Simulating electron and ion temperature in a global ionosphere thermosphere model: validation and modeling an idealized substorm

Jie Zhu^a, Aaron J. Ridley^a, Yue Deng^b

^aDepartment of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, Michigan, USA.

^bDepartment of Physics, University of Texas, Arlington, USA.

Abstract

Electron and ion temperatures control many chemical and physical processes in the ionosphere-thermosphere system. Recently, improved electron and ion energy equations were implemented in the Global Ionosphere Thermosphere Model (GITM). The source energy of the electron temperature (T_e) include thermal conduction, heating due to photoionization, elastic collisions with ions, elastic and inelastic collisions with neutrals, auroral precipitation, and heat flux from inner magnetosphere. The source terms in the ion temperature (T_i) equation include thermal conduction, and elastic collisions with electrons and neutrals. The new implementation of T_e improved the ionospheric density at middle and high latitudes with respect to IRI. The improved GITM also reproduced the diurnal variation in T_e and T_i observed by incoherent scatter radars at low and middle latitudes. The model was used to investigate an idealized substorm statistically described by Clausen et al. [1]. It was found that the responses of the E-region N_e and T_e were highly correlated with the variation in auroral hemispheric power. The change of the F-region T_e was correlated with the E-region T_e and N_e , which was consistent with observations. The response of the F-region N_e to the particle precipitation was delayed by about 30 minutes, and lasted significantly longer than the enhanced precipitation. The variations of T_i in both the E- and F-regions were dominated by IMF-driven ion drifts through frictional energy coupling with the neutrals. It was also found that the increase of the mid-latitude heat flux by one order of magnitude enhanced T_e , electron density and TEC by up to 120%, 80% and 80% respectively between dusk and midnight.

© 2011 Published by Elsevier Ltd.

Keywords: Electron Temperature, Ion Temperature, Ionosphere

1. Introduction

Electron and ion temperatures strongly affect the ionosphere-thermosphere system because they control many chemical and physical processes [2]; therefore, investigating the temporal and spatial variations of the temperatures is important in understanding the coupled system. It has been widely observed that variations exist in the F-region T_e at low and middle latitudes, which are characterized by a "morning overshoot" [3, 4] and an evening enhancement [5].

*Corresponding author. Fax: +1734 647 3083
Email address: zhjie@umich.edu (Jie Zhu)

These morning and evening enhancements are mainly caused by the photoelectron heating of the low-density thermal electrons at dawn and dusk [6, 7, 8]. The morning peak tends to occur in equinox and winter at high solar activity at Millstone Hill, while the evening enhancement is weaker or absent. At Arecibo, the morning enhancement occurs during all seasons, while the evening enhancement only tends to occur in the equinox and winter seasons [9]. Truhlik et al. [10] found an anti-correlation between the daytime T_e and solar activity at mid-latitudes below 700 km during the equinox and winter, while the nighttime T_e increased with solar activity at low and mid-latitudes at all altitudes. T_e can also be significantly enhanced by heat flux from the plasmasphere in regions with low electron density, especially inside the midlatitude electron density trough [11]. The high-latitude T_e is strongly affected by the polar heat flux and field-aligned current (FAC) [12]. A downward polar heat flux can affect the electron density and temperature near the F-region and above [13]. Upward (Downward) FACs increase (decrease) T_e at altitudes higher than the F-region maximum [14].

Banks [15] suggested a transition behavior of T_i , which increased from the neutral temperature near 250 km towards T_e at higher altitudes. The daytime high-latitude T_i generally tends to be higher in summer than in winter, at solar maximum than at solar minimum, and for active magnetic conditions than for quiet conditions [16]. They also found that an upward heat flow from the lower ionosphere due to the meridional electric fields acts to raise T_i at high altitudes. The high-latitude F-region T_i tends to be enhanced by ion-neutral friction heating during geomagnetic storms, leading to an increase in T_e due to the ion-electron energy transfer [11]. T_i is strongly related to the ion-neutral collision frequencies that affect the heat transfer rates between ions and neutrals. The ion energy equation has been approximated by a balance between the energy exchange and frictional heating with neutrals below 400 km at high latitudes [17].

Efforts have been made in modeling T_e and T_i in the ionosphere since the 1980s. The Time-Dependent Ionosphere Model (TDIM) solves the electron energy equation considering thermal conduction, thermoelectric transport, ion Joule heating, heating due to photoelectrons and auroral electrons, and collisions with the thermal ions and neutrals [12, 18, 19, 13]. The Coupled Thermosphere-Ionosphere-Plasmasphere (CTIP) model solves the time-dependent T_e and T_i for O^+ and H^+ in field-aligned coordinates. The sources terms include heating due to collisional interactions with other species, adiabatic heating/cooling and thermal conductivity [20]. SAMI2 solves similar ion and electron energy equations in field-aligned coordinates with a semi-implicit method [21]. T_e in the Thermosphere-Ionosphere Nested Grid (TING) model and the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE-GCM) is solved assuming a steady state with vertical heat conduction and heating due to photoelectrons and particle precipitation, as well as cooling to ions and neutrals [22, 11].

Since the early 1980s, radar and rocket observations have been used to study the ionospheric dynamics during

substorms [23, 24, 25]. Maehlum et al. [26] found that the F-region electron temperature was correlated with the E-region density based on the EISCAT observations during an intense aurora. They suggested that the F-region could be heated by current driven instabilities associated with intense particle precipitation. Rocket observation showed that the ionospheric electron temperature was significantly higher than that would be due to collisional heating with precipitating particles and it was suggested that some wave-particle interaction contributed the extra heating [27]. The F-region T_i measured by EISCAT UHF-radar was found to be dominated by the local electric field [28]. During the expansion phase of an isolated substorm, both T_e and N_e were strongly enhanced [29]. Although the thermal response of the ionosphere during a substorm has been greatly studied, there have been few studies using global ionosphere thermosphere model to investigate the response of the ionospheric temperatures during substorms. In this study, the Global Ionosphere Thermosphere Model (GITM) with the recently implemented ionospheric temperature model, was used to explore the response of the ionosphere to an idealized substorm [1, 30] and the effect of the topside electron heat flux.

2. Model description

The Global Ionosphere Thermosphere Model is a three-dimensional model that couples the ionosphere-thermosphere system in spherical coordinates [31]. GITM solves the continuity, momentum and energy equations with realistic source terms and a modern advection solver. GITM solves for the full chemical reactions for ion species: $O^+(^4S)$, $O^+(^2D)$, $O^+(^2P)$, O_2^+ , N^+ , N_2^+ and NO^+ . The computational domain spans from ~95 km to 650 km in altitude. The ion momentum equation is solved in steady state with pressure gradient, gravity, neutral wind drag and external electric fields. O^+ is currently advected in GITM since it is the dominant ion in the low collision region of the ionosphere. The dynamo electric field is solved for in a self-consistent way by using the technique of Richmond [32], as described by Vichare et al. [33]. Different models of high-latitude potential and aurora precipitation are allowed in GITM. In this study, the Weimer [34] model was used for the high-latitude electric fields, and the Fuller-Rowell and Evans [35] model was employed for produce the auroral precipitation patterns.

2.1. Electron Temperature

Instead of assuming a steady state electron temperature, as was done in earlier version of GITM, the new model solves for a time-dependent electron energy equation. This allows a (possibly) more precise description of the temporal variations of T_e . If chemical reactions and viscous heating of the electron gas are neglected, the electron energy equation can be expressed as [36]:

$$\frac{3}{2}\kappa n_e \frac{\partial T_e}{\partial t} = -\kappa n_e T_e \nabla \cdot \mathbf{u}_e - \frac{3}{2}N_e \kappa \mathbf{u}_e \cdot \nabla T_e - \nabla \cdot \mathbf{q}_e + \Sigma Q_e, \quad (1)$$

where κ is the Boltzmann constant, n_e is the electron density, T_e is the electron temperature, $\mathbf{u}_e$ is the electron velocity, $\mathbf{q}_e$ is the heat flow vector, t is time and z is altitude. The terms on the right-hand side of Eqn(1) represent (from left to right) the adiabatic expansion, heat advection, and the divergence of the electron heat flow vector respectively. ΣQ_e is the sum of all the local heating and cooling rates, respectively. In this model, the adiabatic heating/cooling is neglected. The heat flow vector is expressed as

$$\mathbf{q}_e = -\chi \mathbf{J}_{\parallel} - \lambda_e \nabla T_e. \quad (2)$$

where χ is the thermoelectric coefficient, $\chi = \frac{5}{2}\kappa T_e/e$ [36] and λ_e is the electron thermal conductivity (given in the Appendix). This model also included the thermoelectric heating along the field lines above 45° Magnetic Latitude. The field aligned current is based on the divergence of the ion and electron flows in the plane perpendicular to the field lines. Considering thermal advection only in the radial direction, the electron energy equation implemented in the new model can be simplified to:

$$\frac{3}{2}\kappa n_e \frac{\partial T_e}{\partial t} = -\frac{3}{2}\kappa n_e u_e \frac{\partial T_e}{\partial r} + Q_{J_{\parallel}} + Q_{conduction} + \Sigma Q_e. \quad (3)$$

where r is the unit vector in the radial direction in the Earth's spherical coordinates. The terms on the right side represent (from left to right) the thermal advection in the radial direction, thermoelectric heating, thermal conduction and the sum of other local heating/cooling sources. The field aligned thermal conduction can be written as:

$$Q_{conduction} = \frac{\partial}{\partial s}(\lambda_e \frac{\partial T_e}{\partial s}) = \lambda_e \frac{\partial^2 T_e}{\partial s^2} + \frac{\partial \lambda_e}{\partial s} \frac{\partial T_e}{\partial s} \quad (4)$$

