Equatorial evening prereversal vertical drift and spread F suppression by disturbance penetration electric fields

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[1] This paper presents new evidences on the responses of the evening sector equatorial ionosphere to prompt penetrating (PP) magnetospheric electric fields. In particular we show for the first time that the evening prereversal enhancement in the vertical drift/zonal electric field (PRE) and the consequent spread F (ESF) generation can be totally suppressed by penetration electric field of westward polarity arising from over-shielding processes. In contrast the undershielding PP electric field of eastward polarity is found to enhance the PRE and ESF in agreement with recent findings. These results are evaluated using collisional interchange instability growth rate model calculations. **Citation:** Abdu, M. A., E. A. Kherani, I. S. Batista, and J. H. A. Sobral (2009), Equatorial evening prereversal vertical drift and spread F suppression by disturbance penetration electric fields, *Geophys. Res. Lett.*, *36*, L19103, doi:10.1029/2009GL039919.

1. Introduction

[2] The most important single factor as a precursor condition for the post sunset equatorial spread F (ESF) development is the evening prereversal electric field enhancement (PRE) that causes a rapid uplift of the F region. Plasma instabilities develop, by the Rayleigh-Taylor interchange mechanism initiated at the bottomside upward gradient region of the rapidly rising F layer, so that plasma depleted flux tubes (plasma bubbles) with cascading irregularity structures rise up to the topside ionosphere marking the development of ESF. Observations by different techniques show large degree of day-to-day variability in the intensity and the occurrence of ESF [*Fejer et al.*, 1999; *Tsunoda*, 2005] that can be attributed to the variabilities in (a)- the evening prereversal vertical drift and (b) the ambient ionospheric dynamics due to wave disturbances (such as gravity waves) needed to seed the instability process, as well as the thermospheric meridional winds that could control its growth [*Maruyama*, 1988; *Abdu et al.*, 2006a; *Saito and Maruyama*, 2006). In this paper we focus on the prereversal vertical drift which is known to be produced mainly by the F layer dynamo in which the thermospheric zonal wind (eastward in the evening) and the longitudinal/local time gradient in the E layer conductivity play interactive roles [*Heelis et al.*, 1974] so that the day-to-day variability in these parameters is an important source of the variability in the PRE and hence in the ESF. Under magnetically quiet conditions an important cause of the variability in the PRE has been shown to be the upward propagating planetary waves [*Abdu et al.*, 2006b]. During disturbed conditions magnetospheric/high latitude electric fields that penetrate to equatorial latitudes can be an important cause of variabilities in the PRE and ESF, as such electric fields have large intensity in the dusk sector [e.g., *Richmond et al.*, 2003]. Under the Bz south condition, with a rapid auroral electrojet intensification marking a substorm/storm development, the magnetospheric convection electric fields promptly penetrate to equatorial latitudes. This under-shielding PP electric field has polarity eastward in the day- and evening-sector and westward in night sector. The Region-2 FAC shielding currents develops to balance the convection electric field with a time scale of ∼20–30 minutes. With the Bz turning north and/or with the auroral electrojet recovery the shielding layer electric field (over-shielding electric field) dominates the equatorial region with polarity opposite to that of the under-shielding PP electric field [e.g., *Kelley et al.*, 1979; *Kikuchi et al.*, 2008].

[3] The PP under-shielding electric field, directed eastward at the time of the PRE, can significantly enhance the equatorial F layer vertical uplift and the instability growth leading to bubble development [*Abdu et al.*, 2003]. On the other hand an over-shielding westward electric field can cause suppression of the PRE or even a net downward drift that could stabilize the layer. In this paper we present for the first time, evidence of over-shielding electric field causing suppression of the PRE leading to stability of the post sunset F layer during a spread F instability development season. It also presents a contrasting case of PRE enhancement (and ESF development) due to under-shielding electric field occurring at the local time of the PRE.

