Simulations of the equatorial thermosphere anomaly: Field-aligned ion drag effect

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Received 28 August 2011; revised 20 November 2011; accepted 21 November 2011; published 6 January 2012.

[1] In this paper the impact of the field-aligned ion drag on equatorial thermosphere temperature and density is quantitatively investigated on the basis of the National Center for Atmospheric Research Thermosphere Ionosphere Electrodynamics General Circulation Model (NCAR TIEGCM) simulations under high solar activity (F107 = 180). The increase of upward vertical winds over the magnetic equator associated with the additional divergence of meridional winds, caused by the inclusion of field-aligned ion drag, leads to a reduction in thermosphere temperature and density at the magnetic equator through enhanced adiabatic cooling. We found that the field-aligned ion drag has an obvious impact on the thermosphere only over the magnetic equatorial region in the daytime and evening sectors, whereas it has less effect on the equatorial thermosphere anomaly (ETA) crests. The daytime neutral temperature over the magnetic equator is reduced by about 30 K, for altitudes above 250 km without significant altitudinal variations, when field-aligned ion drag is included in the simulation. The thermosphere density in the magnetic equatorial region starts to change slightly at 300 km and depletes by about 5% at 400 km, while experiencing a greater decrease with altitude. Furthermore, the trough produced in the neutral temperature and density corresponds well with the magnetic dip equator. The ETA features during 12:00–18:00 LT become obvious as a result of the inclusion of the field-aligned ion drag. Specifically, our results show that at 400 km the crest-trough differences in neutral temperature are about 30–60 K, and the crest-trough ratios in thermosphere density are 1.03–1.06, comparable with observations.


1. Introduction

[2] The equatorial thermosphere anomaly (ETA) is a feature of the upper thermosphere with two crests at around ±20°–30° in magnetic latitude and a trough at the magnetic equator. Discovered in the 1970s, the ETA structure and formation have received little attention owing to limited observations and uncertain coupling processes [Philbrick and Mclsaac, 1972; Hedin and Mayr, 1973; Mayr et al., 1974; Raghavarao et al., 1991, 1993]. Recent observations of thermosphere mass density from low-Earth-orbiting satellites have revealed new features of the ETA [Liu et al., 2005, 2007] which enable much more in-depth investigation of its characteristics and its coupling to the more research-established equatorial ionosphere anomaly (EIA). Generally, the formation of the ETA is thought to be related to ion-neutral interactions, but many questions remain regarding the understanding of the remarkably different characteristics in the temporal and spatial variations of the ETA and the EIA [Lei et al., 2010a].

[3] Great efforts have been made to explain and simulate the formation of the ETA [Hedin and Mayr, 1973; Fuller-Rovell et al., 1997; Pant and Sridharan, 2001; Maruyama et al., 2003]. However, none of these studies fully explain the causes of the ETA [Lei et al., 2010a]. To understand the mechanism(s) which produce the ETA, a self-consistent coupled thermosphere-ionosphere general circulation model is highly desirable to systematically revisit the proposed mechanisms mentioned by Lei et al. [2010a]. As a part of our series of studies, the present work will focus on the impact of the field-aligned ion drag effect on the formation of the ETA through a comprehensive analysis of the state-of-the-art National Center for Atmospheric Research Thermosphere Ionosphere Electrodynamics General Circulation Model (NCAR TIEGCM) [Roble et al., 1988; Richmond et al., 1992]. Maruyama et al. [2003] addressed this subject but with limited scope because the electric field used in the model
was not solved self-consistently and electron density in the low-latitude E region was imposed by an empirical ionosphere model. A further objective and inherent capability of the NCAR TIEGCM is to investigate the local time and longitudinal dependence of the field-aligned ion drag effect on the equatorial thermosphere, something not investigated by Maruyama et al. [2003]. More importantly, we elucidate the impact of the field-aligned ion drag on both thermosphere temperature and neutral density in a quantitative, self-consistent way. Thus, previous observations of thermosphere temperature and neutral density [Raghavarao et al., 1991; Liu et al., 2007; Lei et al., 2010a] can be utilized to validate our simulations.

