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Thermospheric meridional wind control of equatorial spread F and evening prereversal electric field

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[1] The role of the evening prereversal zonal electric field enhancement (PRE) as conducive to equatorial spread F (ESF)/plasma bubble development versus that of the magnetic meridional wind as a suppressing factor is examined using digital ionosonde data from an equatorial site, Sao Luis (SL), and a low latitude site, Cachoeira Paulista (CP) in Brazil. The evening vertical plasma drift (*Vz*) over SL is used, together with the F layer peak height (*hmF2*) over CP, to compute the magnetic meridional wind. The analysis performed for two epochs, that is, March-April of 1999 and 2001, provide consistent evidence that the magnetic meridional wind can negatively influence the ESF development in two ways: (a) by reduced development of the PRE and. (b) by direct suppression of the bubble growth

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1. Introduction

[2] The rapid uplift of the evening ionosphere under the action of the PRE is known to be primarily responsible for the development of the spread F/plasma bubble irregularities of the post sunset equatorial ionosphere. The steep bottomside density gradient of the raising F layer becomes unstable to density perturbations leading to instability growth by the Rayleigh-Taylor (R-T) mechanism whereby the rarified plasma of the lower heights rises up to the topside ionosphere in the form of depleted flux tubes/plasma bubbles, with the associated cascading process leading to irregularity scale sizes ranging form a few centimeters to 100's of kilometers [*Haerendel*, 1973], known by the generic name ESF. The ESF irregularities present large degree of variability on seasonal, day-to-day and shorter terms. While the causes of the seasonal variation are reasonably known [e.g., *Abdu*, 2001], those of the day-to-day and shorter term variabilities are far from being identified due to our lack of detailed knowledge on the interdependent variability of the ambient parameters that control the ESF development. The post sunset F layer rise due the PRE results from the combined effects of the thermospheric eastward wind and the longitudinal/local time gradients in the integrated Pedersen conductivity ($\Delta\Sigma_P$) across the sunset terminator [*Rishbeth*, 1971]. The other factors that could contribute to the ESF variability include (a) the thermospheric meridional/trans-equatorial winds that cause asymmetric equatorial anomaly and hence reduced bottomside density gradient that could diminish the linear growth rate of the R-T mechanism, and increased field line integrated conductivity that could suppress the instability nonlinear growth into topside bubbles [*Maruyama*, 1988], and (b) the amplitude of the initial density perturbation of which we will not be discussing here.

[3] In this paper we investigate effect of meridional winds on the ESF development conditions. Since the paper by *Maruyama* [1988] the possible role of meridional/trans-equatorial wind on the ESF development has been the subject of a few previous investigations [e.g., *Mendillo et al.*, 2001], with no definitive answers, however. In a recent paper *Jyoti et al.* [2004] suggested that equatorward meridional wind could contribute to bottomside spread F occurrence for low F layer heights over Trivandrum. *Sastri et al.* [1997] noted that a few cases of ESF occurrence in the season of its non occurrence (June months) in Brazil was caused by magnetic activity rather than by reduced poleward wind. The process of the possible suppression of the instability development by meridional wind involves, as a first phase, the development of an asymmetric equatorial anomaly leading to enhanced field line integrated conductivity [*Maruyama*, 1988], and possibly reduced F layer bottomside density gradient, conditions unfavorable for the instability growth. An important consideration concerns the local time of the meridional wind changes that should precede the post sunset ESF development in view of the response time of the equatorial anomaly to an imposed change in such winds, which should be of the order of 2–3 hours [*Abdu*, 2001]. Thus meridional winds during the late afternoon/pre sunset hours need to be associated with the post-sunset ESF occurrence. No results are so far available on such associations, however. In this paper we address this question by means of magnetic meridional winds calculated from ionospheric sounding data from the Brazilian equatorial site Sao Luis- SL (2.33° S, 44.2° W, dip angle: -.2°) and the low latitude site Cachoeira Paulista- CP (22.6° S, 315° E; dip angle: - 28°), under different spread F occurrence conditions.

