 longitudinal structure, which is almost 180° out of phase in the two hemispheres, as revealed by both CHAMP observations and simulations using the Global Ionosphere-Thermosphere Model (GITM) [Xiong *et al.*, 2015; Wang *et al.*, 2016b]. Similar longitudinal (zonal) differences were reported in sporadic studies in the literature about 50 years ago [e.g., Kohl *et al.*, 1969], which might be related to the mesoscale ionospheric structure as investigated in the present work.

The topology of the geomagnetic field, i.e., the displacement between the magnetic and geographic poles, is believed to play an important role in causing the longitudinal patterns of these thermospheric and ionospheric quantities [Wang *et al.*, 2015]. The offset between the geomagnetic and geographic poles is nearly 8° and 16° in the Northern and Southern Hemispheres, respectively. Owing to the tilt of the geomagnetic field, there are offsets between the magnetic latitude (MLAT) and geographic latitude (GLat) reference frames (IGRF epoch 2010). For example, in the near North Pole longitude at 90°W GLon, 50° MLAT corresponds

to 39° GLat, while in the far-from-pole longitude at 120°E GLon it corresponds to 56° Glat. In the near South Pole longitude sector at 120°E GLon, −50° MLAT corresponds to −37° Glat, while in the far-from-pole longitude sector at 90°W GLon it corresponds to −64° GLat. Differences in GLat cause variations in the intensity of solar illumination, as it is organized in the geographic reference frame. Thus, solar illumination exhibits longitudinal variations when considered in the magnetic reference frame. The solar ionization rate plays an important role in the longitudinal variation in the electron density at the altitude of the CHAMP satellite on the basis of model results [Wang *et al.*, 2015].

Depending on the geomagnetic declination and inclination angles, horizontal neutral winds can contribute to the vertical motion of the plasma. As the ion/electron recombination rate is reduced at higher altitudes, the *F* region electron density can be increased due to upward motion along the magnetic field lines. Conversely, the *F* region densities can be decreased by downward motion of plasma into regions of higher density and higher recombination rates. There are two zones of positive (i.e., eastward) declination and two zones of negative (i.e., westward) declination in the Northern Hemisphere, whereas there is only one positive and one negative zone in the Southern Hemisphere. Therefore, longitudinal variations are induced by the difference in electron density (ΔN_e) as a result of the declination angle exhibiting two zones of increase and two zones of reduction at a constant local time in the Northern Hemisphere, while one zone of increase and one zone of decrease in the Southern Hemisphere. Wang *et al.* [2015] showed that the zonal wind-geomagnetic declination mechanism can account for about 80% of the longitudinal variations in the midlatitude electron density.

The mass density at magnetic midlatitudes exhibits longitudinal changes owing to the nonuniform solar radiation intensity along longitudes. Wang *et al.* [2016b] found that when the $F_{10.7}$ index was increased from 70 to 100, the longitudinal differences in mass density at 400 km altitude were enhanced by a factor of 1.5 and 2.1 in the Northern and Southern Hemispheres, respectively. The ion drag and Joule heating can account for about 40% and 50% of the longitudinal differences in the air mass density in the Northern and Southern Hemispheres, respectively.

However, the effect of the magnetic field strength on the longitudinal variations in ΔN_e and the difference in mass density ($\Delta \rho$) has not been addressed so far. The Earth's magnetic field strength displays obvious longitudinal and hemispheric differences. There are two maxima in flux density in the Northern Hemisphere and one density maximum in the Southern Hemisphere. The mean field strength above 80° MLAT at an altitude of 400 km is 10% less in the Northern than in the Southern Hemisphere. Previous dedicated studies used longitudinal means when studying the effects of the Earth's dipole moment. For example, Cnossen *et al.* [2011] quantified the inverse relationship between the ionospheric conductance, plasma flow, Joule heating, and dipole moment. Cnossen and Förster [2016] reviewed in detail the hemispheric asymmetries in the ionospheric and thermospheric parameters, resulting from the distinct north-south asymmetries in the Earth's magnetic field. The neutral wind, ion drift, and mass densities over the polar cap were found to be greater in the Northern Hemisphere than in the Southern Hemisphere owing to the weaker magnetic field in the Northern Hemisphere [e.g., Thayer and Killeen, 1993; Cnossen *et al.*, 2011; Aa *et al.*, 2012; Förster and Cnossen, 2013].

In this paper, we used the GITM to simulate the longitudinal differences in the ionospheric electron density and thermospheric mass density in response to different magnetic field strengths. With this aim, we performed one simulation with a given field strength (denoted as normal magnetic field), while another with 50% reduced field strength (denoted as weak magnetic field). The magnetic field topology was kept the same for the two runs, i.e., magnetic declination and inclination angles were unchanged. Through comparison between these two runs (weak-standard field), one can discern the longitudinal effect due to magnetic field strength.

