A numerical study of the response of ionospheric electron temperature to geomagnetic activity

W. Wang, A. G. Burns, and T. L. Killeen

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[1] The response of ionospheric electron temperatures to geomagnetic activity has been simulated using the Thermosphere-Ionosphere Nested Grid (TING) model. The cause of this response has been analyzed using a new postprocessor for the TING model that looks at the individual physical terms that drive the electron energy equation. It is found that (1) electron temperatures are significantly enhanced in regions of depleted electron densities, especially inside the middle-latitude electron density trough. The most pronounced electron temperature enhancement occurs at the equatorward edge of the trough; (2) this enhancement is produced by heat flux from the plasmasphere, coupled with the effect of the relatively low thermal electron gas heat capacity there and the inefficient heat conduction in the bottomside of the F region, where electron densities have almost vanished; (3) in regions of enhanced electron densities, electron temperatures are significantly decreased as a result of enhanced energy loss to the ions; this prevents the electron temperature "morning overshoot" from occurring in the middle and low latitudes; (4) upwelling of molecular-species-rich air from the lower thermosphere to higher altitudes during the storm increases mixing ratios of the neutral molecular species in the F region, thus enhances the relative contribution of the neutral molecular species to the overall electron cooling there; (5) ion frictional heating increases high-latitude F region ion temperatures during geomagnetic storms, causing the ions to transfer energy to the electrons and thus enhancing electron temperatures; and (6) there are no significant electron temperature increases in the E region during the storm because of the rapid energy loss from the electrons to the neutrals.


I. Introduction

[2] Ionospheric electron temperatures (T_e) are determined by the thermal balance between heating and cooling processes. Strong large-scale temporal and spatial variations in T_e occur because electron heating and cooling processes change with geophysical conditions [e.g., Schunk and Nagy, 1978, 2000, and references therein]. One example of such variations is the T_e diurnal changes in middle and low latitudes. During daytime, electron temperatures are, in general, higher than ion temperatures, which, in turn, are higher than neutral temperatures. However, at night, electron temperatures are relatively low and closer to ion and neutral temperatures because there is no significant heating source, but there is fast loss of energy from the electrons to the ions and neutrals. In the early morning sector, F region T_e is significantly enhanced to form the so-called T_e "morning overshoot," where low-density thermal electrons are heated up by photoelectrons [Dalgarno and McElroy, 1965; McClure, 1971; Clark et al., 1972; Oyama et al., 1996; Otsuka et al., 1998]. During most of the daytime, electron temperatures are significantly lower than their "morning overshoot" values [e.g., Evans, 1973; Brace and Theis, 1978; Otsuka et al., 1998].

[3] In addition to these large-scale temporal and spatial variations, there are significant short-term variations in T_e that are induced by rapid changes in geophysical conditions. The most pronounced short-term changes are related to geomagnetic storms. During storm times, energy and momentum from the magnetosphere are deposited into the upper atmosphere through enhanced high-latitude ion convective drifts and particle precipitation. The auroral oval expands and strong particle precipitation produces high electron densities in the lower F and E regions. The response of the thermosphere to these energy and momentum inputs is dynamical and nonlinear. One of the features of these storms is a molecular composition bulge (i.e., decreased O/N_2 ratio) in the nighttime sector of the upper thermosphere [e.g., Prölls, 1981].

[4] Ionospheric electron densities also change significantly during storms [e.g., Buonsanto, 1999, and references therein]. Electron density depletions (negative storm effects) occur at high latitudes, as well as at middle latitudes in the
nighttime/early morning time sector. Negative storm effects are frequently associated with regions of increased molecular densities, where enhanced recombination takes place. Electron density enhancements (positive storm effects) occur typically in the daytime and afternoon sectors [e.g., Prössl, 1995; Field et al., 1998; Rishbeth and Müller-Wodarg, 1999].

[5] These storm-time changes in thermospheric composition and ionospheric electron densities affect electron temperature profiles because they represent changes in thermal electron energy sources and sinks. For instance, measurements from the Millstone Hill incoherent scatter radar show that, under disturbed conditions, middle-latitude T_e is often abnormally enhanced at night [e.g., Evans, 1970a, 1973]. These radar-observed, nighttime electron temperature enhancements have also been seen in satellite measurements [e.g., Brinton et al., 1978; Brace et al., 1967, 1988; Kozyra et al., 1986; Fok et al., 1991; Afonin et al., 1997; G. W. Prössl, Subauroral electron temperature enhancement in the nighttime ionosphere, submitted to Annales Geophysicae, 2006, hereinafter referred to as Prössl, submitted manuscript, 2006]. They usually occur in association with the midlatitude electron density trough during active geomagnetic conditions and are commonly located at the equatorward edge of the trough, not at the region of minimum electron densities [Brace et al., 1967, 1988; Evans, 1973; Rees and Roble, 1975; Brinton et al., 1978; Burke et al., 1979; Horwitz et al., 1986; Watanabe et al., 1989]. Electron temperature enhancements inside the troughs are frequently high enough (>3000 K) to excite O^3P to O^D, and subsequently 6300 A photons are emitted to produce ground-observable stable subauroral red (SAR) arcs [Rees and Roble, 1975; Kozyra et al., 1997]. Strong storms push troughs and their associated T_e peaks and SAR arcs to lower latitudes [Afonin et al., 1997; Prössl, submitted manuscript, 2006]. In addition, these T_e enhancements increase with Kp and Dst index [Kozyra et al., 1986; Prössl, submitted manuscript, 2006] and occur more frequently during solar maximum than during solar minimum [Fok et al., 1991].

[6] The midlatitude electron density troughs and their associated T_e peaks occur in the nighttime subauroral region where there are no apparent photoelectron and direct particle heating sources. The downward heat flow from the plasmasphere along magnetic field lines provides the necessary energy to sustain the nighttime electron temperatures [Brace et al., 1988; Watanabe et al., 1989]. This is also the region where the ionospheric footprint of the plasmaspase occurs. Various investigators have indicated that an additional heat flux from the plasmaspase is required during storms to heat up the thermal electrons inside the trough [Kozyra et al., 1986; Horwitz et al., 1986; Green et al., 1986; Brace et al., 1988]. It has been also suggested that this enhanced storm-time downward heat flux results from ring current heating [e.g., Evans, 1970b; Kozyra et al., 1986]. Proposed mechanisms for this electron heating include Coulomb collisions between plasmaspheric electrons and ring current protons [Cole, 1967] and O^+ ions [Kozyra et al., 1987] and Landau damping of ion cyclotron waves by thermal electrons [Cornwall et al., 1971].

[7] Efforts have been made to simulate these observed T_e variations using first principles models. Oyama et al. [1997] and Bailey et al. [2000] applied the Sheffield University Plasmasphere-Ionosphere Model (SUPIM) to the lower latitudes to study the observed T_e trough near the magnetic equator and the T_e crest around 15° magnetic latitude in the winter hemisphere. They found that the T_e trough is caused by adiabatic cooling, whereas the T_e crest is caused by adiabatic heating as the plasma is transported along the field line from the summer hemisphere to the winter hemisphere by the prevailing meridional neutral wind. The same model has also been applied to simulate seasonal, diurnal, and latitudinal variations of T_e measured by the Hinotori satellite [Su et al., 1995; Watanabe et al., 1995].

[8] At middle latitudes, modeling efforts have been focused on simulating Millstone Hill incoherent scatter radar observations. Roble [1975] used winds, topside particle, and heat fluxes measured by the radar to simulate the diurnal variation of T_e and obtained reasonable agreement between model results and measurements. Richards and Khausanova [1997] performed a detailed energy balance study on thermal electrons using the Field Line Interhemispheric Plasma (FLIP) model. They found that the plasmaspheric heat flux must be doubled to reproduce the observed topside electron temperature profiles and to make the F_2 peak electron temperature closer to the measured values at nighttime. Pavlov et al. [2000, 2001] introduced an additional photoelectron heating rate into their time-dependent ionosphere-plasmasphere model in the plasmasphere region, as suggested by Richards and Khausanova [1997], and a revised electron thermal conductivity coefficient to bring the modeled electron densities and temperatures close to the measurements at Millstone Hill for both quiet and disturbed conditions. Schunk et al. [1986] modeled high-latitude T_e for solar maximum, winter, and strong geomagnetic activity conditions and found that one of the important parameters that controls F region electron temperature profiles is the heat flux from the magnetosphere. Hot T_e spots occur inside the auroral oval in the early evening sector in association with a strong dusk convection cell. Mingaleva and Mingalev [1996] also simulated storm-time electron temperature hot spots occurring in the morning sector midlatitude trough. They concluded that three conditions are necessary for ionospheric F region electron temperature hot spots to occur there: low values of electron density, solar illumination of the upper F region and darkness in the lower F region, and low neutral densities.

