GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 22, PAGES 4137-4140, NOVEMBER 15, 1998

Equatorial F region zonal plasma irregularity drifts under magnetospheric disturbances

M. A. Abdu [3,1], P. T. Jayachandran [1,2], J. MacDougall [1,2], J. F. Cecile [1], and J. H. A. Sobral [3]

Abstract. Equatorial F region plasma drift velocities measured by a digital ionosonde (CADI) that was recently installed in Fortaleza, Brazil, are used to investigate magnetospheric disturbance effects in the vertical (zonal) and zonal (vertical) velocities (electric fields). For the first time we report evidence of large fluctuations in irregularity zonal drift velocities (~ 50-180 m/s) associated with magnetospheric disturbances. The fluctuations in the zonal velocity, anti correlated with those in vertical velocity, are unlikely to be produced by prompt penetration of disturbance meridional electric field of high latitude/magnetospheric origin. A mechanism is proposed to explain the velocity fluctuations that involves: (1) Hall polarization vertical electric field in the E-layer that is field line mapped on to F- layer, and (2) electric field caused by vertical current arising from divergence in field line integrated zonal Pedersen current; both produced by the primary disturbance zonal electric field. Enhanced nighttime E region conductivity with possible spatial gradients, a requirement for the functioning of this mechanism, is observed to be present from other simultaneous measurements, whose source is suggested to be particle induced ionization in the south Atlantic Magnetic Anomaly (SAMA) zone, as known also from previous studies.

Introduction

Magnetospheric convection electric fields are known to penetrate to low latitude ionosphere under varying phases of a magnetospheric disturbance development: interplanetary magnetic field variations, sudden storm commencements, the DP 2 fluctuations, substorm onset and recovery phases and ring current developments. [Gonzales et al., 1983; Sastri et al., 1992; Kikuchi et al., 1996; Sobral et al., 1997; Abdu et al., 1998; Fejer and Scherliess, 1998 and references therein]. Direct measurement of electric fields/plasma drifts by radars complemented by electric currents/ magnetic field variations monitored by magnetometers have been the data base more often utilized to investigate the equatorial ionospheric response features. Modern digital ionosondes now provide valuable data on the F layer bottomside plasma drift velocities [Reinisch et al., 1989; MacDougall et al., 1998]. The investigations of disturbance equatorial electric fields carried out so far concerned only the zonal component of the disturbance electric field. Little is known about the meridional/vertical component of the disturbance electric field. In fact Fejer et al. (1981) noted that the disturbance component in the zonal drift velocities over Jicamarca was not particularly perceptible from its day-today fluctuations. In the present paper we investigate magnetospheric disturbance effects on zonal plasma drifts over an equatorial station using the F layer plasma irregularity drift velocities measured by a digital ionosonde at Fortaleza (4° S, 38° W, dip ~9°), Brazil. A noteworthy and surprising result is that the zonal drift velocities, and not just the vertical velocity only, are correlated with the magnetic field variations and that the fluctuations in these two velocities are often anti correlated with each other. We will present in Section-2 an analysis of some cases of the velocity fluctuations. Discussion of the results and an operational mechanism for the observed zonal velocity perturbations will be presented in Section-3, with conclusions presented in Section 4.

[1] Department of Physics and Astronomy, University of Western Ontario, London, Canada
[2] Department of Electrical Engineering, University of Western Ontario, London, Canada
[3] Intituto Nacional de Pesquisas Espaciais - INPE, São José dos Campos, SP, Brazil

Paper number 1998GL900117.
0094-8276/98/1998GL900117$05.00

Observations and Results

The CADI (Canadian Advanced Digital Ionosonde) [Grant et al., 1995] measures the line of sight velocities and angle of arrival of the reflected echoes. The large number of echo sources usually available during spread F irregularity events permits reliable determinations of the three orthogonal components of the drift velocities. The operating mode was set up to record drift measurements at fixed frequency every 30 seconds. All the examples of drift fluctuations to be presented here were taken under conditions of strong presunrise spread F events similar to the example presented in MacDougall et al. (1998). Figure 1 shows an event of drift fluctuations plotted together with auroral activity indices AE (AU/AL). In this example the vertical velocity fluctuations (±~20m/s) are well correlated with the AE/AL index which suggests that the electric field responsible for the vertical drift fluctuations has the same disturbance source as that which produces the AE fluctuations. If we consider each of the decreases in the AL index as representing a substorm intensification, then it is apparent that a negative (positive) deviation is associated with a downward (upward) velocity perturbation, that is, a westward (eastward) electric field perturbation, with a delay of the order of 20 minutes. As an important point it may be noted that significant fluctuation amplitude is present also in the zonal drift, being of the order of 20 m/s, that tends to be anti correlated with those in the vertical drift. The apparent delay in the fluctuations of the drift velocities has perhaps to do with the phase of the penetration electric field response in relation to that of the AE/AL fluctuations. We do not intend to go into details of this relationship, or into aspects of the nature of the magnetospheric disturbance event, since our present objective is restricted to investigating the association (that is, the anti correlation) between the disturbance vertical and east-west drift velocities clearly observed in this event, and in others to be presented below.

