Enhancement of thermospheric mass density by soft electron precipitation

B. Zhang,¹ W. Lotko,¹ O. Brambles,¹ M. Wiltberger,² W. Wang,² P. Schmitt,² and J. Lyon³

Received 24 August 2012; revised 24 September 2012; accepted 25 September 2012; published 26 October 2012.

[1] Enhancements in F-region electron density and temperature and bottomside Pedersen conductivity caused by soft electron precipitation are shown to enhance the Joule heating per unit mass and the mass density of the thermosphere at F-region altitudes. The results are derived from the coupled magnetosphere-ionosphere-thermosphere model (CMIT) including two types of causally specified soft electron precipitation—direct-entry cusp precipitation and Alfvén-wave induced, broadband electron precipitation—the effects of which are self-consistently included for the first time in a coupled global simulation model. The simulation results provide a causal explanation of CHAMP satellite measurements of statistical enhancements in thermospheric mass density at 400 km altitudes in the cusp and premidnight auroral region. Citation: Zhang, B., W. Lotko, O. Brambles, M. Wiltberger, W. Wang, P. Schmitt, and J. Lyon (2012), Enhancement of thermospheric mass density by soft electron precipitation, Geophys. Res. Lett., 39, L20102, doi:10.1029/2012GL053519.

1. Introduction

[2] Thermospheric mass density enhancements have been observed in the dayside cusp region and premidnight auroral zone at 400 km altitude by the CHAMP satellite. A density enhancement of almost a factor of two relative to the MSIS90 empirical model was observed in the dayside cusp region [Lühr et al., 2004; Rentz and Lühr, 2008]. The statistical global distributions of thermospheric mass density derived by Liu et al. [2005] from CHAMP accelerometer measurements also exhibit persistent density enhancements in the cusp and premidnight auroral zone up to 30% relative to the MSIS90 model. During strong IMF Bz driving, a significant thermospheric mass density enhancement in the cusp region has also been reported by Crowley et al. [2010].

[3] These high-latitude thermospheric density enhancements are most likely produced by sources from the magnetosphere. One possible candidate is an increase in Joule heating associated with the enhancement of convection electric field or plasma flow shear [Carlson et al., 2012; Crowley et al., 2010; Knipp et al., 2011; Li et al., 2011]. Another possible candidate is the thermospheric heating by ion neutral friction in the F2 region within SAPS [Wang et al., 2011; Mishin et al., 2012]. These studies did not consider the effects of soft electron precipitation, which is another candidate for the thermospheric mass density enhancement. Soft electron precipitation is commonly observed in the dayside cusp region and in the premidnight sector of the auroral zone by both ground-based [Eather, 1985] and satellite instruments [Newell et al., 1989; Smith and Lockwood, 1996; Newell et al., 2009]. Precipitating soft electrons can influence the F-region ionization and conductivity above 150 km, which affects the distribution of Joule heating. This phenomenon was observed during the CHAMP-EISCAT campaign [Rentz, 2009], which was executed to observe the thermosphere with the CHAMP satellite while simultaneously observing the ionosphere with the EISCAT incoherent-scatter radar. Rentz [2009] suggested that soft particle precipitation can have a significant impact on the thermosphere by raising the effective altitude of Joule heating.

[4] Several studies have estimated the influence of the soft electron precipitation in the dayside cusp region of the ionosphere, with the conclusion that soft electrons can cause a significant increase in the electron density and temperature [Millis et al., 1999; Prölls, 2006]. Recently, Y. Deng et al. (Primary heating mechanisms for the substantial neutral density enhancements in the cusp region, submitted to Journal of Geophysical Research, 2012) investigated a thermospheric heating mechanism associated with soft particle precipitation in the cusp region using the Global Ionosphere Thermosphere Model (GITM) [Ridley et al., 2006]. The GITM simulations suggest that the combined influence of Joule heating and soft particle precipitation may cause a thermospheric mass density enhancement greater than 50% in the cusp region at 400 km altitude, which is similar in magnitude to that observed by the CHAMP. The soft particle precipitation and Joule heating rate implemented in GITM were not causally regulated in that the magnetosphere was not coupled to the ionosphere-thermosphere simulation of GITM. Also, nightside soft electron precipitation was not included in the GITM simulations.