2. Method of Data Analysis

[4] The magnetic meridional wind, U_{mm}, was calculated by the SERVO method proposed by *Rishbeth et al.* [1978] for three cases of post sunset spread F occurrence over the two ionosonde sites. Case 1: Spread F non occurrence at both locations; Case 2: Spread F occurrence over SL only,

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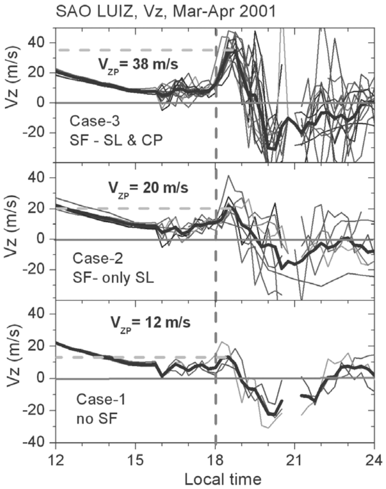

Figure 1. Vertical drift velocity V_Z calculated as d(hF)/dt using the true height data from the Digisonde over SL, for March–April 2001. The results for the Cases 1, 2 and 3 are plotted in the bottom, middle and top plots. The blue thick line represents the mean Vz.

which corresponds the irregularity process restricted to limited altitude (or, the bottomside) and Case 3: Spread F occurrence over SL as well as over CP corresponding to well developed topside bubbles [*Abdu et al.*, 2003]. The spread F intensity was arbitrarily classified as 1, 2 and 3 for increasing height ranges of the spreading. The SERVO method works on the premise that the F layer peak height, in the absence of any vertical transport by winds or electric field, occurs at a balance height, h_0, where the recombination and diffusion terms balance. The measured layer peak height, *hmF2*, could differ from h_0 depending upon the intensity of the meridional wind and the zonal dynamo electric field that cause vertical transport of the F region plasma. Therefore U_{mm} can be calculated from the knowledge of h_0 and *hmF2*. The method by *Rishbeth et al.* [1978] was adapted for low latitude situation, where the zonal electric field has significant effect on hmF2, by a procedure developed by *de Medeiros et al.* [1997], and accordingly:

$$U_{mm} = \frac{1}{\sin I \cos I}\frac{dhmF2}{dt} + \frac{H}{(k+1)\alpha} \cdot [\exp(hmF2 - ho)/H - \lambda \exp(-k(h\max - ho)/H] - \frac{Vz}{\sin I}. \qquad (1)$$

where

$$\alpha = \frac{2H^2 \cos I}{(k+1) D \sin I} \text{ km m}^{-1}$$

where I is the dip angle, *H* the scale height of ionizable gas, *D* the diffusion coefficient, *k* = 1.75 and λ = 1 for night and 3.86 between 0600 and 1800 LT. In analysis starting before 1800LT the values of λ are interpolated for a linear day-to-night transition as per *de Medeiros et al.* [1997].

[5] The vertical drift velocity V_Z was calculated over Sao Luis as d(hf)/dt using the true heights for a given frequency, hf, obtained from Digisonde [*Reinisch*, 1996], which is reliable for F layer heights >300 km that applies for the evening hours of our main interest, when the F layer rises due to the PRE. The equatorial vertical drift was extrapolated to the F-layer peak over CP (as explained by *de Medeiros et al.* [1997]) for which the U_{mm} was calculated. The reliability of the method has been validated against Fabry-Perot interferometer wind measurements at the same location [*de Medeiros et al.*, 1997]. The advantage of the method is that it can provide winds at all local times, which is very crucial for identifying the effects of pre sunset winds on the post sunset spread F development.

3. Results and Discussion

[6] The data analyzed here cover two equinoctial months, March-April, during the years 1999 and 2001. The vertical drift variations over SL for the three cases considered above are presented in Figure 1, for the year 2001. The vertical drifts by the *Scherliess and Fejer* [1999] model are used before 16 LT. We note that the mean amplitude of the peak drift velocity, *Vzp*, is the smallest (∼12 m/s) for the case of non occurrence of spread F over both stations. The mean *Vzp* increases to the order of 20 m/s for the Case 2 of spread F occurrence only over SL [see also *Abdu et al.*, 1983]. For the Case 3 of well developed topside bubbles the mean Vzp needs to attain the order of 38 m/s, which is in reasonable agreement with the Jicamarca vertical drift values for topside bubbles classified as "strong spread F" by *Fejer et al.* [1999].