2. Results

[4] Vertical plasma drifts were calculated as $d(h_F)/dt$ from true heights at specific plasma frequencies, h_F, as obtained from ionograms. The vertical drifts so obtained are reliable representations of the true plasma drifts when the h_F is near and above 300 km which generally is the case in the evening hours of the PRE [*Abdu et al.*, 2006b]. Figure 1 shows the interplanetary magnetic field Bz (from the ACE satellite data base), the auroral electrojet AU and AL indices and the F layer vertical drift from ionograms over São Luis (2.33°S, 44.2°W, dip angle: −.5°), Brazil. The vertical drifts were calculated at the plasma frequencies 5, 6, 7, 10 and 11 MHz. We note intense Bz south conditions starting at 14 UT on 31 March 2001 that lasted until 22 UT of the same day, during which there were several auroral activity intensifications of approximately one hour duration that produced varying degrees of responses in the vertical drifts. We may point out that the response in $d(h_F)/dt$ during the

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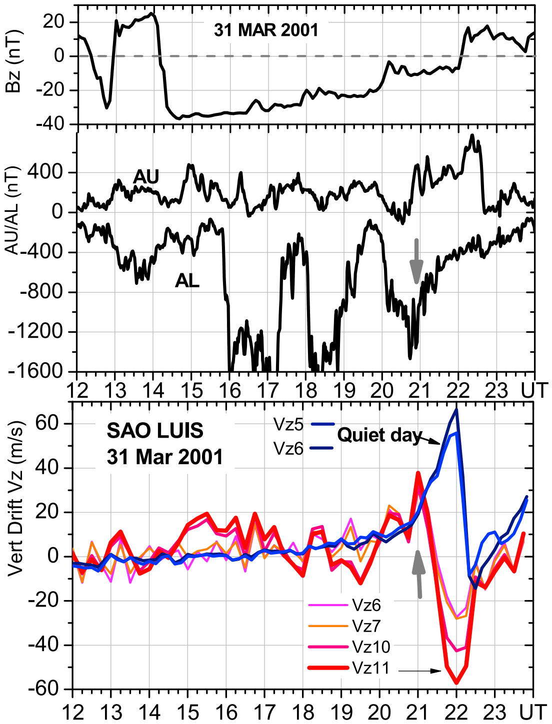

Figure 1. Variations in the IMF Bz from (top) ACE satellite, (middle) auroral indices AU/AL, and (bottom) vertical drift Vz, (that is, d(h_F)/dt) over São Luís. The Vz was calculated at plasma frequencies 6, 7, 10 and 11 MHz. The negative peak in Vz at 22 UT is higher at 11 MHz (58 m/s) than at lower frequencies. The quiet day mean vertical drift for March 2001 calculated at 5 and 6 MHz shows PRE amplitude of ~60 m/ at 22 UT/19 LT.

daytime is severely limited due to photochemical processes, but improves with increasing altitude so that the drifts calculated at the plasma frequency pair 10 and 11 MHz show better response than at the lower frequency pair 6 and 7 MHz, as can be noted in Figure 1. Also, starting from 17–18 LT (LT = UT − 3 hours) these drifts are closely comparable with the real plasma drifts (when $h_F > 300$ km). With the Bz prevailing southward an AL recovery set in at 21 UT (18 LT) accompanied by a strong over-shielding westward electric field which caused, starting at this time, a spectacular downward drift with peak value of ~−60 m/s at 19 LT. We note that the quiet day PRE amplitude peaking at 22 UT (19 LT) was also ~60 m/s. The over-shielding electric field presented a growth rate dependent on the AL recovery rate and a decay time of the order of one hour. The negative drift condition prevailed from ~1830 to 20 LT and there was no spread F development on this evening in contrast to the quiet time situation in March when a vertical drift of 60 m/s invariably produces ESF/bubble development.

[5] Figure 2 shows the IMF Bz, the AU/AL indices and the vertical drift during 9–10 November 2004, a period of severe storm. Over SL an enhanced vertical drift was in progress starting at ~19 UT (16 LT) due to a PP eastward electric field arising from the Bz south and the AL intensification. The rapid northward turning of the Bz near 21 UT (18 LT) caused a rapid AL recovery which is accompanied by an intense over-shielding westward electric field responsible for an abrupt decrease in Vz. The Vz turned downward attaining a value of ~−50 m/s at the time of the quiet time peak in the PRE that has a typical upward drift of ~50 m/s. The negative vertical drift established a stable F layer on this evening over SL in contrast to the quiet days when spread F occurrence is a regular feature in this month. The plots in Figure 2 extend to the morning hours of 10 November. We note that the positive Vz values of ~2 hours duration near midnight initiated spread F activity that was disrupted by a rapid downward drift near 0715 UT (0415 LT). A PP electric field of westward polarity associated with an AL intensification under Bz south conditions [e.g., *Sastri et al.*, 2002] was responsible for the disruption of the ESF in this case.