In our present solar system, Earth provides an ionosphere-thermosphere system with a standard planetary dipole field, while Mars and Venus represent cases without global magnetic dipole fields. However, other field configurations may have appeared during the evolution of a planet over billions of years. For example, there is evidence that Mars had a strong magnetic field in the past. Rishbeth [1985] has theoretically explored the response of an ionosphere-thermosphere system to the extreme case of a "magnetic reversal," during which the Earth's magnetic field might be dominated by a quadrupole field and the strength decreased by 1 order of magnitude. Here we would emphasize that the extreme case persists only for a relatively short interval. However, the fact that the Earth's magnetic field strength is presently decreasing at a relatively high rate is important enough to warrant a dedicated study [e.g., Olsen and Manda, 2007]. According to the

Figure 1. The IGRF magnetic field strength at an altitude of 400 km as a function of the geographical longitude and magnetic latitude.

International Geomagnetic Reference Field (IGRF) model, the geomagnetic field strength declined on average by 6.3% from 1910 to 2010, but with a significantly stronger reduction occurring over the region of South Atlantic Anomaly [e.g., *Cnossen and Förster*, 2016]. *Cnossen and Richmond* [2008] investigated the effect of changes in the Earth's magnetic field between 1957 and 1997 on the ionosphere by using the thermosphere-ionosphere-electrodynamics general circulation model. They found that the field changes had a substantial effect on the ionosphere over South America and the southern Atlantic Ocean where magnetic field changes had been relatively large, while they were negligible in other parts of the world. The present study will be another stepping stone in improving our understanding of the response of the upper atmosphere

to changes in Earth's magnetic field strength, which might have occurred historically or might occur in the future. This might be instructive for interpreting long term trends in the upper thermosphere and ionosphere that have occurred or that may occur. It may also help to advance our understanding of the coupling mechanism between the ionosphere and thermosphere.

2. Model

The GITM is a three-dimensional model that simulates the dynamics of the ionosphere and thermosphere, which was developed at the University of Michigan. A complete description of the model can be found in *Ridley et al.* [2006]. The model solves the continuity, momentum, and energy equations in the thermosphere and ionosphere using realistic source terms. The neutral momentum equation is solved by considering the pressure gradient, ion drag, viscous force, and Coriolis force. The GITM is driven by the high-latitude electric field [Weimer, 2005], precipitation of auroral particles [Fuller-Rowell and Evans, 1987], solar extreme ultraviolet radiation, and tides (global-scale wave model) at the lower boundary [Hagan et al., 1999]. The GITM is initiated by using the mass spectrometer-incoherent scatter [Hedin, 1991] and International Reference Ionosphere [Bilitza, 2001] models for neutral and ion densities and temperatures. The magnetic field topology is described by the International Geomagnetic Reference Field (IGRF) [Maus et al., 2005]. The results are ordered in the frame of apex magnetic coordinates, which are based on the IGRF [Richmond, 1995].

Figure 1 shows the magnetic field strength, B , calculated within GITM from the IGRF epoch 2010 model, in the MLAT and GLon frame at an altitude of 400 km. The magnetic field strength increases toward higher MLAT. The longitudinal changes are stronger in the Southern Hemisphere than in the Northern Hemisphere. The magnetic field decreases significantly toward the South Atlantic region. The present work concentrates on the magnetic middle latitudes from 40° to 60° MLAT and the auroral belts from 60° to 70° MLAT. All of the cells are averaged within the latitudinal ranges. It can be seen that there are two peaks, which are located at 120°W and 120°E GLon, respectively, in the Northern Hemisphere. There is only one peak, which is located at 140°E GLon in the Southern Hemisphere. In the weak magnetic field simulation, the field topology was kept unchanged, but the field strength was reduced by 50%.

For this study, the GITM was run with a resolution of 5° in latitude by 10° in longitude and with a stretched altitude, resolving the vertical scales with approximately one third of a scale height. It was run for 48 h to reach a quasi steady state. Simulations were then continued for another 24 h after the quasi steady state point at the September equinox and June/December solstices. The input parameters for a quiet time run were as follows: $F_{10.7} = 100$ solar flux unit (sfu) and hemispheric power = 20 GW. The tides at the lower boundary were turned off in order to isolate the in situ physical processes.

Figure 2. Distribution of the electron density (ΔNe) as a function of geographic longitude and magnetic local time for September equinox are (a and b) at middle $\pm(40^\circ$ to 60° MLAT) and (c and d) at auroral latitudes $\pm(60^\circ$ to 70° MLAT). The longitudinal mean values were subtracted for each hour of magnetic local time. Figures 2a, 2c, 2e, and 2g are in the Northern Hemisphere, and in Figures 2b, 2d, 2f, and 2h are in the Southern Hemisphere. Figures 2a–2d are ΔNe for standard magnetic field, and Figures 2e–2h are residual ΔNe from weak minus standard field.