2. Numerical Experiments

[4] We conducted two TIEGCM simulations: one without and the other with field-aligned ion drag in the momentum equations of the neutral gas, which are hereafter referred to as run 1 and run 2. As we know, the ion drag force per unit mass, \( F_{ni} \), in the momentum equations of the neutral gas can be described in directions perpendicular and parallel to the magnetic field as follows [also see Maruyama et al., 2003]:

\[
F_{ni} = \frac{\mathbf{J} \times \mathbf{B}}{\rho} + \mathbf{b} \left( N_i m_i g \sin f - \frac{\partial p_i}{\partial s} \right) = \frac{\mathbf{J} \times \mathbf{B}}{\rho} - v_{ni}(U_i - V_i) = \frac{\mathbf{J} \times \mathbf{B}}{\rho} + v_{ni} W_{d||}
\]

where \( \mathbf{J} \) is the electric current density; \( \mathbf{B} \) is the magnetic field; \( \mathbf{b} \) is a unit vector along \( \mathbf{B} \); \( \rho \) is the neutral mass density; \( v_{ni} \) is the collision frequency of momentum transfer for the neutral gas with ions; \( U_i, V_i \), and \( W_{d||} \) are the field-aligned components of neutral wind, ion velocity, and ion diffusion velocity; \( N_i \) is the ion density; \( m_i \) is the ion mass; \( g \) is the acceleration of gravity; \( I \) is the downward inclination of the geomagnetic field; \( p_i \) is plasma pressure (the sum of ion and electron pressures); and \( s \) is distance along the magnetic field. In each form of the right-hand side of equation (1), the first and second terms represent the perpendicular and field-aligned components of ion drag, respectively. In the default TIEGCM, the ion drag component along magnetic field lines is ignored. However, this force involves large accelerations associated with field-aligned gravity and plasma pressure gradients, part of which effectively gets transferred to the horizontal direction because of field line inclination.

[5] The numerical experiments were conducted under high solar activity and equinox conditions when the ETA is more evident [Liu et al., 2007]. Specifically, the solar activity index F10.7 is 180 on the day of year 80. In addition, in our simulations the cross polar cap potential and hemispheric power are 1 kV and 1 GW, respectively, which represent extremely quiet geomagnetic conditions. The horizontal resolution of the TIEGCM is \( 5^\circ \times 5^\circ \), and the vertical resolution is one-half scale height; the time step of the model simulation is 2 min. The geomagnetic field model is specified by the International Geomagnetic Reference Field (IGRF 2000) using magnetic apex coordinates [Richmond, 1995]. We carried out the TIEGCM simulations by specifying the amplitudes and phases of migrating tides from the lower atmosphere from the Global Scale Wave Model (GSWM02) [Hagan and Forbes, 2002] at the lower boundary of the TIEGCM. Both diurnal and semidiurnal tides are applied in the simulations. In addition, the TIEGCM includes neutral wind dynamo effects so that the electric field can be self-consistently solved. In section 3, the impact of the field-aligned ion drag on the ETA formation in neutral temperature and density is presented.

3. Results

[6] Figure 1 shows neutral temperature (Figures 1a–1c) and density (Figures 1d–1f) as a function of latitude and altitude at the longitude of 60°W and 14:00 LT for run 1 (Figures 1a and 1d) and run 2 (Figures 1b and 1e). The corresponding differences in neutral temperature and density between the two simulations are displayed in Figures 1c and 1f. For the default TIEGCM simulation (Figure 1a), two weak peaks are seen in neutral temperature at high altitudes, occurring at the geographic latitudes of \( \sim 25^\circ \)N and 35°S, respectively. When the field-aligned ion drag is included in the simulation, both the crests and trough are clearly seen in neutral temperature (Figure 1b). As further illustrated in Figure 1c, neutral temperature is reduced by about 30 K above the altitude of 250 km over the magnetic equator due to the inclusion of the field-aligned ion drag, whereas neutral temperature only increases by a few kelvins at higher latitudes. This indicates that the field-aligned ion drag plays an important role in producing the equatorial trough of the thermosphere, while it has little effect on the formation of the ETA crests. These results are consistent with those of Maruyama et al. [2003].