Two other cases of drift fluctuations are presented in Fig.2.

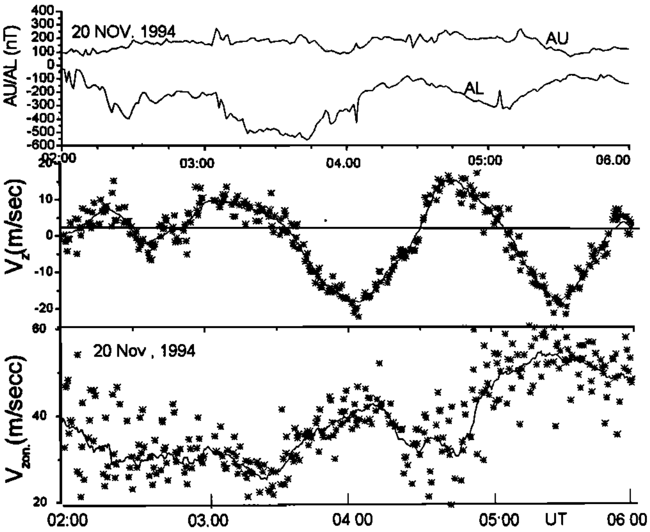

Figure1. - Zonal and vertical drift velocities during a pre sunrise spread F event measured by a CADI over Fortaleza (bottom and middle panels). The solid line is a polynomial fit of the raw data denoted by stars. AE-AU/AL indices (top panel).

The Kp indices for these events varied from 4 to 5+ and from 5+ to 6+. During these events as in the first one the zonal velocities show significant fluctuations, as do the vertical velocities, and they are largely anti correlated. There are intervals when their relationship is not defined clearly though, as seen in the scatter plots in Figure 3 of all vertical versus zonal velocities for the three cases discussed above, their overall correlation coefficients being 0.71, 0.59 and 0.61. For selected intervals when almost perfect anti correlation is evident the ratio of the fluctuation amplitudes of the zonal to vertical velocities varied from ~0.5 during the event in Fig.1 to larger values (approximately 3) during the events of Figure 2.

Discussion

Magnetospheric electric field penetration to equatorial latitudes seems to be more efficient for zonal electric field as compared to meridional electric field. From incoherent scatter radar observations Gonzales et al. (1983) showed the amplitude ratio for zonal electric field between Arecibo (L=1.46) and Jicamarca during two active nighttime periods to be 2.4 and 3.5, which is larger than the ratio of $(1.46)^{3/2} = 1.7$ expected for the mapping of a constant electric field in the equatorial plane (Mozer, 1970). Disturbances in meridional electric field were of less amplitude than those of the zonal component over Arecibo but were of larger amplitude over a higher mid-latitude station (St Santin) as reported by Blanc (1983). From a recent analysis of DE-2 satellite ion drift observations Fejer and Scherliess (1998) showed that sudden increases in magnetospheric convection lead to predominantly westward drift which decreased equator-ward (from 55° to 35°). The disturbance meridional/vertical electric field observed over Fortaleza, however, seems to contain only minor contribution (if any) from the equatorward propagation of such electric field as part of a polar disturbance electric field. Rather, much of it seems to be accounted for by the electrodynamics processes peculiar to the equatorial ionosphere.

A mechanism for the zonal drift perturbations.

A disturbance in zonal electric field produces corresponding disturbance in vertical plasma drift in the F-region over the equator. Below the F region, with decreasing altitude, the different mobilities of ions and electrons lead to their differential drifts and the generation of Hall and Pedersen currents and electric fields. We shall examine below the roles of such electric fields and currents in the observed zonal velocity fluctuations.