Since the electron thermal conduction primarily occurs along magnetic field lines [12], there has been no global ionosphere thermosphere model that includes the thermal conduction perpendicular to field lines, to the authors' knowledge. In this model, thermal conduction both along and perpendicular to the field lines are implemented. Projecting the field-aligned conduction to spherical coordinates gives:

$$\begin{aligned}
Q_{conduction} = & \sin^2 \alpha (\lambda_e \frac{\partial^2 T_e}{\partial r^2} + \frac{\partial T_e}{\partial r} \frac{\partial \lambda_e}{\partial r}) \\
& + \lambda_e \cos^2 \alpha (\frac{1}{r^2} \cos^2 \beta \frac{\partial^2 T_e}{\partial \theta^2} + \frac{\sin^2 \beta}{r^2 \cos^2 \theta} \frac{\partial^2 T_e}{\partial \phi^2} + \frac{2 \sin \beta \cos \beta}{r^2 \cos \theta} \frac{\partial^2 T_e}{\partial \theta \partial \phi} - \frac{\sin \beta \cos \beta \sin \theta}{r^2 \cos^2 \theta} \frac{\partial T_e}{\partial \phi}) \\
& + \cos^2 \alpha (\cos^2 \beta \frac{1}{r^2} \frac{\partial \lambda_e}{\partial \theta} \frac{\partial T_e}{\partial \theta} + \sin^2 \beta \frac{1}{r^2 \cos^2 \theta} \frac{\partial \lambda_e}{\partial \phi} \frac{\partial T_e}{\partial \phi} + \sin \beta \cos \beta \frac{1}{r^2 \cos \theta} (\frac{\partial \lambda_e}{\partial \theta} \frac{\partial T_e}{\partial \phi} + \frac{\partial \lambda_e}{\partial \phi} \frac{\partial T_e}{\partial \theta})) \\
& + \sin \alpha \cos \alpha \cos \beta \frac{1}{r} (\frac{\partial T_e}{\partial \theta} \frac{\partial \lambda_e}{\partial r} + \frac{\partial T_e}{\partial r} \frac{\partial \lambda_e}{\partial \theta}) + \sin \alpha \cos \alpha \sin \beta \frac{1}{r \cos \theta} (\frac{\partial T_e}{\partial \phi} \frac{\partial \lambda_e}{\partial r} + \frac{\partial T_e}{\partial r} \frac{\partial \lambda_e}{\partial \phi}),
\end{aligned} \tag{5}$$

where α and β are the magnetic dip and declination angle, respectively. θ and ϕ are the latitude and longitude in the Earth's spherical coordinates, respectively. The cross terms between the radial direction and the horizontal plane, i.e., the last two terms in Eqn(5), were ignored for simplicity.

Considering the field-aligned currents are prominent in high latitudes, the heating/cooling due to field-aligned current as considered above 45° Magnetic Latitude. The field aligned current $J_{//}$ was calculated as:

$$J_{//} = \int_{r_0}^{r_1} \nabla \cdot J_{\perp}, \tag{6}$$

where r_0 and r_1 are the lower and upper boundary of the ionosphere, respectively. $J_{\perp}$ is the current perpendicular to the field lines, and $J_{\perp} = n_e |e| (u_{i\perp} - u_{e\perp})$. Assuming the field aligned current is mainly contributed by electron flow and using the relation $J_{//} = -n_e |e| u_e$, the thermal advection term as expressed as a function of $J_{//}$:

$$-\frac{3}{2} \kappa n_e u_e \frac{\partial T_e}{\partial r} = \frac{3}{2} \kappa \frac{J_{//}}{|e|} \frac{\partial T_e}{\partial r}, \tag{7}$$

and was included above 45° Magnetic Latitude.

The local heating/cooling rates are given by:

$$\Sigma Q_e = Q_{phe} + Q_{auro} + Q_{ei} + [Q_{en}]_{elas} + [Q_{en}]_{inelas}, \tag{8}$$

where Q_{phe} is heating due to photoelectrons, Q_{auro} is heating due to auroral ionization, Q_{ei} is the heat transfer between electrons and ions due to elastic collisions, and $[Q_{en}]_{elas}$ and $[Q_{en}]_{inelas}$ represent cooling rates due elastic and inelastic collisions with neutrals. The new model adds cooling due to elastic collisions with neutrals and heating due to auroral ionization, and calculates the photoelectron heating using an improved parameterization model of photoelectron heating efficiency described by Smithtro and Solomon [37], which allows for a change in the heating efficiency as a function of altitude due to the changing of the ratio between the electron and neutral densities. The photoelectron heating can be expressed as:

$$Q_{phe} = \epsilon P_{photo}, \quad (9)$$

where ϵ is a thermal electron heating efficiency and P_{photo} is the local photoionization rate [38]. The heating efficiency is specified by an improved parameterization derived by Smithtro and Solomon [37]:

$$\epsilon = \exp(5.342 + 1.056x - 4.392 \times 10^{-2}x^2 - 5.900 \times 10^{-2}x^3 - 9.346 \times 10^{-3}x^4 - 5.755 \times 10^{-4}x^5 - 1.249 \times 10^{-5}x^6), \quad (10)$$

where

$$x = \ln(R), \quad R = \frac{n_e}{n(N_2) + n(O_2) + n(O)}. \quad (11)$$

This parameterization performs over a wide altitude range of ~ 100 km to ~ 750 km [39, 40]. The domain of GITM, from ~ 90 km to ~ 700 km, is basically within its applicable range. The maximum of the ratio R in Eqn(11) is limited to 10 in the model, which rarely, if ever, actually happens, even at high solar activity. The auroral heating rate is expressed as

$$Q_{auro} = \epsilon P_{auro}, \quad (12)$$

where P_{auro} is the auroral ionization rate, and the heating efficiency ϵ is the same as shown in Eqn(10).

The heat transfer due to elastic collisions with ions is given by:

$$Q_{ei} = 3kn_e m_e \sum_t \nu_{et} \frac{(T_i - T_e)}{m_e + m_t}, \quad (13)$$

where m_e is the electron mass, and T_i is the ion temperature (note that GITM only has a single bulk ion temperature).

The coulomb collision frequency (ν_{et}) between electrons and ion species t is given in Appendix A.

The heating term due to collisions with neutrals consists of two parts: elastic collisions and inelastic collisions.

The elastic collision term is given by:

$$[Q_{en}]_{elas} = 3kn_e m_e \sum_s \nu_{es} \frac{T_n - T_e}{m_e + m_s}, \quad (14)$$

where T_n is the neutral temperature and ν_{es} is the collision frequency between electrons and neutral species s and is given in Appendix A. This elastic collision term is almost always a cooling term, due to the fact that the neutrals are almost always cooler than the electrons. The corresponding heating rate for neutrals due to elastic collisions with

electrons is a source term in the neutral energy equation.

The inelastic collision term is given by:

$$[Q_{en}]_{inelas} = L_e(N_2)_{rot} + L_e(O_2)_{rot} + L_e(N_2)_{vib} + L_e(O_2)_{vib} + L_e(O)_{fine} + L_e(O(^1D)), \quad (15)$$

where $L_e(N_2)_{rot}$ and $L_e(O_2)_{rot}$ are the cooling rates due to the rotational excitation of the molecular neutrals N_2 and O_2 , $L_e(N_2)_{vib}$ and $L_e(O_2)_{vib}$ are due to vibrational excitation of N_2 and O_2 , $L_e(O)_{fine}$ and $L_e(O(^1D))$ are due to the fine structure and the excitation of atomic oxygen to the $O(^1D)$ state (given in Appendix A).

2.2. Ion Temperature

The old T_i calculation in GITM was based on a statistical formula assuming a balance between the neutral energy exchange term and the neutral frictional heating term [17]. In the new model, the physical ion energy equation including thermal diffusion and collisional heat transfer between the ions and the electrons and neutrals is implemented. All the ion species sharing the same grid volume are assumed to have the same temperature. The ion temperature equation can be expressed as:

$$\frac{3}{2} \kappa n_i \frac{\partial T_i}{\partial t} = -\kappa n_i T_i \nabla \cdot \mathbf{u}_i - \frac{3}{2} N_i \kappa \mathbf{u}_i \cdot \nabla T_i - \nabla \cdot \mathbf{q}_i + \Sigma Q_i. \quad (16)$$

In GITM, the adiabatic expansion and heat advection were neglected. Also, considering field-aligned currents were mainly driven by electron motion, the thermoelectric heating was ignored in GITM. Thus, the heat flow vector $\mathbf{q}_i$ is:

$$\mathbf{q}_i = -\lambda_i \nabla T_i, \quad (17)$$

where λ_i is the ion thermal conductivity given in Appendix B.

Similar to electrons, the ion thermal conduction was considered along the magnetic field, both in the vertical and horizontal directions. With these assumptions, the ion energy equation can be written as:

$$\frac{3}{2} \kappa n_i \frac{\partial T_i}{\partial t} = Q_{conduction} + \Sigma Q_i. \quad (18)$$

where n_i is the total ion density (equal to the electron density) and T_i is the ion temperature. The ion thermal conduction is in the same format as the electron thermal conduction in Eqn (5). Q_i represents the total local ion heating/cooling rate, which is the sum of the heat transfer due to collisions with electrons and with neutrals.

The elastic collisional heating of the ions by the electrons is:

$$Q_{ie} = 3\kappa \sum_t \frac{n_t m_t v_{te}}{m_t + m_e} (T_e - T_i), \quad (19)$$

156 where the subscript t refers to the ion species. Given that the collision frequencies satisfy the relationship [2]:

$$n_t m_t v_{te} = n_e m_e v_{et}, \quad (20)$$

157 Q_{ie} can be further expressed as

$$Q_{ie} = 3n_e m_e \kappa (T_e - T_i) \sum_t \frac{v_{et}}{m_e + m_t}. \quad (21)$$

158 The heating term accounting for collisions with neutrals consists of two parts: collisional heat transfer and fric-
159 tional heating:

$$Q_{in} = \sum_t n_t m_t \sum_k \frac{v_{tk} [3\kappa (T_n - T_i) + m_k (u_n - u_i)^2]}{m_t + m_k} \quad (22)$$

160 where n_t and m_t are the number density and mass of ion species t , u_n and u_i are the neutral and ion velocities, and the
161 subscripts t and k denotes the ion and neutral species respectively. The ion-neutral collision frequencies are given in
162 Appendix B. The corresponding heating rate for the neutrals due to collisions with the ions was added to the heating
163 sources in the neutral energy equation.

164 2.3. Numerical Method

165 The energy equations are solved using a semi-implicit method, which was described by Huba and Joyce [21].
166 Schematically, the model uses the backward difference at the current time t^n and second-order central difference for
167 the spatial derivative at altitude z_j in the conduction calculation at t^n . Each source term with a linear dependence on
168 the temperature is split into two parts, one with a linear dependence on the variable T_j^n being solved, and the other
169 without the linear dependence. The linear terms are evaluated at t^n , while the other terms are evaluated at the previous
170 time step t^{n-1} . This semi-implicit method performs well in limiting the stiff source terms, and is numerical stable and
171 convergent.