[9] These theoretical studies have greatly advanced our understanding of the physical processes that determine as well as perturb global ionospheric electron temperature profiles. However, these studies were either single field line, one-dimensional (1-D) simulations or limited to certain latitude ranges with coarse spatial resolutions. In addition, most of them so far have been performed under quiet geomagnetic conditions using empirical neutral atmospheric models such as MSIS. Thus there is a need for 3-D calculations of term analyses of the processes forcing T_e with an interactive thermosphere/ionosphere during geomagnetically active periods. The thermosphere significantly affects not only ionospheric electron densities and their vertical profiles by photochemical and molecular recombination processes but also the electron energy budget through direct collisions between the electrons and the neutrals. There are also large spatial and temporal variations in the
thermosphere that occur in response to changes in geophysical conditions, as we have discussed earlier.

[10] In this paper we will discuss storm-time electron temperature variations and their associated neutral composition and electron density changes using the time-dependent, high-resolution Thermosphere-Ionosphere Nested Grid (TING) model. The heat flux from the plasma-osphere is the same for both quiet-time and storm conditions, so the simulated storm-time variations in electron densities and temperatures are induced solely by the changes in high-latitude inputs. We also introduce a new postprocessor to the TING model diagnostic packages. This processor deals with term-by-term analyses of cooling and heating processes in the electron energy equation solved in the model. This electron temperature diagnostic capability, coupled with other postanalysis tools, allows us to investigate processes that are responsible for the simulated ionospheric electron temperature variations induced by geomagnetic storms.

2. Simulation Tools

2.1. Thermosphere-Ionosphere Nested Grid (TING) Model

[11] The TING model was developed to study mesoscale processes occurring in the thermosphere-ionosphere system. Wang et al. [1999] described the TING model and some of its simulation results in detail. The TING model is an extension of the NCAR-TIGCM (National Center for Atmospheric Research-Thermosphere/Ionosphere General Circulation Model) [Roble et al., 1988] that performs high-resolution simulations in selected regions (nested grid domains) where mesoscale processes play important roles.

[12] The TING model is comprised of two coupled grids: a global coarse grid and an adjustable nested grid whose domain and levels of nesting are predetermined based on the physical processes of interest to be simulated. The coarse grid and nested grid use the same numerical scheme to solve a set of momentum, energy, and mass conservation equations for the neutrals and ions. The coarse grid solves these equations globally, whereas nested grids calculate in a local limited area. The required time-dependent lateral boundary conditions for the nested grid are provided by the coarse grid simulation, which is run simultaneously with the nested grid. The coarse grid also provides initial conditions for the nested grid. In this study we use only one level of nested grid with a coarse to fine grid resolution ratio of 1:3. The nested grid spatial resolution is (5/3)° in both latitude and longitude. The nested grid domain for this study is chosen as 2.5°N to 82.5°N in latitude and −175° to 170° in longitude.

[13] The time-dependent neutral and plasma momentum, energy, and composition equations of the TING model are expressed in a geocentric reference frame using a spherical coordinate system. At each pressure level and time step all variables are calculated with a 5° spatial resolution for the global coarse grid and (5/3)° for the nested grid. In the vertical direction the TING model consists of 25 pressure levels (half scale height steps) with heights ranging from approximately 97 km to 500 km. The geometric height is a function of atmospheric pressure, which is an independent variable that is closely related to the thermospheric temperature. Hence the geometric height of each pressure level varies at each grid point with local time, season, and solar cycle. The TING model employs a corrected geomagnetic coordinate system that uses offset magnetic poles that are located at (79°N, 70°W) and (74.5°S, 127°E), respectively. The output fields of the TING model are three-dimensional global (coarse grid) and local (nested grid) distributions of mass mixing ratios of neutral species O, O₂, N₂, NO, N(2D), and N(2S), neutral temperature and velocity, pressure level height, as well as ion and electron densities and temperatures.

2.2. Electron Temperature Diagnostic Package

[14] Diagnostic processors have been developed to assist in the interpretation of TIGCM calculations [Killeen and Roble, 1984; Burns et al., 1989; Killeen et al., 1997]. The output from the TIGCM comprises a set of “history” data that contain the calculated neutral and ionospheric fields at each model grid point. Diagnostic processors read in these values and perform term-by-term analyses to determine the physical and chemical processes that are responsible for establishing upper atmospheric structures seen in the model simulation and for introducing perturbations to these structures. Killeen and Roble [1984] first introduced a diagnostic processor to study the contributions of various forcing terms to thermospheric dynamics. Later, postprocessors for neutral major species composition and thermodynamics were added to the original diagnostic processor to form a comprehensive diagnostic package for the TIGCM simulations [Burns et al., 1989; Killeen et al., 1997]. Postprocessors have also been developed to trace the paths of neutral parcels through the TIGCM output fields along constant pressure surfaces [Killeen and Roble, 1985, 1986; Burns et al., 1991]. This diagnostic package has been used to study changes of neutral composition, temperature, and winds induced by geomagnetic storms [Burns et al., 1995a, 1995b], the effect of neutral inertia on ionospheric currents [Deng et al., 1991, 1993], polar cap neutral thermodynamics [McCormac et al., 1988], and ion outflows at high latitudes [Cannata et al., 1988]. A similar diagnostic package, which has the ability to deal with changes in the size and location of the nested grid, has also been developed for the analyses of the TING model output. Most recently, these diagnostic packages have been used to study the solar cycle dependence of the response of the thermosphere to storms [Burns et al., 2004] and the variations of thermospheric viscosity and horizontal winds during geomagnetic storms (W. Wang et al., manuscript in preparation, 2006).

[15] In this study, we introduce into this diagnostic package a new term-by-term postanalysis processor that deals with the electron energy equation solved in the TING model. Under the steady state assumption, the electron energy equation can be expressed as [Schunk and Nagy, 1978]:

\[
\sin^2 I \frac{\partial}{\partial Z} \left( K^* \frac{\partial T_e}{\partial Z} \right) + \sum Q_e - \sum L_e = 0 \quad (1)
\]

where \(\sum Q_e\) and \(\sum L_e\) are the sums of electron heating and cooling rates, respectively. \(K^*\) is the electron thermal conductivity coefficient [Rees and Roble, 1975], \(I\) is the geomagnetic dip angle, and \(H\) is the neutral scale height and \(Z\) is the vertical grid. The first term in equation (1) describes
vertical heat conduction of the thermal electron gas. The steady state equation (1) for thermal electrons is solved in the TING model at each time step to obtain electron temperatures. In other words, it is assumed that at each model time step electron thermal equilibrium is achieved.

[16] The total thermal electron heating rates \( \sum Q_e \) are calculated in the TING model using a simple empirical model of Swartz and Nisbet [1972], which includes heating by superthermal electrons produced by both solar EUV radiation and particle precipitation. For simplicity, we will call this heating photoelectron heating and will not detail the energy transfer processes that are associated with photoionization and energy degradation of the precipitating particles. The Swartz and Nisbet [1972] model relates electron heating rates to neutral and electron densities and ionization rates. The electron heating rates calculated from this model thus change with both geomagnetic and solar activity. Heating by deactivation of excited neutral and ion species and dissociative recombination of the electrons are much smaller than electron heating due to photoelectrons, and Joule heating is negligible for electrons because of their small mass [Schunk and Nagy, 1978]. Thus these terms are neglected in our simulation. The electron cooling rates \( \sum L_e \) are determined by a number of processes and include electron cooling by elastic and inelastic collisions of electrons with ions and neutrals. These electron collision processes are collisions with a mixture of ions: \( O^+ \), \( O_2^+ \), and \( NO^+ \), elastic collisions with \( N_2 \), \( O_2 \), and \( O \), collisional vibration excitation of \( N_2 \) and \( O_2 \), \( O \) fine structure excitation, electronic excitation of \( O(1D) \), and collisional rotation excitation of \( N_2 \) and \( O_2 \). The corresponding cooling rates are obtained from Schunk and Nagy [1978, 2000] and Rees and Roble [1975]. The lower boundary condition for the electron energy equation is that the electron temperature equals to the neutral temperature which is, in turn, perturbed by semidiurnal tides. Individual heating and cooling terms are calculated in the TING model diagnostic package from model history files to evaluate their relative contributions to the local electron energy balance, as well as their changes with local time, altitude, latitude, and geomagnetic activity.