[7] Compared with run 1 (Figure 1d), the ETA features in thermosphere density become clearer in run 2 with the thermosphere density beginning to change at 300 km and decreasing more and more at higher altitudes in the equatorial region (see Figures 1e and 1f). Obviously, the altitudinal behavior in thermosphere density response is largely dependent on changes in the pressure scale height, while the neutral temperature response is dependent on heating and cooling terms with heat conduction being a dominant process at these altitudes working to remove vertical temperature gradients. Thus, for run 2, the decreased temperature over the magnetic equator is nearly constant with altitude (Figure 1c). The response in thermosphere density at a fixed altitude can be described by considering the number of scale height increments between the considered altitude and the source region [Lei et al., 2010b]. Thus at higher altitudes, the change in thermosphere density becomes greater because a larger number of increments in scale height lie between the higher altitude and the source region, while the changes in neutral temperature are similar at all altitudes demonstrating the dominant role of downward heat conduction.

[8] In order to examine how the impact of the field-aligned ion drag on the ETA changes with local time, the variations of neutral temperature and density at 400 km versus local time and latitude are depicted in Figure 2 for run 1 (Figures 2a and 2d) and run 2 (Figures 2b and 2e). These are global snapshots at 18:00 UT, when the eastern Pacific, American, and Atlantic sectors are in daytime. For the default TIEGCM simulation (run 1), the ETA features are either absent or weak in neutral temperature (Figure 2a) and thermosphere density (Figure 2d), although in the daytime there is a temperature peak in the Southern Hemisphere and there are two weak crests in thermosphere density. When the
field-aligned ion drag is included in the simulation, the ETA features become pronounced in both neutral temperature (Figure 2b) and density (Figure 2e) in the daytime. In addition, the equatorial trough is aligned with the dip equator. This feature becomes immediately apparent in the difference plots between run 2 and run 1. As seen in Figures 2c and 2f, the neutral temperature and density decrease by around 30 K and $0.3 \times 10^{-12}$ kg m$^{-3}$ (around 5% of the background density), respectively, during 10:00–23:00 LT due to the inclusion of the field-aligned ion drag. Notice that the inclusion of the field-aligned ion drag has no obvious impact on the equatorial thermosphere during the postmidnight period (see Figures 2c and 2f), when the EIA tends to disappear.

Next, the variations of daytime neutral temperature at 400 km are given in a fixed local time frame (as a Sun-synchronous satellite observes) to further examine the local time dependence of the ETA (Figure 3). Figure 3 is plotted as a function of geographic latitude and universal time (UT), and UT time in this plot runs from right to left; thus, the world map shifts toward the left as the fixed local time increases. The same convention is used in the remainder of the paper for the fixed local time frame plots. The changes of the simulated field (in each fixed local time frame) at different UTs actually represent its longitudinal variations given that nonvarying solar and magnetic activity forcing with time has been applied in our simulations. As shown in Figure 3 (left), the neutral temperature from run 1 does not exhibit evident ETA features except that both the crests and a weak trough appear during the periods around 12:00 and 18:00 LT. Neutral temperature also shows an equatorial trough along the dip equator in the morning (10:00 LT) and the late evening (20:00 LT); however temperature is higher at high latitudes, such that no crest stands out at middle latitudes during these local times. When the field-aligned ion drag is included in the simulation, the neutral temperature (Figure 3, right) shows a clear equatorial trough from 10:00 to 20:00 LT, and the ETA features are evident during 12:00–18:00 LT. Also, it is clear that the crests in neutral temperature are usually lower at the Atlantic and west African sectors in the Northern Hemisphere and over the American sector in the Southern Hemisphere. This longitudinal variation of the ETA crests might be associated with the magnetic field configuration and auroral effect [Wang et al., 2008] and will be discussed in a future paper focused on ETA crest structure.

