SOUTH ATLANTIC MAGNETIC ANOMALY IONIZATION EFFECTS ON THE ELECTRODYNAMICS OF THE EQUATORIAL IONOSPHERE.

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Abstract.
Satellite observations of enhanced energetic particle fluxes in the south Atlantic Magnetic Anomaly (SAMA) region has been supported from ground based observations of enhanced ionization induced by particle precipitation in the ionosphere over this region. Past observations using a variety of instruments such as vertical sounding ionosondes, riometers and VLF receivers have provided evidences on the enhanced ionization due to energetic particle precipitation in the ionosphere over Brazil. The extra ionization at E layer heights could produce enhanced ionospheric conductivity within and around the SAMA region. The energetic particle ionization source that is operative even under "quiet" conditions can undergo drastic/significant enhancements during magnetospheric storm disturbances, when the geographic region of enhanced ionospheric conductivity could extend to magnetic latitudes closer the equator where the magnetic field line coupling of the E and F region plays key roles in the electrodynamics of the equatorial ionosphere. Of particular interest is the sunset electrodynamics processes responsible for the equatorial spread F/plasma bubble irregularity generation and related dynamics (zonal and vertical drifts etc.). SAMA represents a source of significant longitudinal variability in global description of the equatorial spread F irregularity phenomenon. Recent results from digital ionosondes operated at Fortaleza and Cachoeira Paulista have provided evidence that enhanced ionization due to particle precipitation associated with magnetic disturbances, in the SAMA region, can indeed significantly influence the equatorial electrodynamic processes leading to plasma irregularity generation and dynamics. Disturbance magnetospheric electric fields that penetrate to equatorial latitude during storm events seem to be intensified in the SAMA region based on ground based and satellite born measurements. This paper will review our current understanding of role of SAMA on the equatorial electrodynamics processes from the perspective outlined above.

1. Introduction:

Large degree of longitudinal variation in the major phenomena of the equatorial ionosphere has been verified in the past from various types of observations, both ground based and satellite based. They reflect a corresponding variation in the electrodynamics processes that control those phenomena. A major source of such variations could reside in the well known longitudinal variations in the geomagnetic field intensity and declination angle. A possibly significant role of south Atlantic Magnetic Anomaly (SAMA) in contributing to such longitudinal variations has not been addressed so far. In this paper we intend to focus on this question. Based on ionosonde and radar data it was shown that Ionospheric dynamo electric field enhancement in the evening hours, and the consequent ESF /plasma bubble irregularity generation and dynamics, present significant longitudinal difference between the west- and east- coast of south America, that is, between Peru and Brazil-Atlantic longitudes sectors, that was attributed to the large longitudinal variation in the magnetic declination angle that characterize this sector (Abdu, et al., 1983, Batista et al., 1986). Longitudinal variation in ionospheric scintillation occurrence at VHF on global bases has been attributed to the associated variation of the magnetic declination angle (Tsunoda, 1985). Magnetospheric electric fields that penetrate to equatorial latitudes during disturbed/storm conditions also seem to present significant longitudinal variations in this longitude sectors (Abdu, et al., 1994; Basu, et al., 2001). Enhanced ionospheric conductivity over the SAMA region could result from precipitation of energetic particles from the inner radiation belt in spatial scale that may extend several degrees in longitude and latitude around the central region of the anomaly. Presence of enhanced ionization at E layer heights under magnetically quiet condition has been verified from analysis of ionosnde data over Cachoeira Paulista located inside the SAMA region (Abdu and Batista, 1977), that could signify a corresponding background pattern of enhanced conductivity structure in the region. Such quiet time/background conductivity distribution can become significantly enhanced under magnetospherically disturbed conditions (Abdu, et al., 1998; 2003). As a result, the quiet and disturbed electric fields, plasma irregularity development and dynamics (related to the equatorial spread F processes) over the longitude sector of the SAMA seem to differ from those of the other longitudes (especially those in the immediate vicinity of SAMA). In this paper we will present a brief review of the evidences available, based on different observational databases, for enhanced ionization by energetic particle precipitation in the SAMA region under quiet and disturbed conditions (see for example, Abdu, et al., 1973, 1979,1981a; Gledhill and Torr, 1966; Paulikas, 1975). We will then consider the effect of such enhanced ionization to cause enhanced ionospheric conductivities that in turn could modify the electrodynamics of plasma irregularity development conditions and plasma drifts of the post sunset equatorial ionosphere of the SAMA longitude sector.

2. SAMA magnetic field configuration and particle precipitation.

Fig.1: Shows the configuration of the geomagnetic field total intensity distribution over the globe, in which the lowest value of the total magnetic field intensity defines the position of the center of the SAMA. Its present location in the southern part of Brazil resulted from the steady and secular westward drift of the SAMA from its location in the South Atlantic Ocean a few years ago. An associated aspect/characteristic of the SAMA field configuration is the large magnetic declination angle, and the associated feature of the dip equator crossing the geographic equator and extending deeper down to the south American continent to ~12°S over Jicamarca in Peru. As a result the magnetic declination angle over eastern part of Brazil attains ~21°W whereas it reverts to ~4°E over Peruvian longitude sector as shown in **Fig. 2**.

