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Research paper

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

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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) includes 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. (2014). 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 min, 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.

1. Introduction

Electron and ion temperatures strongly affect the ionosphere–thermosphere system because they control many chemical and physical processes (Schunk and Nagy, 2009); 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" (MaClure, 1971; Oyama et al., 1996) and an evening enhancement (Fukao et al., 1991). These morning and evening enhancements are mainly caused by the photoelectron heating of the low-density thermal electrons at dawn and dusk (Dalgarno et al., 1963; Rosa, 1966; Otsuka et al., 1998). 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 (Lei et al., 2007). Truhlik et al. (2009) 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 (Wang et al., 2006). The high-latitude T_e is strongly affected by the polar heat flux and field-aligned current (FAC) (Schunk and Sojka, 1986). A downward polar heat flux can affect the electron density and temperature near the F-region and above (David et al., 2011). Upward (Downward) FACs increase (decrease) T_e at altitudes higher than the F-region maximum (Zhang and Kamide, 2003).

Banks (1967) 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 (Schunk and Sojka, 1962). They also found that an upward

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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 (Wang et al., 2006). 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 the frictional heating with neutrals below 400 km at high latitudes (Thayer and Semeter, 2004).

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 (Schunk and Sojka, 1986; Schunk, 1988; Sojka, 1989; David et al., 2011). 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 (Millward et al., 1996). SAMI2 solves similar ion and electron energy equations in field-aligned coordinates with a semi-implicit method (Huba and Joyce, 2000). 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 (Observatory, 2011; Wang et al., 2006).

Since the early 1980s, radar and rocket observations have been used to study the ionospheric dynamics during substorms (Baumjohann et al., 1981; Inhester et al., 1981; Opgenoorth et al., 1990). Maehlum et al. (1984) 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 (Svenes et al., 1992a). The F-region T_i measured by EISCAT UHF-radar was found to be dominated by the local electric field (Svenes et al., 1992b). During the expansion phase of an isolated substorm, both T_e and N_e were strongly enhanced (Yeoman et al., 2000). Although the thermal response of the ionosphere during a substorm has been greatly studied, there have been few studies using the 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 (Clausen et al., 2014; Liu and Ridley, 2015) 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 (Ridley et al., 2006). 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 (1995), as described by Vichare et al. (2012). Different models of high-latitude potential and aurora precipitation are allowed in GITM. In this study, the Weimer (2005) model was used for the high-latitude electric fields, and the Fuller-Rowell and Evans (1987) model was employed to 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 (Schunk and Walker, 1970)

$$\frac{3}{2}\kappa n_e\frac{\partial T_e}{\partial t} = -\kappa n_e T_e\nabla\cdot\boldsymbol{u_e} - \frac{3}{2}N_e\kappa\boldsymbol{u_e}\cdot\nabla T_e - \nabla\cdot\boldsymbol{q_e} + \Sigma Q_e, \tag{1}$$

where κ is the Boltzmann constant, n_e is the electron density, T_e is the electron temperature, $\boldsymbol{u_e}$ is the electron velocity, $\boldsymbol{q_e}$ is the heat flow vector, t is time and z is altitude. The terms on the right-hand side of Eq. (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. In this model, the adiabatic heating/cooling is neglected. The heat flow vector is expressed as

$$\boldsymbol{q_e} = -\chi\boldsymbol{J}_{\parallel} - \lambda_e\nabla T_e. \tag{2}$$

where χ is the thermoelectric coefficient, $\chi = \frac{5}{2}\kappa T_e/e$ (Schunk and Walker, 1970) 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

$$\frac{3}{2}\kappa n_e\frac{\partial T_e}{\partial t} = -\frac{3}{2}\kappa n_e u_e\frac{\partial T_e}{\partial r} + Q_{J_{//}} + Q_{conduction} + \Sigma Q_e \tag{3}$$

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

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

Since the electron thermal conduction primarily occurs along magnetic field lines (Schunk and Sojka, 1986), 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 is implemented. Projecting the field-aligned conduction to spherical coordinates gives