Numerical Modeling of the disappearance of equatorial plasma bubble by the nighttime medium-scale traveling ionospheric disturbances

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Abstract

The Naval Research Laboratory first-principles ionosphere model SAMI3/ESF is performed to study the interaction between the nighttime medium-scale traveling ionospheric disturbances (MSTIDs) and equatorial plasma bubbles (EPBs). The synthetic Es layer instability driven by the external dynamo currents are imposed into the potential equation to induce polarization electric fields for generating the MSTIDs. Simulations demonstrate that the MSTIDs alone can inhibit the upward growth of EPBs, but are insufficient to explain the disappearance of EPBs. The meridional winds are necessary to comprehend the underlying mechanism. The zonal and vertical $\mathbf{E} \times \mathbf{B}$ drifts of MSTIDs also affect the morphology of EPBs that could result in a reverse-C shape structure.

Keywords

1. Equatorial Plasma Bubble
2. Nighttime medium-scale traveling ionospheric disturbances
3. Electrodynamical coupling
4. Numerical simulation

Main Text

1. Introduction

Ionospheric irregularities associated with equatorial plasma bubbles (EPBs) and nighttime medium-scale traveling ionospheric disturbances (MSTIDs) are often observed in the nighttime equatorial and mid-latitude ionospheric F region. They are electrodynamical structures that are generated by the generalized Rayleigh-Taylor instability (e.g., Kelley, 1989) and Perkins instability (Perkins, 1978), respectively. Dungey (1956) first proposed the Rayleigh-Taylor instability as the mechanism responsible for driving EPBs. The low-density plasma moves upward into the high-density plasma region via $\mathbf{E} \times \mathbf{B}$ drifts driven by gravitational force-induced ion currents, creating ionospheric plasma depletions along magnetic flux tubes. The meridionally-elongated wedges of plasma depletions displaying geomagnetic conjugacy have been observed by ground- and space-based airglow imagers (Otsuka et al., 2002; Ogawa et al., 2005). Various seeding mechanisms have been proposed to explain the generation of EPBs, such as the neutral winds, gravity waves, and electric and magnetic fields (Sultan, 1996; Rama Rao et al., 1997; Abdu et al., 2009). The pre-reversal enhancement (PRE) is considered to play a dominant role in causing the post-sunset rise of the ionospheric layer, resulting in the steep vertical gradient of electron density favorable for the development of EPBs (e.g., Rajesh et al., 2017).

On the other hand, the nighttime MSTIDs have been investigated for many years (e.g., Behnke et al. 1979; Miller et al. 1997; Saito et al. 1998; Shiokawa et al. 2003a; Rajesh et al. 2016; Chou et al. 2017). Space- and ground-based observations have shown the oscillation of polarization electric fields within the MSTIDs (Saito et al. 1995; Kelley et al. 2000; Shiokawa et al. 2003b), supporting the hypothesis that the Perkins instability plays a crucial role in the generation of MSTIDs. The polarization electric fields can further map along the geomagnetic field lines, displaying conjugate structures in both hemispheres (Otsuka et al. 2004). Since the theoretical growth rate of the Perkins instability is quite small, gravity wave seeding (Kelley and Fukao, 1991; Huang et al. 1994; Miller et al. 1997; Li et al. 2016; Chou et al. 2017; 2018) or coupling between the F and sporadic-E layers (*EsL*) (Cosgrove and Tsunoda, 2004; Tsunoda, 2004; Yokoyama et al. 2009) are suggested to be the plausible mechanisms to accelerate the growth of nighttime MSTIDs.