2.3. Electron Heat Fluxes

[17] Photoelectrons produced by the absorption of solar EUV radiation in the thermosphere can move along magnetic field lines to populate the plasmasphere. These photoelectrons may also experience heating inside the plasmasphere by interactions with the ring current [e.g., Cole, 1967; Cornwall et al., 1971; Kozyra et al., 1987]. Therefore electron temperatures in the plasmasphere are much higher than those in the ionosphere. These hot electrons from the plasmasphere are transported along field lines down into the ionosphere to heat the thermal electrons there. In fact, electron heat flux from the plasmasphere is a major factor in sustaining the nighttime ionospheric electron temperatures. Thus electron heat flux is a critical upper boundary condition for both global and local simulations of ionospheric electron temperatures.

[18] In this study the upper boundary condition for the electron energy equation is

\[
-K_e \frac{\partial T_e}{\partial Z} = F^e
\]

where \( F^e \) is the heat flux in the topside of the ionosphere. Figure 1 illustrates global distributions of the electron heat fluxes applied at the model top boundary (~500 km) at UT midnight in geographic coordinates. It is assumed here that electrons conduct heat from the plasmasphere down to the ionosphere with a specified flux. This flux maximizes during the daytime at middle latitudes and decreases with latitude and becomes zero at the magnetic equator. The nighttime flux is set to be one fifth of the daytime flux at the same geomagnetic latitudes. It is also assumed that electron heat flux is proportional to solar \( F_{10.7} \) flux, and thus more heat is conducted down to the ionosphere during solar maximum years than during solar minimum years [e.g., Nisbet, 1968; Evans, 1973]. In this study, \( F_{10.7} \) is set to 166 and the corresponding maximum electron heat flux is about \( 7.5 \times 10^9 \) eV cm\(^{-2}\) s\(^{-1}\) in the daytime.

[19] Very few topside ionospheric heat flux data have been observed or calculated in theoretical studies. Therefore it has been difficult to draw a picture of the global distribution of this heat flux either spatially or temporally. A limited number of heat flux measurements have been obtained by applying equation (2) to incoherent scatter radar or satellite \( T_e \) data at two heights [e.g., Evans, 1973; Titheridge, 1976; Brace and Theis, 1981]. Evans [1973] used several years of solar minimum observations at Millstone Hill and found that at midlatitudes, most of the daytime electron heat flux values lie in the range of \( 4-7 \times 10^9 \) eV cm\(^{-2}\) s\(^{-1}\); winter values exceed summer values and heat fluxes increase toward solar maximum. Nighttime heat fluxes have strong seasonal variations.
Summer night values are 5–10 times lower than daytime values, whereas winter night values are only about 2 times lower than daytime values. Titheridge [1976] used ALOUETTE satellite observations to show that during solar minimum at \( C_2 \), downward electron heat fluxes increased from about zero at \( C_1 \) geomagnetic latitude to a maximum of \( 4 \times 10^7 \) eV cm\(^{-2}\) s\(^{-1}\) in the plasmapause region at subauroral latitudes and that the nighttime values were about 2–8 times lower than the daytime values.

Figure 1 is produced by taking into account these isolated measurements and assuming that electron heat flux varies with solar zenith angle, geophysical location, and local time. The behavior of electron heat fluxes during geomagnetic storms is also not very clear. Intense fluxes up to \( 1 \times 10^{10} \) eV cm\(^{-2}\) s\(^{-1}\) are observed at Millstone Hill during the main phase of geomagnetic storms [Evans, 1970b]. There have been some studies investigating the ionospheric response to intense electron heat flux inputs and their associated effects on SAR arc excitation [Kozyra et al., 1997; Lobzin and Pavlov, 1999]. In this paper we keep our storm-time top boundary electron heat fluxes from the plasmasphere the same as those during nonstorm times to avoid any unnecessary complexity in our discussion of electron temperature variations during storms. High-latitude particle precipitation (and thus electron heating by particle precipitation) and ion convection pattern, however, increase with geomagnetic activity as described in detail in section 2.4. The ionospheric and thermospheric response to variations of the electron heat flux will be discussed in a separate paper.

2.4. Geophysical Conditions

In this study a 4-day (96 hours) simulation was carried out. The computations started at 0000 UT of day 1 from model history files that had been run to a diurnally reproducible, steady state. The solar \( F_{10.7} \) flux and its

![Figure 2. High-latitude hemispheric power (HP, top) and cross polar cap potential (CP, bottom) inputs to the model. The dashed lines indicate the two time periods (nonstorm and storm times) that will be studied in detail later.](image)

![Figure 3. Ion convection pattern and ion drift velocity at UT midnight specified by the imposed high-latitude HP and CP inputs for (a) nonstorm time and (b) storm time, respectively, corresponding to the dashed lines in Figure 2.](image)
average (81-day running mean) used were 166 and 199, respectively. The model was run for days 41–44 of the year, corresponding to solar maximum, northern hemispheric winter conditions. Figure 2 illustrates high-latitude inputs, which were specified as cross polar cap potentials (CP) and hemispheric power (HP). At the beginning (day 1) and the end (day 4) of the simulation, CP and HP were set to 60 KV and 10 GW, respectively, which are typical values for nonstorm conditions (Kp = C24 3). In the middle of the simulation CP and HP were set to values of 120 KV and 75 GW, respectively, typical for a fairly large geomagnetic storm (Kp ~ 6 +)

[21] Figure 3 shows ion convection patterns from the TING model for nonstorm (Figure 3a) and storm (Figure 3b) conditions at UT midnight, respectively. The convection pattern is specified using the Heelis model for IMF B_z southward conditions [Heelis et al., 1982]. The maximum ion drift velocities for nonstorm and storm times are 900 m/s and 1440 m/s, respectively. The ion convection pattern expands to lower latitudes during the storm. This expansion

**Figure 4.** Simulated F_2 peak electron densities in logarithm scale (log_{10}[N_e cm^{-3}]) at UT midnight for (a) nonstorm and (b) storm times, respectively. (c) Percentage changes of F_2 peak electron densities during the storm at UT midnight (solid lines are for values greater than or equal to zero, dashed lines are for values less than zero).
of the ion convection pattern will have an effect on the storm-time electron densities and temperatures (see section 1). Particle precipitation in the model is specified using two parameters, cross polar cap potential (CP) and hemispheric power (HP). Both CP and HP change with geomagnetic activity (Kp or solar wind conditions) and so does the particle precipitation. The auroral precipitation pattern and auroral oval boundaries are all specified to be aligned with the ion convection pattern (electric fields) and vary with HP and CP (thus geomagnetic conditions). Roble and Ridley [1987] described in great detail the procedures used to specify auroral particle precipitation and ion convection patterns in the model. Ionization and heating by solar EUV radiation are included in the model, as well as by auroral particle precipitation, to calculate ionospheric electron densities and temperatures.