172 Both T_e and T_i are set equal to the neutral temperature at the bottom boundary. T_e has a heat flux boundary at the
173 top, such that:

$$\frac{T_j^n - T_{j-1}^n}{\delta z} = \frac{F_e}{\lambda_e}, \quad (23)$$

where F_e is the heat flux rate. The upper boundary of T_i is set as a constant gradient boundary condition (i.e., only local source terms and no heat flux):

$$\left(\frac{\partial T^n}{\partial z}\right)_j = \left(\frac{\partial T^n}{\partial z}\right)_{j-1}. \quad (24)$$

Table 1 and 2 present a comparison of the implementation of T_e and T_i between the old and new model. Four advantages of the new model include: (a) it is capable of simulating T_e stably using the same time step as the thermosphere (1-3s); (b) it incorporates the thermoelectric heating in a global I-T model for the first time; (c) it incorporates the horizontal component of the heat conduction along the field lines for T_e and T_i ; (d) it allows energy coupling self-consistently between electrons, ions and neutrals.

Table 1. Comparison of T_e Calculation between New and Old Methods

Sources(Method) \ Model	NEW	OLD
Time Derivative	✓	×
Vertical Conduction	✓	✓
Horizontal Conduction	✓	×
Photoelectron Heating	✓	✓
Auroral Ionization Heating	✓	×
Electron-Ion Collisional Heating	✓	✓
Electron-Neutral Elastic Collisional Heating	✓	×
Electron-Neutral Inelastic Collisional Heating	✓	✓
Thermoelectric Heating	✓	×
Magnetospheric Heat Flux	✓	✓
Two-way Coupling with Ions	✓	×
Two-way Coupling with Neutrals	✓	×
Scheme for Vertical Conduction	Implicit	Implicit
Scheme for Other Source Terms	Implicit	Explicit

Table 2. Comparison of T_i Calculation between New and Old Methods

Sources(Method) \ Model	NEW	OLD
Time Derivative	✓	×
Vertical Conduction	✓	×
Horizontal Conduction	✓	×
Ion-Electron Collisional Heating	✓	×
Ion-Neutral Elastic Collisional Heating	✓	✓
Two-way Coupling with Electrons	✓	×
Two-way Coupling with Neutrals	✓	✓
Scheme	Implicit	Steady-State

3. Validation with IRI

Figure 1 shows comparisons of N_e (top), T_e (middle) and T_i (bottom) using the old model (left), the new model (middle) and the International Reference Ionosphere (IRI) model [41] (right) at an altitude of 400 km at 00:00 UT on Dec 23, 2012. The simulation was driven by a constant $F_{10.7}$ index of 110.3 and constant solar wind conditions: $V_x = 400$ km/s and $B_x = 0$ nT, $B_y = 0$ nT and $B_z = -2$ nT. The T_e produced by the new model was significantly larger than the previous model, especially in the middle and high latitudes on the dayside. Moreover, due to an increase in the ionospheric scale height and a decrease of recombination rates, the magnitude of the ion density in the new model was also increased and had a better agreement with that in IRI. However, the general distributions of the ion densities were similar between the previous and the improved model. The new model reproduced the diurnal variation in the F-region T_e at low latitudes, which was characterized by a morning and an evening enhancement. The morning peaks were more pronounced in the winter hemisphere than in the summer hemisphere in both the new model and in IRI, which agrees with Oyama et al. [4]. Compared to IRI, the morning enhancement of the new T_e was approximately 500 K cooler and had a narrower zonal extension at low latitudes. Both the new GITM and IRI show a cooler region of T_e in the dayside equatorial region. This feature was caused the inverse correlation between T_e and N_e in the F-region [42, 43]. Specifically, the cooling of the electrons exceeds the photoionization heating when N_e increases to a certain level [44]. T_i in the new model was higher than it was in the old model in both the dayside middle and high latitude regions. The ion Joule heating effect was enhanced in the polar regions in the new model. The new T_i has a similar magnitude as IRI on the low-latitude dayside and the south polar region, but was about 500 K cooler in the north polar region. The difference in T_i between the south and north polar regions in GITM was due to the seasonal effect, i.e., the asymmetric solar insolation and geomagnetic forcing [45]. There was more N_e in IRI in the northern polar region than in GITM, which would cause a difference in the Joule Heating rate and T_i .

Figure 2 shows a comparison of electron density (top), electron temperature (middle) and ion temperature (bottom) between the old GITM (left), the new GITM (middle) and IRI (right) at a longitudinal slice of 180° at 00 UT (i.e., at noon local time). In both the new GITM and IRI, a region filled with denser and cooler electrons existed at low latitudes. However, the topside ionosphere in the new GITM was approximately 500 K cooler than in IRI in this region. This was due to the inverse relation between T_e and N_e : a denser ionosphere existed above 400 km in GITM. Once again, the ion density in the improved model was raised to a more comparable value to IRI due to the increase in T_e . The distribution of T_i in GITM and IRI look very consistent except for the northern polar region, which could be due to the difference in N_e , thus causing a difference in Joule heating and T_i in this region between the two models.

4. Validation with Incoherent Scatter Radars

A time period from April 13th and 14th, 2013 was simulated with the new model when observations from four incoherent scatter radar (ISR) sites were available. The four ISR sites were Arecibo (18.4°N, 66.6°W), Jicamarca ISR (11.9°S, 76.8°W), Millstone Hill ISR (40.6°N, 71.5°W) and Sondrestrom ISR (67.0°N, 50.7°W). ISRs are capable of measuring the altitudinal profiles of electron density, electron temperature, and ion temperature, to heights of several hundred kilometers by detecting the incoherent backscatter from free electrons in the ionosphere [46]. The simulation was driven by the hemispheric power (HP) obtained by the National Oceanic and Atmospheric Administration (NOAA) POES satellites, as well as the solar wind and interplanetary magnetic field data measured by the Advanced Composition Explorer (ACE), delayed by an appropriate amount of time. The IMF, hemispheric power, and solar wind velocity for April 13 and 14, 2013 are shown in Figure 3. The geomagnetic condition was relatively quiet on April 13th, 2013, with hemispheric power less than 10 GW most of the day, solar wind speed about 400 km/s and the magnitude of IMF below 5 nT. On April 14, the hemispheric power and solar wind speed increased to about 40 GW and to about 500 km/s early in the day. Both B_y and B_z turned more positive with larger variability. The $F_{10.7}$ indexes were 125 and 117 on April 13th and 14th, respectively. Figure 4 shows the electron heat flux pattern at the top boundary at 12:00 UT. This pattern was fixed in solar magnetic coordinates but moved in geographic coordinates through the day [31]. The pattern was constructed based on the modeled energy deposition rates from the ring current into the ionospheric thermal electrons during the June 1991 storm [47].

Figure 5 shows a comparison between GITM, IRI and measurement by the Arecibo ISR from 100 km to 650 km on April 13th and 14th, 2013. The missing data in the observations were filled by an altitudinal linear interpolation. GITM reproduced the diurnal variation of T_e observed by the ISR, but with a weaker morning peak. In both GITM and the ISR data, the morning enhancement occurred at the same local time at all altitudes. However, the local time of the morning enhancement varied with altitudes in IRI. The T_e in IRI was about 500 K higher than GITM and the ISR data. GITM, IRI and the ISR data had a similar diurnal variation of T_i below 400 km: T_i began to raise around 6 LT, peaked around 16 UT and decreased to the nightside temperature around 20 LT. Above 500 km, GITM underestimated T_i by about 300 K compared to IRI and the ISR data. Also, a distinct morning enhancement in T_i was present in GITM, but not IRI or the ISR data.

A comparison between GITM, IRI and the Jicamarca ISR on April 13, 2013 is shown in Figure 6. A morning enhancement in T_e existed between 300 km and 500 km in GITM, ISI and ISR. However, the morning enhancement in IRI was about 500 K cooler than GITM and the ISR data. Also, the morning enhancement occurred approximately at the same local time throughout the altitudes in GITM. In IRI, it occurred earlier at higher altitudes, which was opposite of the ISR observation. There were scattered structures of enhanced T_e on the nightside in the observations, which were

not shown in GITM and IRI. This could be equatorial ionospheric perturbations caused by physics that may not be included in the models, or uncertainty in the measurements. The dayside ion temperatures were comparable between the models and the observation. Similar to T_e , structures of high T_i on the nightside were measured by the radar, but were not present in the GITM or IRI.

T_e in the F-region highly depends on the downward electron heat flux from the magnetosphere throughout the mid- and high-latitudes [12, 48, 13]. Two simulations with different heat fluxes specified were conducted to compare the model with mid-latitude observations by the Millstone Hill ISR. Figure 7 shows the diurnal pattern of the heat flux: the small (left y-axis) and large (right y-axis) share the same pattern but with a one order of magnitude difference. The large heat flux was closer to a realistic value of 10^{-5} W m^{-2} [48]. Figure 8 shows the GITM results driven by the small and large electron heat fluxes, with comparison to IRI and the Millstone Hill ISR measurements. The time shown is from 16-24 Local Time, which is from the dashed line to the end of the day in Figure 7. Before about 22 LT, the observed T_e was approximately 1000 K higher than GITM driven by the small heat flux above 400 km. The ion temperature was also underestimated by about 500 K above 400 km compared to IRI and the ISR data. T_e in IRI had a similar magnitude as observation above 400 km, but was about 1000 K warmer below.

Driven by the large heat flux, the dayside T_e increased significantly above 400 km, which significantly improved the comparison with the observation compared to the small-flux case. Moreover, T_i was raised to a similar magnitude as observed by the radar through the heat transfer between electrons and ions. This was especially true at high altitudes, where the collisional heating between electrons and ions is more important. Since a simple empirical heat flux model was used in this simulation, differences between GITM and ISR results can be expected. In order to simulate both T_e and T_i at mid-latitudes, a well-specified electron heat flux at the top is needed.