Earlier studies have reported the interaction between EPBs and MSTIDs. MSTIDs can be one of the seeding mechanisms to trigger EPBs (Miller et al. 2009; Krall et al. 2011; Takahashi et al. 2018). Krall et al. (2011) suggested that the coupling between the MSTIDs and equatorial ionosphere can lead to the growth of EPBs. Interestingly, some other studies have reported that MSTIDs can suppress or aid the extension of EPBs (Otsuka et al. 2012; Shiokawa et al. 2015; Aa et al. 2019). Otsuka et al. (2012) suggested that the plasma motion of MSTIDs can cause the disappearance of the EPBs by transporting the ambient plasma into the plasma-depleted region across the geomagnetic field lines via $\mathbf{E} \times \mathbf{B}$ drifts. However, the EPBs usually cause significant plasma depletions over 10 TECu (e.g., Nishioka et al. 2008) while the amplitudes of MSTIDs are within the ranges of ~0.2–1 TECu (e.g., Tsugawa et al. 2007; Chou et al. 2017), making it difficult to fade out the EPBs by filling the plasma depletions up with ambient plasma along the flux tubes. Additionally, plasma diffusion across the geomagnetic field line is relatively slow compared to the field-aligned diffusion and may take a longer time to fill the depletion up.

To understand how MSTIDs affect the electrodynamics of EPBs, we use the Naval Research Laboratory (NRL) SAMI3/ESF (Sami3 is Also a Model of the Ionosphere/Equatorial Spread F) model (Huba et al. 2008) to investigate the coupling between the nighttime MSTIDs and EPBs. We found that the $\mathbf{E} \times \mathbf{B}$ drifts within MSTIDs can suppress the upward motion of EPBs and affect the morphology of EPBs. However, the meridional winds also play an essential role in the disappearance of EPBs. Concerning the observations reported by Otsuka et al. (2012) and

Shiokawa et al. (2015), both MSTIDs and transequatorial winds appear to be necessary conditions to explain the disappearance of EPBs.

2. The SAMI3/ESF Model

The NRL self-consistent SAMI3/ESF model based on the 2-D SAMI2 (Sami2 is Another Model of the Ionosphere) and 3-D SAMI3 (Huba et al. 2000; Huba and Joyce, 2010) has applied to study the evolution and generation of ESF (Huba et al. 2008, 2009a; Krall et al. 2013; Wu et al. 2015) and nighttime MSTIDs (Duly et al. 2014; Chou et al. 2018). In this study, the SAMI2 model is run for 43 h to initial the SAMI3/ESF model. The geophysical indices used are F10.7 = 105 (s.f.u), F10.7A = 105 (s.f.u), Ap = 37, and day-of-year = 70. The SAMI3/ESF model uses a grid (nz, nf, nl) = (101, 200, 128) where nz is the number of grid points along each geomagnetic field line (s direction), nf is the number of geomagnetic field lines in altitude (p direction), and nl is the number in longitude (ϕ direction). Since the 3D model uses an aligned diploe magnetic field with a magnetic apex height from 85 km to 2400 km, the geomagnetic latitude and geographic latitude are the same, and the longitudinal and latitudinal width are limited to 4° and ±30° in both hemispheres. The simulations are run for 7 h from ~19:09 LT to ~2:07 LT.

The SAMI3/ESF potential equation is based on current conservation $\nabla \cdot J = 0$ (Krall et al. 2009a; Kuo et al. 2011; Huba et al. 2015). The electric current J can be written as $J = J_E+J_g+J_v$, where J_E, J_g, and J_v represent current terms driven by electric field, gravity, and neutral wind. In this study, the *EsL* current terms (J_{ES}) are included to act as the *EsL* instability for generating MSTIDs through the *EsL*-F coupling (e.g., Yokoyama et al. 2009). Similar method was used by Huba et al. (2015) that they imposed a dynamo current $J_{v'}$ driven by wind perturbations to simulate the gravity wave perturbations.