[5] In this paper, the effects of precipitating soft electrons on thermospheric mass density are investigated self-consistently using the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model, including implementation of two causally regulated soft electron precipitation models. The CMIT model provides a means of globally investigating thermospheric heating processes associated with precipitating soft electrons, and specifically in the cusp and premidnight auroral sectors. It also connects the distributions of soft electron precipitation to causal magnetospheric processes. Controlled CMIT
simulations driven by ideal solar wind and IMF conditions with soft electron precipitation models included are compared to otherwise identical simulations without soft electron precipitation in order to investigate the effects of soft electron precipitation on the ionospheric plasma state and thermospheric mass density.

2. Simulation Description

[6] The CMIT model combines the Lyon-Fedder-Mobarry (LFM) global magnetosphere simulation and the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) via the Magnetosphere-Ionosphere Coupler/Solver (MIX) module. LFM solves ideal MHD equations for the three-dimensional solar wind - magnetosphere interaction using a finite volume scheme [Lyons et al., 2004]. TIEGCM solves the three-dimensional, fully coupled, hydrodynamic, thermodynamic, and continuity equations of the neutral gas self-consistently with the ion energy, ion momentum, and ion continuity equations using a finite difference scheme [Roble et al., 1988]. MIX computes the two-dimensional high-latitude electric potential and acts as the interface between LFM and TIEGCM [Merkin and Lyon, 2010]. Details of the coupling between LFM and TIEGCM can be found in Wittberger et al. [2004] and Wang et al. [2004].

[7] Causally driven models of direct-entry cusp and broadband precipitating electrons [Newell et al., 2009] are implemented in the CMIT simulation. The precipitating cusp electron number flux is modeled as an electron thermal flux \( N_e V_{th, e} \) in the cusp region assuming a full loss cone. The electron density \( N_e \) and thermal velocity \( V_{th, e} \) are dynamically scaled to the one-fluid MHD density and thermal velocity at the low-altitude computational boundary of LFM using empirically optimized proportionality constants. The simulated cusp region is determined dynamically as the mapping to low altitude from a high-altitude fiducial surface (6 Re for the simulation results here) of the diamagnetic depression of the simulated magnetic field relative to an earth-centered dipole field. The cusp is defined as the mapped region where the magnetic depression \( \Delta B \) satisfies \( 0.2 \leq \Delta B/\Delta B_{max} \leq 1 \), where \( \Delta B_{max} \) is the maximum magnetic depression, corresponding to the cusp center.

[8] The broadband electron precipitation flux is regulated by the field-aligned AC Poynting flux \( S_N [mW/m^2] = \mathbf{E} \times \mathbf{B} \cdot \mathbf{B}/\mu_0 B \) calculated in the simulation at an altitude of 3.5 Re and magnetically mapped to low altitude [Zhang et al., 2012]. The employed relationship, \( F_N [cm^{-2}s^{-1}] = 3 \times 10^8 s_{14}^{0.46} \), between simulated precipitating broadband electron number flux \( F_N \) and downward flowing AC Poynting flux follows from empirical relations between electron energy flux and AC Poynting flux \( (F_E = 2S_{0.5}) \) derived from Polar satellite data and between electron energy flux, number flux and AC Poynting flux \( (F_N = 2.4 \times 10^8 F_E^{1/3} s_{20}^{0.29}) \) derived from FAST satellite measurements. The average energy of precipitating soft electrons is defined as \( F_E/F_N \). Details of the methodology and validation of the soft electron precipitation models can be found in Zhang [2012].

[9] The CMIT simulation is driven by ideal solar wind and IMF conditions with \( N_{SW} = 5 \, cm^{-3}, V_{SW} = 400 \, km/s, B = 5 \, nT \) and \( F10.7 = 150 \) (SW \( V_\parallel = 0 \) and IMF \( B_x = B_y = 0 \)). The CMIT model is driven by IMF \( B_z = \pm 5 \, nT \) for two hours and then \( B_z = -5 \, nT \) for two hours. The results shown in the next section are derived from the last simulation hour during southward IMF. The initial conditions for TIEGCM are chosen to be March equinox with median solar driving (corresponding to \( F10.7 = 150 \)). Since a point dipole field is used in LFM to represent Earth’s internal magnetic field, the simulated soft electron precipitation patterns are symmetric between the two hemispheres. Therefore, the results shown in the following section are derived from the northern hemisphere.

