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

Min-Yang Chou (✉ chou@ucar.edu)

University Corporation for Atmospheric Research <https://orcid.org/0000-0001-7172-9569>

Charles C. H. Lin

National Cheng Kung University Department of Earth Sciences

Joseph D. Huba

Syntek Technologies

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1 **Numerical modeling of the disappearance of equatorial plasma bubble by**

2 **nighttime medium-scale traveling ionospheric disturbances**

3 Author #1: Min-Yang Chou, COSMIC Program Office, University Corporation for

4 Atmospheric Research, Boulder, CO, USA, chou@ucar.edu

5 Author #2: Charles C. H. Lin, Department of Earth Sciences, National Cheng Kung University,

6 Tainan, Taiwan, tipegcm@gmail.com

7 Author #3: Joseph D. Huba, Syntek Technologies, Fairfax, VA, USA, jdhuba@gmail.com

8 **corresponding author**

9 Min-Yang Chou

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 dynamo currents are imposed into the potential equation to induce polarization electric fields for generating the MSTIDs. Simulations demonstrate that the MSTIDs can inhibit the upward growth of EPBs; however, MSTIDs alone are insufficient to explain the disappearance of EPBs. We found that the meridional winds likely contribute to the disappearance of MSTIDs by reducing the background electron density and polarization electric fields within the EPBs. Then, the MSTIDs transport plasma to fill the EPB depletions up via $\mathbf{E} \times \mathbf{B}$ drifts. Both MSTIDs and meridional winds are necessary to comprehend the underlying mechanism of EPB disappearance. We also found that the zonal and vertical $\mathbf{E} \times \mathbf{B}$ drifts within the MSTIDs affect the morphology of EPBs, leading to a reverse-C shape structure.

Keywords

1. Equatorial Plasma Bubble

26 2. Nighttime medium-scale traveling ionospheric disturbances

27 3. Electrodynamical coupling

28 4. Numerical simulation

29

30 **Main Text**

31 **1. Introduction**

32 Ionospheric irregularities associated with equatorial plasma bubbles (EPBs) and nighttime
33 medium-scale traveling ionospheric disturbances (MSTIDs) are often observed in the nighttime
34 equatorial and mid-latitude ionosphere. They are electrodynamical structures generated by the
35 generalized Rayleigh-Taylor instability (e.g., Kelley, 1989) and Perkins instability (Perkins, 1978),
36 respectively. Dungey (1956) first proposed the Rayleigh-Taylor instability as the mechanism
37 responsible for driving EPBs. The low-density plasma moves upward into the high-density
38 plasma region via $\mathbf{E} \times \mathbf{B}$ drifts driven by gravitational force-induced ion currents, creating
39 ionospheric plasma depletions along magnetic flux tubes. The meridionally-elongated wedges of
40 plasma depletions displaying geomagnetic conjugacy have been observed by ground- and space-
41 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

58 growth of nighttime MSTIDs.

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

72 To understand how MSTIDs affect the electrodynamics of EPBs, we use the Naval Research
73 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), $A_p = 37$, 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 dipole 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 $\pm 30^\circ$ in both hemispheres. The simulations are run for 7 h from $\sim 19:09$ LT to $\sim 2:07$ LT.

The SAMI3/ESF potential equation is solved based on current conservation $\nabla \cdot \mathbf{J} = 0$ and equipotential field lines (Krall et al. 2009a; Kuo et al. 2011; Huba et al. 2015). The electric current $\mathbf{J}$ can be written as $\mathbf{J} = \mathbf{J}_E + \mathbf{J}_g + \mathbf{J}_v$, where $\mathbf{J}_E$, $\mathbf{J}_g$, and $\mathbf{J}_v$ represent current terms driven by the electric field, gravity, and neutral wind. In this study, the external MSTID current terms ($\mathbf{J}_{\text{MSTID}}$) are included in the potential equation to act as the *EsL*-F coupling for generating MSTIDs (e.g., Yokoyama et al. 2009). The modified integrated potential equation used in this study is