The integrated potential equation used in this study is

$$\frac{\partial}{\partial p} p\Sigma_{pp}\frac{\partial\Phi}{\partial p} - \frac{\partial}{\partial p}\Sigma_H\frac{\partial\Phi}{\partial\phi} + \frac{\partial}{\partial\phi}\frac{1}{p}\Sigma_{p\phi}\frac{\partial\Phi}{\partial\phi} + \frac{\partial}{\partial\phi}\Sigma_H\frac{\partial\Phi}{\partial p}$$

$$= \frac{\partial F_{\phi g}}{\partial\phi} + \frac{\partial F_{\phi V}}{\partial\phi} - \frac{\partial F_{pg}}{\partial p} + \frac{\partial F_{pV}}{\partial p} + \frac{\partial F_{pE}}{\partial p} + \frac{\partial F_{\phi E}}{\partial\phi} \qquad (1)$$

where $F_{\phi g} = \int(r_E\sin^3\theta/\Delta)\,(B_0/c)\sigma_{Hc}g_p ds$, $F_{\phi V} = \int(r_E\sin^3\theta/\Delta)\,(B_0/c)(\sigma_H V_{n\phi} - \sigma_P V_{np})\,ds$, $F_{pg} = -\int r\sin\theta(B_0/c)\sigma_{Pc}g_p ds$, and $F_{pV} = \int r\sin\theta(B_0/c)\,(\sigma_P V_{n\phi} + \sigma_H V_{np})\,ds$, Φ is the electrostatic potential, g_p is the component of gravity perpendicular to **B**, V_n is perpendicular wind component. The detailed definitions of the variables are given by Huba and Joyce (2010).

The *EsL* current terms are $F_{\phi E} = \int r^3/r_E^3(\sin^3\theta/\Delta^2)(\sigma_P E_\phi + \sigma_H E_p)ds$ and $F_{pE} = \int r\sin\theta/\Delta(r/r_E)^3(\sigma_P E_p - \sigma_H E_\phi)ds$. The E_p and E_ϕ are defined as

$$E_{[\mathrm{p},\phi]} = -A_E \frac{1}{1+e^{-(lat-lat_0)}} e^{-\frac{(lon-lon_0)^2}{2w^2}} \frac{k_{[x,y]}}{k} \sin\left(k_x x + k_y y - \omega t\right) \quad (2)$$

where A_E is the amplitude of electric field, $k_x = k \cos\theta_{TID}$, $k_y = k \sin\theta_{TID}$, $\omega = \frac{2\pi}{T}$, t is time, k is the wavenumber, lon and lat are longitude and latitude, and θ_{TID} is the angle between the direction normal to the frontal structure of MSTIDs and the geomagnetic east. We assume $k = \frac{2\pi}{2°}$, $\theta_{TID} = 30°$ and T = 70 min, which are similar to the MSTIDs observations (e.g., Shiokawa et al. 2003b). The A_E is set to 2 mV/m (Pfaff et al. 2005). The *EsL* currents are localized below 130 km in the northern hemisphere. The smooth function $\frac{1}{1+e^{-(lat-lat_0)}} e^{-\frac{(lon-lon_0)^2}{2\times w^2}}$ is used to limit the latitudinal and longitudinal extension of Es oscillations. w, lat_0, and lon_0 are set to 1.25°, 17° and 2°, respectively, so that the *EsL* currents will gradually decrease to zero below 17°N and the boundary effect will be reduced. The *EsL* currents will self-consistently generate an electrostatic potential along the field lines that is consistent with $\nabla \cdot J = 0$, leading to a conjugate effect (e.g., Otsuka et al. 2004).

The EPBs are simulated by imposing a Gaussian perturbation in the ion density with an amplitude A_m of 10% in the bottomside F layer.

$$N' = N_0(1 - A_m e^{-\frac{(lon-lon_0)^2}{2w^2}}) \quad (3)$$

where N_0 and N' are the initial and perturbed ion densities. The perturbation is centered at lon_0

= 2°, and w = 0.3°. The gravity-driven current terms (F_{pg}, $F_{\phi g}$) of equation (1) drive the growth of EPBs.

3. Results

Three SAMI3/ESF numerical simulations are performed using zero neutral wind conditions. Case 1 simulates the generation and evolution of EPB; case 2 and case 3 simulate the impacts of MSTIDs on the EPBs in the onset and structure (or mature) phases by imposing synthetic MSTIDs at 22:00 LT and 23:30 LT, respectively. The onset phase demonstrates that the EPBs develop from the crest of upwellings and continuously grow upward and poleward; the structure phase demonstrates that the EPBs are well-developed and will become fossil (e.g., Tsunoda et al. 2015).