3. Simulation Results

3.1. Storm-Time Electron Density Variations

[22] We first examine storm-time variations of electron densities to see how they affect electron temperatures. Electron densities determine the thermal electron gas heat capacity, and also they are one of the factors that control the energy loss to the ions and neutrals. In fact, an anticorrelation between ionospheric electron temperatures and concentrations has long been established under certain conditions [e.g., Taylor and Risk, 1974; McDonald and Williams, 1986; Breen et al., 1990]. Figure 4 shows F2 peak electron densities simulated by the TING model nested grid at UT midnight during nonstorm (Figure 4a) and storm (Figure 4b) times, and the percentage changes of F2 peak electron densities induced by the storm: \((N_\text{es} - N_\text{eq})/N_\text{eq} \times 100\) (Figure 4c), where \(N_\text{es}\) and \(N_\text{eq}\) stand for storm-time and nonstorm-time \(F_2\) peak electron densities, respectively. Nonstorm-time values are obtained from UT midnight of day 1. Storm-time values are obtained at UT midnight of day 2, 12 hours after the storm commencement (illustrated by the dashed lines in Figure 2). In these plots, latitudinal circles are drawn with 10° increments; the perimeter latitude is 2.5°. The latitude circles drawn on the plots are selected to represent grid points in the TING model coarse grid. During nonstorm times (Figure 4a), middle- and low-latitude electron densities increase gradually after dawn and reach maximum values in the afternoon. Electron densities then decrease gradually after sunset. The lowest densities occur just before sunrise. At high latitudes a tongue of ionization [Sojka et al., 1993], which transports plasma from the dayside into the nightside polar cap, is evident. Equatorward of the auroral oval a middle-latitude electron density trough occurs. All these features are consistent with previous studies of nonstorm-time and storm-time ionospheric plasma distributions [e.g., Schunk and Nagy, 1978, 2002]. The exact location of the auroral ovals and their boundaries during both nonstorm and storm times can be inferred from Figure 6a and Figure 6b. The enhanced electron density bands seen at high latitudes in these plots are produced by particle precipitation and occur in the same locations as the auroral ovals. During storm time (Figure 4b), \(F_2\) peak electron densities increase (positive storm effects) during most of the daytime in low and middle latitudes. The most significant ionospheric positive storm effects occur in the early morning sector between about 0330 and 0630 local time (LT) in middle and low latitudes. For instance, at 0600 LT and about 32.5°N, the percentage change of \(F_2\) peak electron densities is close to +200% (Figure 4c), which is a 3 times increase in electron densities. There is about a 20% to 50% increase in \(F_2\) peak electron densities in the morning sector and about a 5% to 20% increase in the afternoon sector. This set of positive storm effects continues well into the evening sector until about 2200 LT.

[23] Storm-time \(F_2\) peak electron density depletions (negative storm effects) prevail in almost the entire high-latitude region, as well as at middle and low latitudes between 2200 LT and 0300 LT (Figure 4c). Two notable exceptions to this trend occur on the dayside in middle latitudes and inside the auroral oval, where the tongue of ionization is intensified during the storm [Tsunoda, 1988]. This, in turn, leads to enhanced electron densities in the nighttime auroral zone because of the intensified storm-time ion convection pattern (Figures 4b and 4c). The occurrence of high electron densities in the auroral oval region is consistent with observations of auroral boundary blobs by radars and other measurements [e.g., Tsunoda, 1988, and references therein]. They are produced by the transportation of dayside plasma into the nightside auroral oval region by the enhanced ion convection pattern during storms. Another interesting feature of the storm-time, ionospheric electron density distribution is the deepening of the middle-latitude electron density trough seen in Figure 4a. A comprehensive review of the middle-latitude electron density trough can be found in the work of Rodger et al. [1992]. In general, the trough moves to lower latitudes and its density depletion becomes deeper in stronger storms. In this simulation study we see that nighttime \(F_2\) peak electron densities
inside the trough region are 40% to 90% lower than those during nonstorm times due to the negative storm effects (Figure 4c).

Henceforth, we will focus our discussion of the TING model simulated ionospheric and neutral fields on constant pressure levels, instead of at the $F_2$ peak or at constant heights. Figure 5 gives storm-induced percent changes of the $(O/(N_2 + O_3))$ ratio on pressure level 2.0 ($\sim$300 km) at 0000 UT. $F_2$-region electron densities are influenced by this ratio, although plasma transport effects are also important. Figure 5 illustrates that molecular-species-rich air expands into the middle latitudes during the storm. Two bulges of molecular-species-rich air occur in the evening sector just before midnight and in the morning sector before dawn. The two lowest middle-latitude electron density regions shown in Figure 4b take place in the same locations. This suggests that molecular density bulges play an important role in developing negative ionospheric storm effects and strengthening the middle-latitude trough by molecular recombination. In fact, the equatorward boundary of the electron density trough follows the outer boundary of the compositional budge quite closely in the postmidnight sector.

### 3.2. Storm-Time Electron Temperature Variations

Figure 6a shows nonstorm-time electron densities on pressure level 2.0 ($\sim$300 km) and at UT midnight. This plot is almost identical to Figure 4a, indicating that the $F_2$ peak is located near this pressure level. The $F_2$ peak occurs at altitudes where the ambipolar diffusion time is approximately equal to the time constant of plasma loss due to recombination. Ambipolar diffusion and recombination processes and the resulting $F_2$ peak heights nevertheless are more readily described on constant pressure surfaces [Rishbeth and Edwards, 1989, 1990; Rishbeth et al., 2000]. These heights, however, can be modified by other transport processes [Schunk and Nagy, 2000]. During storm times, the peak still mostly occurs on the same pressure level [Rishbeth and Edwards, 1989, 1990], but there are a few significant deviations in electron densities on the Z = 2.0 pressure surface ($\sim$300 km) from those at the $F_2$ peak which imply that transport processes have changed the pressure level on which the peak occurs. Daytime electron densities on pressure level 2.0 ($\sim$300 km, Figure 6b) are close to those at the $F_2$ peak shown in Figure 4b, but nighttime electron densities on this pressure level are significantly lower, indicating that the nighttime $F_2$ peak is located at higher pressure levels. Thus the low electron density region around midnight at low latitudes shown in Figure 6b is the result of these changes in the $F_2$ peak pressure level. This is more evident in electron density vertical profiles at local midnight (see Figure 8a and Figure 8b).

Figure 6c gives the nonstorm-time $F_2$-region electron temperatures on pressure level 2.0 ($\sim$300 km). At polar latitudes inside the auroral oval, electron temperatures are higher than those at other locations. The most distinct feature of the nonstorm-time $T_e$, however, is the “morning overshoot.” Photoelectrons produced by solar EUV radiation heat up ambient thermal electrons because of the very low electron densities in this early morning region. This heat is partitioned amongst relatively few electrons, and the energy loss to the ions and the neutrals is also not significant. Thus electron temperatures are high. This $T_e$ overshoot extends from high latitudes just outside the auroral oval to lower latitudes and is about 10 degrees wide in the zonal direction. The magnitude of the $T_e$ overshoot is related to the solar zenith angle: higher temperatures occur in lower latitudes, and the altitude of the $T_e$ peak increases with latitude (cf. Figure 11c). $T_e$ then decreases to about 1100 K through most of the daytime due to high daytime electron densities that increase the thermal electron gas heat capacity and cause enhanced energy transfer from the electrons to the ions. $T_e$ then experiences a slight increase in the dusk sector. At night, $T_e$ is further decreased and has values that are close to those of the neutral and ion temperatures. The modeled global nonstorm-time $T_e$ distribution is, in general, consistent with observations and other theoretical results [e.g., Schunk and Nagy, 1978, 2000, and references therein; Su et al., 1995; Watanabe et al., 1995]. The simulated daytime electron temperatures are, however, significantly lower than observations; this is probably caused by underestimating the daytime photoelectron heating rate and/or overestimating the daytime electron densities in the model.

During storm times $T_e$ shows significant changes on the same pressure level ($\sim$300 km, Figure 6d). $T_e$ in the auroral oval is much higher than the nonstorm-time $T_e$, and this enhanced $T_e$ zone is expanded to lower latitudes. This is expected since the auroral oval is both expanded and enhanced during the storm. During the daytime, storm-time electron temperatures are slightly lower than the equivalent nonstorm-time values in the middle and low latitudes (Figure 6c and Figure 6d) due to ionospheric positive storm effects, whereas nighttime temperatures in the same latitudes increase by about 100 K, in regions where negative storm effects also occur.

$T_e$ is significantly enhanced inside the middle-latitude trough during the storm, especially within the two lowest electron density regions, 2200 LT and 0600 LT (Figure 6b). Storm-time electron temperatures there are a factor of 2 to 4 higher than those during nonstorm-times. The highest electron temperature is close to 3800 K, whereas the nonstorm-time $T_e$ in the same region is about 900 K. The midlatitude $T_e$ enhancement extends from higher latitudes (about 62.5°N) around 2200 LT to lower latitudes at midnight ($\sim$52.5°N), then moves back to higher latitudes in the early morning. The shape of this nighttime midlatitude $T_e$ enhancement zone follows that of the midlatitude trough.