The trapped and azimuthally drifting energetic particles, bouncing between hemispheres, comes deeper down into the atmosphere of low field intensity over SAMA (in conservation of its second adiabatic invariant) thereby interacting with the dense atmosphere resulting in ionization production. Other processes, such as wave-particle interaction leading to enhanced loss cone of the drifting particles has also been suggested as a mechanism for the loss of inner radiation belt particles in the SAMA region. Evidence of enhanced energetic particle population in the SAMA region has come from early Russian COSMOS satellite observations. Contours of constant omni directional flux of fission electron, derived for 0.29 MeV energy at altitudes 320+-45km by one of the COSMOS satellites in the South Atlantic Anomaly region is shown in **Figu.3** (Vernov et al. 1967). The region of maximum particle flux close to the Brazilian South Atlantic Coast can be noted. With westward secular drift of the SAMA the center region of maximum particle flux should have moved well into the Brazilian land mass.

Evidence of enhanced ionization in the D region over SAMA due to azimuthally drifting energetic particles was first obtained during the great storm of August 1972, from spaced antenna riometer measurements by Abdu, et al., (1973). Subsequent measurements by ionospheric vertical sounding by ionosondes and measurement of VLF (very low frequency) phase in earth-ionosphere wave guide mode propagation path, monitored by ground based VLF receivers, have verified the occurrence of significant ionization enhancement in the ionospheric D- and E –regions (~70-120 km) over the SAMA. An example of simultaneous observation of energetic particle precipitation, as manifested in enhanced sporadic E layer intensity over Cachoeira Paulista (22.6 S, 315 E; dip angle: - 28°) and phase advance of VLF signals received at Atibaia (23ºS, 45ºW, dip angle: - 28°) are shown in **Fig.4** (Abdu, et al., 1981a). Increases in sporadic E layer frequencies, the f_tEs (the top frequency backscattered by the layer) and the f_bEs (the blanketing frequency which indicates the plasma frequency of the reflecting layer) occur in events of a few hours duration during enhanced magnetic activity indicated by large Kp values, which suggested a corresponding increase in the E layer ionization. Oscillatory variation in the intensity of the E_s layer can be noted especially on the night of 3-4 May 1978. Their occurrence during night hours suggests particle precipitation in the E region as the source of the enhanced ionization needed to produce them. Simultaneous increase of D region ionization is indicated by the VLF phase decrease in events of varying intensity at the same rate as that of the Es layer. In fact, significant lowering of the VLF reflection height (phase decrease) during entire night with respect to the quiet time reflection height of ~90 km persists on many nights in the examples shown in this figure. The effect seems to last even after the Kp has decreased to its “quiet” time values. Modulation of the precipitating particle flux intensity by several minutes to few-hour duration is indicated in these results.

Extensive analysis of the sporadic E layer characteristics over Cachoeira Paulista has established that the occurrence as well as the intensity of this layer present significant enhancements during magnetically disturbed conditions (Batista and Abdu, 1977; Abdu, et al., 2003a). The plasma frequency of the layer at such times could becomes comparable to, or even exceed, its nighttime values. Further, such Es layers are identified by traces of range spreading echoes similar to those of auroral type sporadic E layers, that are well known to be produced by auroral zone particle precipitation, as shown in the example of **Figure 5**. Our analysis of Es layers over Cachoeira Paulista under magnetically quiet conditions has revealed that their regular occurrence during night hours could only be explained by a nighttime source of ionization that could be attributed to particle precipitation in the SAMA region (Abdu and Batista 1977). Thus, there is accumulating evidence that energetic particle induced ionization is a regular feature of the ionosphere over the SAMA even under magnetically quiet conditions that should result in a correspondingly modified/enhanced ionospheric conductivity distribution over this region, and that significant enhancement of the conductivity distribution pattern could occur during magnetic disturbances.

3- Electro-dynamic effects due to the SAMA

The influence of the SAMA on the equatorial ionospheric electrodynamics processes could operate mainly in two ways: 1- the Magnetic declination angle that control the F layer dynamo development in the evening hours, which is a regular quiet time feature; and 2- the enhanced ionization by particle precipitation with enhanced conductivity adding to the background conductivity distribution in the ionosphere over the SAMA region under quiet conditions, and additional enhancements of the ionization and the conductivities with their modified spatial distributions that could dominate during magnetic disturbances.