Figure 1 shows the time sequence of electron density contours and vertical **E** × **B** drifts in contour lines (black and white lines) as a function of longitude and altitude on a magnetic equatorial plane for cases 1 (left column), 2 (middle column), and 3 (right column), respectively (see also additional files 1-3 in supporting information). The black and white contour lines indicate the downward and upward **E** × **B** drifts, respectively. The yellow and red stars indicate the positions of peak upward **E** × **B** drifts of the EPB and topside EPB (>850 km). Dense white contour lines within the plume structures are visible, demonstrating strong upward **E** × **B** drifts within the EPB. The EPB starts to grow from the bottomside ionosphere after ~22:00 LT. Case 1 shows that the EPB intrudes into ~1200 km altitude at 01:49 LT, displaying a distinct plume structure. Bifurcations can be identified along the west wall of the plume. The morphology of EPB resembles the turbulent bubble structures shown in Figure 2 of Yokoyama et al. (2015). The EPB in the onset phase has a peak upward **E** × **B** drift of ~686 m/s in the F region at 22:47 LT and eventually decrease to 364 m/s in the structure phase at 01:49 LT. The topside EPB has weaker vertical drifts ranging from 245 to 344 m/s.

It is noteworthy that EPBs usually occur during ~19:00-20:00 LT because the PRE can accelerate the growth rate. The simulated EPBs develop after 22:00 LT are due to the background conditions (e.g., Sultan, 1996). However, EPBs could occur after 22:00 LT in June solstice (Yizengaw et al., 2013), making the MSTIDs that often occur after 21:00 LT around solstice to have a higher probability of encountering the EPBs. Nevertheless, the onset time of EPBs will not affect the electrodynamics between the EPBs and MSTIDs.

In case 2, ionospheric undulations due to the MSTIDs are discernible in the topside ionosphere. The MSTIDs have vertical **E** × **B** drifts of ~20-40 m/s, which is consistent with the

MSTIDs observations (e.g., Shiokawa et al., 2003b). While the MSTIDs encounter the EPB in the onset phase, the MSTIDs suppress the EPB growth and eventually confine the EPB within ~1100 km altitude at 01:49 LT. The upward $\mathbf{E} \times \mathbf{B}$ drifts of the topside EPB decrease to ~168 m/s while encountering the downward $\mathbf{E} \times \mathbf{B}$ drifts of MSTIDs at 23:48 LT. Bifurcations on the east wall of the plume are suppressed as well. However, the upward $\mathbf{E} \times \mathbf{B}$ drifts of MSTIDs also aid the growth of EPB at 00:48 and 01:49 LT. Of particular interest is that the MSTIDs affect the morphology of EPB, making the EPB stretch along with the band structure of MSTIDs and leading to a westward tilted EPB. In case 3, the MSTIDs also distort and suppress the EPB in the structure phase. The primary plume is confined within ~1100 km altitude, and the upward $\mathbf{E} \times \mathbf{B}$ drifts of topside EPB decrease to ~107 m/s at 01:49 LT. In general, the peak upward $\mathbf{E} \times \mathbf{B}$ drifts of the bottomside EPBs are similar for three cases; however, the MSTIDs significantly impact the morphology of EPBs in the onset and structure phases.

We further calculate the OI 630-nm airglow emission rate based on Sobral et al. (1993) to compare with the results of Otsuka et al. (2012). Figure 2 shows the time sequence of the airglow intensity deviation maps at 250 km altitude as a function of longitude and latitude for cases 1 (left column), 2 (middle column), and 3 (right column). Additional movie files show this in more detail [see Additional files 4-6]. The airglow intensity deviation (I_p) is defined as I_p=(I-I_c)/I_c, where I_c is the control run without the EPBs, and I is the OI 630-nm airglow emission rate for cases 1-3. Case 1 shows the evolution of EPB with airglow depletion. The EPB extends to about 21°N at 01:49 LT. MSTIDs can be identified with airglow enhancements and depletions above 13°N in cases 2 and 3. Cases 2 and 3 show that MSTIDs affect the latitudinal extent and morphology of EPBs, confining the EPBs within 21°N. However, the EPBs are still distinct, implying that MSTIDs alone are insufficient to explain the disappearance of EPBs.