Finally, a comparison between GITM, IRI and the Sondrestrom ISR is shown in Figure 9. The heat flux at this location was a constant small value of 10^{-9} W m^{-2} as shown in Figure 4. T_e in GITM was smaller than IRI and the ISR data, which could be caused by a few reasons: an underestimation in the driver of particle precipitation, or the fact that the top heat flux specified in the simulation was too low. T_i in GITM agreed pretty well with IRI: the T_i above 450 km was about 500 K higher than the T_i below. However, both GITM and IRI underestimated T_i around midnight. This could have been caused by not capturing the ion frictional heating term well, which could arise from a non-precise description of the ion or neutral flows in GITM [49]. An underestimation of T_e could also lead to a lower value of T_i , since energy from the electrons flows to the ions through the temperature difference. Further study is needed to determine the high-latitude drivers of the ionospheric temperatures.

5. Ionospheric temperature response to an idealized substorm

GITM with the improved electron and ion energy equations was used to investigate the ionospheric response to an idealized substorm, which was the same as Substorm 4 investigated by Liu and Ridley [30]. The prototypical substorm was constructed based on the superposed epoch variations of IMF B_z and HP during substorms using 5-years of Challenging Minisatellite Payload (CHAMP) [50] satellite data [1]. The geomagnetic conditions used for the simulation are shown in Figure 10. B_z began to decrease at 1 hour before onset, reached a minimum of -3 nT at -25 min, and recovered to the initial value of zero at 80 minute. The background HP was 20 GW. It steadily increased after substorm onset, peaked at 55 GW at 20 min, and recovered to 20 GW at 2 hours epoch time.

In order to explore the effects of just the substorm, two simulations were conducted: one using the idealized substorm input as shown in Figure 10, termed Simulation 1, and the other using constant geomagnetic conditions with $B_z=0$ nT and HP=20 GW, termed Simulation 0. The response to the substorm was expressed as the percentage difference between the two simulations:

$$T\% = \frac{T_1 - T_0}{T_0} \times 100\%, \quad (25)$$

where T_1 is a specific ionospheric/thermospheric parameter in Simulation 1 and T_0 is the parameter in Simulation 0. Figure 11 shows the ionospheric response to the substorm at 140 km geometrically averaged over the northern polar cap (i.e., above 50° Latitude). N_e had an immediate response to the HP variation due to the small time scale of the E region (i.e., in seconds). The response of T_e was highly correlated with the HP, with a cross correlation of 0.99, because the auroral ionization heating was the dominant source for T_e and the time scale of the E-region T_e modification was small ($\sim$ s). The percentage change of T_e peaked around 4% when the HP reached its maximum value. There was a small enhancement that appeared in T_e before the substorm onset. This was due to the ion-electron energy transfer during the growth phase of the substorm. Different than T_e , T_i started to respond during the growth phase of the substorm when the IMF B_z turned southward. The percentage difference of T_i peaked at 3% around the same time when B_z became most southward. The IMF-driven electric field was calculated as [51]:

$$E_{IMF} = V_s B_s \sin(\theta/2), \quad (26)$$

where V_s is the solar wind speed in the sunward direction, $B_s = (B_y^2 + B_z^2)^{1/2}$, and θ is the angle between the two components of the IMF, B_y and B_z . The response of T_i and the square of IMF electric field were highly correlated with a correlation coefficient of 0.97. This was because ions in the high-latitude E-region were in a quasi-energy balance with neutrals [28]. With this assumption, T_i can be approximated as [2, 17]:

$$T_i = T_n + \frac{m_n}{3k}(\mathbf{u}_n - \mathbf{u}_i)^2. \quad (27)$$

The estimated T_i was dependent on the neutral temperature and the difference in bulk velocity between the ions and neutrals. The responding profiles of the estimated T_i and the simulated T_i had a high correlation of 0.99. The estimated T_i was always cooler than the simulated T_i because the energy balance assumption was not completely accurate for ions in the E region where electrons were sufficiently dense to affect the ion temperature through heat transfer. The temporal profile of T_i variation was quite similar to the variation of δV^2 , which is $(\mathbf{u}_n - \mathbf{u}_i)^2$. This indicates that the velocity difference between the ions and neutrals, which represents the ion-neutral collisional heating, was the dominant heat source for ions during the substorm. As shown in the bottom panel in Figure 11, the variation of the velocity difference was controlled by the IMF-induced electric field. This was expected because the IMF electric field driver changed the ion drift significantly, while the neutral winds did not change much during the substorm [52]. During the recovery phase of the substorm (i.e., about 60 min), the neutrals started to ramp up [30] affecting the velocity difference and altering T_i .

Figure 12 shows the spatial variation of the ionospheric response at 6 times around the substorm onset. The leftmost column shows the background ionospheric state 60 min before the substorm onset, while the after plots show perturbations of the state variables with respect to Simulation 0. The perturbation in N_e was relatively small until after the substorm onset. N_e was enhanced by $\sim 100\%$ within the auroral oval when the HP reached maximum value. The red bands on the inner and outer boundaries were due to an expansion of the auroral oval and a low N_e background in these regions. Similar to N_e , T_e did not show noticeable perturbation until the HP increased when the auroral heating increased T_e by about 25% in the auroral oval. The perturbation in T_i started during the growth phase of the substorm as a response to the southward turning of IMF. The maximum enhancement occurred in the low-latitude convection zone, where large shears existed between the day-to-night neutral wind and the sunward ion flows. The perturbation died down before the onset time when B_z recovered.

Figure 13 shows the ionospheric response at 300 km in the same format as Figure 11. The response of N_e at 300 km was relatively sluggish compared to the response at 140 km. The cross correlation between HP and the N_e perturbation peaked at 0.78 with a time delay of 30 minutes. This is because $\sim \text{keV}$ precipitating electrons mainly deposited their energy in the E-region [53]. Three factors could account for the enhancement of N_e in the F-region: (a) an increase of T_e led to a decrease in the dissociative recombination rate, which is discussed in detail below; (b) plasma was transported from the E-region due to diffusion along the magnetic field; (c) the lower energy precipitating particles in the distribution caused some ionization in the F-region. Further investigation is needed to determine how these processes combine to influence the response of the F-region. However, the relatively large chemical time scale

of the ions in the F-region led to a long production and life time of the electron density perturbation in the F-region.

As shown in the second panel in Figure 13, the response of T_e was in phase with the variation of the HP, which suggested that a major source of T_e in the F region was heat conducted from the E region since there was little auroral heating in the F-region. The fact that the F-region temperature was highly correlated with the E-region density instead of the F-region density was also observed by Maehlum et al. [26] and Wahlund et al. [54] during an intense aurora observed by EISCAT. A slightly negative perturbation of T_e occurred between 1 hour and 4 hour epoch time. What probably happened was that the heat conduction was into the F-region during the first part of the substorm and then out of the F-region during the second part of the substorm.

The estimate T_i was quite similar to the simulated T_i during the substorm, which indicates that the electron-ion heat transfer was negligible in the high-latitude F-region [2], and that the ion-neutral coupling was the dominant process. The major heat source to T_i was ion Joule heating and the major cooling term was heat transfer to neutrals. Before the substorm onset, the ion Joule heating driven by the IMF electric field primarily contributed to the enhancement of T_i . After 0 hour epoch time, the neutral temperature gradually increased, which reduced the speed of the cooling process of T_i . A slight difference between the simulated and estimate T_i appeared between 0 and 1.5 hours because the electron-ion heat transfer was enhanced due to an increase in N_e and T_e after the substorm onset.

Figure 14 shows the spatial distribution of the F-region ionospheric perturbation in the same format as Figure 12. A prominent increase in N_e appeared after HP reached a maximum. At 60 min, a perturbation of about 100% existed around the auroral oval, as well as a bright band of about 300% on the outer boundary. The width of the perturbed region was about 4 times the width of the background auroral oval, similar to what was observed in the E-region. The F-region perturbation lasted for more than 2 hours due to relatively slow charge exchange and recombination rates. The response of T_e in the F-region was similar to the E-region. The percentage change in T_e reached about 30% in the main oval and around the high-latitude boundary of the auroral oval, and about 60% near the low-latitude boundary of the auroral oval when HP peaked at 20 min. The response of T_i maximized at -25 min when the IMF was most southward. The ion temperature then gradually died down after the peak.

6. Heat flux effect

In order to investigate the influence of the electron heat flux on the ionosphere, two simulations of the idealized substorm (as shown in Figure 10) were conducted, one with a small heat flux and one with a large heat flux during the substorm. The heat flux distributions were the same, but the large heat flux was one order of magnitude larger than the smaller heat flux, as shown in Figure 4. Figure 15 shows the ionospheric response to the two different heat fluxes. The increased heat flux was most effective on increasing T_e on the nightside in the mid-latitudes where N_e

was approximately 100 times smaller than on the dayside. T_e was enhanced by $\sim 100\%$ at maximum in the dusk and midnight regions. No obvious enhancement in T_e existed on the dayside. The increase in the heat flux also raised N_e and TEC, especially on the nightside. The enhancement in the electron density reached $\sim 80\%$ at maximum, but occurred in the region in which the density was very low.

Figure 16 shows vertical profiles of T_e (left) and N_e (right) at 150° Lon and 55° Lat at 1200 UT (i.e., 2200 LT), which is in the middle of the electron heat flux region on the nightside. The dotted and the solid lines represent the simulation results with the small and large heat fluxes, respectively. The increase in the heat flux raised T_e above approximately 140 km. The enhancement increased with altitude, and reached over 1000 K at 600 km. N_e was also increased above 140 km. The enhancement in N_e due to the increase in the heat flux was about $3 \times 10^9 \text{ m}^{-3}$ ($\sim 60\%$) above 230 km. This result agreed well with David et al. [13].

The fact that the increase in the heat flux increased N_e was due to the combination of three factors in the ionosphere [2]:

1. An increase in T_e can increase the ionospheric scale height, which reduces the exponential decrease of N_e with altitude above the F-region peak.
2. An increase in T_e can raise T_i through the electron-ion collisional heat transfer. The increase of T_i accelerates the charge exchange ratio between O^+ and molecular neutrals N_2 , O_2 and NO . As the dissociative recombination rates of the resulting molecular ions are approximately five orders of magnitude faster than the radiative recombination rates of O^+ , the increase in T_e could result in a decrease of N_e by raising T_i .
3. The radiative and dissociative recombination rates of atomic and molecular ion, respectively, are inversely proportional to T_e . Therefore, an increase of T_e could lead to an increase of N_e by reducing the recombination rates.

Here, a simple calculation was done to determine the net effect of changing either the electron or ion temperature on the F-region density due to the charge exchange and dissociative recombination reactions. All the other ionospheric processes, such as transport and photoionization, were ignored.