[6] Contrasting responses to prompt penetration electric fields arising from IMF Bz changes and auroral electrojet activity occurring in the proximity of the PRE are presented in Figure 3. The IMF Bz (top panel), the AE/AO indices (lower two panels) and the corresponding Vz values over Fortaleza (3.9°S, 38.45°W, dip angle: −9°) are plotted (bottom panel) for 23 and 25 September 2001. The Vz was calculated at 6 and 7 MHz for these cases. The mean Vz variations representative of some quiet days of September are also shown for reference. The onset of a storm on 25 September can be noted as a small increase in AE at 1920 UT (second panel) under a weak Bz south condition. The AE presented a sharp increase (by ~1700 nT) at ~2020 UT (1720 LT) that was followed by a series of intensification and recovery phases, with the Bz also presenting such phases. We note that the evening vertical drift on 25 Sept started to increase well before the quiet day Vz increase, and it was caused by an eastward PP (under-shielding) electric field arising from the storm onset (at 1920 UT). With the 2020 UT sharp rise in AE the Vz increased to large values attaining a peak of ~75 m/s (an eastward electric field of ~2 mV/m) at 2130 UT (1830) LT. A minor AE recovery starting at this time appears to have caused a sharp fall in the Vz that briefly turned negative and then increased to large positive values nearly accompanying

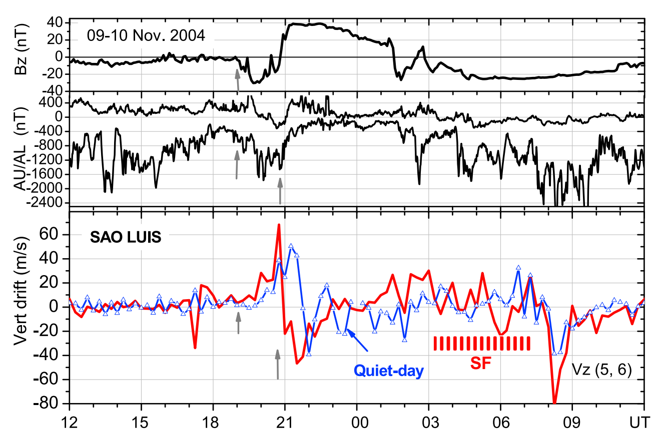

Figure 2. Similar to Figure 1, but for 09–10 Nov. 2004. The Vz variation in the bottom panel was calculated from true heights at 5 and 6 MHz. The Vz increase at the start of AL increase at 19 UT and its sudden decrease at the 21 UT AL recovery are indicated by arrows. The ESF onset near local midnight (03 UT) of 09–10 Nov. and its suppression near 0715 UT are indicated by vertical bars.

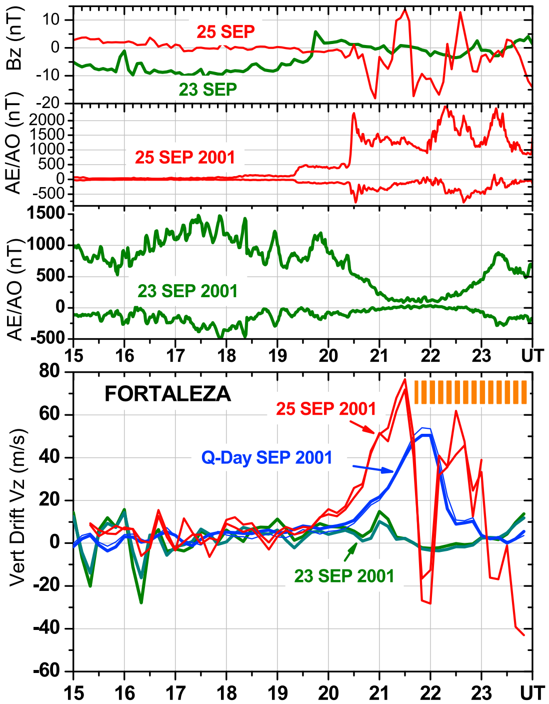

Figure 3. Similar to Figures 1 and 2, but for the two days, 23 and 25 September 2001. The Vz values (bottom panel) are for Fortaleza calculated at 6 and 7 MHz. They are shown together with a quiet day reference. The ESF occurrence staring at 2140 UT is indicated by vertical bars.