$$\begin{aligned} & \frac{\partial}{\partial p} p \Sigma_{pp} \frac{\partial \Phi}{\partial p} - \frac{\partial}{\partial p} \Sigma_H \frac{\partial \Phi}{\partial \phi} + \frac{\partial}{\partial \phi} \frac{1}{p} \Sigma_{p\phi} \frac{\partial \Phi}{\partial \phi} + \frac{\partial}{\partial \phi} \Sigma_H \frac{\partial \Phi}{\partial p} \\ & = \frac{\partial F_{\phi g}}{\partial \phi} + \frac{\partial F_{\phi v}}{\partial \phi} - \frac{\partial F_{pg}}{\partial p} + \frac{\partial F_{pv}}{\partial p} + \frac{\partial F_{pE}}{\partial p} + \frac{\partial F_{\phi E}}{\partial \phi} \end{aligned} \quad (1)$$

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 $\mathbf{B}$, V_n is perpendicular wind component.

The detailed definitions of the variables are given by Huba and Joyce (2010). The MSTID current

106 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

107 and E_ϕ are defined as

$$108 \quad E_{[p,\phi]} = -A_E \frac{1}{1+e^{-(lat-lat_0)}} e^{-\frac{(lon-lon_0)^2}{2w^2}} \frac{k_{[x,y]}}{k} \sin(k_x x + k_y y - \omega t) \quad (2)$$

109 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

110 time, k is the wavenumber, lon and lat are longitude and latitude, and θ_{TID} is the angle between

111 the direction normal to the frontal structure of MSTIDs and the geomagnetic east. We assume

112 $k = \frac{2\pi}{2^\circ}$, $\theta_{TID} = 30^\circ$ and $T = 70$ min, which are similar to the MSTIDs observations (e.g.,

113 Shiokawa et al. 2003b). The A_E is set to 2 mV/m (cf. Pfaff et al. 2005). The smooth function

114 $\frac{1}{1+e^{-(lat-lat_0)}} e^{-\frac{(lon-lon_0)^2}{2w^2}}$ is used to limit the latitudinal and longitudinal extension of current

115 oscillations. w , lat_0 , and lon_0 are set to 1.25° , 17° and 2° , respectively, so that the currents will

116 gradually decrease to zero below $17^\circ N$ at 85 km and the boundary effect will be reduced. The

117 MSTID current terms are confined to the altitudes of 85-450 km in the northern hemisphere and

118 will self-consistently generate polarization electric fields ($E = -\nabla \Phi$) along the field lines to satisfy

119 $\nabla \cdot J = 0$ and equipotential field line assumption, leading to a conjugate effect (e.g., Saito et al.,

120 1995; Otsuka et al. 2004).

121 Similar methods were used by Huba et al. (2015) and Kuo et al. (2011). Huba et al. (2015)

simulated the tsunami-induced gravity waves by imposing neutral wind perturbations (U') in the ionospheric F region. The dynamo currents driven by wind perturbations self-consistently induce polarization electric fields mapping to the conjugate region. Kuo et al. (2011) studied the lithosphere-atmosphere-ionosphere coupling by imposed an external dynamo current from the atmosphere at 85 km altitude (the lower boundary for the SAMI3 ionosphere). The dynamo current flowing into the ionosphere causes significant ionospheric perturbations in both hemispheres and leads to the EPB formation.

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.

$$N' = N_0 \left(1 - A_m e^{-\frac{(\text{lon} - \text{lon}_0)^2}{2w^2}} \right) \quad (3)$$

where N_0 and N' are the initial and perturbed ion densities. The perturbation is centered at $\text{lon}_0 = 2^\circ$, and $w = 0.3^\circ$. The gravity-driven current terms (F_{pg} , $F_{\phi g}$) of equation (1) are the primary source terms to drive the growth of EPBs.

3. Results

Three SAMI3/ESF numerical simulations are performed using zero neutral wind conditions.