Three charge exchange reactions were considered:

where the reaction rates κ_1 , κ_2 , and κ_3 are T_i dependent, and given in Appendix C. Two dissociative recombination reactions and the O^+ radiative recombination reaction were considered:

where the reaction rates κ_4 , κ_5 , κ_6 are T_e dependent, and given in Appendix C. The initial ion densities (in m^{-3}) were set as: $n(O^+) = 1.0 \times 10^{12}$, $n(NO^+) = 0.0$ and $n(O_2^+) = 0.0$. The initial neutral densities (in m^{-3}) were set as $n(NO) = 1.0 \times 10^{10}$, $n(O_2) = 1.0 \times 10^{11}$ and $n(N_2) = 1.0 \times 10^{12}$. The background O^+ number density and neutral densities were typical F-region values from the simulation. Two steps were taken: (a) the charge exchange reactions were processed for one second, converting O^+ to NO^+ and O_2^+ ; and (b) the recombination reactions were then processed for one second. The ion loss rate was obtained by subtracting the initial total ion density from the final total ion density. The calculation was conducted in the range of: $T_e \sim [1000 \text{ K}, 6000 \text{ K}]$ and $T_i \sim [1000 \text{ K}, 3000 \text{ K}]$. The loss rate was normalized at the state of $T_e = 1000 \text{ K}$ and $T_i = 1000 \text{ K}$, as given in Figure 17. The highest ion loss rate existed in the up left corner (i.e., ion temperature much larger than electron temperature), where both the charge exchange rates were most enhanced but the dissociative recombination rates were most reduced. This could happen in regions with strong Joule heating, raising T_i even higher than T_e [44, 12]. A strong decrease in ion density would be expected in such a region. Likewise, the lowest ion loss rate occurred in the lower right corner (i.e., electron temperature much larger than ion temperature), where the charge exchange rates were mostly suppressed, but the dissociative recombination rates were enhanced. This circumstance can be expected in regions with strong downward electron heat flux [13] or upward field-aligned currents, where T_e could be significantly increased [12, 14]. The GITM simulation results shown in Figure 16 showed a positive relationship between T_e and N_e , which indicates that the effects of T_e on N_e caused by the change of the dissociative recombination rates (and the change of the ionospheric scale height) were dominant over the change of the charge exchange rates.

7. Summary and Conclusion

The improvement of the electron and ion temperature calculation in the Global Ionosphere Thermosphere Model has been described in this paper. Time-dependent energy equations for T_e and T_i with heating and cooling rates, as well as field-aligned thermal conduction were implemented. The sources of energy in the electron equation include heating due to photoionization and ionization due to particle precipitation, elastic collisions with ions, elastic and inelastic collisions with neutrals, as well as energy flux from the ring current/plasmasphere interaction. The sources of the ion temperature equation include elastic collisions with electrons and neutrals as well as frictional heating with neutrals.

The new GITM produced higher T_e and T_i at middle and high latitudes than the old model, which led to a denser ionosphere that was more comparable to the ionosphere in IRI. The new GITM reproduced the global structure of T_e observed in IRI including morning and evening enhancements at low and mid-latitudes. An expected anti-correlation between T_e and N_e was also observed in the new model. The temporal variations of the vertical distribution of T_e and T_i were similar to the Arecibo ISR observations. Compared to the observations by the Jicamarca ISR, GITM generally captured the magnitudes and the diurnal variations of T_e and T_i , but missed the small-scale structures on the nightside. It was also found that the mid-latitude T_e and T_i were strongly related to the electron heat flux. GITM needed a larger, more realistic heat flux input at the top boundary in order to reproduce similar magnitudes of T_e and T_i compared to the Millstone ISR observations. GITM also reproduced the general variations observed by the Sondrestrom ISR, but underestimated T_e and T_i , which was probably due to the lack of the heat flux in the auroral oval in the model and a lack of proper electric field description to capture the realistic frictional heating.

The ionospheric response to an idealized substorm was investigated using the new version of GITM. The variation in N_e and T_e in the E-region were highly correlated with the variation in HP due to rapid auroral ionization processes and the short chemical time scale ($\sim$ s) in this region. T_i began to respond during the growth phase of the substorm when the IMF B_z turned southward. The variation of T_i was mainly controlled by the IMF-driven electric field because the ion Joule heating rate was dependent on the ion velocity and the change of ion drift was mainly driven by the IMF, assuming a relatively steady neutral wind pattern. The response of the F-region T_e was not correlated with the F-region N_e , but was correlated with the E-region T_e and N_e , which is consistent with observations by Maehlum et al. [26] and Wahlund et al. [54]. This was because there was little auroral deposition in the F-region. The electron thermal conduction efficiently and rapidly transported heat from the E-region to the F-region, while the time scale of the electron density variations in the F-region was hours. The variations of the F-region T_i were also dominated by the IMF-driven electric field through the ion flow velocity and the frictional energy coupling with the neutrals.

The increase of the topside heat flux by one order of magnitude in the mid-latitudes raised T_e , N_e and TEC by

Figure 1. Comparisons of electron density (top), electron temperature (mid) and ion temperature (bottom) among the old GITM, the new GITM old and IRI at an altitudinal cut at 400 km at 00:00 UT on Nov 25, 2012.

approximately 120%, 80% and 80% (maximum), respectively in the dusk-to-midnight sector. The influence of the increased heat flux on the nightside penetrated down to about 140 km. The dayside ionosphere did not show significant changes in any of the variables in the increased heat flux region, due to the large electron density. The charge exchange and dissociative recombination reactions, which are T_i and T_e dependent respectively, are the two important chemical processes controlling the loss rate of the F-region ionosphere [2]. High T_e and relatively low T_i tend to reduce the F-region ion loss rate, which can cause the F-region density in the heat flux region to reduce at a slower rate than it would with minimal heat flux.

Appendix A. Source Terms in the Calculation of the Electron Temperature

The electron thermal conductivity λ_e is given by Schunk and Nagy [2]:

$$\lambda_e = \frac{7.7 \times 10^7 T_e^{5/2}}{1 + 3.22 \times 10^8 \frac{T_e^2}{n_e} \sum_n n_n < Q_{en}^{(1)} >}, \quad (\text{A.1})$$

Figure 2. Comparisons of electron density (top), electron temperature (mid) and ion temperature (bottom) among the old GITM, the new GITM and IRI at a longitudinal cut at 180° at 00:00 UT on Nov 25, 2012.

where T_e , n_e and n_n are the electron temperature, electron density and neutral densities, respectively. The densities are in m^{-3} , and λ_e is in $\text{eV m}^{-1}\text{s}^{-1}\text{K}^{-1}$. $\langle Q_{en}^{(1)} \rangle$ is a Maxwellian average of the momentum transfer cross section, which was simplified as $1.0 \times 10^{-20} \text{ m}^2$ for all the neutral species in the model. For the theoretical momentum transfer cross sections for some neutral species (not used here), please refer to [55].

The electron-ion collision frequency is given by Schunk and Nagy [2]:

$$\nu_{et} = 5.45 \times 10^{-5} \frac{n_t Z_t^2}{T_e^{3/2}}, \quad (\text{A.2})$$

where n_t is the number density of ion species t in m^{-3} and Z_t is the particle charge number.

The electron-neutral collision frequencies are given by [56, 57]:

$$\nu_{en}(O) = 8.9 \times 10^{-17} n(O) (1 + 5.7 \times 10^{-4} T_e) T_e^{1/2}, \quad (\text{A.3})$$

Figure 3. Temporal variations of hemispheric power, solar wind velocity V_x , IMF B_y and IMF B_z in GSE coordinates from top to bottom on April 13-14, 2013.

$$v_{en}(N_2) = 2.33 \times 10^{-17} n(N_2) (1 - 1.21 \times 10^{-4} T_e) T_e, \quad (\text{A.4})$$

$$v_{en}(O_2) = 1.82 \times 10^{-16} n(O_2) (1 + 3.6 \times 10^{-2} T_e^{1/2}) T_e^{1/2}, \quad (\text{A.5})$$

where $n(O)$, $n(N_2)$ and $n(O_2)$ are the number densities of atomic oxygen, molecular nitrogen and molecular oxygen, respectively. The neutral densities are in m^{-3} .

The electron cooling rates in $\text{eV m}^{-3} \text{s}^{-1}$ due to inelastic collisions with neutrals are given by the following expressions (densities in m^{-3}):

N_2 rotation [58]:

Figure 4. Global distribution of the electron heating flux at the top boundary at 12:00 UT.

$$L_e(N_2)_{rot} = 3.5 \times 10^{-26} n_e n(N_2) (T_e - T_n) T_e^{1/2}. \quad (\text{A.6})$$

451 where T_n is the neutral temperature.

452 **O₂ rotation** [59]:

$$L_e(O_2)_{rot} = 5.2 \times 10^{-27} n_e n(O_2) (T_e - T_n) T_e^{1/2}. \quad (\text{A.7})$$

453 **N₂ vibration** [58]:

$$\begin{aligned} L_e(N_2)_{vib} = & 1 \times 10^{-12} n_e n(N_2) (1 - e^{(-E_1/T_{vib})}) \\ & \sum_{v=1}^{10} Q_{0v} (1 - e^{(vE_1(T_e^{-1} - T_{vib}^{-1}))}) \\ & + 1 \times 10^{-12} n_e n(N_2) (1 - e^{(-E_1/T_{vib})}) e^{(-E_1/T_{vib})} \\ & \sum_{v=2}^9 Q_{1v} (1 - e^{((v-1)E_1(T_e^{-1} - T_{vib}^{-1}))}), \end{aligned} \quad (\text{A.8})$$

454 where $E_1 = 3353$ K, $T_{vib} = T_n$ and

$$\log_{10} Q_{0v} = A_{0v} + B_{0v} T_e + C_{0v} T_e^2 + D_{0v} T_e^3 + F_{0v} T_e^4 - 16, \quad (\text{A.9})$$

$$\log_{10} Q_{1v} = A_{1v} + B_{1v} T_e + C_{1v} T_e^2 + D_{1v} T_e^3 + F_{1v} T_e^4 - 16. \quad (\text{A.10})$$

455 The A, B, C, D and F coefficients are given in Tables A.3, A.4, and A.5.

Figure 5. Comparisons of temporal variations in the electron density (top), electron temperature (mid) and ion temperature (bottom) between GITM (left column), IRI (middle column) and observation by the Arecibo ISR (right column) from 100 km to 650 km on April 13th and 14th, 2013.