the AE phases. Intense spread F was triggered at ~2140 UT following the peak in the drift velocity. The transient decrease in the Vz did not cause any noticeable decrease in the SF intensity. On a typical quiet day the spread F occurs immediately after the peak in prereversal drift normally at ~22 UT (19 LT). We note that the earlier (by ~20–30 minutes) occurrence of the spread F on 25 September that followed the Vz peak due to the penetrating electric field is also consistent with such a pattern. In sharp contrast to this a northward turning of the IMF Bz at 1940 UT (1640 LT) with a prompt recovery in the AE activity (panel 3) on 23 September was accompanied by a strong over-shielding (westward) electric field that contributed to the total suppression of the prereversal vertical drift that reached negative values near its expected peak time, exactly similar to the results in Figures 1 and 2. The westward electric field on this day, however, could arise also from a disturbance wind dynamo as the auroral electrojet activity was strong and of extended duration before its relatively slower recovery phase during the PRE period. As to be expected no spread F was initiated on this evening.

3. Discussion

[7] The results presented above show clearly that the PP electric fields in the equatorial sunset sector are an important cause of the variability in the PRE, the prime driver of the ESF. The PRE can be either enhanced or suppressed. The latter situation can arise from a westward electric field originating from either a disturbance dynamo electric field that is known to have large amplitude in the evening hours [*Richmond et al.*, 2003], or from a penetrating over-shielding electric field associated with Bz turning north and/or substorm recovery, as shown here for the first time. For a better understanding of the observed ESF behaviour we will examine below the Rayleigh-Taylor or collisional interchange instability (CII) linear growth conditions under such electric fields. The governing equation for the polarization electric field δE_x associated with CII is written in the following form [*Abdu et al.*, 2009]:

$$\frac{\partial \delta E_x}{\partial t} - \gamma_R \delta E_x = s_x \tag{1}$$

where

$$\gamma_R = \left(-\frac{E_{ox}}{B_o} - W_z + \frac{g}{\nu_i}\right)\frac{1}{l_o}; \quad s_x \approx \frac{B_0 \Delta U_{0x}}{l_0}\left(\frac{\delta W_z}{\kappa_i} - \delta W_x\right);$$
$$1/l_o = d \log n_o/dz$$

[8] E_{ox} is the prereversal zonal electric field (positive westward), ΔU_{0x} is the differential ion-electron zonal velocity; W_z is the vertical neutral wind; $\delta W_{x,z}$ are the gravity wave associated winds; n_o is the electron density; l_0 is the electron density scale length; B_0 is the magnetic field; $\kappa_i = \nu_i/\omega_i$ (the ratio of the ion collision-to-gyro-frequency).

[9] The most important parameter in the growth rate and that is most severely altered by penetration electric field episodes under consideration is the zonal electric field E_{ox}. In order to study its effect on the growth of CII, the equation (1) is solved numerically using Crank-Nicolson implicit scheme [see also *Kherani et al.*, 2009], with the time variation of E_{ox} retained in the calculation. It means that the growth rate γ_R depends on time through the background electric field. The calculation of the time variation in δE_x considers also the gravity wave winds as discussed by *Abdu et al.* [2009] and *Kherani et al.* [2009]. This approach is still linear since time variations in the electron density and the polarization field are not considered in the expression for γ_R.

[10] Calculations were performed for conditions representative of three of the four events discussed above, that is, the event of 31 March 2001 (event 1) and those of 23 and 25 September 2001 (events 2 and 3). To understand the storm effects in the development or suppression of CII, the following cases are chosen:

[11] Event 1:

[12] Case 1a: Quiet-time vertical drift $Vz = -E_{ox}/B_0$ as in March 2001;

[13] Case 1b: Storm-time Vz corresponding to 31 March 2001.

[14] Event 2:

[15] Case 2a: Quiet-time vertical drift $Vz = -E_{ox}/B_0$ as in September 2001;

[16] Case 2b: Storm-time Vz corresponding to 23 Sep 2001.