We note that Otsuka et al. (2012) showed an increase of OI 630-nm airglow intensity while the EPB encountered the MSTIDs. Shiokawa et al. (2015) also showed clearly airglow intensity decrease at Darwin, Australia, and slightly increase at Sata, Japan, while the EPBs encountered the TIDs at geomagnetically conjugate points. The sudden F-layer rise (descent) can cause a decrease (increase) of the 630-nm airglow intensity because the 630-nm airglow intensity is proportional to the O^+ and O_2 density and rising (descending) F-layer will encounter decreasing (increasing) ambient O_2 density. The airglow intensity enhancement implies that the transequatorial wind may contribute to the disappearance of EPBs.

To further understand the transequatorial wind effects on the disappearance of EPB, we focus on the EPBs in the structure phase and incorporate the southward winds $V = -60\tanh\big(0.02 \times (altitude - 100)\big)$ m/s into case 1 and case 3 at 23:30 LT, referred to as case 4 and case 5. The southward winds can reach a peak of 60 m/s above 250 km and are assumed to be 0 m/s under 100 km. Figure 3 is the same as Figure 2 but for case 4 (top panel) and case 5 (bottom panel) in both hemispheres. Additional movie files show this in more detail [see Additional files 7-8]. Transparent meridionally-elongated wedges of airglow depletions related to EPBs are visible in both cases. Significant airglow enhancements on either side of EPBs are visible due to the downward **E** × **B** drifts outside the EPBs pushing the plasma downward. In case 4, the airglow deviations of EPB in the northern hemisphere significantly become less significant in comparison with the EPB in the southern hemisphere, displaying a hemispheric asymmetry of EPB. However, the EPB is still distinct in both hemispheres, suggesting that meridional wind alone is insufficient to suppress EPB as well. In case 5, it shows that the EPB is almost evanescent in the northern hemisphere while MSTIDs are included. This demonstrates that both MSTIDs and meridional wind are necessary to comprehend the disappearance of EPB.

4. Discussion and Conclusion

Otsuka et al. (2012) and Shiokawa et al. (2015) suggested that MSTIDs can fill the EPBs up by transporting plasma into the depletions via $\mathbf{E} \times \mathbf{B}$ drifts. In our simulations, we found that the EPB depletions are still distinct while interacting with MSTIDs. The meridional winds are necessary to comprehend the disappearance of EPBs in the airglow observations. These processes involve (1) the suppression of upward $\mathbf{E} \times \mathbf{B}$ drifts within the EPBs, (2) the decrease in background electron density, (3) the transport of ambient plasma by MSTIDs.