Table A.3. Coefficients for calculations of $Q_{0\nu}$ for $300 \leq T_e \leq 1500$ K

ν	$A_{0\nu}$	$B_{0\nu}, K^{-1}$	$C_{0\nu}, K^{-2}$	$D_{0\nu}, K^{-3}$	$F_{0\nu}, K^{-4}$	$\delta_{0\nu}$
1	-6.462	$3.151 \cdot 10^{-2}$	$-4.075 \cdot 10^{-5}$	$2.439 \cdot 10^{-8}$	$-5.479 \cdot 10^{-12}$	0.14

Table A.4. Coefficients for calculations of $Q_{0\nu}$ for $1500 \leq T_e \leq 6000$ K

ν	$A_{0\nu}$	$B_{0\nu}, K^{-1}$	$C_{0\nu}, K^{-2}$	$D_{0\nu}, K^{-3}$	$F_{0\nu}, K^{-4}$	$\delta_{0\nu}$
1	2.025	$8.782 \cdot 10^{-4}$	$2.954 \cdot 10^{-7}$	$-9.562 \cdot 10^{-11}$	$7.252 \cdot 10^{-15}$	0.06
2	-7.066	$1.001 \cdot 10^{-2}$	$-3.066 \cdot 10^{-6}$	$4.436 \cdot 10^{-10}$	$-2.449 \cdot 10^{-14}$	0.08
3	-8.211	$1.092 \cdot 10^{-2}$	$-3.369 \cdot 10^{-6}$	$4.891 \cdot 10^{-10}$	$-2.706 \cdot 10^{-14}$	0.10
4	-9.713	$1.204 \cdot 10^{-2}$	$-3.732 \cdot 10^{-6}$	$5.431 \cdot 10^{-10}$	$-3.008 \cdot 10^{-14}$	0.10
5	-10.353	$1.243 \cdot 10^{-2}$	$-3.850 \cdot 10^{-6}$	$5.600 \cdot 10^{-10}$	$-3.100 \cdot 10^{-14}$	0.13
6	-10.819	$1.244 \cdot 10^{-2}$	$-3.771 \cdot 10^{-6}$	$5.385 \cdot 10^{-10}$	$-2.936 \cdot 10^{-14}$	0.15
7	-10.183	$1.185 \cdot 10^{-2}$	$-3.570 \cdot 10^{-6}$	$5.086 \cdot 10^{-10}$	$-2.769 \cdot 10^{-14}$	0.15
8	-12.698	$1.309 \cdot 10^{-2}$	$-3.952 \cdot 10^{-6}$	$5.636 \cdot 10^{-10}$	$-3.071 \cdot 10^{-14}$	0.15
9	-14.710	$1.409 \cdot 10^{-2}$	$-4.249 \cdot 10^{-6}$	$6.058 \cdot 10^{-10}$	$-3.300 \cdot 10^{-14}$	0.15
10	-17.538	$1.600 \cdot 10^{-2}$	$-4.916 \cdot 10^{-6}$	$7.128 \cdot 10^{-10}$	$-3.941 \cdot 10^{-14}$	0.15

456 **O₂ vibration** [60]:

$$L_e(O_2)_{vib} = 1 \times 10^{-12} n_e n(O_2) Q(T_e) (1 - e^{(2239(T_e^{-1} - T_n^{-1}))}), \quad (\text{A.11})$$

Figure 6. Comparisons of temporal variations in the electron density (top), electron temperature (mid) and ion temperature (bottom) between GITM (left column), IRI (center column) and observation by the Jicamarca ISR (right column) from 100 km to 650 km on April 13th, 2013.

Table A.5. Coefficients for calculations of $Q_{1\nu}$ for $1500 \leq T_e \leq 6000$ K

ν	$A_{1\nu}$	$B_{1\nu}, K^{-1}$	$C_{1\nu}, K^{-2}$	$D_{1\nu}, K^{-3}$	$F_{1\nu}, K^{-4}$	$\delta_{1\nu}$
2	-3.413	$7.326 \cdot 10^{-3}$	$-2.200 \cdot 10^{-6}$	$3.128 \cdot 10^{-10}$	$-1.702 \cdot 10^{-14}$	0.11
3	-4.160	$7.803 \cdot 10^{-3}$	$-2.352 \cdot 10^{-6}$	$3.352 \cdot 10^{-10}$	$-1.828 \cdot 10^{-14}$	0.11
4	-5.193	$8.360 \cdot 10^{-3}$	$-2.526 \cdot 10^{-6}$	$3.606 \cdot 10^{-10}$	$-1.968 \cdot 10^{-14}$	0.12
5	-5.939	$8.807 \cdot 10^{-3}$	$-2.669 \cdot 10^{-6}$	$3.806 \cdot 10^{-10}$	$-2.073 \cdot 10^{-14}$	0.08
6	-8.261	$1.010 \cdot 10^{-2}$	$-3.039 \cdot 10^{-6}$	$4.318 \cdot 10^{-10}$	$-2.347 \cdot 10^{-14}$	0.10
7	-8.185	$1.010 \cdot 10^{-2}$	$-3.039 \cdot 10^{-6}$	$4.318 \cdot 10^{-10}$	$-2.347 \cdot 10^{-14}$	0.12
8	-10.823	$1.199 \cdot 10^{-2}$	$-3.620 \cdot 10^{-6}$	$5.159 \cdot 10^{-10}$	$-2.810 \cdot 10^{-14}$	0.09
9	-11.273	$1.283 \cdot 10^{-2}$	$-3.879 \cdot 10^{-6}$	$5.534 \cdot 10^{-10}$	$-3.016 \cdot 10^{-14}$	0.09

457 where

$$\begin{aligned}
 \log_{10} Q(T_e) = & -19.9171 + 0.0267T_e - 3.9960 \times 10^{-5}T_e^2 \\
 & + 3.5187 \times 10^{-8}T_e^3 - 1.9228 \times 10^{-11}T_e^4 \\
 & + 6.6864 \times 10^{-22}T_e^7 - 1.5346 \times 10^{-26}T_e^8 \\
 & + 5.0148 \times 10^{-31}T_e^9.
 \end{aligned}
 \tag{A.12}$$

458 **O fine structure** [61]:

Figure 7. The electron heat flux specified on the topside of the ionosphere at Millstone ISR from 00 to 24 LT on April 13th, 2013. The left (right) Y-axis shows the magnitude of the small (large) heat flux. The dashed line marks 16 LT.

$$\begin{aligned}
 L_e(O)_{fine} = & 1 \times 10^{-12} n_e n(O) D^{-1} (S_{10} (1 - e^{(98.9(T_e^{-1} - T_n^{-1}))}) \\
 & + S_{20} (1 - e^{(326.6(T_e^{-1} - T_n^{-1}))}) \\
 & + S_{21} (1 - e^{(227.7(T_e^{-1} - T_n^{-1}))})),
 \end{aligned} \tag{A.13}$$

459 where

$$D = 5 + e^{(-326.6 T_n^{-1})} + 3e^{(-227.7 T_n^{-1})}, \tag{A.14}$$

$$S_{21} = 1.863 \cdot 10^{-11}, \tag{A.15}$$

$$S_{20} = 1.191 \cdot 10^{-11}, \tag{A.16}$$

$$S_{10} = 8.249 \cdot 10^{-16} T_e^{0.6} e^{(-227.7 T_n^{-1})}. \tag{A.17}$$

460 **O(¹D) excitation** [62]:

$$L_e(O(^1D)) = 1.57 \times 10^{-24} n_e n(O) e^{(d \frac{T_e - 3000}{3000 T_e})} (e^{(-22713 \frac{T_e - T_n}{T_e T_n})} - 1), \tag{A.18}$$

461 where

$$d = 2.4 \times 10^4 + 0.3(T_e - 1500) - 1.947 \times 10^{-5}(T_e - 1500)(T_e - 4000). \tag{A.19}$$

Figure 8. Comparisons of temporal variations in the electron temperature (top) and ion temperature (bottom) between the simulations (left three columns) and the Millstone observation (right column) from 100 km to 650 km from 16 to 24 LT on April 13th, 2013. The leftmost column shows T_e and T_i of the simulation driven by the small heat flux, while the second column from the left shows T_e and T_i of the simulation driven by the large heat flux. The third column column for the left shows results from IRI.

Appendix B. Source Terms in the Calculation of the Ion Temperature

The ion thermal conductivity λ_i is the sum of the thermal conductivity of the major ions weighed by their number densities:

$$\lambda_i = \frac{\sum_t n_t \lambda_t}{\sum_t n_t}, \quad (\text{B.1})$$

where n_t and λ_t are the number density and the thermal conductivity of ion species t . The numerical expression for λ_t is given by [2]:

$$\lambda_t = 3.1 \times 10^6 \frac{T_t^{5/2}}{M_t^{1/2} Z_t^4} \left(1 + 1.75 \sum_{j \neq t} \frac{Z_j^2 n_j}{Z_t^2 n_t} \left(\frac{M_j}{M_t + M_j} \right)^{1/2} \times \frac{3M_t^2 + 1.6M_t M_j + 1.3M_j^2}{(M_t + M_j)^2} \right)^{-1}, \quad (\text{B.2})$$

where the unit is $\text{eV m}^{-1} \text{s}^{-1} \text{K}^{-1}$, the subscripts t and j refer to different ion species. Note that this expression is obtained for a fully ionized plasma in which ion-ion collisions are dominant. This expression may not apply well to the ionosphere at low altitudes, but is used anyways.

The collision frequencies for resonant ion-neutral interactions are given in Table Appendix B [63, 2]. The non-resonant collision frequencies are given by Schunk and Nagy [2]:

Figure 9. Comparisons of temporal variations in the electron density (top), electron temperature (mid) and ion temperature (bottom) between GITM (left column), IRI (center column) and observation by the Sondrestrom ISR (right column) from 100 km to 650 km on April 13th and 14th, 2013.

Table B.6. Collision frequencies for resonant ion-neutral interactions. $T_r = (T_i + T_n)/2$ and densities are in m^{-3} .