Table 1. Peak West-East Differences in Electron Densities at Midlatitudes for Different Seasons^a

	Northern Hemisphere			Southern Hemisphere		
	September Equinox	June Solstice	December Solstice	September Equinox	June Solstice	December Solstice
Standard <i>B</i>	23.6 (27.8)	9.0 (11.1)	22.0 (24.5)	43.0 (46.6)	27.9 (5.8)	13.1 (24.7)
Weak <i>B</i>	19.0 (31.2)	7.8 (11.0)	20.5 (25.6)	39.1 (51.2)	28.9 (7.8)	10.5 (25.3)
Weak standard	−4.6 (3.4)	−1.2 (−0.1)	−1.5 (1.1)	−3.9 (4.6)	1.0 (2.0)	−2.6 (0.6)
Weak standard (%)	−19(12)	−13 (1)	−6 (4)	−9 (10)	4 (34)	−20 (2)

^aThe values outside (inside) the parenthesis are for daytime (nighttime). Densities are given in 10^{10}m^{-3} .

3. Results

The midlatitudes $\pm(40^\circ - 60^\circ \text{ MLAT})$ and auroral belts $\pm(60^\circ - 70^\circ \text{ MLAT})$ are separately considered. The electron density is sorted into geographic longitude (GLon) and magnetic local time (MLT) bins with a resolution of 15° longitude by 1 h MLT. Longitudinal means are subtracted separately for every MLT to give ΔNe values in order to suppress diurnal variations and to emphasize longitudinal patterns. Figure 2 shows the longitudinal distribution of ΔNe versus magnetic local time (MLT) at September equinox for a standard magnetic field in both hemispheres. It can be seen that ΔNe for a standard magnetic field shows quite similar structures at midlatitudes (Figures 2a and 2b) and auroral latitudes (Figures 2c and 2d).

As can be seen in Figures 2a and 2c, there are wave-2 (two peaks and troughs) structures emerging in the Northern Hemisphere, and in Figures 2b and 2d there are wave-1 structures (one peak and trough) appearing in the Southern Hemisphere. In the Northern Hemisphere the peak-trough pair in the eastern hemisphere ($0^\circ - 180^\circ \text{ GLon}$) is weaker than that in the western hemisphere ($-180^\circ - 0^\circ \text{ GLon}$). The variation in ΔNe is stronger in the Southern Hemisphere than in the Northern Hemisphere. This is because there are larger declination angles in the Southern Hemisphere than in the Northern Hemisphere. Consequently, the longitudinal difference of Ne is more prominent in the Southern Hemisphere than in the Northern Hemisphere. As can be seen in Figures 2a–2d, the wave phases shift eastward as the MLT increases, such that the peak occurs either westward of the trough (termed as type 1) or eastward of the trough (termed as type 2). In Figures 2a and 2c, type 1 can be found within 04–16 MLT (day), while type 2 mainly within 16–04 MLT (night) in the Northern Hemisphere. In Figures 2b and 2d in the Southern Hemisphere, one can find that type 2 within 04–16 MLT (day), while type 1 within 16–04 MLT (night). As an example, in the Northern Hemisphere ΔNe at -30° GLon is smaller than that at -150° GLon around 10 MLT (type 1) but larger around 20 MLT (type 2). In the Southern Hemisphere, ΔNe at 60° GLon is larger than that at -120° GLon around 10 MLT (type 2) but smaller around 20 MLT (type 1). These longitudinal and diurnal patterns at midlatitudes are consistent with CHAMP and COSMIC observations [Xiong and Lühr, 2014; Wang et al., 2015, 2016a].

The difference between the largest peak and trough of ΔNe in each magnetic local time sector can be calculated, from which the peak difference can be determined, separately for type 1 and 2 in the day and night sectors (termed as peak west-east difference of ΔNe). For example, in Figure 2a in the Northern Hemisphere, the peak west-east difference for type 1 (i.e., the peak is westward of the trough) can be found at 13 MLT with the value of $23.6 \times 10^{10}\text{m}^{-3}$, while for type 2 (i.e., the peak is eastward of the trough) the peak west-east difference can be found at 20 MLT with the value of $27.8 \times 10^{10}\text{m}^{-3}$. These peak west-east differences for type 1 and 2 in the day and night sectors are chosen to represent the longitudinal differences in ΔNe , which are listed in Tables 1 and 2 for both middle and auroral latitudes. The percentage change can be calculated as $(\Delta\text{Ne}_m - \Delta\text{Ne}_a)/\Delta\text{Ne}_m$, where Ne_m and Ne_a denote electron density, Ne at middle and auroral latitudes, respectively. It turns out that the peak west-east differences are on average about 20% smaller at auroral latitudes than at middle latitudes at September equinox.