3.1 Magnetic declination effect on the evening equatorial electrodynamics:

Significant difference in the evening electrodynamics processes that control the equatorial spread F development conditions have been noted between the Peruvian and Brazilian longitude sectors, which was attributed to the significant variation of the magnetic declination angle between the two longitude sectors (Abdu, et al., 1981b). The longitudinal variation of the magnetic declination angle in the South American sector is part of the SAMA magnetic field configuration, and it varies drastically between the west and east coasts of South America, as was shown in **Fig. 2**. The associated effects on the sunset electrodynamics processes can be explained as follows. The F-layer undergoes rapid uplift in the evening hours, which is a prerequisite for the development of the post sunset spread

F/plasma bubble irregularities under the Rayleigh-Taylor instability mechanism. The layer uplift/vertical plasma drift is caused by an enhanced zonal electric field produced by the F layer dynamo, known as prereversal electric field enhancement (PRE), that develops under the combined action of an eastward thermospheric wind and the longitudinal gradient in the field line integrated Pedersen conductivity that exists across the sunset terminator (Rishbeth, 1971). This integrated conductivity gradient, has major contribution from conjugate E layers, and therefore attains its largest values (leading to the largest amplitude of the PRE) when the sunset terminator moves parallel to (aligned with) the magnetic meridian, which corresponds to near simultaneous sunset at conjugate E layers. The large westward declination angle (~ 21°W) in the Brazilian Atlantic sector causes this condition to prevail during a period close to December month, when, therefore, a seasonal maximum occurs in the intensity of the prereversal electric field enhancement (F region vertical drift) and hence in the spread F irregularity (ESF) occurrence. In the Peruvian sector, where the magnetic declination angle is small (and eastward), such propitious conditions for seasonal maxima occur during equinoctial months. Thus when a broad seasonal maximum in spread F occurs around December months over Brazil, two equinoctial maxima occur over Peru as shown in **Fig. 6.** In Fig.6 the left hand panel shows plot of monthly mean percentage occurrence of ESF over Cachoeira Paulista (CP) in month versus local time format. It should be noted that the bottom side spread F statistics over CP in fact represents the statistics of well developed flux tube aligned plasma bubbles extending from their equatorial apex height to the F region bottom side over this station (Abdu, et al., 1983). A seasonal maximum centered around December-January months is a well-defined feature here. The right panel presenting similar statistical plots of UHF scintillation over Peru (Basu, et al., 1980) shows two equinoctial maxima as to be expected.

3.2 SAMA associated conductivity gradient and the enhancement of the quiet time PRE .

Besides the difference in the seasonal pattern of the PRE between the east and west cost of South America (brought about by the difference in the magnetic declination angle) just explained above, there is also significant and systematic difference in the amplitude of the PRE between the two sectors, the amplitude in the Brazilian sector being generally higher than in the Peruvian sector. Monthly mean vertical drift velocities obtained as the time rate of change of plasma frequency heights measured by Digisondes (Reinisch, 1996) over Sao Luis (Brazil) and Jicamarca (Peru) are compared in **Fig. 7** for the four seasons, that is, two equinoctial and two solstice months. The vertical drift velocities around the evening PRE maximum are only of interest to us here. (The Vz values obtained from digisondes at other local times can differ significantly from the real drift velocities for reasons explained by Bittencourt and Abdu, 1981, and Abdu, et al., 2004). Seasonal as well as solar flux dependence of the PRE amplitude (in agreement with the results of Fejer et al., 1991) can be noted in the figure. The PRE amplitude over Jicamarca, even during its expected seasonal maxima, in March and September, is smaller than that over Sao Luis. The difference becomes more marked when the seasonal maximum of Vz occurs over Sao Luis during December. Thus the PRE amplitude over the eastern longitude sector of South America tends to be always higher than that over the western sector. An explanation for this difference can be sought in terms of the possible difference in ionospheric conductivity spatial distribution over the two longitude sectors arising from the proximity of the SAMA to the eastern longitude sector, as follows:

Thermospheric zonal winds produce, by dynamo action, a vertical polarization field in the *F*-region whose magnitude is dependent upon field line integrated conductivities and current flow between *E*- and *F*- region. The associated *E*- *F*-region electrical coupling processes leading the generation of the PRE was first modeled by Heelis, et al. [1974] (see, also, Farley et al. [1986]; Batista, et al. [1986]; Crain, et al. [1993]). As explained in Abdu, et al. [2003b] the vertical electric field is given by: $E_V = U_y B_0 [\Sigma_F / (\Sigma_F + \Sigma_E)]$, where Σ_F is the field line integrated conductivity of the *F*-region and Σ_E is that of the conjugate *E*- regions, U_y is the thermospheric zonal wind and B_0 is the magnetic field intensity. During post sunset hours Σ_E decays faster than Σ_F thus contributing to the development of a vertical electric field whose intensity increases towards the night side (that is, across the sunset terminator). The application of curl-free condition to such an electric field variation could result in the enhanced evening zonal electric field, the PRE, as suggested by Rishbeth [1971] and recently modeled by Eccles [1998]. The local time variation of the E_v arises largely from that of the conductivity local time/longitude gradient.

In considering the difference in PRE amplitude between the west and east cost of South America we need to consider the possible role of the thermospheric zonal wind as well as that of the conductivity gradient (ΔΣ). While there is no strong reason for U_y amplitude to differ significantly within a relatively short longitude span, we have strong reason to expect that ