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Hemisphere-coupled modeling of nighttime medium-scale traveling ionospheric disturbances

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Abstract

Nighttime medium-scale traveling ionospheric disturbances (MSTIDs), which have tilted frontal structures in the midlatitude ionosphere, are investigated by the midlatitude ionosphere electrodynamics coupling (MIECO) model in this study. It has been proposed that the electrodynamic coupling between the *E* and *F* regions plays an important role in generating MSTIDs within a few hours. An intriguing aspect of MSTIDs is that they were simultaneously observed at magnetic conjugate locations in the Northern and Southern Hemispheres. In order to study the hemisphere-coupled electrodynamics, the MIECO model has been upgraded to consist of two simulation domains for both hemispheres in which the electrostatic potential is solved by considering electrodynamics in both hemispheres. The simultaneous occurrence of MSTIDs at the magnetic conjugate stations has clearly been reproduced when the *F*-region neutral wind satisfies the unstable condition in both hemispheres and a sporadic-*E* layer is given only at the Northern (summer) Hemisphere. Even if the unstable condition is satisfied in the summer hemisphere, an unfavorable *F*-region neutral wind in the winter hemisphere largely suppresses the growth of MSTIDs in both hemispheres.

Keywords: Midlatitude ionosphere; *E*–*F* coupling; MSTID; Sporadic-*E* layer; Perkins instability

1. Introduction

Ionospheric plasma density irregularities are known to cause scintillation on satellite signals and errors in positioning/navigation systems. It has been expected to understand ionospheric physics and to forecast such irregularities from the "space weather" point of view. However, some ionospheric phenomena frequently occur even during a low solar/geomagnetic activity condition, which is difficult to forecast based on solar and magnetospheric observations. One of such phenomena is nighttime medium-scale traveling ionospheric disturbances (MSTIDs) and associated plasma density irregularities in the midlatitude ionosphere (e.g., Tsunoda, 2006 and references therein). Two-dimensional characteristics of MSTIDs have been identified by GPS-TEC maps (e.g., Saito et al., 2001) and all-sky airglow imagers (e.g., Miller et al., 1997). One of the important aspects of MSTIDs is their frontal structures which are not elongated along the magnetic meridian but from northwest to southeast (NW-SE) (northeast to southwest; NE–SW) in the Northern (Southern) Hemisphere, and southwestward (northwestward) propagation with a velocity of approximately 100 m s^{-1} (e.g., Saito et al., 2001). Another important finding on MSTIDs is that they were simultaneously observed by all-sky imagers at magnetic conjugate locations in the Northern and Southern Hemispheres and their crests and troughs matched very well (Otsuka et al., 2004; Shiokawa et al., 2005). It suggests that nighttime MSTIDs are not simply caused by gravity wave modulation but by electrodynamic forces which act on a magnetic flux tube.

Regarding the generation mechanism of MSTIDs, Perkins instability is the only mechanism that can explain the tilted NW–SE plasma density structures in the

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Northern Hemisphere (Perkins, 1973). The linear growth rate of the Perkins instability can be written as

$$\gamma = \frac{|\mathbf{E}| \cos I}{BH} \sin(\theta - \alpha) \sin \alpha \tag{1}$$

where $\mathbf{E} = \mathbf{E}_0 + \mathbf{U}^F \times \mathbf{B}$ is the total effective electric field, $\mathbf{E}_0$ is the background electric field, $\mathbf{U}^F$ is the F-region neutral wind, $\mathbf{B}$ is the geomagnetic field with a strength of B, I is the magnetic inclination angle, H is the atmospheric scale height, θ is the angle between $\mathbf{E}$ and the magnetic east direction, and α is the angle between the direction normal to the frontal structure and the magnetic east direction with the maximum γ occurring where $\alpha = \theta/2$. In order to sustain the nighttime ionosphere against the gravitational acceleration, eastward $\mathbf{E}_0$ or southward $\mathbf{U}^F$ is required, and additional northward $\mathbf{E}_0$ or eastward $\mathbf{U}^F$ makes the NW-SE frontal structure unstable. In the Southern Hemisphere, the NE-SW structure becomes unstable by southeastward $\mathbf{E}_0$ or northeastward $\mathbf{U}^F$. Modeling studies on the Perkins instability successfully reproduced the tilted structures from random perturbation (Miller et al., 1996; Yokoyama et al., 2008), but the growth rate of the Perkins instability itself is too small compared with the growth of typical MSTIDs.