The electron density figures for a weak magnetic field are not shown. They exhibit structures similar to those for the standard magnetic field at both middle and auroral latitudes in the Northern and Southern Hemispheres, except that the magnitudes are changed. The peak west-east differences are determined in the same way as for the standard magnetic field, and they are listed in Tables 1 and 2 for the weak *B* field in the second rows for the middle and auroral latitudes, respectively.

In Figures 2e–2h the residuals for the weak minus standard magnetic field are shown. Here weak-standard *B* means the difference between the ΔNe distributions for the two magnetic fields configurations. There are

Table 2. Peak West-East Differences in Electron Densities at Auroral Latitudes for Different Seasons^a

	Northern Hemisphere			Southern Hemisphere		
	September Equinox	June Solstice	December Solstice	September Equinox	June Solstice	December Solstice
Standard <i>B</i>	18.3 (21.2)	8.4 (7.9)	14.0 (15.7)	31.4 (42.1)	25.5 (6.9)	16.4 (18.9)
Weak <i>B</i>	15.1 (18.9)	7.3 (7.1)	12.4 (15.4)	21.2 (37.2)	22.8 (7.5)	11.9 (16.8)
Weak standard	−3.2 (−2.3)	−1.1 (−0.8)	−1.6 (−0.3)	−10.2 (−4.9)	−2.7 (0.6)	−4.5 (−2.1)
Weak standard (%)	−17 (−11)	−13 (−10)	−11 (−2)	−32 (−12)	−11 (9)	−27 (−11)

^aThe values outside (inside) the parenthesis are for daytime (nighttime). Densities are given in 10^{10}m^{-3} .

clear differences between the original patterns (Figures 2a–2c) and the ones resulting from the differences (Figures 2e–2h). The original patterns are dominated by eastward propagating structures, while the differences exhibit more stationary structures, at midlatitudes (Figures 2e and 2f). This indicates a geomagnetic field effect on ΔN_e that is local time dependent, i.e., the eastward propagation seen in Figures 2a–2d is the local time-dependent observation. During daytime the west-east difference is reduced for weak field and during nighttime enhanced. At auroral latitudes we find for the differences patterns with signs opposite to the standard field configuration (Figures 2g and 2h). This means that longitudinal variations are significantly smaller here at all local times for reduced *B* fields. Quantitative values for the weak field effect are listed in Tables 1 and 2 (rows 3 and 4). The percentage change between the weak and standard magnetic field conditions is calculated as $(\Delta N_{e_w} - \Delta N_{e_n}) / \Delta N_{e_n}$, where N_{e_w} and N_{e_n} denote electron densities during weak and standard magnetic field conditions, respectively. For example, as listed in Table 1, during daytime in the Northern Hemisphere, the peak west-east difference is decreased by 19% when the magnetic field strength is reduced, whereas at night the peak longitudinal difference is increased by 12%. In the Southern Hemisphere, the peak longitudinal differences in ΔN_e are reduced by 9% at daytime, whereas increase by 10% during night. In contrast at the auroral regions, when the geomagnetic field strength is reduced, the longitudinal differences in ΔN_e are reduced at both day and night sectors. According to Table 2, the peak east-west differences in ΔN_e are reduced by 17% at daytime and 11% during night in the Northern Hemisphere, while they are reduced by 32% and 12% during these two time sectors in the Southern Hemisphere. Obviously, different mechanisms are dominant in these two regions, which will be addressed in section 4.

The peak west-east longitudinal differences in ΔN_e during equinox and solstices are presented in Tables 1 and 2. At midlatitudes (Table 1), ΔN_e in the daytime is generally smaller for a weak dipole, while is generally larger in the nighttime, except at the June solstice. At auroral latitudes (Table 2), ΔN_e is generally smaller for a weak dipole except for the nighttime in the Southern Hemisphere at the June solstice. ΔN_e is generally smaller at solstices when compared to those at the equinoxes.

Figures 3a–3d show the longitudinal variations in mass density, i.e., $\Delta \rho$, in the same format as Figures 2a–2d. A wave-1 (one peak and one trough) pattern emerges in both hemispheres but almost 180° out of phase with each other. The model results are consistent with CHAMP observations [Wang et al., 2016b]. The differences in $\Delta \rho$ for the weak field are similar to those during the standard magnetic field except for the enhanced magnitude (figure not shown). This can be clearly seen in Figures 3e–3h, where the differences in $\Delta \rho$ between weak and standard field are shown. The reduced magnetic field tends to enhance the longitudinal variations in ρ at middle and auroral latitudes in both hemispheres. The largest west-east longitudinal differences in $\Delta \rho$ at middle and auroral latitudes are listed in Table 3 for both standard and weak magnetic fields during different seasons. $\Delta \rho$ is generally larger for a weak dipole than for a standard dipole, except in the Southern Hemisphere at midlatitudes at the June solstice.