The variations of thermosphere density at 400 km in the fixed local time frame are shown in Figure 4 with the same format as in Figure 3. It can be seen that the variations of thermosphere density for both cases are generally consistent with those of neutral temperature from 10:00 to 20:00 LT. However, there are some differences. For run 1, the weak crest and trough in thermosphere density appear at 10:00 and 12:00 LT, whereas in neutral temperature they are most obvious at 18:00 LT. In addition, the crests of the mass density do not always collocate with those of neutral temperature. The potential causes for these differences in their latitudinal structure might be the modulation in density

Figure 1. (a–c) Neutral temperature and (d–f) density as a function of latitude and altitude at the longitude of 60°W and 14:00 LT for run 1 (Figures 1a and 1d) and run 2 (Figures 1b and 1e). The corresponding differences between the two simulations are displayed in Figures 1c and 1f. Note that the magnetic equator lies at a geographic latitude of around 11°S at this longitude.
caused by changing neutral composition. As shown by Lei et al. [2010b], the variation of thermosphere density can be altered by neutral composition, albeit the change of thermosphere density at a fixed altitude is an integrated effect of temperature and composition change below. In run 2, besides similar features as those from the simulation without field-aligned ion drag, thermosphere density shows a clear equatorial trough organized by the magnetic equator during the entire daytime (Figure 4, left). As a result, the ETA features in thermosphere density become evident from 10:00 to 18:00 LT.

The differences between the two simulations of neutral temperature and density at 400 km in the fixed local time frame are shown in Figure 5. Obviously, after including the field-aligned ion drag, neutral temperature and density decrease by around 30–40 K and 0.4×10^{-12} kg m^{-3} during 12:00–20:00 LT, and the decrease is relatively weaker at 10:00 LT. It is apparent that the equatorial depletion in both neutral temperature and density differences is well aligned with the dip equator, with little longitudinal dependence. Meanwhile, weak enhancements in neutral temperature and density appear at middle and high latitudes. However, the enhancements are even weaker in the African sector. This is suggestive of effects of the displacement between the magnetic and geographic poles.

Figure 6 further provides a quantitative comparison between run 1 (dashed line) and run 2 (solid line) for neutral temperature and density at 400 km and 14:00 LT. After including the field-aligned ion drag (i.e., run 2), the equatorial neutral temperature decreases by 26, 27, and 31 K at the longitudes of 60°W, 30°E, and 120° E, respectively, whereas the decrease of thermosphere density is roughly the same (around 0.28×10^{-12} kg m^{-3}) at these three longitudes. Also in run 2 (red lines), the crest-trough differences in neutral temperature are about 34, 42, and 46 K, and the crest-trough ratios in thermosphere density are 1.05, 1.06, and 1.06 at the longitudes of 60°W, 30°E, and 120° E, respectively. Figure 7 gives a similar line plot as Figure 6 but for 18:00 LT and some differences between 14:00 and 18:00 LT are evident when comparing Figures 6 and 7 for run 1 (dashed lines). The crest-trough differences in neutral temperature at 18:00 LT at the considered longitudes (60°W, 30°E, and 120° E) are a little stronger than those at 14:00 LT; in contrast, they become less evident in thermosphere density at 18:00 LT with respect to those at 14:00 LT. Nevertheless, the reduction of neutral temperature and density at 18:00 LT due to the inclusion of the field-aligned ion drag is similar to that at 14:00 LT. This is consistent with the results of Figure 5. At 18:00 LT, in run 2 (solid lines) the crest-trough differences in neutral temperature are 42, 50, and 54 K at the longitudes of 60°W, 30°E, and 120° E, and the crest-trough ratios in thermosphere density are about 1.03–1.06.

4. Discussion

Now we turn our attention to address the cause of the equatorial depletion in thermosphere temperature and density due to the inclusion of field-aligned ion drag. Figure 8a shows
the variations of electron density at 14:00 LT as a function of latitude and altitude for run 2 at the longitude of 60°W, where the magnetic equator lies at a geographic latitude of around 11°S. Clearly, the EIA is well formed at this local time, and we can expect large downward/poleward diffusive plasma fluxes in the EIA that produce a poleward component of field-aligned ion drag (see Figure 8b), which we call $F_n$.