There is a $T_e$ hot spot between 52.5°N and 72.5°N just after 0600 LT. This $T_e$ hot spot occurs around the terminator in the early morning and is due to two coupled effects: depleted electron densities inside the trough and the enhanced heat fluxes from the plasmasphere after sunrise that were shown in Figure 1. For instance, at 62.5°N and 0600 LT, the nonstorm-time electron density is about $4 \times 10^5$ cm$^{-3}$, whereas the storm-time density is $4 \times 10^4$ cm$^{-3}$, which is an order of magnitude decrease in the electron density. Electron temperatures in the same region are enhanced from about 1700 K during the nonstorm time to more than 3500 K during the storm. The hot spot is found at the eastward edge of the most depleted
density region in the early morning sector. The deepest density depletion occurs before 0600 LT, whereas the highest value of $T_e$ occurs just after that time. The $T_e$ hot spot is also elongated in the meridional direction in the same way as the nonstorm-time, $T_e$ “morning overshoot” is. The simulated occurrence of electron temperature enhancements inside the ionospheric negative storm region has also been reported by Prölls et al. [1975] and Prölls [2006] using satellite measurements. In fact, these authors found a close linear relationship between the observed depletion in electron densities and the enhancement in electron temperatures.

Another distinct feature of the storm-time $T_e$ is the complete disappearance of the “morning overshoot” in the middle latitudes (Figure 6c and Figure 6d). There are still some traces of the “morning overshoot” in the lower latitudes, but they are very weak. The storm-time temperatures are only about 40% of the nonstorm-time temperatures. This difference in nonstorm-time and storm-time electron temperatures is caused by ionospheric positive storm effects. Electron densities increase by almost a factor of 3 during storm time around the morning terminator from middle to low latitudes at the $F_2$ peak and by a factor of 2 on pressure level 2.0 (~300 km, see Figure 4c, as well as

Figure 6. Electron densities ($\log_{10}[N_e(\text{cm}^{-3})]$) and temperatures (K) on pressure 2.0 (~300 km) at UT midnight. (a) Nonstorm-time electron densities, (b) storm-time electron densities, (c) nonstorm-time electron temperatures, and (d) storm-time electron temperatures.
Figures 6a and 6b). Therefore the necessary condition for the occurrence of the T_e "morning overshoot," lower ambient thermal electron densities, is significantly weakened during the storm.

[31] Electron densities and temperatures on pressure level −4.0 (≈120 km) are shown in Figure 7 for both storm and nonstorm times. On this pressure level, storm effects on electron densities are not evident globally (cf. Figures 7b and 7a). The only significant difference is that the storm-time auroral oval is expanded to lower latitudes and high electron densities occur in the auroral oval due to enhanced particle precipitation. Electrons collide frequently with the neutrals and ions on this pressure level, resulting in electron temperatures that are close to those of the neutrals (Figures 7c and 7d). The horizontal distributions of the electron temperatures follow the pattern of the neutral temperatures, which are shown in Figures 7e and 7f for nonstorm and storm times, respectively. It is also clear that tides have a strong influence on both neutral and electron temperature structures. There are two low-temperature regions in the early morning and afternoon sectors, with two high-temperature regions in the noon and night sectors. This pattern is consistent with semidiurnal tides.

[32] Electron temperatures are almost equal to neutral temperatures during nonstorm times, except at the noon in the middle to low latitudes, where electron temperatures are slightly higher than those of the neutrals. At high latitudes inside the auroral oval, electron temperatures are higher than neutral temperatures mainly due to the direct heating of electrons by precipitating particles. Both neutral and electron temperatures increase almost globally during the storm, but the semidiurnal tide pattern still dominates with a slightly reduced amplitude. A low electron temperature region occurs just outside the auroral oval around 2200 LT which does not exist during nonstorm times. This is caused by an upwelling of molecular-species-rich air forced by Joule heating below that height. When upwelling, the air expands and undergoes adiabatic cooling, lowering the neutral temperatures. This increases temperature differences between the neutrals and the electrons, enhances the energy transfer from the electrons to the neutrals, and subsequently lowers the electron temperatures.

4. Vertical Variations of the Electron Temperatures

[33] The distinct signatures of electron temperatures in the E and F regions shown in the previous section indicate that different cooling and heating processes dominate on each pressure level (at different heights). In this section we will present how these heating and cooling processes vary with local time, latitude, and altitude, and how geomagnetic storms change their global distributions.

4.1. Midnight Electron Temperatures

[34] Figure 8 illustrates local midnight and 0.0° longitude (0000 UT) electron density and temperature profiles during both nonstorm and storm times. In the lower F and E regions (below pressure level −1.0, ≈180 km) storm-time electron densities in the low and middle latitudes (<45°N) are almost the same as those during nonstorm time. The F_2 peak electron densities, on the other hand, are significantly depleted from their nonstorm time values. These are negative storm effects. For instance, at 30°N storm-time F_2 peak electron densities are about 1.6 × 10^5 cm^−2, a factor of 6 smaller than the corresponding nonstorm time values. In the auroral oval, it is evident that electron densities in the E and lower F regions are greatly enhanced and that the oval expands to lower latitudes during the storm. Inside the polar cap, in regions above about 70°, the differences between storm-time and nonstorm-time electron densities are not significant. In addition, auroral oval F_2-region electron density enhancements occur at higher altitudes and lower latitudes during the storm. A steep density gradient occurs between the middle-latitude density trough and the auroral oval density enhancements. The lowest F_2 electron densities occur in the middle-latitude electron density troughs for both nonstorm and storm times. The storm-time trough, however, occurs at lower latitudes and higher altitudes with an electron density that is less than 20% of its nonstorm time value. Furthermore, a high-latitude electron density trough occurs just at the inner edge of the auroral oval during the storm, a phenomenon that was called the high-latitude electron density trough by Rodger et al. [1992].

[35] Ionospheric F_2-region electron temperatures are, in general, anticorrelated with electron densities, since the energy loss to the ions is proportional to the electron density. Therefore storm-time, F_2-region electron temperatures at this local time are, in general, higher than those during nonstorm times (Figures 8c and 8d) due to the depleted storm-time electron densities. At lower and middle latitudes in the lower F and E regions, electron temperatures are higher than those during nonstorm times (cf. Figures 6c and 6d). The electrons are in thermal balance with the neutrals and the ions because of the high collisional frequencies in this altitude range, but both the neutrals and ions are considerably warmer than they are during nonstorm times.

[36] Highest temperatures occur at the inner edge of the auroral oval, with the storm-time F_2-region T_e being more elevated. This temperature enhancement is located in the electron density depletion region where the high-latitude trough occurs [Rodger et al., 1992]. Electron temperatures are also greatly enhanced inside the middle-latitude trough around 45°N during the storm. This latitudinal double peak structure of the storm-time electron temperatures is consistent with observations by the DE 2 satellite [e.g., Horwitz et al., 1986]. In nonstorm times, F_2-region electron temperature are much less enhanced on the inner edge of the auroral oval, and the T_e peak in the middle-latitude F_2 region almost totally disappears [e.g., Brace and Theis, 1981].

[37] Electron heating and cooling rates are plotted for the same longitude and UT in Figure 9. The values of cooling rates for each species shown in the plots are the sum of all cooling processes affecting each individual species. Thus the electron cooling rates of N_2 and O_2 are the sum of cooling by elastic collision and cooling by rotational and vibrational excitation of N_2 and O_2, respectively. The electron cooling rate of O is the sum of cooling by elastic collisions, electronic excitation, and fine structure excitation of O, respectively. The dominant heating process is the direct particle heating inside the auroral oval (Figures 9a and 9b) since there is no photoelectron heating at night. The
Figure 7. Electron densities ($\log_{10}[N_e (\text{cm}^{-3})]$), electron and neutral temperatures (K) on pressure $-4.0$ ($\sim 120 \text{ km}$) at UT midnight. (a) Nonstorm-time electron densities, (b) storm-time electron densities, (c) nonstorm-time electron temperatures, (d) storm-time electron temperatures, (e) nonstorm-time neutral temperatures, and (f) storm-time neutral temperatures.
storm-time particle heating rate is almost a factor of 4 higher than its nonstorm-time value. The highest heating rate occurs at a lower altitude during the storm since the precipitating electrons are more energetic and thus can penetrate deeper into the atmosphere. The region of particle heating is also much broader and moves to lower latitudes during the storm. The electron temperature peak, however, occurs in the $F_2$ region for both nonstorm and storm times (Figure 8c and 8d). There is a noticeable increase in $T_e$ in the upper $E$ and lower $F$ regions above pressure level $4.0$ ($\sim 120$ km) in the auroral oval during the storm (see also Figure 6d). Nevertheless, the rapid collision between the electrons and the neutrals in these regions leads to a fast energy loss of the thermal electrons and thus prevents any significant temperature enhancement from occurring at the peak altitude of particle heating (Figures 9b, 9f, and 9j).