138 Case 1 simulates the generation and evolution of EPB; case 2 and case 3 simulate the impacts of
139 MSTIDs on the EPBs in the onset and structure (or mature) phases by imposing synthetic MSTIDs
140 at 22:00 LT and 23:30 LT, respectively. The onset phase demonstrates that the EPBs develop from
141 the crest of upwellings and continuously grow upward and poleward; the structure phase
142 demonstrates that the EPBs are well-developed and will become fossil (e.g., Tsunoda et al. 2015).

143 Figure 1 shows the time sequence of electron density contours and vertical $\mathbf{E} \times \mathbf{B}$ drifts in
144 contour lines (black and white lines) as a function of longitude and altitude on a magnetic
145 equatorial plane for cases 1 (left column), 2 (middle column), and 3 (right column), respectively
146 (see also additional files 1-3 in supporting information). The black and white contour lines
147 indicate the downward and upward $\mathbf{E} \times \mathbf{B}$ drifts, respectively. The yellow and red stars indicate
148 the positions of peak upward $\mathbf{E} \times \mathbf{B}$ drifts of the EPB and topside EPB (>900 km). Dense white
149 contour lines within the plume structures are visible, demonstrating strong upward $\mathbf{E} \times \mathbf{B}$ drifts
150 within the EPB. The EPB starts to grow from the bottomside ionosphere after $\sim 22:00$ LT. Case 1
151 shows that the EPB intrudes into ~ 1200 km altitude at 01:49 LT, displaying a distinct plume
152 structure. Bifurcations can be identified along the west wall of the plume. The morphology of
153 EPB resembles the turbulent bubble structures shown in Figure 2 of Yokoyama et al. (2015). The

154 EPB in the onset phase has a peak upward $\mathbf{E} \times \mathbf{B}$ drift of ~ 686 m/s in the F region at 22:47 LT
155 and eventually decrease to 364 m/s in the structure phase at 01:49 LT. The topside EPB above
156 900 km has weaker peak vertical drifts ranging from 136 to 156 m/s.

157 It is noteworthy that EPBs usually occur during $\sim 19:00$ - $20:00$ LT because the PRE can
158 accelerate the growth rate. The simulated EPBs develop after 22:00 LT are due to the background
159 conditions (e.g., Sultan, 1996). SAMI3/ESF uses the empirical thermosphere models
160 NRLMSIS00 (Picone et al., 2002) to specify the neutral species. The background conditions may
161 be different from the real situation, which in turn affect the growth rate (e.g., Huba and Liu, 2020).
162 However, EPBs could occur after 22:00 LT in June solstice (Yizengaw et al., 2013), making the
163 MSTIDs that often occur after 21:00 LT around solstice to have a higher probability of
164 encountering the EPBs. Nevertheless, the onset time of EPBs will not affect the electrodynamic
165 between the EPBs and MSTIDs.

166 In case 2, ionospheric undulations due to the MSTIDs are discernible in the topside
167 ionosphere. The MSTIDs have vertical $\mathbf{E} \times \mathbf{B}$ drifts of $\sim \pm 10$ -50 m/s, which agrees reasonably
168 well with the MSTIDs observations (e.g., Shiokawa et al., 2003b). While the MSTIDs encounter
169 the EPB in the onset phase, the MSTIDs suppress the EPB growth and eventually confine the

170 EPB within ~ 1100 km altitude at 01:49 LT. The peak upward $\mathbf{E} \times \mathbf{B}$ drifts of the topside EPB
171 decrease to ~ 122 m/s while encountering the downward $\mathbf{E} \times \mathbf{B}$ drifts of MSTIDs at 23:48 LT.
172 Bifurcations on the east wall of the plume are suppressed as well. However, the upward $\mathbf{E} \times \mathbf{B}$
173 drifts of MSTIDs also favor the growth of EPB at 00:48 and 01:49 LT, leading to the increase of
174 peak upward $\mathbf{E} \times \mathbf{B}$ drifts within the topside EPB. Of particular interest is that the MSTIDs affect
175 the morphology of EPB. The EPB stretches along with the band structure of MSTIDs, displaying
176 a reverse C shape of EPB. In case 3, the MSTIDs also distort and suppress the EPB in the structure
177 phase. The primary plume is confined within ~ 1100 km altitude, and the upward $\mathbf{E} \times \mathbf{B}$ drifts of
178 topside EPB decrease to ~ 91 m/s at 01:49 LT. In general, the peak upward $\mathbf{E} \times \mathbf{B}$ drifts of the
179 bottomside EPBs are similar for three cases; however, the MSTIDs significantly impact the
180 morphology of EPBs above the F region in the onset and structure phases.