Figure 8c shows the differences between run 2 and run 1 for the meridional pressure gradient ($\delta Z_p$, positive northward). The unit for $\delta Z_p$ is $10^{-2}$ m s$^{-2}$. It is clear that the tendency for the pressure gradient to offset the meridional component of parallel ion drag force $F_n$ is fairly strong. Figure 8d depicts the sum of $\delta Z_p$ and $F_n$ on the same scale as Figure 8b and 8c. Obviously, $\delta Z_p$ cannot completely balance $F_n$ in the EIA region and above. Figures 8e and 8f show the differences between run 2 and run 1 for meridional and vertical winds, respectively. The additional poleward ion drag, introduced by the inclusion of field-aligned ion drag, accelerates meridional winds by about 10 m s$^{-1}$ around the crest regions of the EIA (Figure 8e). The small changes of meridional winds above the EIA crests, where the imbalance between $\delta Z_p$ and $F_n$ is obvious, is associated with redistribution of momentum vertically due to viscosity. The resultant divergence of meridional winds induces a change in vertical winds by 1 m s$^{-1}$ around the magnetic equator.

As expected, stronger adiabatic cooling (or a reduction of adiabatic heating) takes place over the magnetic equator as given by $-W_n RT_n/C_p H m$ (where $W_n$, $T_n$, $H$, and $m$ are the}

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**Figure 3.** Neutral temperature (K) at 400 km from (left) run 1 and (right) run 2 as a function of latitude at the fixed local time frame from 10:00 to 20:00 LT. The dashed white lines indicate the location of the magnetic equator. This is plotted as a function of geographic latitude and universal time (UT), and UT time in this plot is equivalent to the corresponding longitude in the fixed local time frame. The same convention is used in the fixed local time frame plots in Figures 4 and 5.
vertical wind, neutral temperature, pressure scale height, and mean atmospheric mass, respectively; \( R \) and \( C_p \) are the universal gas constant and specific heat at constant pressure surface per unit mass). Note that Figure 8f shows the wind perturbation between run 2 and run 1. We also checked the vertical winds from the TIEGCM simulations, and found that the vertical winds over the magnetic equator are upward during daytime and downward in the evening. Our results are consistent with those of Raghavarao et al. [1993], who reported downward vertical winds around the equator and at 21:00 LT.

We also carried out a term analysis of the energy equation for the neutral gas in order to see the changes in the energy budget in the equatorial region due to the effect of the field-aligned ion drag. These terms are conduction heating, advection heating, adiabatic heating/cooling, solar, collision heating between thermal electrons, ions and neutrals, Joule heating and radiational cooling. A detailed discussion of these heating and cooling terms will be given in a future study. Figure 9 shows the changes of adiabatic and conduction heating rates of the simulations between run 2 and run 1 as a function of latitude and altitude at the longitude of 60°W for 10:00, 14:00 and 18:00 LT. Other heating and cooling terms are not shown in the figure because they almost remain the same at the magnetic equator in these two simulations. As shown in Figure 9, the change of adiabatic cooling between run 2 and run 1 is mainly presented at the equatorial region at 14:00 and 18:00 LT, whereas it is weak at 10:00 LT when the changes of neutral temperature and density between run 2 and run 1 are small (Figure 5). Given that heat conduction always acts to redistribute the heat vertically in the upper thermosphere [Roble et al., 1987], the
increase of conduction heating (Figure 9, right) seen at the magnetic equator at 14:00 and 18:00 LT is a reaction to adiabatic cooling (or a reduction of adiabatic heating) due to adiabatic expansion (Figure 9, left).