4. Discussion

When comparing the two model simulations, it becomes clear that the magnetic field strength does affect longitudinal differences in both ΔN_e and $\Delta \rho$. From Figure 2 it is evident that a weaker magnetic field can enhance the longitudinal differences in ΔN_e at midlatitudes in the night sector, whereas it reduces them in the daytime sector. However, at auroral latitudes, a weaker magnetic field smoothes out longitudinal differences in electron density at all local times. This indicates that different mechanisms are active at middle and auroral latitudes. On comparing the mass density results from the two model simulations, as shown in Figure 3, it is

Figure 3. The same format as Figure 2 but for the mass density, ρ .

Table 3. Peak West-East Differences in Air Mass Densities ρ at Both Middle and Auroral Latitudes for Different Seasons^a

	Northern Hemisphere			Southern Hemisphere		
	September Equinox	June Solstice	December Solstice	September Equinox	June Solstice	December Solstice
Standard B	5.1 (4.7)	2.1 (2.5)	6.7 (4.9)	6.0 (6.0)	7.4 (5.7)	4.4 (5.4)
Weak B	6.0 (5.4)	2.4 (3.0)	7.4 (5.5)	6.0 (6.6)	7.3 (5.7)	5.7 (6.0)
Weak standard	0.9 (0.7)	0.3 (0.5)	0.7 (0.6)	0 (0.6)	-0.1 (0)	1.3 (0.6)
Weak standard (%)	18 (15)	14 (20)	10 (12)	0 (10)	-1 (0)	38 (11)

^aThe values outside (inside) the parenthesis are for the middle (auroral) latitudes. Densities are given in $10^{-13} \text{ kg m}^{-3}$.

clear that a weaker magnetic field can lead to larger longitudinal differences in mass density at both middle and auroral latitudes.

On the basis of previous works, as outlined in section 1, some components of ΔN_e and $\Delta \rho$ may be associated with changes in the neutral wind, neutral composition, and Joule heating. These processes are associated with the plasma convection velocity ($\vec{E} \times \vec{B} / B^2$), which can be increased as a result of a weak magnetic field. *Cnossen et al.* [2011] estimated that the ion velocity can be increased by 13–15% when the magnetic field strength is reduced by 25% in the Northern Hemisphere under equinox conditions for 13–15 UT. They also found that the neutral wind pattern at high latitudes appears to be enhanced in a way similar to the high-latitude $\vec{E} \times \vec{B}$ drifts. Changes in plasma and neutral velocities can also affect Joule heating. *Cnossen et al.* [2011] found that Joule heating is 13–30% stronger for a field reduced in strength by 25% than for a standard field. This increase in high-latitude heating is expected to cause higher temperatures, which should strengthen the meridional winds. In addition, energy inputs in auroral regions and changes in transport processes modify the oxygen/molecular nitrogen (O/N_2) ratio.

4.1. The $\vec{E} \times \vec{B}$ Effect

First of all, we investigated the role of the plasma drift in the longitudinal modulation of ΔN_e and $\Delta \rho$. For this purpose, we turned off the term of $\vec{E} \times \vec{B}$ in the model and resimulated the two cases for standard and weak magnetic fields. Figure 4 shows the residual ΔN_e and $\Delta \rho$ for the weak minus standard magnetic field when the plasma drift is suppressed in the simulation. The color scale is kept the same as that in Figures 2 and 3. It appears that ΔN_e and $\Delta \rho$ exhibit negligible variations with both longitude and local time. This confirms the speculation that the changes in plasma drift in response to the magnetic field plays a vital role in the longitudinal modulation of ΔN_e and $\Delta \rho$ at both middle and auroral latitudes. In the following sections, the mechanisms are discussed in more details.

4.2. Changes in Neutral Winds and Composition Ratio

Some of the changes with longitude and MLT in ΔN_e can be related to changes in the neutral winds. The plasma velocity scales as $1/B$, which can be increased in a weak field. An increase in the plasma drift velocity can cause changes in the neutral winds via ion drag forces.

Figure 5 shows the longitudinal distributions of the residual meridional winds versus MLT at both middle (a and b) and auroral latitudes (c and d). Positive values denote enhanced equatorward winds in the presentation of the results. In Figures 5c and 5d, it can be seen that there are enhanced equatorward winds centered around 0° GLon in the Northern Hemisphere and -150° GLon in the Southern Hemisphere. The equatorward winds at midlatitudes (Figures 5a and 5b) are similar to but weaker than those in auroral regions (Figures 5c and 5d).

The vertical ion drift caused by the horizontal component of the wind parallel to the magnetic field ($(\vec{U} \cdot \vec{b})\vec{b} \cdot \vec{z}$, where $\vec{U}$ is the velocity of the neutral wind, $\vec{b}$ is the direction of the magnetic field, and $\vec{z}$ is the component directed radially outward from the Earth) is dependent on the orientation of the magnetic field lines. This effect is named the vertical wind effect in the following discussion. As the recombination rate of ions is smaller at higher altitudes and larger at lower altitudes, the density of the plasma can be increased when it is uplifted to higher altitudes, whereas it is decreased when the plasma is forced downward.