181 We further calculate the OI 630-nm airglow emission rate based on Sobral et al. (1993) to
182 compare with the results of Otsuka et al. (2012). Figure 2 shows the time sequence of the airglow
183 intensity deviation maps at 250 km altitude as a function of longitude and latitude for cases 1 (left
184 column), 2 (middle column), and 3 (right column). Additional movie files show this in more detail
185 [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

186 the control run without the EPBs, and I is the OI 630-nm airglow emission rate for cases 1-3. Note
187 that the background airglow intensity deviation can reach over 20%; we limit the color ranges
188 between -1–2% to highlight the EPB variations. Case 1 shows the evolution of EPB with airglow
189 depletion. The EPB extends to about 21°N at 01:49 LT. MSTIDs can be identified with airglow
190 enhancements and depletions above 13°N in cases 2 and 3. Cases 2 and 3 show that MSTIDs
191 affect the latitudinal extent and morphology of EPBs, confining the EPBs within 21°N. However,
192 the EPBs are still distinct, implying that MSTIDs alone are insufficient to explain the
193 disappearance of EPBs.

194 Otsuka et al. (2012) showed an increase of OI 630-nm airglow intensity while the EPB
195 encountered the MSTIDs. Shiokawa et al. (2015) also showed clearly airglow intensity decrease
196 at Darwin, Australia, and a slight increase at Sata, Japan, while the EPBs encountered the TIDs
197 at geomagnetically conjugate points. The sudden F-layer rise (descent) can cause a decrease
198 (increase) of the 630-nm airglow intensity because the 630-nm airglow intensity is proportional
199 to the O^+ and O_2 density, and rising (descending) F-layer will encounter decreasing (increasing)
200 ambient O_2 density. The airglow intensity enhancement implies that the transequatorial wind may
201 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 $V = -60 \tanh(0.02 \times (\text{altitude} - 100))$ 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 $\mathbf{E} \times \mathbf{B}$ drifts outside the EPBs pushing the plasma downward. In case 4, the airglow deviations of EPB in the northern hemisphere significantly become less significant compared to 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 fade the EPB out. In case 5, it shows that the EPB is almost evanescent in the northern hemisphere while interacting with the MSTIDs. Simulations reveal that both MSTIDs and meridional wind are likely necessary to comprehend the disappearance of EPB.

218

219 **4. Discussion and Conclusion**

220 Otsuka et al. (2012) and Shiokawa et al. (2015) suggested that MSTIDs can fill the EPBs up
221 by transporting plasma into the depletions via $\mathbf{E} \times \mathbf{B}$ drifts. In our simulations, we found that
222 MSTIDs can suppress the upward motion of EPBs; however, MSTIDs alone are insufficient to
223 explain the disappearance of EPBs. The meridional winds should be included in the processes to
224 fully explain the disappearance of EPBs in the airglow observations. These processes involve (1)
225 the suppression of upward $\mathbf{E} \times \mathbf{B}$ drifts within the EPBs, (2) the decrease in background electron
226 density, (3) and the transport of ambient plasma by MSTIDs.

227 First, the suppression of upward $\mathbf{E} \times \mathbf{B}$ drifts occurred when EPBs interact with MSTIDs and
228 meridional winds. Figure 4 shows the local time variations of peak vertical $\mathbf{E} \times \mathbf{B}$ drifts of the
229 topside EPBs for cases 1-5. Cases 2 and 3 show significant fluctuations due to the interactions of
230 upward and downward $\mathbf{E} \times \mathbf{B}$ drifts within the MSTIDs. The MSTIDs can suppress or aid the
231 upward motion of EPBs by reducing or increasing the upward $\mathbf{E} \times \mathbf{B}$ drifts in comparison with
232 case 1. When the southward winds are applied, cases 4 and 5 show that the southward winds can
233 significantly suppress the EPBs by reducing the vertical $\mathbf{E} \times \mathbf{B}$ drifts to ~ 250 m/s. Krall et al.