[16] As shown in Figure 9, there is a quasi-steady state energy balance, with adiabatic cooling largely offset by heat conduction. However, it is unclear whether adiabatic cooling combined with heat conduction is the acting cause of the equatorial reduction of neutral temperature and density, given that our results are from steady state simulations of the TIEGCM. Figure 10 shows the evolution of the differences in the daytime meridional and vertical winds, meridional pressure gradient, heat conduction, adiabatic cooling and neutral temperature on the model pressure surface 2 (around 390 km) between run 2 and run 1 during the first 55 min of the simulations at 210°E and around 14:00 LT. It is immediately apparent that meridional winds respond to the activation of the field-aligned ion drag almost simultaneously. The response is then seen in vertical winds and the associated adiabatic cooling, followed by the response of meridional
Figure 6. Comparison of (a–c) neutral temperature and (d–f) density at 400 km from run 1 (dashed line) and run 2 (solid line) at 14:00 LT. The simulations at longitudes of 60°W (Figures 6a and 6d), 30°E (Figures 6b and 6e), and 120°E (Figures 6c and 6f) are shown.

Figure 7. Same as Figure 6 but at 18:00 LT.
pressure gradient and heat conduction. Note that the strong
depletion of the equatorial neutral temperature is seen at a
later time, given that the neutral gas takes time to accumulate
the effect of the changes in heating/cooling. The changes of
meridional pressure gradient against the parallel ion drag are
associated with the changes in neutral temperature. There-
fore, during the first 20 min, the acting cause for the depletion
of daytime neutral temperature and density at the magnetic
equator in run 2 is mainly due to the increase of adiabatic
cooling at the magnetic equator. As the pressure gradient
grows to counteract the field-aligned ion drag, the vertical
velocity and adiabatic cooling lessen. A few more words
should be added regarding the contribution of the reactive
pressure gradient to the equatorial depletion in thermosphere
temperature. After about 50 min, the dynamics and thermo-
dynamics should approach a quasi-steady state, if other
conditions are not changing. The maintenance of the tem-
perature perturbation is associated with the maintenance of
the reactive pressure gradient. As shown in Figure 8, the
reactive pressure gradient roughly balances the parallel ion
drag force. Thus the magnitude of the quasi-steady state
temperature perturbation can be considered to be mainly
determined by the strength of the parallel ion drag force. On
this longer time scale the adiabatic cooling is proportional to
the strength of the winds, but the wind magnitude is related to
the difference between the ion drag and pressure gradient
forces, which have a strong tendency approximately to balance.

[17] It is worth comparing our simulation results (run 2) with
neutral temperature and density observations. Raghavarao
et al. [1991] reported DE 2 observations obtained from
three orbits in which neutral temperature and wind had
obvious ETA features at 300–400 km. They showed the
crest-trough differences in neutral temperature were about
56, 110, and 45 K for those three DE 2 orbits. Obviously, the
crest-trough differences in neutral temperature for the first
and third orbits are in agreement with our simulations (see
Figures 6 and 7), whereas they are much stronger for the
second orbit. It should be kept in mind that these three-orbit
observations from DE 2 may not represent common condi-
tions, given that the crest-trough ratios in electron density
for the first two orbits are larger by an order of 2. In addi-
tion, the first two cases took place at solstice, whereas our
simulations represent the situation at equinox.

[18] Liu et al. [2007] did a statistical analysis of CHAMP
data during 2002–2005 and investigated the climatology of
the ETA variations. The local time dependence of the ETA

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**Figure 8.** (a) Electron density and (b) meridional component of the field-aligned ion drag $F_n$ from run 2,
(c) the changes in meridional pressure gradient $\delta Zp$ between runs 2 and 1, (d) the sum of $\delta Zp$ and $F_n$, and
the changes in (e) meridional winds and (f) vertical winds between runs 2 and 1 (run 2 minus run 1) as a
function of latitude and altitude at the longitude of 60°W and 14:00 LT. Positive values from Figures 8b to
8e represent northward direction, and positive vertical winds in Figure 8f represent upward direction. Note
that the magnetic equator lies at a geographic latitude of around 11°S at this longitude.
from our run 2 (Figures 2 and 4) is in agreement with that of the CHAMP observations. More importantly, Liu et al. found the crest-trough ratio in thermosphere density is about 1.05 under high solar activity. Their statistical result for the crest-trough ratio is generally consistent with our simulation. Lei et al. [2010a] examined the detailed similarities and differences between the ETA and EIA from 20 March to 6 April 2002, when both the ETA and the EIA are distinct in the CHAMP observations. The averaged crest-trough ratio during that period is about 1.086, which is larger than our simulations. It should be noted that our simulations were carried out under extremely quiet geomagnetic conditions. As expected, the geomagnetic activity can have significant influence on modulating the variations of the ETA.