Particle heating, which primarily occurs below 150 km, is balanced primarily by electron energy loss to $N_2$ and $O$ (Figures 9c–9j) for both nonstorm and storm times. Cooling by collisions with $O_2$ during nonstorm time is roughly 20% of that with $O$, and this cooling is increased to about 25% of the cooling by collisions with $O$ during storms. The relative increase in electron energy loss to the molecular components of the thermosphere in the auroral region during the storm is related to the upwelling of the molecular-species-rich air resulting from auroral zone Joule heating. However, there are significant uncertainties in the cooling coefficients currently used [e.g., Richards et al., 1986; Bailey et al., 1987; Moffett, 1988]. Thus the relative contributions of cooling processes by each species to the thermal electron energy budget may vary significantly if a different set of cooling coefficients is used in the simulation.

Heat conduction and cooling by collisions with the ions are only a minor factor in the electron energy budget in the high-latitude $E$ and lower $F$ regions (below pressure level 0.0, $\sim 220$ km) for both nonstorm and disturbed conditions, even though small amounts of heat are transferred from the ions to the electrons during storms in this region (2 orders of magnitude lower than the direct particle heating) (Figure 9l). Therefore the dominant processes for the electron energy balance in this region at this local time are cooling by collisions with the neutrals and heating by precipitating particles. This energy balance leads to an
[40] Electron temperatures have significant latitudinal and height variations in the $F_2$ region above pressure level 0.0 (≈220 km, Figure 8 and Figure 4). Cooling by collisions with molecular species is, in general, not as important as it is in the $E$ region due primarily to the decrease of neutral densities at these heights (Figure 9). However, in regions of

**Figure 9.** Thermal electron heating and cooling rates (eV cm$^{-3}$ s$^{-1}$) at local midnight and 0.0$^\circ$ longitude (0000 UT) (solid lines are for values greater than or equal to zero, dashed lines are for values less than zero). (a) Nonstorm-time total electron heating, (b) storm-time total electron heating, (c) nonstorm-time heat conduction, (d) storm-time heat conduction, (e) nonstorm-time N$_2$ cooling, (f) storm-time N$_2$ cooling, (g) nonstorm-time O$_2$ cooling, (h) storm-time O$_2$ cooling, (i) nonstorm-time O cooling, (j) storm-time O cooling, (k) nonstorm-time ion heat transfer rate, and (l) storm-time ion heat transfer rate.
intense Joule heating during storms, upwelling of molecular species occurs, and cooling by molecular species plays an important role in the overall electron energy balance (Figure 9e and Figure 9f). Because of the high plasma densities and because atomic oxygen is the dominant neutral species there, energy exchanges between the electrons and the ions and the electrons and atomic oxygen are the primary cooling processes for thermal electrons in the $F_2$ region (Figure 9i to Figure 9l). Heat conduction also shows significant variations in the middle- and high-latitude $F_2$ regions, especially during the storm time, caused by the complicated electron temperature altitude profiles in these regions.

[41] Figure 10 shows storm-time electron heating and cooling rates on pressure level 2.0 ($\sim$300 km) at midnight. Total heating in Figure 10, as well as in Figure 13, includes both photoelectron heating and heating by particle precipitation. Heating by particle precipitation occurs only at high
ion temperatures. This drives heat exchange from the ions to the neutral gas (and thermal electrons). Thus Joule heating is the total electromagnetic energy that is dissipated in the thermosphere-ionosphere system [Kelley, 1989]. Joule heating and frictional heating warm up the neutrals and the ions more efficiently than the electrons. Thus collisions between the ions and the electrons result in energy transfer from the ions to the electrons, in contrast to other regions in the ionosphere where electron temperatures are normally higher than ion temperatures, and heat flows from the electrons to the ions. This reverse energy transfer from the ions to the electrons was also reported by Moffett et al. [1998]. They investigated a significant ion frictional heating event caused by SAIDs occurring inside the middle-latitude electron density trough and the subsequent energy transfer from the ions to the electrons.

[43] This electron heating by the ions is balanced by the cooling due to heat conduction to lower altitudes and collisions with O and N\textsubscript{2}. The contributions from electron collisions with O and N\textsubscript{2} are about equal in this latitudinally very narrow region around 70\degree N. In general, collisions with the ions and atomic oxygen are the most important energy loss processes for the electrons in the F\textsubscript{2} region; cooling by collisions with N\textsubscript{2} is insignificant since densities of molecular species drop rapidly with altitude. However, during storms, molecular-species-rich air can move upward from lower altitudes into the F\textsubscript{2} region, and thus the contribution to the electron energy balance from the electron energy loss due to collisions between the electrons and neutral molecular species becomes relatively significant (see Figure 10 at about 70\degree N).

### 4.2. Morningside Electron Temperatures

[44] Figure 11 illustrates altitude-latitude contours of electron densities and temperatures in the early morning (0600 LT and 0000 UT) for both nonstorm and storm times. These profiles exhibit significantly different features at this local time compared with those at midnight (Figure 8). Below pressure level ~2.0 (~160 km), nonstorm and storm-time electron densities look very similar. In the F\textsubscript{2} region, however, electron density distributions are significantly different. Storm-time T\textsubscript{e} peak electron densities are a factor of 2–3 larger than those during the nonstorm time at lower latitudes. This corresponds to positive storm effects. F\textsubscript{2} region negative storm effects occur at latitudes higher than about 45\degree N. A deep electron density trough, with electron densities less than 6.0 \times 10\textsuperscript{4} cm\textsuperscript{-3}, appears at about 60\degree N. This electron density is about a factor of three lower than that of the nonstorm time case. This corresponds to the morningside midlatitude electron density trough shown in Figure 6b and is consistent with observations [e.g., Moffett and Quegan, 1983; Rodger et al., 1992].

[45] Electron temperature profiles at this local time are significantly different from those at local midnight. The F\textsubscript{2} region electron temperature “morningside overshoot” is evident in almost all latitudes during nonstorm times. The same T\textsubscript{e} peak also occurs at low latitudes (~20\degree N) at a slightly lower altitude during the storm, though with significantly lower temperatures due to positive ionospheric effects (Figures 11c and 11d). The high electron densities associated with positive storm effects between 20\degree N and 45\degree N, however, completely destroy the “morningside overshoot” effect.
there during storms. Photoelectron heating rates are almost the same in the low and middle latitudes for both storm and nonstorm conditions (Figures 12a and 12b); thus the simulated variations in electron temperatures are caused primarily by changes in electron densities. This storm-time enhancement in electron densities lowers the electron temperatures in two ways: enhanced collisions with the ions and the neutrals lead to more energy loss, and a higher thermal electron gas heat capacity that requires more energy to heat up the electrons.

There is a very broad region of electron temperature enhancements that is centered at about 60°N (cf. Figure 6d). These temperature enhancements are associated with the middle-latitude electron density trough and have a steeper gradient at the poleward boundary than on the low-latitude edge. This is related to the latitudinal distribution of electron densities. The electron density gradient is larger on the poleward side of the trough than on the equatorward side (cf. Figure 11b). The high electron temperature is the result of the combined effects of downward heat conduction from the plasmasphere and the low electron density in the trough region that lowers the thermal electron gas heat capacity (cf. Figure 12d) and reduces the energy loss to the ions and the neutrals. Also, electron densities on the bottomside of the $F_2$ region are much smaller than those at the $F_2$ peak; hence the amount of heat that is conducted downward to the lower ionosphere is limited. Another high electron temperature region occurs at the poleward boundary of the auroral oval, which is produced by the energy transfer from the ions to the electrons that was discussed in the previous section. Electron temperatures in the $E$ and lower $F$ regions below pressure level −2.0 (−160 km) do not change much from low to high latitudes and there are no significant variations between storm-time and nonstorm-time values.