Species	T_r, K	ν_{in}, s^{-1}
N^+, N	> 275	$3.83 \times 10^{-17} n(N) T_r^{1/2} (1 - 0.063 \log_{10} T_r)^2$
O^+, O	> 235	$3.36 \times 10^{-17} n(O) T_r^{1/2} (1 - 0.064 \log_{10} T_r)^2$
N_2^+, N_2	> 170	$5.14 \times 10^{-17} n(N_2) T_r^{1/2} (1 - 0.069 \log_{10} T_r)^2$
O_2^+, O_2	> 800	$2.59 \times 10^{-17} n(N_2) T_r^{1/2} (1 - 0.073 \log_{10} T_r)^2$

$$\nu(O^+, O_2) = 6.64 \times 10^4 n(O_2), \quad (\text{B.3})$$

$$\nu(O^+, N_2) = 6.82 \times 10^4 n(N_2), \quad (\text{B.4})$$

$$\nu(O_2^+, N_2) = 4.13 \times 10^4 n(N_2), \quad (\text{B.5})$$

$$\nu(O_2^+, O) = 2.31 \times 10^4 n(O), \quad (\text{B.6})$$

472 where the neutral densities are in m^{-3} .

Figure 10. Temporal variations of IMF B_Z and hemispheric power (HP) during an idealized substorm. The onset occurred at 0 epoch time, as indicated as the vertical dashed line.

473 Appendix C. Charge Exchange and Recombination Reaction Rates

The charge exchange rates κ_1 , κ_2 , κ_3 are given by [64, 65]:

$$\kappa_1 = 1.533 \times 10^{-12} - 5.92 \times 10^{-13}(T/300) + 8.6 \times 10^{-14}(T/300)^2 \quad (\text{C.1})$$

474 for $350\text{K} \leq T \leq 1700\text{ K}$;

$$\kappa_1 = 2.73 \times 10^{-12} - 1.155 \times 10^{-12}(T/300) + 1.483 \times 10^{-13}(T/300)^2 \quad (\text{C.2})$$

475 for $1700\text{ K} < T < 6000\text{ K}$.

$$\kappa_2 = 2.82 \times 10^{-11} - 7.74 \times 10^{-12}(T/300) + 1.073 \times 10^{-12}(T/300)^2 - 5.17 \times 10^{-14}(T/300)^3 + 9.65 \times 10^{-16}(T/300)^4 \quad (\text{C.3})$$

476 for $350\text{ K} \leq T \leq 6000\text{ K}$.

$$\kappa_3 = 8.36 \times 10^{-13} - 2.02 \times 10^{-13}(T/300) + 6.95 \times 10^{-14}(T/300)^2 \quad (\text{C.4})$$

477 for $320\text{ K} \leq T \leq 1500\text{ K}$;

Figure 11. Solid lines show from top to bottom temporal variations of percentage difference in N_e , T_e , T_i , T_n and square of velocity difference between ions and neutrals (δV^2); dotted lines show from top to bottom HP, HP, the percentage difference in estimated T_i , δV^2 and square of IMF driven electric field. The ionospheric and thermospheric parameters are geometrically averaged over the north polar cap (above 40° Latitude) at 140 km.

$$\kappa_3 = 5.33 \times 10^{-13} - 1.64 \times 10^{-14}(T/300) + 4.72 \times 10^{-14}(T/300)^2 - 7.05 \times 10^{-16}(T/300)^3 \quad (\text{C.5})$$

478 for $1500\text{K} < T < 6000\text{K}$. In Eqn(C.1)-(C.5), T is the effective temperature, which is given by:

$$T = T(O^+) + \frac{m(O^+)}{m(O^+) + m_r} \frac{m_r - m_b}{3\kappa} u_\perp^2(O^+), \quad (\text{C.6})$$

479 where

$$m_b = \frac{\sum_m \frac{m_n v(O^+, n)}{m(O^+) + m_n}}{\sum_m \frac{v(O^+, n)}{m(O^+) + m_n}}, \quad (\text{C.7})$$

Figure 12. From top to bottom: spatial variations of N_e , T_e and T_i at 140-km altitude at 6 epoch times during the substorm. The leftmost column shows the background ionosphere one hour before the substorm onset. Columns 2-6 show the percentage difference between the substorm simulation and the background simulation at -20 min, 0 min, 20 min, 60 min and 180 min epoch times, respectively.

m_r is the reactant mass of N_2 , O_2 or NO , and $T(O^+)$ is the O^+ temperature. Here, the transport effect was ignored, thus the effective temperature T was reduced to the O^+ temperature (equal the the bulk ion temperature in GITM).

The dissociative recombination rate (in m^{-3}) of NO^+ is given by:

$$\kappa_4 = 4.0 \times 10^{-13} \left(\frac{300}{T_e} \right)^{0.5}. \quad (C.8)$$

The dissociative recombination rate (in m^{-3}) of O_2^+ is given by:

$$\kappa_5 = 2.4 \times 10^{-13} \left(\frac{300}{T_e} \right)^{0.7}. \quad (C.9)$$

The radiative recombination rate (in m^{-3}) of O^+ is given by:

$$\kappa_4 = 3.7 \times 10^{-18} \left(\frac{300}{T_e} \right)^{0.7}. \quad (C.10)$$

Acknowledgement

This work was partially supported by NASA Grant NNX09AJ59G and NSF grants AGS1242787 and AGS1138938. GITM utilized the ACE magnetometer and SWEPAM measurements as well. The link to the ACE data deposi-

Figure 13. Same as Figure 11 but at 300 km.

485 tory is <http://www.srl.caltech.edu/ACE/ASC/level2/index.html>, and the data are also available at <http://cdaweb.gsfc.nasa.gov/>. The National Oceanic and Atmospheric Administration (NOAA) provided hemi-
 486 spheric power index data (<http://www.swpc.noaa.gov/ftpmenu/lists/hpi.html>) to drive the high-latitude
 487 auroral precipitation for this event. The ionospheric data measured by the Arecibo, Jicarmaca, Millstone and Sondre-
 488 strom incoherent scatter radars are available at <http://cedar.openmadrigal.org/>. We would like to acknowledge
 489 high-performance computing support from Yellowstone (ark:/90890) provided by NCAR's Computational and Infor-
 490 mation Systems Laboratory, sponsored by the National Science Foundation. We would also like to thank NASA's
 491 supercomputers, Pleiades (<http://www.nas.nasa.gov/hecc/resources/pleiades.html>) for conducting the
 492 simulations in this study. The GITM simulation data for this case are available upon request from the authors.
 493

Figure 14. Same as Figure 12 but at 300 km.

References

- [1] L. B. N. Clausen, S. E. Milan, A. Grocott, Thermospheric density perturbations in response to substorms, *Jgr* 119 (2014) 4441–4445.
- [2] R. Schunk, A. Nagy, *Ionospheres: Physics, Plasma Physics, and Chemistry*, Cambridge University Press, 2009.
- [3] J. P. MaClure, Thermospheric Temperature Variations Inferred from Incoherent Scatter Observations, *J. Geophys. Res.* 76 (1971) 3106.
- [4] K. I. Oyama, S. Watanabe, Y. Su, T. Takahashi, K. Hirao, Season, local time, and longitude variations of electron temperature at the height of ~600 km in the low latitude region, *Adv. Space Res.* 18 (1996) (6)269.
- [5] S. Fukao, W. L. Oliver, Y. Onishi, T. Takami, t. Sato, T. Tsuda, M. Yamamoto, S. Kato, F-region seasonal behavior as measured by the MU radar, *J. Atmos. Terr. Phys.* 53 (1991) 599.
- [6] A. Dalgarno, M. G. McElroy, R. J. Moffett, Electron Temperatures in the Ionosphere, *Planet. Space Sci.* 11 (1963) 463–484.
- [7] A. V. D. Rosa, The theoretical time-dependent thermal behavior of the ionospheric electron gas, *J. Geophys. Res.* 71 (1966) 4107.
- [8] Y. Otsuka, S. Kawamura, N. Balan, S. Fukao, G. J. Bailey, Plasma temperature variations in the ionosphere over the middle and upper atmosphere radar, *J. Geophys. Res.* 103 (1998) 20705.
- [9] J. Lei, R. G. Roble, W. Wang, B. A. Emery, S.-R. Zhang, Electron temperature climatology at Millstone Hill and Arecibo, *J. Geophys. Res.* 112 (2007) A02302.
- [10] V. Truhlik, L. Triskova, D. Bilitza, K. Podolska, Variations of daytime and nighttime electron temperature and heat flux in the upper ionosphere, topside ionosphere and lower plasmasphere for low and high solar activity, *Journal of Atmospheric and Solar-Terrestrial Physics*. 71 (2009) 17–18.
- [11] W. Wang, A. G. Burns, T. L. Killeen, A numerical study of the response of ionospheric electron temperature to geomagnetic activity, *Geophys. Res. Lett.* 111 (2006) A11301.
- [12] R. W. Schunk, J. J. Sojka, M. D. Bowline, Theoretical Study of the Electron Temperature in the, High-Latitude Ionosphere for Solar Maximum and Winter Conditions, *J. Geophys. Res.* 91 (1986) 12041–12054.