First, the suppression of upward $\mathbf{E} \times \mathbf{B}$ drifts occurred when EPBs interact with MSTIDs and meridional winds. Figure 4 shows peak vertical $\mathbf{E} \times \mathbf{B}$ drifts of the topside EPBs (>850 km) as a function of time for cases 1-5. Cases 2 and 3 show significant fluctuations due to the interactions of upward and downward $\mathbf{E} \times \mathbf{B}$ drifts within the MSTIDs. The MSTIDs can suppress the upward motion of EPBs by reducing the upward $\mathbf{E} \times \mathbf{B}$ drifts up to 200 m/s in comparison with case 1. When the southward winds are applied, cases 4 and 5 show that the southward winds can suppress the EPBs by reducing the vertical $\mathbf{E} \times \mathbf{B}$ drifts up to ~250 m/s. A uniform meridional wind perpendicular to the magnetic field has a direct stabilizing effect on EPB development (Krall et al. 2009b; Huba and Krall, 2013). The meridional wind parallel to the magnetic field can also indirectly stabilize the EPBs by altering the Pedersen conductivity. Figure 5 shows the distributions of Pedersen conductivity (top) and vertical **E** × **B** drift (bottom) as a function of latitude and altitude in 2°E for case 1 (left), case 4 (middle), and case 5 (right) at 01:49 LT. In comparison with case 1, case 4 shows that the Pedersen conductivity is decreased (increased) when the southward winds move the plasma to higher (lower) altitude in the northern (southern) hemisphere. The increase of electron density in lower altitude will lead to the increase of field-line integrated Pedersen conductivity since the Pedersen conductivity is proportional to electron and neutral densities (Kelley, 1989), which, in turn, suppress the EPB growth (e.g., Huba et al. 2020). Case 5 also shows that the MSTIDs can increase (decrease) the Pedersen conductivity in the bottomside ionosphere (below 300 km) by transporting the plasma to lower (higher) altitude via downward (upward) **E** × **B** drifts, which is consistent with the Perkins instability.

Second, the meridional winds can significantly reduce the background electron density and airglow intensity. The southward winds move the plasma upward (downward) in the northern (southern) hemisphere, leading to a decrease (increase) of plasma density and airglow intensity below the F region. The top panel of Figure 3 shows that the EPBs in both hemispheres are asymmetric. The relative airglow deviations of EPB become smaller in the northern hemisphere, demonstrating that the decrease in plasma density and airglow intensity would make EPB inconspicuous.

Third, since the EPBs usually have large upward $\mathbf{E} \times \mathbf{B}$ drifts, MSTIDs are more able to fade the EPBs out when the upward $\mathbf{E} \times \mathbf{B}$ drifts of EPBs and background electron density are reduced. Then, the MSTIDs move plasma downward to fill the EPB depletions up via $\mathbf{E} \times \mathbf{B}$ drifts, which, in turn, lead to the enhancement of the 630-nm airglow intensity (bottom panel of Figure 3). Our simulated OI 630-nm results essentially agree with the airglow observations reported by Otsuka et al. (2012) and Shiokawa et al. (2015). It should be mentioned that Otsuka et al. (2012) showed that the EPB is nearly fossil state when encountering the MSTIDs, implying that the upward $\mathbf{E} \times \mathbf{B}$ drifts within the EPB should be weak. This demonstrates that the MSTIDs and meridional winds can more efficiently suppress the EPB. The decrease in background electron density by meridional wind and transportation of plasma by MSTIDs should dominate the disappearance of EPB.

Although the meridional winds and MSTIDs contribute to the disappearance of EPBs in the OI 630-nm airglow observations, Figure 4 shows clear depletions in Pedersen conductivity above ~300 km in the northern hemisphere (case 5), suggesting that the EPBs still persist due to abundant background electron density. This can explain why the strong spread-F were still present in ionograms after the EPBs had disappeared in the airglow images (Shiokawa et al. 2015).

On the other hand, we found that the MSTIDs can also lead to the west-tilted EPBs. The west-tilted EPBs are usually considered to be related to the latitudinal variation of eastward plasma flow due to zonal wind (Kelley et al. 2003; Huba et al. 2009b). The eastward plasma flow peaks at the equatorial region can lead to a reverse C- or arc-shape EPBs (Kil et al. 2009). Figure 5 shows the variation of zonal **E** × **B** drifts as a function of longitude and altitude for case 2. The EPB initially grows eastward due to the eastward **E** × **B** drifts within the EPB (Figure 5a). As the EPB grows upward and encounters the MSTIDs, the primary plume turns into westward and stretches along with the band structure of MSTIDs with westward **E** × **B** drifts (Figures 5b-d). The bifurcations on the east wall of the plume are mainly eastward because of encountering the eastward **E** × **B** drifts of MSTIDs; however, they do not grow along with the band structure due to the suppression of downward **E** × **B** drifts of MSTIDs (Figure 1). A similar phenomenon was observed by Aa et al. (2019) that they found the EPBs stretched along with the MSTIDs.