In general, a vertical electric field, E_V in the F region can arise from: (a)- Hall conduction, (b)- neutral wind dynamo, and (c)- vertical currents arising from divergence of horizontal currents. As explained by Haerendel et al. (1992), it can be expressed, using field line integrated quantities, as:

$$E_v = \frac{\Sigma_H}{\Sigma_P} E_{EW} - BU^P_{EW} + \frac{J_V}{\Sigma_P} \qquad (1)$$

where Σ_H and Σ_P are the field line integrated Hall and Pedersen conductivities; B is the magnetic field; J_V is the field line integrated current in *vertical* (that is, perpendicular to field line in meridian plane) direction, and U^P_{EW} is field line integrated conductivity weighted zonal wind. In the present case of the nighttime velocity fluctuations being produced by disturbance penetration electric field we shall ignore any contribution from (b). We consider that the primary zonal disturbance electric field that produces the F region vertical plasma drift also induces a Hall electric field in the E region which, when mapped (by the highly conducting field line) on to the F layer, could cause the zonal plasma drift as sketched in Figure 4. For this mechanism to be operative in the night ionosphere the required ionospheric conductivity is considered to arise from enhanced ionization at E layer heights as will be discussed later. If the vertical electric field arises entirely from Hall conduction (that is, vertical current being

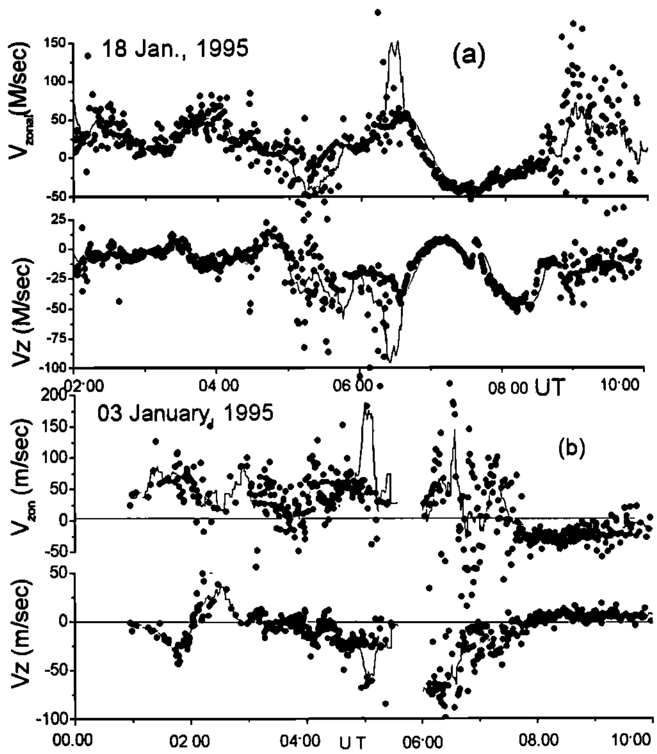

Figure 2. - Zonal and vertical drift velocities as in Fig.1 but for two additional days, 18 and 3 January 1995; (velocities higher than the limits of the y-axis are not shown).

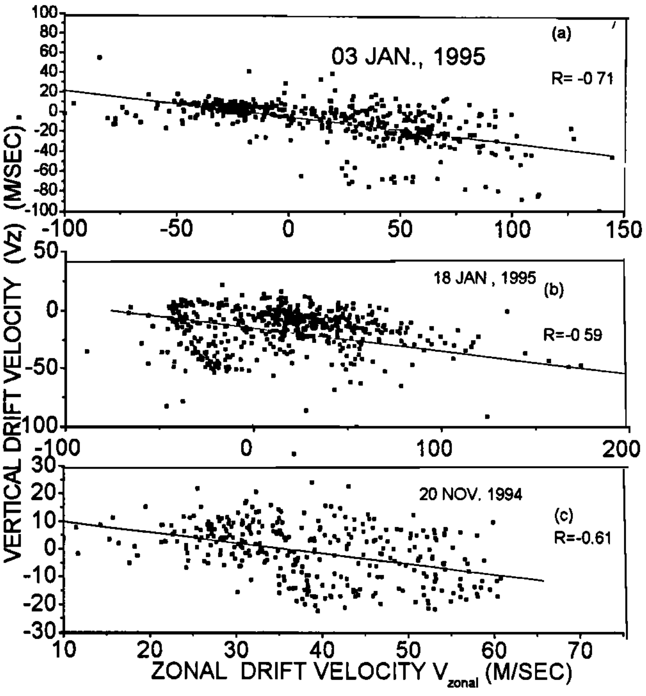

Figure 3. - Scatter plots of zonal versus vertical velocities for the three cases presented in Figs. 1 & 2; A low-pass filter has been applied to remove the fluctuation with periods less than 10 min.

neglected) and drives the fluctuation component of the zonal velocity, ΔV_{EW}, with associated ΔV_V, we have the following condition from the Eq.1:

$$\frac{E_V}{E_{EW}} = \frac{\sum_H}{\sum_P} = -\frac{\Delta V_{EW}}{\Delta V_V} \qquad (2)$$

The ratio of the fluctuation velocities, of Eqn.2, is found to be varying (as stated earlier) from approximately 0.5 to 3.0. The ratio of the field line integrated conductivities was calculated for the local time range of our observation for a field line at 300 km over Fortaleza (down to 90 km at the conjugate points in both hemispheres). This calculation that used, as a trial, the International Reference Ionosphere- IRI (Bilitza, 1986) yielded a value ~0.15. Under disturbed conditions, however, large enhancements in the E layer electron densities occur. Typical densities of the order of $1.3(10^{10})$ el/m^3 have been observed during some events (as inferred from the blanketing frequencies of the sporadic E layers that some times accompany such events), which is a factor of ~30 larger than that predicted by the IRI. Such density enhancements can cause significant increase in Σ_H/Σ_P due to the fact that Σ_H arises mainly from a narrow height region of the E layer (subjected to enhanced ionization) whereas Σ_P involves the entire field line roughly as an increasing function of height. Assuming, for example, that the 30-fold increase (with respect to the IRI prediction) in the E region electron density occurs along about 5% of the field line length between the conjugate points, the ratio Σ_H/Σ_P can increase by a factor of 6, rising its value in Eq.2 to around unity. Of course a different degree of the electron density enhancements would yield a correspondingly different value for this ratio. Based on the observed ratio of the velocity fluctuations, $-\Delta V_{EW}/\Delta V_V$, that often exceeds unity, it appears that additional contribution to E_V could arise from the vertical current term in the Eq.1. Vertical Pedersen current arises from divergence in horizontal current that results from the spatial gradients inherent in the enhanced ionization (conductivity). Since Fortaleza seems to be within reach of the effect of Soth Atlantic Magnetic Anomaly (SAMA) (Greenspan et al., 1991) the conductivity enhancement could have significant spatial gradients, possibly positive southward, and positive or negative in the east-west direction. The east-west gradient is responsible for the divergence in the zonal Pedersen current which could contribute to vertical Pedersen current and hence to the vertical electric field. Thus, applying the condition: $Div.J = 0$, where, $J = J_{EW} + J_V$; $J_V = E_V \Sigma_P$ and $J_{EW} = E_{EW} \Sigma_P$, and assuming that E_{EW} is constant in height, and $E_V = 0$ at the base of the ionosphere (h_0 = 90 km), we can show that E_V at a height h > h_0 is given by:

$$E_V = -E_{EW} \int_{90}^{h} \frac{1}{\sum_P} \frac{d}{dy} \sum_P dh \qquad (3)$$

Assuming, as an example, that Σp changes by 50% in an east-west distance of, say, 200 km, an integration over 100 km would yield $E_V/E_{EW} \cong 0.25$. Still larger gradients in the form of transient increases, which seems to be likely, will be helpful to explain higher magnitudes of the ratio $\Delta V_{EW}/\Delta V_V$ that are often observed.

Thus, we have the vertical electric field arising from both the Hall conduction and current divergence terms of Eq.1, and their added contributions, depending upon the intensity of the ionization and spatial gradients in it, could account for the magnitude of the observed ratio $\Delta V_{EW}/\Delta V_V$. A more quantitative evaluation could be made if we have more precise knowledge of the density enhancement and its spatial distributions for specific cases.

There are different types of evidences suggesting enhanced nighttime plasma densities over Fortaleza. During all the three events analyzed here the magnetic field H-component showed