To investigate the role of the vertical wind effect, we turned off the vertical wind term in the ion momentum function in the model (i.e., $(\vec{U} \cdot \vec{b})\vec{b} \cdot \vec{z} = 0$). The resulting variations in ΔN_e at middle latitudes for the weak minus standard magnetic field runs are shown in Figures 6a and 6b, which can be compared with the original distribution, with the vertical wind effects included, as shown in Figures 2e and 2f. The longitudinal patterns

Figure 4. Residual (a–d) electron density (ΔN_e) and (e–h) mass density ($\Delta \rho$) distribution for weak minus standard magnetic field condition as a function of geographic longitude and magnetic local time. Figures 4a, 4b, 4e, and 4f are at middle $\pm(40^\circ$ to 60° MLAT) and Figures 4c, 4d, 4g, and 4h are at high latitudes $\pm(60^\circ$ to 70° MLAT). In this simulation the $\vec{E} \times \vec{B}$ plasma drift is turned off.

Figure 5. Longitudinal variations of meridional wind (ΔU_m) for weak minus standard fields as a function of geographic longitude and magnetic local time. (a, b) For midlatitudes and (c, d) for auroral latitudes. Figures 5a and 5c are for Northern Hemisphere, and Figures 5b and 5d are for Southern Hemisphere.

in ΔN_e versus local time in the Northern Hemisphere midlatitudes (Figure 6a) resemble those in Figure 2e. This indicates that the vertical wind transport process is not the dominant factor in the Northern Hemisphere. However, in the Southern Hemisphere, when the vertical wind effect is suppressed, an obvious wave-1 pattern emerges in longitudinal variation (Figure 6b), which is different from that shown in Figure 2b when the vertical wind is active. This indicates that the vertical wind effect plays a more dominant role in the Southern Hemisphere.

The vertical wind effect is modulated by the magnetic inclination and declination angles, $(\vec{U} \cdot \vec{b})\vec{b} \cdot \vec{z} = U_m \cos D \cos I |\sin I| \mp U_z \sin D \cos I |\sin I|$, where negative and positive signs correspond to the Northern and Southern Hemispheres, respectively, U_m and U_z are the meridional and zonal components of the wind (positive for equatorward and eastward winds), D is the magnetic declination (positive for eastward), and I is magnetic inclination angle (positive in the north and negative in the south). Because the longitudinal variation in magnetic declination (D) is larger in the Southern Hemisphere than in the Northern Hemisphere, a larger vertical wind effect can be produced in the south. Therefore, the resulting electron density modulation is stronger in the Southern Hemisphere than in the Northern Hemisphere.

The residual ΔN_e for the weak minus standard magnetic field when the vertical wind effect is excluded might arise from changes in the neutral composition. In Figures 6c and 6d, the O/N_2 column ratios are shown in response to the weak minus standard magnetic field. In the Northern Hemisphere midlatitudes (Figure 6c), the O/N_2 ratio is larger in the longitudinal sectors centered around -90° and 120° GLon than in other longitudinal sectors. In the Southern Hemisphere (Figure 6d), the O/N_2 ratio is larger in the range of $\pm 60^\circ$ GLon. The longitudinal patterns in the O/N_2 ratio (Figures 6c and 6d) are consistent with those of ΔN_e in Figures 6a and 6b, which shows the importance of the neutral composition in determining the longitudinal modulation

Figure 6. (a, b, e, and f) Longitudinal differences in the residual electron density (ΔN_e) for weak minus standard magnetic field condition are shown as a function of geographical longitude and magnetic local time at midlatitudes. Figures 6a and 6b are simulated ΔN_e excluding the vertical wind transport process. (c and d) Longitudinal and magnetic local time variations in the ratio between atom oxygen and molecular nitrogen $\Delta O/N_2$. Figures 6e and 6f are ΔN_e due to vertical transport induced by neutral winds.

of the electron density. A larger O/N_2 ratio indicates lower recombination rates and leads to a high ion density. A certain antiphase relationship is observed between the O/N_2 ratio and meridional wind (Figure 5), with larger equatorward wind (positive) corresponding to smaller O/N_2 (negative). This indicates that the longitudinal variations in the O/N_2 ratio are caused by longitudinal variations in thermosphere circulation, which arise due to the influence of the geomagnetic field geometry on the spatial distribution of the high-latitude energy input.

The effects of the vertical wind on ΔN_e can be determined by comparing the two runs with and without the vertical wind transport terms. We subtracted the results without winds from the original simulation (i.e., Figures 2e and 2f minus Figures 6a and 6b). The results are shown in Figures 6e and 6f. It can be seen that the vertical wind causes a wave-1 structure in ΔN_e , which is about 180° out of phase in the two hemispheres. The effect of the vertical wind on ΔN_e is weaker in the Northern Hemisphere than in the Southern Hemisphere. As described in section 3, when the magnetic field strength is reduced, ΔN_e gets enhanced in the nighttime sector and reduced in the dayside sector. The dependence on local time of the effect of the magnetic field strength on ΔN_e in the Northern Hemisphere midlatitudes is mainly caused by the O/N₂ ratio, whereas in the Southern Hemisphere it is due to the combined effects of both the vertical wind and the O/N₂ ratio.

The variations in ΔN_e for the weak minus standard magnetic field in auroral regions owing to the physical processes that have been discussed are presented in Figure 7. From top to bottom are shown the effects of nonvertical winds, the O/N₂ ratio, and vertical winds in the same format as Figure 6. It is found that the effects of both neutral winds (Figures 7e and 7f) and nonneutral wind (Figures 7a and 7b) play comparable roles in the longitudinal reduction in ΔN_e at auroral latitudes in both hemispheres. When the plasma convection is enhanced owing to a reduction in field strength, the directions of the neutral wind at high latitudes are changed owing to an increase in ion drag forces. The winds become more westward at dusk and eastward at dawn, which acts in opposite direction to the wind pattern induced by solar heating. Subsequently, the vertical wind effect is reversed in direction. This can explain the reduction in the longitudinal difference in ΔN_e . The residual structures of ΔN_e (Figures 7a and 7b) and $\Delta O/N_2$ (Figures 7c and 7d) are not consistent with each other at auroral latitudes, as they are at midlatitudes. This suggests that other physical processes are more important for composition change at auroral latitudes, an example might be the $\vec{E} \times \vec{B}$ horizontal transport processes (the vertical transport of $\vec{E} \times \vec{B}$ is not coincident with ΔN_e in the auroral belts, figure not shown). When the magnetic field strength is reduced, the enhanced horizontal convection might help to eliminate the longitudinal differences in ΔN_e at high latitudes.

4.3. Joule Heating

The changes in $\Delta \rho$ may arise from Joule heating, which is one of the most important heating mechanisms in auroral regions. As a result of an increase in Joule heating, the thermosphere can expand upward. Figure 8 shows the variation in Joule heating (ΔJH) with longitudinal and local time in auroral regions for both standard and for weak minus standard magnetic fields. ΔJH exhibits obvious wave-1 patterns in both hemispheres, which are in phase with those of $\Delta \rho$. This indicates an important role of Joule heating in the longitudinal modulation of mass density. Joule heating is dependent on both ionospheric conductivity and plasma velocity, which are both inversely proportional to the field strength. When the field strength is reduced, ΔJH increases. *Cnossen et al.* [2011] found that the global mean Joule heating is 26–30% stronger for a field with a dipole reduced by 25% than for standard dipole. In our study, we found that the longitudinal differences in Joule heating are enhanced by a factor of 3–4 for a field reduced in strength by 50% in both hemispheres. A magnetic field reduced in strength by 50% might result in questionable values of conductivity in the GITM. Thus, the model might overestimate the Joule heating owing to uncertainties in the conductivity.

As listed in Tables 1 and 2, the responses of ΔN_e to a weak field are larger at equinoxes than at solstices for both middle and high latitudes. The smaller response can be associated with a weaker longitudinal difference in Ne occurring in summer hemisphere relative to other seasons for both standard field and weak field conditions. This is because the electron density is proportional to $\cos^{1/2}(SZA)$ (solar zenith angle), which varies smoothly when $SZA < 60^\circ$ (in the local summer) but quite steeply near the terminator (at equinox and in the local winter). Thus, the longitudinal differences in electron density due to solar illumination are expected to be minimal in the local summer. In addition, the plasma convection is weaker in summer owing to higher conductivity. This might balance the reduction in the effect of the magnetic field on the plasma velocity. Our results are consistent with the results of *Cnossen and Förster* [2016]. They investigated the seasonal dependence and the dependence on solar/geomagnetic activity of the north-south asymmetry. They found that the hemispheric asymmetry disappears around June solstice at high solar activity. The lower magnetic field strength at northern hemispheric high latitudes acts to produce larger ion drifts in the Northern Hemisphere than in the Southern Hemisphere. The ion drift in the summer hemisphere is smaller than that in the winter hemisphere owing to the inverse relationship between the electric field and the ionospheric conductivity. Around June solstice the effect of the conductivity in the summer (northern) and winter (southern) hemispheres is opposite to the effect of the magnetic field strength in the respective hemispheres. In winter, the

Figure 7. The same format as Figure 6 but at auroral latitudes.

lower plasma and neutral densities are expected to result in weaker coupling between the ion and neutral densities. Moreover, the summer-to-winter poleward wind might dampen the effect of the equatorward winds that result from auroral heating in the winter hemisphere. These two factors act in opposite direction to the influence of a weak magnetic field, which might explain the weaker response in ΔN_e in local winter.

Finally, we would like to add some words on the relation of our work to planetary studies and other major questions in geospace. It might be related to the escape of O^+ (oxygen ion) in response to a greatly weakened geomagnetic field, like on Mars. The enhanced O^+ escape is important for us to understand the linkage

Figure 8. Longitudinal variation in Joule heating as a function of geographical longitude and magnetic local time at auroral latitudes. The energy is in unit of $10^{-12} \text{ Wattm}^{-3}$. (a and b) For standard magnetic field strength and (c and d) residuals from weak minus standard field runs.

between the mass extinction and the reversal and reduction in the magnetic field. *Wei et al.* [2014] simulated the O^+ escape rate for the Triassic-Jurassic event by using a modified Martian ion escape model. They revealed, the O^+ escape rate can be enhanced by 3–4 orders of magnitude if the magnetic field was extremely weak.

In our Earth, the ionospheric upflow plays an important role in the magnetosphere-ionosphere coupling process, providing ionospheric O^+ for the magnetosphere. The ion upflow prefers to occur in the cusp and auroral region [e.g., *Yau et al.*, 1984; *Kervishvili and Lühr*, 2013] and at the auroral oval poleward boundary [e.g., *Lockwood et al.*, 1985], and at subauroral latitudes [e.g., *Wang and Lühr*, 2013]. O^+ ions in the topside ionosphere can be energized and accelerated into the magnetosphere [e.g., *Wahlund et al.*, 1992]. As Figures 2a–2d show, O^+ in the topside ionosphere at both auroral and subauroral latitudes show obvious regional differences, with larger densities in some areas, but not in others, under normal magnetic field strength condition. When the magnetic field strength is reduced, the regional differences are reduced at high latitudes, while they display a mixed response, depending on the local time sector at subauroral latitudes. These results indicate that the magnetic field strength can change the spatial distribution of O^+ ions densities in the topside ionosphere. These changes are expected to alter the total O^+ upflow rate and amount, from the perspective of the ionosphere background. Thus, our work may contribute to our understanding of the escape of O^+ from the ionosphere, which might have occurred historically or might occur in the future.

5. Summary

In this study the effects of differences in magnetic field strength on the longitudinal ΔNe and $\Delta \rho$ at middle and auroral latitudes are investigated. The GITM model was employed for the theoretical study. In a first simulation

we used an IGRF magnetic field configuration, whereas in the second run we used an IGRF field with the strength reduced by 50%. Conditions at September equinox and June and December solstices were analyzed. The modelling results show obvious differences in the longitudinal ΔN_e and $\Delta \rho$ at auroral and midlatitudes.

1. A reduction in geomagnetic field strength causes significant changes in the longitudinal modulation of important ionospheric and thermospheric quantities. We find a general increase in thermospheric mass density, whereas the electron density decreases at auroral latitudes but displays a mixed response, depending on the local time sector, at midlatitudes.
2. Larger effects of the magnetic field on ΔN_e are observed during equinox seasons and smaller effects are observed during solstice seasons. The smaller response in the local summer may be associated with the minimal longitudinal differences in ΔN_e caused by solar insulation occurring in summer in comparison to other seasons. The smaller response in the winter might be associated with inefficient ion-neutral coupling.
3. The peak west-east differences in ΔN_e are increased (reduced) by about 2–34% (7–20%) in the night (day) sector at midlatitudes in both hemispheres while being reduced by 2–32% at all local times at auroral latitudes. These numbers are differences between two different simulations. The peak west-east differences in $\Delta \rho$ are increased at both middle and auroral latitudes.
4. Different mechanisms are active at middle and high latitudes. The most important effects on ΔN_e are changes in the O/N_2 ratio in the midlatitude Northern Hemisphere and the combination of vertical wind effects and changes in the O/N_2 ratio in the Southern Hemisphere. Both vertical winds and horizontal $\vec{E} \times \vec{B}$ convection eliminate ΔN_e at high latitudes. For $\Delta \rho$ the dominant mechanism is Joule heating.

It is not the aim of the present work to compare directly with observation. Wang and Liu [2015] have studied the longitudinal differences in ΔN_e at middle latitudes during both solar maximum and medium conditions. It was revealed that the peak west-east differences of ΔN_e were enhanced by a factor of 1.7 and 60% in the dayside and nightside sector in the Northern Hemisphere and were enhanced by 71% and a factor of 1.2 in these two MLT sectors in the Southern Hemisphere, when solar flux $F_{10.7}$ was increased from 99 to 154 sfu at middle latitudes. In the present work, it is shown that the variation in the geomagnetic field strength can also affect ΔN_e , which might contribute to our understanding of the physical mechanisms driving long-term variations of these mesoscale structures in the ionosphere and thermosphere. In future work we might perform simulations with historic magnetic fields to quantify more precisely the effect of changes in the magnetic field on the magnetosphere-ionosphere-thermosphere system for comparison with observations.

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