3. Results and Discussions

[10] The patterns of soft electron number flux are shown in Figure 1a. The simulated one-hour average fluxes of cusp electron precipitation peak at \( 78^\circ \) MLAT, 1200 MLT on the dayside, with an average energy \( (F_N/F_N) \) of approximately 200 eV and an average number flux of \( 7.6 \times 10^8 \, cm^{-2} \, s^{-1} \). The average fluxes of broadband electron precipitation peak at \( 72^\circ \) MLAT, 2100 MLT in the premidnight sector, with an average energy of approximately 410 eV and a number flux of \( 7.7 \times 10^8 \, cm^{-2} \, s^{-1} \).

[11] The direct effect of soft electron precipitation is the enhancement of the F-region electron density. Figure 1b (left) shows the simulated height profiles of electron density calculated at the locations of peak soft electron flux. When the soft electron precipitation models are switched on, the enhancement in F-region peak electron density 1) exceeds 100% at 225 km in the premidnight region of broadband electron precipitation and 2) is approximately 50% greater at 270 km altitude in the dayside cusp region. Since the average energy of precipitating broadband electrons is greater than that of the cusp electrons, the altitude of F-region peak density in the broadband electron precipitation zone is approximately 45 km lower than that in the cusp region. The electron temperature in the F region is also enhanced by soft electron precipitation since precipitating soft electrons directly heat the ambient plasma at F-region altitudes [Fontehin et al., 1987; Vonrat-Reberac et al., 2001]. As shown in Figure 1b (right), above 250 km, the electron temperature is enhanced approximately 19% in the premidnight sector and 5% in the cusp region.

[12] The enhancement of electron density and temperature causes the Pedersen conductivity to increase in the regions where soft electrons precipitate. Figure 1c shows the height profiles of Pedersen conductivity calculated at the locations of peak soft electron fluxes. The height profiles of Pedersen conductivity show a clear response to the precipitating soft electrons. The conductivity is significantly enhanced between 130 to 300 km. In the premidnight auroral sector, the Pedersen conductivity increases approximately 200% near 200 km. Similar enhancements in Pedersen conductivity occur in the cusp region except that the magnitude of the Pedersen conductivity is approximately 5 times lower than that in the premidnight sector in both base and controlled runs.

[13] The enhancement of F-region Pedersen conductivity modifies the altitude distribution of the Joule heating rate in the ionosphere. The controlled simulation shows that in the cusp region, the Joule heating rate per unit mass mainly increases in the F region; in the premidnight region, the Joule heating rate per unit mass increases in both the E region and
region, and the enhancement in the $F$ region is greater than in the $E$ region. Above 150 km, the magnitude of the Joule heating rate increases approximately by a factor of 2 to 3, and the peak Joule heating rate occurs at approximately the same location as the peak electron density.

The electric field is essentially constant throughout the $E$ and $F$ regions because the magnetic field lines are approximately equalpotentials. Therefore, given that the soft electron precipitation has a relatively minor effect ($-12\%$) on the convection electric field and a major effect ($+200\%$) on the Pedersen conductivity in the $F$ region, the Joule heating rate increases in the $F$ region where soft electrons precipitate. As a consequence of enhanced Joule heating in the $F$-region, the neutral temperature also increases. Above 200 km, the neutral temperature increases approximately by 3% in the nightside region of broadband electron precipitation and approximately 5% in the region of cusp electron precipitation (not shown in the figures). The thermospheric mass density is directly influenced by the neutral temperature. Deng et al. [2011] found that the energy deposited in the $F$ region changes the thermospheric neutral density at 400 km. Therefore, the thermospheric neutral density in the $F$-region is expected to be enhanced in CMIT simulations in regions of soft electron precipitation.