[7] Mass plots of the U_{mm} for the three cases, obtained from equation (1), are presented in Figure 2. The average quiet time winds over CP are generally pole-ward during the day and equatorward during the night [*Pincheira et al.*, 2002] as is evident also in the three cases presented here. The small amplitude of the V_{ZP} for the Case 1 (see Figure 1) is not conducive to spread F generation and hence no meridional wind influence on spread F can be perceived. Comparing the Cases 2 and 3 we note that the evening poleward U_{mm} near sunset (∼18 LT) has a mean amplitude of the order of 190 m/s for the Case 2 as compared to 100 m/s for the Case 3. For a better comparison we have

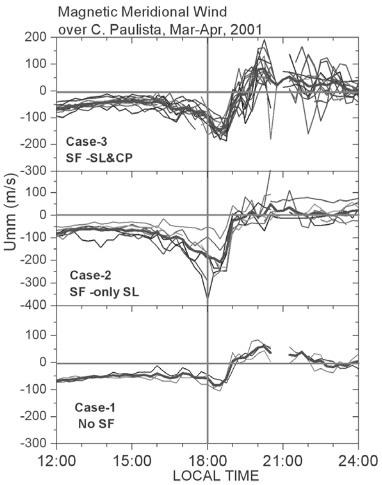

Figure 2. Mass plots of the magnetic meridian winds, U_{mm}, over CP for the three cases of spread F occurrences, during March–April of 2001.

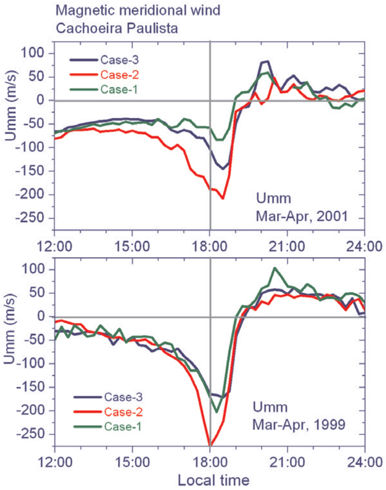

Figure 3. Mean values of the U_{mm}, for the three cases plotted in Figure 2, and similar results for 1999.

plotted in Figure 3 the mean U_{mm} values of Figure 2 together with the results from similar analysis for 1999, which clearly show that the average wind for the Case 2 is appreciably more poleward than for Case 3 during a few hours around and before the sunset. The V_{ZP} and the U_{mm} values near sunset for the two periods, in 1999 and 2001, are given in Table 1.

[8] We note that an association of larger evening poleward wind for the Case-2 as compared to the smaller wind for the Case-3 is consistently present in the results from the two independent data sets of 1999 and 2001.This would suggest that an increase in the poleward wind is capable of inhibiting the vertical bubble growth, thereby confining the ESF to the latitude closer to the dip equator.

[9] Larger meridional winds can cause increase of flux tube integrated conductivity that could reduce the R-T instability growth rate as well as suppress the nonlinear bubble development to topside ionosphere [*Maruyama*, 1988], thereby limiting the latitudinal extension of the irregularities as represented by the Case-2. This rather direct control by the meridional wind is unlikely to be the major cause of the limited latitudinal extension of the ESF for the Case-2 situation under consideration. Here the most notable effect is an association between the larger pole-ward wind and reduced amplitude of the V_{ZP} which is evident individually during the two periods (1999 and 2001), as well as by inter-comparing the two periods. The mechanism by which an enhanced poleward wind could cause reduced PRE needs to be investigated. It may be recalled here that $\Delta\Sigma_P$ together with the thermospheric zonal/eastward wind in the evening hours is mainly responsible for controlling the amplitude of the PRE [*Batista et al.*, 1986]. Therefore a reduction of the PRE amplitude could arise from a decrease in the effective $\Delta\Sigma_P$ caused by an increase in meridional wind. Alternatively, an increase of meridional wind might be the consequence of a reduction in the zonal component of the wind (to maintain the total wind conserved) so that the latter could as well be responsible for a reduction in the PRE amplitude.