- [13] M. David, R. W. Schunk, J. J. Sojka, The effect of downward electron heat flow and electron cooling processes in the high-latitude ionosphere, *Journal of Atmospheric and Solar-Terrestrial Physics*. 73 (2011) 1029–1048.
- [14] B.-C. Zhang, Y. Kamide, Response of electron temperature to field-aligned current, *J. Geophys. Res.* 108 (2003) 1169.
- [15] P. M. Banks, Ion Temperature in the Upper Atmosphere, *J. Geophys. Res.* 72 (1967) 3365–3385.
- [16] R. W. Schunk, J. J. Sojka, Ion Temperature Variations in the Daytime High-latitude F Region, *J. Geophys. Res.* 87 (1962) 5169.
- [17] J. P. Thayer, J. Semeter, The convergence of magnetospheric energy flux in the polar atmosphere, *Journal of Atmospheric and Solar-Terrestrial Physics*. 66 (2004) 807–824.
- [18] R. W. Schunk, A mathematical model of middle and high-latitude ionosphere, *Pure and Applied Geophysics* 127 (1988) 255–303.
- [19] J. J. Sojka, Global scale physical models of the F region ionosphere, *Rev. Geophys.* 27 (1989) 371–403.
- [20] G. H. Millward, R. J. Moffett, W. Quegan, T. J. Fuller-Rowell, A Coupled Thermosphere-Ionosphere-Plasmasphere Model, in *STEP: Handbook of Ionospheric Models*, National Technical Information Service, 5285 Port Pryal Road, Springfield, VA 22161, 1996.
- [21] J. D. Huba, G. Joyce, Sami2 is Another Model of the Ionosphere (SAMI2): A new low-latitude ionosphere model, *J. Geophys. Res.* 105 (2000) 23,035–23,053.
- [22] H. A. Observatory, TIEGCM V 1.94 Model Description, National Center for Atmospheric Research, Boulder, CO, 2011.
- [23] W. Baumjohann, R. Pelunen, H. Opgenoorth, E. Nielsen, Joint two-dimensional observations of ground magnetic and ionospheric electric fields associated with auroral zone currents: Current systems associated with local auroral break-ups, *Planetary and Space Science* 29 (4) (1981) 431–447.
- [24] B. Inhester, W. Baumjohann, R. Greenwald, E. Nielsen, Joint two-dimensional observations of ground magnetic and ionospheric electric fields associated with auroral zone currents. III- Auroral zone currents during the passage of a westward travelling surge, *Journal of Geophysics-Zeitschrift fuer Geophysik* 49 (3) (1981) 155–162.
- [25] H. Opgenoorth, I. Hägström, P. Williams, G. Jones, Regions of strongly enhanced perpendicular electric fields adjacent to auroral arcs, *Journal of Atmospheric and Terrestrial Physics* 52 (6) (1990) 449–458.
- [26] B. N. Maehlum, T. Hansen, A. Brekke, O. Holt, K. Folkestad, Preliminary results from a study of the F-region heating during an intense aurora observed by EISCAT, *jatp* 40.
- [27] K. R. Svenes, B. N. Maehlum, J. Trøim, G. Holmgren, R. L. Arnoldy, U. P. Løvhaug, M. T. Rietveld, Combined rocket and ground observations of electron heating in the ionospheric F-layer, *pss* 40.
- [28] K. R. Svenes, B. N. Maehlum, U. P. Løvhaug, M. T. Rietveld, C. Hall, An investigation of two different electron heating events in the ionospheric F-layer, *Advances in Space Research* 12.
- [29] T. Yeoman, J. Davies, N. Wade, G. Provan, S. E. Milan, Combined CUTLASS, EISCAT and ESR observations of ionospheric plasma flows at the onset of an isolated substorm, in: *Annales Geophysicae*, vol. 18, Springer, 1073–1087, 2000.
- [30] X. Liu, A. Ridley, A simulation study of the thermosphere mass density response to substorms using GITM, *jgr* 120.
- [31] A. Ridley, Y. Deng, G. Tóth, The global ionosphere-thermosphere model, *Journal of Atmospheric and Solar-Terrestrial Physics*. 68 (2006) 839.
- [32] A. D. Richmond, Ionospheric Electrodynamics Using Magnetic Apex Coordinates, *J. Geomagn. Geoelectr.* 47.
- [33] G. Vichare, A. J. Ridley, E. Yiğit, Quiet-time low latitude ionospheric electrodynamics in the non-hydrostatic Global IonosphereThermosphere Model, *Journal of Atmospheric and Solar-Terrestrial Physics*. 80 (2012) 161–172.
- [34] D. R. Weimer, Improved ionospheric electrodynamic models and application to calculating Joule heating rates, *J. Geophys. Res.* 110.
- [35] T. J. Fuller-Rowell, D. S. Evans, Height-Integrated Pedersen and Hall Conductivity Patterns Inferred From the TIROS-NOAA Satellite Data, *J. Geophys. Res.* 92.

- [36] R. W. Schunk, J. C. G. Walker, Transport properties of the ionospheric electron gas, *Planet. Space Sci.* 18 (1970) 1535–1550.
- [37] C. G. Smithtro, S. C. Solomon, An improved parameterization of thermal electron heating by photoelectrons, with application to an X17 flare, *J. Geophys. Res.* 113 (2008) A08307.
- [38] W. E. Swartz, J. S. Nisbet, Revised calculations of F region ambient electron heating by photoelectrons, *J. Geophys. Res.* 77 (1972) 6259–6261.
- [39] S. C. Solomon, P. B. Hays, V. J. Abreu, The auroral 6300 Å emission: Observations and modeling, *J. Geophys. Res.* 93 (1988) 9867–9882.
- [40] S. C. Solomon, V. J. Abreu, The auroral 630-nm dayglow, *J. Geophys. Res.* 94 (1989) 6817–6824.
- [41] D. Bilitza, D. Altadill, Y. Zhang, C. Mertens, V. Truhlik, P. Richards, L.-A. McKinnell, B. Reinisch, The International Reference Ionosphere 2012—a model of international collaboration, *Journal of Space Weather and Space Climate* 4 (2014) A07.
- [42] K. K. Mahajan, Models of electron temperature in the ionospheric F-region using electron density height profiles, *J. Atmos. Terr. Phys.* 139 (1976) 637–639.
- [43] D. Bilitza, Electron and ion temperature data for ionospheric modelling, *Adv. Space Res.* 11 (1991) 139–148.
- [44] R. W. Schunk, A. F. Nagy, Electron temperatures in the F region of the ionosphere: Theory and observations, *Rev. Geophys.* 16 (1978) 355–399.
- [45] D. Rees, T. J. Fuller-Rowell, The Response of the Thermosphere and Ionosphere to Magnetospheric Forcing, *The Royal Society* 328.
- [46] W. E. Gordon, Incoherent Scattering of Radio Waves by Free Electrons with Applications to Space Exploration by Radar, *Proceedings of the IRE* 48 (1958) 1824–1829.
- [47] M. W. Liemohn, J. U. Kozyra, P. G. Richards, G. V. Khazanov, M. J. Buonsanto, V. K. Jordanova, Ring current heating of the thermal electrons at solar maximum, *J. Geophys. Res.* 105 (2000) 27767–27776.
- [48] H. A. Bekerat, R. W. Schunk, L. Scherliess, Estimation of the high-latitude topside electron heat flux using DMSP plasma density measurements, *Journal of Atmospheric and Solar-Terrestrial Physics* 69 (2007) 1029–1048.
- [49] L. R. Liuzzo, A. J. Ridley, N. J. Perlono, E. J. Mitchell, M. Conde, D. L. Hampton, W. A. Bristow, M. J. Nicolls, High-latitude ionospheric drivers and their effects on wind patterns in the thermosphere, *J. Geophys. Res.* 120 (2015) 715735.
- [50] C. Reigber, H. Lühr, P. Schwintzer, CHAMP mission status, *Advances in Space Research* 30.
- [51] J. R. Kan, L. C. Lee, Energy Coupling Function and Solar Wind-magnetosphere Dynamo, *Geophys. Res. Lett.* 6 (1979) 577–580, doi: \bibinfo{doi}{10.1029/GL006i007p00577}.
- [52] J. St-Maurice, R. Schunk, Ion velocity distributions in the high-latitude ionosphere, *Reviews of Geophysics and Space Physics* 17 (1) (1979) 99–133.
- [53] T. I. Gombosi, *Physics of the Space Environment*, Cambridge University Press, 1998.
- [54] J.-E. Wahlund, H. Opgenoorth, F. Forme, M. Persson, I. Häggström, J. Lilén, Electron energization in the topside auroral ionosphere: on the importance of ion-acoustic turbulence, *Journal of atmospheric and terrestrial physics* 55 (4) (1993) 623–645.
- [55] Y. Itikawa, Momentum-transfer cross sections for electron collisions with atoms and molecules, *Atomic Data and Nuclear Data Tables* 14 (1972) 1–10.
- [56] Y. Itikawa, Momentum transfer cross sections for electron collisions with atoms and molecules, *At. Data Nucl. Data Tables* 14 (1978) 1–10.
- [57] R. W. Schunk, A. F. Nagy, Ionospheres of the terrestrial planets, *Rev. Geophys. Space Phys.* 18 (1980) 813–852.
- [58] A. V. Pavlov, New electron energy transfer rates for vibrational excitations of N_2 , *Ann. Geophys.* 16 (1998) 176–182.
- [59] A. V. Pavlov, New electron energy transfer and cooling rates by excitation of O_2 , *Ann. Geophys.* 16 (1999) 1007–1013.
- [60] D. B. Jones, L. Campbell, M. J. Bottema, M. J. Brunger, New electron-energy transfer rates for vibrational excitation of O_2 , *New Journal of Physics* 5 (2003) 1007–1013.

- 593 [61] A. V. Pavlov, K. A. Berrington, Cooling rate of thermal electrons by electrons by electron impact excitation of fine structure levels of atomic
594 oxygen, *Ann. Geophys.* 17 (1999) 919–924.
- 595 [62] R. J. W. Henry, P. G. Burke, A. L. Sinfailam, Scattering of electrons by C, N, O, N^+ , O^+ , and O^{++} , *Phys. Rev.* 178 (1969) 218–225.
- 596 [63] P. M. Banks, G. Kockarts, *Aeronomy*, Academic Press, 1973.
- 597 [64] M. McFarland, D. L. Albritton, E. E. F. C. Fehsenfeld, A. L. Schmeltekopf, lowdrift technique for ion mobility and ionmolecule reaction
598 rate constant measurements. II. Positive ion reactions of N^+ , O^+ , and H_2^+ with O_2 and O^+ with N_2 from thermal to ~ 2 eV, *J. Chem. Phys.* 59
599 (1973) 6620.
- 600 [65] R. W. Schunk, W. J. Raitt, P. M. Bank, Effect of electric fields on the daytime high-latitude E and F regions, *J. Geophys. Res.* 80 (1975)
601 31213130.

Figure 15. From top to bottom shows the electron heat flux into the ionosphere, T_e and N_e at an altitude of 300 km and the total electron content (TEC) at 12:00 UT. The first (second) column shows the simulation results driven by the small (large) heat flux, and the third column shows the percentage difference between the two.

Figure 16. Altitudinal profiles of the electron temperature and electron density at 150° Lon 55° Lat at 12:00 UT (i.e., 22:00 LT). The dotted lines represent the top heat flux of $2.9 \times 10^{-7} \text{ Jm}^{-2}\text{s}^{-1}$, while the solid lines represent the top heat flux of $2.9 \times 10^{-6} \text{ Jm}^{-2}\text{s}^{-1}$.

Figure 17. The electron density loss rate normalized to the value at $T_e=1000$ K, $T_i=1000$ K. Level = 1.0 is contoured by the solid line.