Figure 1d shows the simulated averaged ratio of the Joule heating rate per unit mass (i.e., ratio of Joule heating rate with soft electron precipitation to that without soft electron precipitation) and the percentage increase of thermospheric mass density with soft electron precipitation relative to that without. The results show that where cusp electrons precipitate, the $F$-region Joule heating rate per unit mass increases by approximately 50% above 300 km and the maximum Joule heating rate enhancement occurs at approximately 170 km. The increase in Joule heating produces an enhancement in thermospheric neutral density above 200 km. At 400 km, the neutral density enhancement is approximately 25% in the
The Editor thanks Jiuhou Lei and an anonymous reviewer for their component, soft
Acknowledgments. The research was supported by the following driving conditions. The cusp region. In the nightside broadband electron precipitation region, a similar enhancement of both Joule heating and thermospheric mass density occur as well. However, at 400 km, the neutral density enhancement in the premidnight sector is approximately 15%, which is lower than that on the dayside. The difference is mainly due to the fact that the average energy of precipitating broadband electrons is greater than that of the direct-entry cusp electrons.

Figure 2a shows the distribution of percent difference of thermospheric mass density at 400 km. When soft electron precipitation models are switched on, the thermospheric neutral density at 400 km is enhanced approximately 25% in the cusp region and approximately 20% in the premidnight auroral sector. The distributions of the neutral density enhancement and the soft electron precipitation patterns are not identical, owing to the circulation of the thermosphere.

Figure 2b shows the distribution of the percent difference between the thermospheric mass density at 400 km derived from the CHAMP observations and the MSIS90 empirical model [Liu et al., 2005]. The MSIS90 model is capable of reproducing the large-scale structures seen in observations at high latitudes, but it exhibits significant deviations from CHAMP statistical results in the dayside cusp region (30%) and premidnight sector (20%). The difference between the CHAMP measurement and the MSIS90 is not fully understood yet. It is possible that MSIS90 smooths out the high-latitude structures, especially in the narrow cusp region. It is also possible that the difference is a consequence of different sampling periods during a solar cycle for CHAMP and MSIS90. However, it is interesting to notice that when soft electron precipitation models are switched on, CMIT is capable of reproducing the density enhancement structures in Figure 2b. These thermospheric density enhancement structures are seen in the same locations as the intense soft electron precipitation. Therefore, the CMIT simulation might explain, at least partially, the cusp and premidnight differences in thermospheric mass density in the CHAMP-MSIS90 comparison.

Given the differences in the cusp and premidnight thermospheric mass density enhancements in Figure 1, and the different average energies of precipitating cusp electrons (200 eV) and premidnight broadband electrons (410 eV), it seems likely that the average energy of the soft electron precipitation affects the enhancement in thermospheric mass density at 400 km altitude. Numerical experiments show that when the average energy of soft electron precipitation is artificially increased from 200 eV to 2000 eV, with the same energy flux, the electrons precipitate at lower altitude and the enhancement of the F-region electron and neutral temperature decreases. The enhancement of thermospheric mass density also decreases. When the average energy of soft electron precipitation is greater than 800 eV, the thermospheric mass density enhancement at 400 km is almost negligible. This inverse relation between the neutral density enhancement and the average energy of soft electron precipitation is reasonable because when the particles are more energetic, they penetrate deeper in the upper atmosphere [Roble and Ridley, 1987; Millward et al., 1999; Fang et al., 2008].

The results shown in this section are derived from simulations with due southward IMF. When the CMIT model is driven by IMF conditions with a $B_y$ component, soft electron precipitation also occurs in the dayside cusp region and nightside auroral region. Therefore, a similar thermospheric mass density enhancement occurs in the CMIT simulation with IMF $B_y$ driving conditions.

4. Summary

Controlled CMIT simulations show that precipitating soft electrons significantly enhance the F-region thermospheric mass density, both in the cusp and premidnight regions, as observed by the CHAMP satellite. In the regions where soft electron precipitation occurs, F-region ionospheric electron density, temperature and Pedersen conductivity are enhanced. As a consequence, the Joule heating rate per unit mass of the thermosphere is enhanced in the F region by soft electron precipitation, which leads to the thermospheric mass density enhancement.

Acknowledgments. The research was supported by the following projects: NASA grants NNX11AO59G and NNX11AJ10G; NSF grant AGS-1023346 (NSWP); ATM-0120950 (CISM-STC). Computing resources were provided by NCAR under CISL Projects 36761008 and 3761009. B. Zhang and W. Lotko would like to acknowledge the hospitality of the UCAR Advanced Study Program during summer 2011. NCAR is sponsored by the NSF.

The Editor thanks Jiuhou Lei and an anonymous reviewer for their assistance in evaluating this paper.
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