[10] As regards the possible direct control of the meridional wind on the ESF, we sought to identify situations in which the Case-2 and Case-3 can occur under identical amplitudes of the PRE. Such cases are rare indeed, but two examples that meet closely this condition are presented in Figure 4 for 2001 and 1999. Figure 4a shows the V_Z variations for two Case-3 days (March 02 and 15) and for one Case -2 day (March 22). The spread F intensity is plotted over SL for the Case 2 and over CP for the Case 3 (color coded to match that of the V_Z). Figure 4b shows the U_{mm} for the same three days. We note that the V_{ZP} amplitude on Mar. 22 (Case 2) when spread F was limited to SL is comparable to, but even slightly higher than, those on the other two evenings when the spread F represented fully developed topside bubble (Case-3). Yet the U_{mm} during the pre sunset hours of Mar 22 was more pole-ward (by 40–50 m/s) than on the other two days, which points to the possibility of enhanced pole-ward wind being responsible for confining the spread F to SL on this day. A similar conclusion can be drawn from the results for 1999 plotted in Figures 4c and 4d. Here the V_Z amplitude around its peak and before is slightly smaller for the Case 2 (April 5) than for Case 3 (March 27), but is not sufficient to account for the large increase of the pole-ward wind, for the Case 2 than the Case 3, obtained during and prior to sunset. These results thus appear to provide convincing evidence that the increased pole-ward winds, occurring before and around sunset, do in fact contribute directly to inhibit the vertical growth of the plasma bubbles leading to the confinement of

Table 1. V_{ZP} and U_{mm} Values Near Sunset for 1999 and 2001

	1999 (March–April)		2001 (March–April)	
	Case-2	Case-3	Case-2	Case-3
V_{ZP} (m/s)	29	39	20	38
U_{mm} (m/s)	275	170	185	100

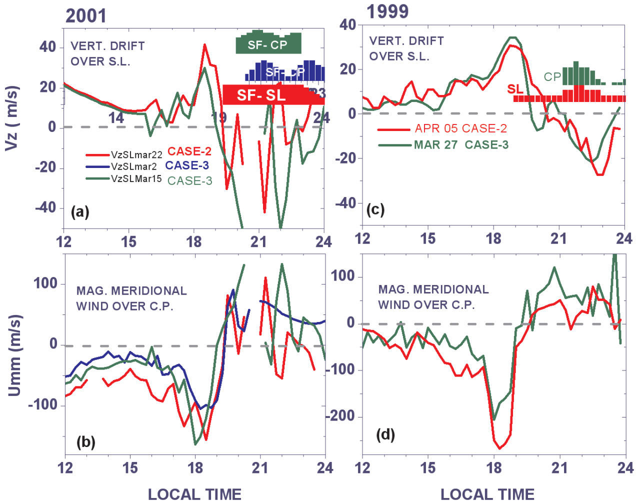

Figure 4. (a) Variations of V_Z over SL for the three days, March 22 (Case-2) and March 02 and 15 (Case-3) in 2001, and the corresponding spread F intensities, on a scale of 0 to 3, on the upper right; (b) Umm over CP for the same three days; and (c and d) same as Figures 4a and 4b but for March 5 (Case 2) and March 27 (Case3) in 1999.

the spread F irregularities to latitudes closer to the magnetic equator.

4. Conclusions

[11] The main conclusions of this study are the following: Topside bubbles can be produced by an average prereversal vertical drift amplitude of 38–39 m/s. For lower vertical drift velocities (20–29 m/s) the spread F irregularities are limited to lower heights/latitudes. Vertical drift velocities <20 m/s on an average are not sufficient to cause development of bottom-side spread F. Meridional neutral winds tend to limit the spread F latitudinal belt to regions closer to the dip equator in two ways: (a)- by causing reduced prereversal vertical drift that reduces the linear growth rate of the instability process, and (b) by directly contributing to suppress the bubble development through the effect of enhanced flux tube integrated conductivity which could cause reduced linear growth rate of the R-T instability process as well as limit the nonlinear development of the bubbles. The excellent agreement between the results from the two independent data sets picked from the two years, 1999 and 2001, reinforces the validity of these conclusions.

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