(2009b) and Huba and Krall (2013) suggested that a uniform meridional wind perpendicular to the magnetic field has a direct stabilizing effect on EPB development. 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 $\mathbf{E} \times \mathbf{B}$ 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) altitudes 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) $\mathbf{E} \times \mathbf{B}$ 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, providing conditions favorable for MSTIDs to fade out the EPBs.

Third, since the EPBs usually have large upward $\mathbf{E} \times \mathbf{B}$ drifts, MSTIDs can efficiently fade the EPBs out when the upward $\mathbf{E} \times \mathbf{B}$ drifts within the EPBs and background electron density are reduced. The decrease in background electron density can also lead to a decrease in upward $\mathbf{E} \times \mathbf{B}$ drifts within the EPBs (e.g., Krall et al., 2010). 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 the fossil state when encountering the MSTIDs, implying that the upward $\mathbf{E} \times \mathbf{B}$ drifts within the EPB should be weak. The MSTIDs and meridional winds should be more efficiently suppressing the EPB.

Although the meridional winds and MSTIDs contribute to the disappearance of EPBs in the

266 OI 630-nm airglow observations, Figure 4 shows clear depletions in Pedersen conductivity above
267 ~300 km in the northern hemisphere (case 5), suggesting that the EPBs still persist due to
268 abundant background electron density in the F region. This can explain why the strong spread-F
269 was still present in ionograms when the EPBs were disappeared in the airglow images (Shiokawa
270 et al. 2015).

271 On the other hand, we found that MSTIDs can also lead to west-tilted EPBs. The west-tilted
272 EPBs are usually considered to be related to the latitudinal variation of eastward plasma flow due
273 to zonal wind (Kelley et al. 2003; Huba et al. 2009b). The eastward plasma flow peaks at the
274 equatorial region can lead to a reverse C- or arc-shape EPBs (Kil et al. 2009). Figure 6 shows the
275 variation of zonal $\mathbf{E} \times \mathbf{B}$ drifts as a function of longitude and altitude for cases 1 (top panel) and
276 2 (bottom panel). In case 1, the primary plume tilts eastward due to the eastward $\mathbf{E} \times \mathbf{B}$ drifts
277 within the EPB. The bifurcations on the west wall of the plume can be identified with the
278 westward $\mathbf{E} \times \mathbf{B}$ drifts. In case 2, the primary plume initially grows eastward due to the eastward
279 $\mathbf{E} \times \mathbf{B}$ drifts within the EPB (Figure 6e). As the EPB grows upward and encounters the MSTIDs
280 with westward $\mathbf{E} \times \mathbf{B}$ drifts, the primary plume turns westward and stretches along with the band
281 structure of MSTIDs (Figures 6f-h). The bifurcations on the east wall of the plume are mainly

eastward while encountering the MSTIDs with eastward $\mathbf{E} \times \mathbf{B}$ drifts. However, they are suppressed by the downward $\mathbf{E} \times \mathbf{B}$ drifts of MSTIDs as shown in Figure 1. A similar phenomenon was observed by Aa et al. (2019) that they found the EPBs merged and stretched along with the mid-latitude TIDs.

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 $\mathbf{E} \times \mathbf{B}$ drifts within the EPBs and reduce the background electron density, providing conditions favorable for the MSTIDs to fill the plasma depletion up through $\mathbf{E} \times \mathbf{B}$ drifts. Besides, the vertical and zonal $\mathbf{E} \times \mathbf{B}$ drifts within the MSTIDs can affect the morphology of EPBs in the 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

299 Not applicable

300 **List of abbreviations**

301 MSTIDs: Medium-Scale Traveling Ionospheric Disturbances

302 EPBs: Equatorial Plasma Bubbles

303 PRE: Pre-Reversal Enhancement

304 EsL: Sporadic-E Layer

305 NRL: Naval Research Laboratory

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

307 SAMI2: Sami2 is Another Model of the Ionosphere

308 LT: Local Time

309 **Availability of data and materials**

310 The datasets used during this study were constructed from the SAMI3/ESF model and

311 are available from the corresponding author on reasonable request.