Profiles of electron heating and cooling rates are shown in Figure 12. Daytime heating by photoelectrons is about the same for both nonstorm and disturbed conditions, as expected. Direct heating by precipitating particles is enhanced at high latitudes in the $E$ region during the storm. This enhanced heating, however, does not significantly increase local electron temperatures due to the frequent collisions between the electrons and the neutrals and thus enhanced energy loss to the neutrals (Figures 12f and 12j), as discussed in section 4.1. Particle heating is balanced almost entirely by energy loss to atomic oxygen and molecular nitrogen with negligible contributions from loss to molecular oxygen. This energy balance results in an electron temperature that is very close to the neutral temperature, and thus there are no significant variations in electron temperatures in the ionospheric $E$ region even under disturbed conditions. In the $F_2$ region, however, photoelectron heating is mostly balanced by the energy loss to the ions.

Figure 11. Same as Figure 8, but for 0600 LT.
nonstorm times the energy loss to neutral molecular species also contributes to the general energy budget (Figures 12e and 12g). During storm times, however, contributions to electron cooling from the energy loss to molecular species are reduced at this local time (Figures 12f and 12h).

[48] Heat conduction shows remarkable changes under different geophysical conditions at this local time. During nonstorm times, in the lower and middle latitudes, the latitudinal and vertical variations of $T_e$ give rise to (Figure 12c) heating by thermal conduction at higher altitudes and lower latitudes and cooling at lower altitudes and higher latitudes. This pattern is consistent with the temperature profiles shown in Figure 11c, which are, in turn, controlled by solar zenith angle variations. Bailey et al. [1981, 1987] also found that in daytime, heat conduction produces net heating in the lower $F$ region and cooling near the $F_2$ peak. During the storm, however, there are almost no $T_e$ variations in the same region and thus these is

Figure 12. Same as Figure 9, but for 0600 LT.
little net heat conduction as positive storm effects almost completely remove the electron temperature "morning overshoot." At high latitudes, heat conduction plays a crucial role in shaping the storm-time $T_e$ profile. Heat is transported downward inside the electron density trough and enhances electron temperatures at lower heights (Figure 11d). It is also interesting to note that significant heat conduction occurs only above about pressure level $2.0$ ($\sim 160$ km) because the relatively low electron densities below this pressure surface prevent heat from being conducted further down to lower altitudes.

[49] Figure 13 illustrates storm-time electron heating and cooling rates on pressure level $2.0$ ($\sim 300$ km) in the morning sector (0600 LT). It is evident that heating by photoelectrons is the dominant process from low latitudes to about $55^\circ$N. This heating is balanced primarily by the energy loss to the ions, with a minor contribution from the loss of energy to atomic oxygen. In the electron density
trough region around 60°N, where electron temperatures are high, the electron energy balance is more complicated. Heat conduction and molecular cooling appear to be the dominant processes. Ion densities are low there, so less energy is transferred to the ions. In the auroral oval, heating by precipitating electrons and heat conduction are the primary heat sources, with cooling to the ions and atomic oxygen balancing them (Figure 11b). At even higher latitudes, energy transfer from the ions begins to dominate, a process that has been discussed in detail in section 4.1 (Figure 10).

4.3. Electron Temperatures Inside Midlatitude Electron Density Trough

[50] Figure 14 shows storm-time height profiles of electron densities (Figure 14a) and temperatures (Figure 14b) at 2200 LT and 30°W (0000 UT). The dashed and dotted lines show the latitudinal positions of the T_e peak and N_e minimum on pressure level 2.0 (~300 km), respectively. On this pressure level (shown in Figure 15), significant electron density depletions and temperature enhancements occur in the middle latitudes. The T_e peak occurs on TING model grid point at 47.5°N and N_e at 50.8°N. There are three distinct electron density regions in Figure 14. Between 32.5°N and 52.5°N, electron densities decrease when moving poleward and the F_2 peak becomes less pronounced compared with densities below and above the peak. In addition, no apparent F_2 peak can be seen in the trough region. At high latitudes (>52.5°N), nighttime auroral electron density enhancements or boundary blobs occur in the F region. There are also E region electron density peaks produced by precipitation particles under the boundary blobs.

[51] Figure 16 illustrates electron heat conduction and electron cooling by collisions with the ions at the same longitude equatorward of 55°N. In this region, electron temperatures are higher than ion temperatures; thus collisions between the electrons and the ions result in a net energy loss from the electrons or a “cooling to ions” process. Other heating and cooling sources are not shown here since they are less important inside the trough region.

In addition, high-latitude cooling due to collisions with the ions above 55°N, which is not our present focus, is not shown in this plot as the high values there dominate lower-latitude features. As expected, in the F_2 region, cooling by collisions with the ions dominates outside the trough region, at latitudes equatorward of about 47°N and poleward of about 52°N (Figure 16b). However, there is almost no energy loss to the ions inside the trough due to the depleted electron densities there.

[52] It is evident from both Figure 14b and Figure 15 that equatorward of 45°N electron temperatures are significantly lower than those inside the trough and a steep temperature gradient occurs at about 47.5°N. The high-latitude decrease of electron temperature is more gradual due to the presence of other heating sources as we have discussed in previous sections. The electron temperature peak inside the trough is produced by heat flux from the upper boundary. A constant downward heat flux is assumed to simulate the external heat source from the plasmasphere. The thermal electron gas heat capacity is low due to the depleted electron densities there, and thus local energy loss to the ions is also insignificant. High electron temperatures occur at a particular height as soon as the heat that is conducted from higher altitudes dominates over the local heat loss. Heat is then conducted downward from this height to lower altitudes.

Figure 13. Same as Figure 10, but for 0600 LT.

Figure 14. (a) Electron densities (log_{10}[N_e(cm^{-3})]) and (b) temperatures (K) at 2200 LT and 30°W (0000 UT).
The electron temperature peak is displaced slightly from the nadir of the density trough: it occurs in the equatorward edge of the trough. This displacement is the result of electron density profile and its associated heat conductivity. Figure 17 shows electron density and electron thermal conductivity coefficient vertical profiles at two latitudes inside the trough, 47.5°N corresponding to the location of the $T_e$ peak on pressure level 2.0 ($\sim$300 km), dashed lines in Figures 14 and 16), and 50.8°N, the location of the $N_e$ minimum on the same pressure level (dotted lines in Figures 14 and 16). At 47.5°N, electron densities are only about $8.0 \times 10^3$ cm$^{-3}$ on pressure level 0.0 ($\sim$220 km) and the surrounding pressure levels (heights) at this latitude, resulting in a very low thermal conductivity. Thus energy is not easily conducted downward to lower altitudes. The lower $F$ region ionosphere thus serves as a thermal barrier or insulator preventing the heat being transferred to regions where it can easily be lost to the neutrals. At 50.8°N, however, electron thermal conductivity coefficient remains very high at lower altitudes due to ionization in the lower $F$ and $E$ regions ($2.5 \times 10^4$ cm$^{-3}$ on pressure level 0.0 ($\sim$220 km), Figure 14b). These electrons conduct heat to lower altitudes from higher altitudes, resulting in a greater heat loss from the $F_2$ region and hence relatively low electron temperatures at the $F_2$ peak. Therefore the location of the electron temperature peak is related to how rapidly the heat can be conducted out of the high-temperature regions. At the equatorward edge of the trough, electron densities are sufficiently low in the $F_2$ region, so they do not allow much energy loss to the ions, and electron densities are also very low on the bottom side of the $F_2$ region so heat can not be readily conducted to lower altitudes. This lack of a loss mechanism results in high electron temperatures in the equatorward edge of the trough.