In the last decade, the electrodynamic coupling process between the ionospheric E and F regions has been considered as an important factor to accelerate the growth of the Perkins instability (e.g., Cosgrove and Tsunoda, 2004; Tsunoda, 2006). The key mechanisms for the coupling process are the Perkins instability and the so-called sporadic-E(E_s)-layer instability (Cosgrove and Tsunoda, 2002), both of which can account for the NW–SE plasma density structures. The series of modeling studies successfully reproduced the fast growth of the tilted frontal structures of MSTIDs through the E_s-layer and Perkins instabilities (Yokoyama et al., 2009; Yokoyama and Hysell, 2010). The recent version developed by Yokoyama and Hysell (2010) is named as the midlatitude ionosphere electrodynamics coupling (MIECO) model which can simulate the coupling process between the E and F regions with dipole magnetic field lines in a domain of 10° longitude and 20° latitude coverage. However, the previous modeling studies deal with the Northern Hemisphere only, which means that the model domain is implicitly coupled with the Southern Hemisphere with symmetrically identical conditions for both the E and F regions. As the occurrence of E_s layers and MSTIDs is largest in summer, the symmetric background condition in both hemispheres is not realistic. In order to investigate the conjugate occurrence of MSTIDs (Otsuka et al., 2004; Shiokawa et al., 2005), the MIECO model is upgraded to consist of two simulation domains for both hemispheres and is now able to study the hemisphere-coupled electrodynamics.

2. Model description

The numerical model used in this study is an upgraded version of the midlatitude ionosphere electrodynamics coupling (MIECO) model developed by Yokoyama and Hysell (2010). The governing equations and numerical schemes are the same as the previous version:

$$\frac{\partial N_j}{\partial t} + \nabla \cdot (N_j \mathbf{V}_j) = S_j \tag{2}$$

$$e(\mathbf{E} + \mathbf{V}_j \times \mathbf{B}) + M_j g - \frac{\nabla(N_j k_B T)}{N_j} + M_j \nu_{jn}(\mathbf{U} - \mathbf{V}_j) = 0 \tag{3}$$

$$-e(\mathbf{E} + \mathbf{V}_e \times \mathbf{B}) + M_e g - \frac{\nabla(N_e k_B T)}{N_e} + M_e \nu_{en}(\mathbf{U} - \mathbf{V}_e) = 0 \tag{4}$$

$$\nabla \cdot \mathbf{J} = \nabla \cdot \left[e \left(\sum_j N_j \mathbf{V}_j - N_e \mathbf{V}_e \right) \right] = 0 \tag{5}$$

where j stands for each ion species (Fe^+, NO^+, and O^+), N_j, e is the ion/electron density, $\mathbf{V}_{j,e}$ is the ion/electron velocity, S_j represents the chemical terms, e is an electron charge, $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the dipole magnetic field, $M_{j,e}$ is the ion/electron mass, g is the gravitational acceleration, k_B is the Boltzmann constant, $T = T_j = T_e$ is the ion/electron temperature (isothermal condition), $\nu_{jn,en}$ is the ion/electron collision frequency with neutrals, $\mathbf{U}$ is the neutral wind velocity, and $\mathbf{J}$ is the total current density. The grid configuration on a magnetic meridian plane is a non-orthogonal, hybrid spherical and dipole coordinate system, where one coordinate is along a constant altitude and the other is along the magnetic field line. The horizontal grid spacing is 0.02° in longitude and latitude (roughly 2 km) at 90 km altitude and increases slightly with altitude because of the dipole magnetic field structure. The radial grid spacing is 2–3 km in the F-region altitude, and it is 100 m around 102 km altitude where an E_s layer could be located. See Yokoyama et al. (2009) and Yokoyama and Hysell (2010) for the detailed numerical schemes to solve the above equations.

In order to simulate hemisphere-coupled MSTIDs, a mirror image of the model domain is set up for the Southern Hemisphere, and all parameters except for the electric field are given independently at each hemisphere. Assuming that the electrostatic potential ϕ, which is defined as $\mathbf{E} = -\nabla\phi$, is constant along each magnetic field line throughout both hemispheres, differentiating Eq. (5) in terms of the unknown ϕ can be reduced to a two-dimensional problem on the $\mathbf{B}$-perpendicular plane. Background conditions are applied from NRLMSISE-00 and IRI-2007 under the low solar activity condition (F10.7=80) in the June solstice. An E_s layer with a peak density of $2.8 \times 10^4\ \mathrm{cm}^{-3}$ is added at 102 km altitude for the Northern Hemisphere. Horizontally uniform neutral wind is then applied to obtain the equilibrium state of plasma density