Finally, it should be pointed out that Miyoshi et al. [2011] recently suggested that in situ diurnal tides and terdiurnal tides propagating from the lower atmosphere play an important role in producing the equatorial anomaly in mass density. However, they did not predict the equatorial anomaly in thermosphere temperature as observed by the DE 2 [Raghavarao et al., 1991] and AE [Suhasini et al., 2001] satellites. Our simulations illustrate that the field-aligned ion drag is crucial in producing the equatorial troughs in both thermosphere temperature and density. Albeit the effect of the in situ diurnal tides on the equatorial trough in mass density may not be fully taken into account since there is no terdiurnal tide forcing at the model boundary in this study. Further investigation is required to evaluate whether this aspect is significant.

5. Conclusions

In this paper we extended the study of Maruyama et al. [2003] to examine the impact of field-aligned ion drag on both thermosphere temperature and neutral density under high solar activity and geomagnetically quiet conditions in a quantitative way. It is found that the field-aligned ion drag has an obvious impact on the thermosphere only over the magnetic equatorial region during the daytime and evening periods. The inclusion of the field-aligned ion drag accelerates meridional winds in the crest regions of the EIA and causes an increase of adiabatic cooling over the magnetic equator as a result of the enhanced divergence of meridional winds.

When the field-aligned ion drag is included in the simulation, the daytime neutral temperature over the magnetic equator is reduced by about 30 K above 250 km without significant altitudinal variations, whereas thermosphere density starts to change slightly at 300 km and declines with altitude in the magnetic equatorial region. Additionally, the trough produced in thermosphere temperature and density is collocated with the magnetic dip equator with little magnetic longitudinal dependence. After including the field-aligned ion drag in the simulation, our results revealed that at 400 km the crest-trough differences in neutral temperature

![Figure 9. Differences between runs 2 and 1 (run 2 minus run 1) for (left) adiabatic and (right) conduction heating rates as a function of latitude and altitude at the longitude of 60°W for 10:00, 14:00, and 18:00 LT. Note that the magnetic equator lies at a geographic latitude of around 11°S at this longitude.](image-url)
Figure 10. Evolution of the differences in the daytime meridional and vertical winds (m s\(^{-1}\)), meridional pressure gradient (10\(^{-2}\) m s\(^{-2}\)), positive northward, adiabatic cooling, heat conduction and neutral temperature (K) on the model pressure surface 2 (at around 390 km) between run 2 and run 1 during the first 55 min of the model simulations. Positive meridional winds represent northward direction, and positive vertical winds represent upward direction. The heating rates are in unit of 10\(^7\) ergs g\(^{-1}\) s\(^{-1}\).

are about 30–60 K, and the crest-trough ratios in thermosphere density are 1.03–1.06. These results agree fairly well with observations. Since the equatorial cooling is directly related to the strength of the field-aligned ion drag, which depends on ion density, this effect likely is weaker at solar minimum than solar maximum. Finally, this study elucidated that the field-aligned ion drag mainly contributes to the formation of the ETA trough, while the causes for the production of the ETA crests in thermosphere temperature will be addressed in a future study.

Acknowledgments. This work was supported by National Natural Science Foundation of China (41174139, 41121003, 41104107, 41025016, 4080165), the Project of Chinese Academy of Sciences KZCX2-EW-QN509, Thousand Young Talents Program of China, NASA grant NNX10AQ52G, AFOSR MURI Award FA9550-07-1-0565 and AFOSR contract FA9550-08-C-0046. This work is also supported in part by the Center for Integrated Space Weather Modeling (CISM) which is funded by the STC Program of the National Science Foundation under Agreement ATM-0120950. The National Center for Atmospheric Research is sponsored by the National Science Foundation. The authors wish to thank Naomi Maruyama, Huixin Liu, and Alan G. Burns for their useful discussions.

Robert Lysak thanks the reviewers for their assistance in evaluating this paper.

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