[17] Event 3:

[18] Case 3: Storm-time Vz corresponding to 25 Sep 2001

[19] Simplified Vz profiles for all the above five cases based on their derivation from digisonde measurements are

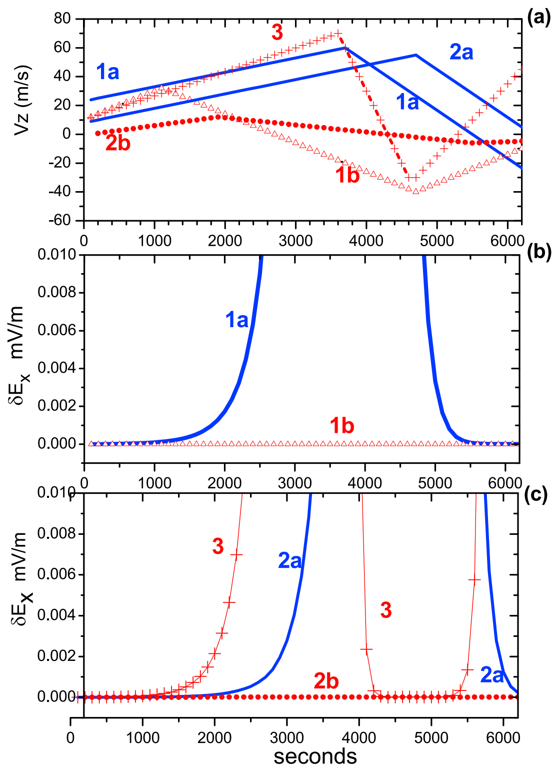

Figure 4. (a) Simplified Vz (E_{ox}/B_0) curves based on the measurements by Digisondes for the five cases: 1a and 2a represent the quiet day means for March and September 2001 respectively. The curves 1b, 2b and 3 correspond to the storm disturbances of 31 March, 23 Sept. and 25 Sept. respectively. (b and c) The polarization electric field variations corresponding to Figure 4a.

presented Figure 4a (the zero time corresponds to the approximate starting time of the PRE). Initial density profiles for these events are also derived using digisonde measurements. The linear growth of δE_x as a function of time for event 1 is shown in Figure 4b. We note that polarization field grows exponentially for the Case 1a which represents quiet time ionospheric condition during March 2001. However, δE_x could not develop for case 1b, which is caused by the abnormal E_{ox} behaviour (that is, storm associated strong westward electric field) and there was no spread F on this night. (It is to be noted that density profile is kept same for both the cases 1a–b).

[20] The linear growth rates for the event 2 are shown in Figure 4c. The curve 2a corresponds to the quiet condition of September 2001 and it shows the polarization electric field growing exponential which is an indication of linear growth of CII guarantying spread F development (as observed in March). However, for case 2b representing 23 September the δE_x does not show any growth indicating suppression of CII resulting in a stable F layer as verified observationally. The ESF absence resulted from the suppression of the PRE by the over-shielding electric field of westward polarity which in this case is weaker than on 31 March. In contrast to this the curve 3 in Figure 4c shows a rapid exponential growth as a result of a large vertical drift representative of the prompt penetrating eastward electric field associated with the development phase of the 25 September storm event. The rapid exponential growth of the δE_x guaranteed spread F development which indeed was observed (Figure 3). After the initial increase the vertical drift reverses for a short time. We note in Figure 4c that during this reversal phase, δE_x amplitude decreases, which is expected in linear approach. In nonlinear approach, once δE_x grows as rapid as found in Figure 4c, any change in ambient electric field may or may not affect the further growth. This aspects needs to be addressed by nonlinear simulation which is out of scope of present study.

4. Conclusions

[21] The main conclusions of this study are the following: IMF Bz south conditions and auroral electrojet activity prevailing in the sunset sector can cause drastic modifications to the equatorial evening prereversal electric field/vertical drift and hence to the ESF instability development. During a storm/substorm development phase, undershielding electric field promptly penetrate to equatorial latitudes with eastward polarity in the sunset sector causing large vertical drift at the time of the PRE, thereby leading to enhanced instability growth and ESF development. The auroral electrojet recovery associated with the Bz turning north (or sometimes even under Bz south condition), that accompany large over-shielding westward electric field, could lead to total suppression of the PRE, or even significant plasma downdraft, guarantying stability of the F layer that otherwise would be unstable, under normal PRE conditions. Late night ESF activity can be disrupted by PP electric field of westward polarity arising from AE activity. The overall results presented in this paper demonstrate the crucial role of the IMF Bz and auroral electrojet activity in the day-to-day and short term variability of the ESF. We may point out that as the causative factors (variations in Bz and AE) discussed here should increase with rising solar activity so should the ESF variability arising there from.

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