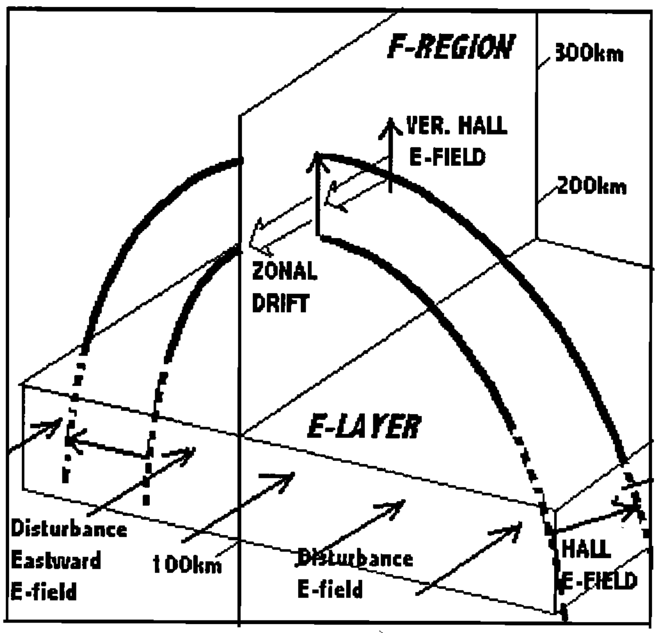

Figure 4 - A sketch to illustrate how Hall electric field produced in the E region (shown in horizontal plane) is mapped as vertical field on to equatorial F region (shown in east-west vertical plane). The open arrows show the direction of plasma drift which is westward in this case. The Eastward pointing arrows represent the primary zonal disturbance electric field.

enhanced electrojet current fluctuation of varying amplitudes (a separate study is being prepared on these results). In the case of the event of Figure.1 the amplitude was of the order of 10nT, which is a factor of 10 smaller than that the normal daytime current strength [Pfaff et al. 1997]. The corresponding E -region peak electron density should be of the order of 3×10^{10} el/m^3. As mentioned before enhanced Es layers, frequently observed under magnetically disturbed condition, also point to electron density enhancement of similar magnitude. It was mentioned above that Fortaleza region is an extension of the SAMA zone where enhanced E and D region ionization by energetic particle precipitation is observed during magnetic disturbance [Abdu et al., 1981, Greenspan et al., 1991]. Such a source of ionization could produce gradients of varying scale sizes (100's to 1000's of km) in north- south and east-west directions over Fortaleza.

There is a situation of hemispheric asymmetry in the E region plasma densities. The southern E region is where the Hall conduction electric field, (that is, source electric field, E_S), is generated. The northern side could act as conductivity load in such a way that the resulting electric field can be expressed (using circuit analogy) as: $E_R = E_S\ (\Sigma_{SP}\ /(\Sigma_{NP} + \Sigma_{SP}))$, where Σ_{SP} and Σ_{NP} are the southern and northern region integrated Pedersen conductivities. This shows that if the northern E region conductivity is significantly smaller than the value for the southern E region (which seems to be the case) then the Hall electric field generated by the primary zonal electric field will not be significantly shorted out and therefore could contribute to the zonal plasma drift. It seems possible that the proposed mechanism should be operative even at other longitudes (that are not under the influence of SAMA) if a north-south asymmetry in the conductivity distribution could be brought about, for example by sporadic E layers.

Conclusions

We have presented for the first time evidence of magnetospheric disturbance associated zonal drift velocity fluctuation in spread F irregularities over Fortaleza. These fluctuations are associated (and anti correlated) with vertical velocity fluctuations. Based on previous results of drift velocity perturbations it is inferred that the zonal velocity fluctuations observed over Fortaleza have only a minor contribution, if any, from prompt penetration of disturbance meridional electric field of magnetospheric origin. The observed zonal drift fluctuations seem to result mostly from processes peculiar to equatorial electrodynamics. A mechanism is proposed to explain the velocity fluctuations that involves: (1)- field line mapped Hall polarization vertical electric field produced at E region altitudes by the primary zonal disturbance electric field; and (2)- vertical current and electric field arising from divergence in the field line integrated zonal Pedersen current driven by the primary disturbance electric field. This latter source of electric field seems to be operative in the presence of spatial gradient in the field line integrated Pedersen conductivity. A source of enhanced E region nighttime conductivity is suggested to arise from particle induced ionization in the SAMA zone that is known to take place under magnetospherically disturbed conditions. These investigations are continuing with a view to better understand the electrodynamics processes of the equatorial ionosphere-thermosphere system.

Acknowledgments. The authors are grateful to Dr K. Yumoto, Kyushu University, Japan for providing magnetometer data. M. A. Abdu thanks Brazilian National Research and Development Council (CNPq) for a senior visiting fellowship and J. A. Macdougall for hospitality at the UWO.

References

Abdu, M. A., I S Batista, L. R. Piazza, O. Massabani, Magnetic storm associated enhanced particle precipitation in the South Atlantic Anomaly: evidence from VLF phase measurements, *J. Geophys. Res.*, *86*, 7533 – 7542, 1981.