5. Discussion

Thermal electrons are heated primarily by photoelectron heating, particle heating, energy transfer from the ions and heat conduction. Each of these heating processes responds differently to geomagnetic activity. The impact of geomagnetic storms on photoelectron heating is very limited (see Figure 12a and Figure 12b), if solar EUV fluxes do not change during these storms. The storm-time variation of this heating comes from thermospheric density changes that affect daytime photoionization rates. On the other hand, heating by particle precipitation is greatly enhanced during the storm. It occurs in a larger area and extends to much lower latitudes with significantly larger magnitudes. This heating, however, happens mainly in the $E$ and lower $F$ region. It is largely balanced by an increased energy transfer from the electrons to the neutrals and hence does not significantly increase local electron temperatures. At high latitudes, storm-time ion temperatures can be very high in a very narrow region of intense ion frictional heating. The ion temperatures sometimes exceed electron temperatures. This leads to a temperature difference between the ions and the electrons and an energy transfer from the ions to the electrons.

Heat conduction in the model includes two processes: heat transfer along the field lines from high-temperature regions to low-temperature regions inside the modeled ionospheric domain and a heat flux that transfers heat from the high-temperature plasmasphere to the low-temperature...
Figure 17. Vertical profiles of electron densities (log10[N_e (cm^-3)]), solid lines) and thermal electron heat conductivity coefficient (log10[K_e (eV cm^-1 s^-1 K^-1)]), dashed lines) at 2200 LT and 30°W (0000 UT).

ionosphere. In this study, only heat conduction along the magnetic field lines is considered; heat conduction perpendicular to the magnetic field lines is neglected. There are significant changes in heat conduction during storms, and heat conduction is one of the major factors determining the shape of electron temperature profiles in regions such as the middle-latitude trough. Heat flux from the plasmasphere is an important source of energy for nighttime thermal electrons. There might be a significant enhancement in the heat flux magnitude during the storm, as suggested by some authors [Kozyra et al., 1986; Horwitz et al., 1986; Green et al., 1986; Brace et al., 1988]. However, our results imply that even without increasing the storm-time heat flux, electron temperatures are considerably enhanced in the equatorward edge of the midlatitude trough.

Changes of cooling rates during the storm are related to the variations in electron densities and neutral densities. The impact of these variations on electron temperatures is threefold: changes in thermal electron gas capacity, changes in energy losses to the ions and neutrals, and changes in thermal heat conductivity. The almost total disappearance of the F_2 region electron temperature “morning overshoot” during the storm is the effect of increasing thermal electron gas heat capacity and the loss of energy to the ions through collisions in the positive storm effect region. The same processes can also be seen at work in the middle-latitude trough region. With a depleted electron density, the thermal electron gas has a lower heat capacity and there is less energy loss to the ions in the F_2 region, electron temperature is thus significantly increased inside the trough. The location of the temperature peak in the trough region, however, is determined by the heat conductivity of the underlying lower F and upper E region electrons. The relatively low electron densities at the equatorward edge of the trough in these regions decrease the heat conduction to lower altitudes and thus maintain the high electron temperatures in the F_2 region.

The thermosphere acts as an energy sink for the thermal electrons. Energy transfer from the electrons to the neutrals depends on the relative differences between electron and neutral temperatures. Joule heating heats up the thermosphere at high latitudes; this changes global neutral wind circulation, inducing downwelling and thus compressional heating in the middle and lower latitudes [Richmond, 1979]. This thermospheric heating process occurs in less than 9 hours after storm commencement [Burns and Killeen, 1992]. The global increase in thermospheric temperature limits energy transfer from the electrons to the neutrals and so increases electron temperatures. The strong response of thermospheric winds to geomagnetic storms drives divergent and convergent flows that induce upwelling (cooling) and downwelling (heating) of the air, resulting in decreased and increased neutral temperatures, respectively. Electron temperatures exhibit the same pattern of variations with the storm. This occurs primarily in the lower F and E regions, where neutral densities are sufficiently high that the collisions between the electrons and the neutrals are the major energy loss process for the electrons. We also observe that storm-induced neutral density changes affect the relative contributions of neutral species to the electron energy balance, although these contributions in the F region are, in most places, not significant compared with other cooling processes.

6. Conclusions

We have introduced an electron energy postprocessor for the TING model. It is used here to study the behavior of ionospheric electron temperatures during geomagnetic storms, and the storm-time changes of heating and cooling processes that cause this electron temperature behavior. In this study, we kept our storm-time, plasmaspheric electron heat fluxes at the top boundary the same as during quiet conditions; thus storm-time electron temperature variations seen in the simulation are the result of the response of the thermosphere-ionosphere system to high-latitude energy and momentum inputs (i.e., enhanced ion convection and particle precipitation during the storm). It is also worthwhile to note that the lack of both observational and theoretical data of the global topside ionospheric electron heat flux leads to uncertainties in specifying the top boundary conditions for the electron energy equation solved in the TING model. These uncertainties may affect the simulation results and our understanding of the complicated behavior of the ionospheric electron temperatures during both nonstorm and storm periods.

We found the following:

1. Significant changes in F_2 region electron temperatures occur during geomagnetic storms. Electron temperatures increase in regions where ionospheric negative storm effects occur and decrease in regions where ionospheric positive storm effects take place.

2. Inside the auroral oval, a zone of enhanced electron temperatures occurs. This zone of high temperatures expands to lower latitudes during the storm. It is caused by heat transfer from the ions to the electrons. Storm-time, ion frictional heating produces high ion temperatures and thus a significant amount of heat is transferred from the ions to the electrons. This heating is partially balanced by enhanced energy loss to atomic oxygen and molecular nitrogen.
[62] 3. Cooling by collisions between the electrons and molecular nitrogen is normally a minor factor in the $F_2$ region. However, in regions of intense Joule heating the upwelling of molecular-species-rich air to higher altitudes increases the mixing ratio of the molecular nitrogen there and thus its importance in the overall local electron energy balance. The increase of molecular-species mass mixing ratio enhances collisions between the neutrals and the electrons. Thus energy transfer from the electrons to the neutrals also increases.

[63] 4. An electron temperature enhancement is seen at the equatorward edge of the midlatitude electron density trough during the geomagnetic storm. As the heat flux from the plasmasphere has not changed in this simulation, this temperature increase is caused mainly by two factors: the depleted $F_2$ region electron densities during the storm which lower the thermal electron gas heat capacity and prevent energy from being lost locally to the ions; and a very low heat conduction in the lower $F$ region that limits the amount of heat that is conducted to lower altitudes and lost to the neutrals.

[64] 5. The electron temperature “morning overshoot” in the early morning sector disappears in the middle latitudes and is greatly weakened at lower latitudes during the storm. This reduction is caused by the positive storm effects, since enhanced electron densities increase both the thermal electron gas heat capacity and the energy loss to the ions. A $T_e$ hot spot occurs in the morning sector at high latitudes. It is produced by the increased daytime heat flux from the plasmasphere and the depleted electron densities there due to negative storm effects.

[65] 6. Storm-time electron temperatures are enhanced in the $E$ region in the high-latitude auroral region due primarily to the greatly enhanced heating by particle precipitation. The magnitude of this electron temperature enhancement is, however, not as pronounced as it is in the $F$ region. High collision frequencies between the electrons and the neutrals in this region result in a rapid electron cooling. The neutral species involved are atomic oxygen and molecular nitrogen. Storm-time electron temperatures increase by less than 30 K in most of other locations at the upper $E$ region height on pressure level $\sim 4.0$ ($\sim 120$ km). This reflects the overall increase of neutral and ion temperatures during the storm. In addition, the global distribution of $E$ region electron temperatures roughly follows the neutral temperature tidal pattern. There is also a region of low electron temperatures in the evening sector just outside the auroral oval during storms. This region is associated with lower neutral temperatures caused by the cooling of the neutral gas as it expands as a result of Joule heating.

[66] In this study, very simple and steady high-latitude inputs are used to illustrate the characteristic changes of ionospheric electron temperatures during storms. Future studies will involve simulating electron temperature variations in real events and comparing model results with observations. We are also working on coupling our model with a physics-based plasmasphere model so a time-varying, global distribution of the electron heat flux from the plasmasphere can be obtained and applied to our model top boundaries. We will also simulate solar cycle and seasonal variations of the electron temperature response to geomagnetic storms.

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A. G. Burns, T. L. Killeen, and W. Wang, High Altitude Observatory, National Center for Atmospheric Research, 3080 Center Green, Boulder, CO 80301, USA. (aburns@ucar.edu; killeen@ucar.edu; wbwang@ucar.edu)