In conclusion, we study the disappearance of EPBs due to the influences of MSTIDs by using the SAMI3/ESF model. Simulations reveal that MSTIDs alone are insufficient to explain the disappearance of EPBs. The inclusion of meridional winds is necessary to comprehend the underlying mechanism. Both MSTIDs and Meridional winds can suppress the upward **E** × **B** drifts within the EPBs and reduce the background electron density, providing conditions favorable for the MSTIDs to fill the plasma depletion up. Besides, the vertical and zonal **E** × **B** drifts within the MSTIDs can affect the morphology of EPBs in onset phase, making EPBs stretch along with the band structure of MSTIDs and display a reverse C-shape.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

List of abbreviations

MSTIDs: Medium-Scale Traveling Ionospheric Disturbances

EPBs: Equatorial Plasma Bubbles

PRE: Pre-Reversal Enhancement

EsL: Sporadic-E Layer

NRL: Naval Research Laboratory

SAMI3/ESF: Sami3 is Also a Model of the Ionosphere/Equatorial Spread F

SAMI2: Sami2 is Another Model of the Ionosphere

Availability of data and materials

The datasets used during this study were constructed from the SAMI3/ESF model and are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

MYC conducted the model simulations and drafted the manuscript. CHL provided expertise in interpreting the modeling results and revised the manuscript. JDH developed the model, provided expertise in interpreting the modeling results, and revised the manuscript. All authors read and approved the final manuscript.

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Figure legends

Figure 1. The time sequence of electron density contours as a function of longitude and altitude at 22:47 LT, 23:48 LT, 00:48 LT, and 01:49 LT for case 1 (left column), case 2 (middle column), and case 3 (right column). The black and white contour lines indicate the downward and upward $\mathbf{E} \times \mathbf{B}$ drifts, respectively. The yellow and red stars indicate the positions of peak upward $\mathbf{E} \times \mathbf{B}$ drifts of the EPB and topside EPB (>850 km). Case 1 simulates the EPB without the MSTIDs. Case 2 and case 3 simulate the interaction between the EPB and MSTIDs by imposing the MSTIDs at 22:30 LT and 23:30 LT, respectively.

Figure 2. The time sequence of airglow intensity perturbation contours at 250 km altitude as a function of longitude and latitude at 22:47 LT, 23:48 LT, 00:48 LT, and 01:49 LT for case 1 (first column), case 2 (second column), and case 3 (third column).

Figure 3. The time sequence of airglow intensity perturbation contours at 250 km altitude as a function of longitude and latitude at 22:48 LT, 23:48 LT, 00:48 LT, and 01:48 LT for case 4 (top row) and case 5 (bottom row).

Figure 4. The peak vertical **E** × **B** drift variations of the topside EPBs (>850 km) as a function of time for cases 1-5.

Figure 5. The Pedersen conductivity contours as a function of latitude and altitude in ~2°E at 01:49 LT for case 1 (left), case 4 (middle), and case 5 (right). The white lines indicate the geomagnetic field line.

Figure 6. The time sequence of zonal **E** × **B** drift contours as a function of longitude and altitude for case 2 at 22:47 LT, 23:48 LT, 00:48 LT, and 01:49 LT. The positive (negative) value indicates eastward (westward) **E** × **B** drifts.

Additional files

- File name: Additional file 1, Additional file 2, Additional file 3, Additional file 4, Additional file 5, Additional file 6, Additional file 7, Additional file 8
- File format: avi
- Title of data: Electron density variations as a function of longitude and altitude for cases 1-3 (Additional files 1-3). Airglow intensity perturbation variations at an altitude of 250 km as a function of longitude and latitude for cases 1-5 (additional files 4-8).
- Description of data: Additional files 1-3 are movies for Figure 1. Additional files 4-6 are movies for Figure 2. Additional files 7-8 are movies for Figure 3.