Abdu, M. A., J. H. Sastri, H. Luhr, H. Tachihara, T. Kitamura, N B. Trivedi, and J. H. A., Sobral, DP 2 electric field fluctuations n the dusk-time dip equatorial ionosphere, *Geophys. Res. Lett.*, *25*, 1511-1514, 1998.

Bilitza, D , International Reference Ionosphere, Recent developments, *Radio Science*, *21*, 343- 346, 1986.

Blanc, M., Magnetospheric convection effects at mid-latitudes, 1. Saint Santin observations, *J. Geophys. Res.*, *88*, 2211- 2213, 1983.

Fejer, B. G., L. Scherliess, Mid- and low-latitude prompt-penetration ionospheric zonal plasma drifts, *Geophys. Res Letts.*, August, 1998.

Gonzales, C. A., M. C. Kelley, R. A. Behnke, J. F. Vickrey, R. Wand, and J. Holt, On the latitudinal variation of the ionospheric electric field during magnetospheric disturbances, *J. Geophys Res.*, *88*, 9135-9144, 1983

Grant, I F., J. W. MacDougall, J. M. Rouhniemi, W. A. Bristow, G. J. Sofko, J. A. Kocher, D Danskin, and D. Andre, Comparison of plasma flow velocities determined by the ionosonde Doppler drift technique, Super DARN radars and patch motion, *Radio Sci.*, *30*, 1537- 1549, 1995

Greenspan, M. E., C. E. Rasmussen, W. J Burke, and M. A. Abdu, Equatorial density depletions observed at 840 km during the great magnetic storm of March 1989, *J. Geophys. Res.*, *96*, 13931- 13942, 1991

Haerendel, G., J. V. Eccles and S. Cakir, Theory of modeling the equatorial evening ionosphere and the origin of the shear in the horizontal plasma flow, *J Geophys Res.*, *97*, 1209- 1223, 1992.

Kikuchi, T., H Luhr, T Kitamura, O Saka, and K. Schlegel, Direct penetration of polar electric field to the equator during a DP 2 event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar, *J. Geophys. Res.*, *101*, 17161- 17173, 1996.

MacDougall, J. W., M. A. Abdu, P. T. Jayachandran, J. –F. Cecile, and I. S. Batista, Pre sunrise spread F over Fortaleza, Brazil, *J. Geophys. Res.*, in press, 1998.

Mozer, F. S., Electric field mapping in the ionosphere at the equatorial plane, *Planet. Space Sci* *18*, 259-263, 1970.

Pfaff, R. F., J. H. A. Sobral, M. A. Abdu, W. E. Swartz, J. W LaBelle M. F. Larsen, R. A. Goldberg, F. J. Schmidlin, The GUARA campaign: A series of rocket-radar investigation of the earth's upper atmosphere at the magnetic equator, *Geophys. Res. Lett.*, *24*, 1663- 1666, 1997.

Reinisch, B. W , K Bible, D. F. Kitrosser, G. S. Sales, J. S. Tang, Z. M. Zang, T. W. Bullett, and J. Ralls, The Digisonde 256 ionospheric sounder, in WITS Handbook, Vol.2, ed. by C. H. Liu, pp 350- 382, ICSU, SCOSTEP, Uni. Illinois, 1989

Sastri, J. H , K. B. Ramesh, and H. N. Ranganath Rao, Transient composite electric field disturbances near dip equator associated with auroral substorms, *Geophys. Res. Lett*, *19*, 1451- 1454, 1992.

Sobral, J. H. A., M. A. Abdu, W. D Gonzalez, B. T. Tsurutani, I. S. Batista, and A. L. Clua Gonzalez, Effects of intense storms and substorms on the equatorial ionosphere/thermosphere system in the American sector from ground-based and satellite data, *J. Geophys. Res*, *102*, 14,305-14313, 1997

M. A Abdu, J. H. A. Sobral, Instituto Nacional de Pesquisas Espaciais-INPE, C. P. 515, 12201-970 São José dos Campos, SP, Brazil. (e-mail: abdu@dae.inpe.br)

P. T. Jayachandran and J. MacDougall, Department of Astronomy and Department of Electrical Engineering, University of Western Ontario, London, Canada.

J. F. Cecile, Department of Physics and Astronomy, University of Western Ontario, London, Canada.

(Received: May 29, 1998; revised: September 11, 1998; accepted: September 16, 1998)