312 **Competing interests**

313 The authors declare that they have no competing interests.

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319 **Authors' contributions**

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

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328 **Authors' information**

329 **COSMIC Program Office, University Corporation for Atmospheric Research, Boulder, CO,**
330 **USA**

331 Min-Yang Chou

332 **Department of Earth Sciences, National Cheng Kung University, Tainan, Taiwan**

333 Charles C. H. Lin

334 **Syntek Technologies, Fairfax, VA, USA**

335 Joseph D. Huba

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495 **Figure legends**

496 Figure 1. The time sequence of electron density contours as a function of longitude and altitude
497 at 22:47 LT, 23:48 LT, 00:48 LT, and 01:49 LT for case 1 (left column), case 2 (middle column),
498 and case 3 (right column). The black and white contour lines indicate the downward and upward
499 $\mathbf{E} \times \mathbf{B}$ drifts, respectively. The yellow and red stars indicate the positions of peak upward $\mathbf{E} \times \mathbf{B}$
500 drifts of the EPB and topside EPB (>900 km). Case 1 simulates the EPB without the MSTIDs.
501 Case 2 and case 3 simulate the interaction between the EPB and MSTIDs at 22:30 LT and 23:30
502 LT, respectively.

503

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

507

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

511

512 Figure 4. The peak vertical $\mathbf{E} \times \mathbf{B}$ drift variations of the topside EPBs (>900 km) as a function
513 of time for cases 1-5.

514

515 Figure 5. The Pedersen conductivity contours as a function of latitude and altitude in $\sim 2^\circ\text{E}$ at
516 01:49 LT for case 1 (left), case 4 (middle), and case 5 (right). The white (top panel) and black
517 lines (bottom panel) indicate the geomagnetic field line.

518

519 Figure 6. The time sequence of zonal $\mathbf{E} \times \mathbf{B}$ drift contours as a function of longitude and altitude
520 for case 2 at 22:47 LT, 23:48 LT, 00:48 LT, and 01:49 LT for cases 1 (top panel) and 2 (bottom
521 panel). The positive and negative values indicate eastward and westward $\mathbf{E} \times \mathbf{B}$ drifts,
522 respectively.

523

524 **Additional files**

525 • File name: Additional file 1, Additional file 2, Additional file 3, Additional file

526 4, Additional file 5, Additional file 6, Additional file 7, Additional file 8

527 • File format: avi

528 • Title of data: Electron density variations as a function of longitude and altitude for

529 cases 1-3 (Additional files 1-3). Airglow intensity perturbation variations at an altitude

530 of 250 km as a function of longitude and latitude for cases 1-5 (additional files 4-8).

531 • Description of data: Additional files 1-3 are movies for Figure 1. Additional

532 files 4-6 are movies for Figure 2. Additional files 7-8 are movies for Figure 3.

533

Figures

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 $E \times B$ drifts, respectively. The

yellow and red stars indicate the positions of peak upward $E \times B$ drifts of the EPB and topside EPB (>900 km). Case 1 simulates the EPB without the MSTIDs. Case 2 and case 3 simulate the interaction between the EPB and 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 panel) and case 5 (bottom panel).

Figure 4

The peak vertical $E \times B$ drift variations of the topside EPBs (>900 km) as a function of time for cases 1-5.

Figure 5

The Pedersen conductivity contours as a function of latitude and altitude in $\sim 2^{\circ}$ E at 01:49 LT for case 1 (left), case 4 (middle), and case 5 (right). The white (top panel) and black lines (bottom panel) indicate the geomagnetic field line.

Figure 6

The time sequence of zonal $E \times B$ 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 for cases 1 (top panel) and 2 (bottom panel). The positive and negative values indicate eastward and westward $E \times B$ drifts, respectively.

Supplementary Files

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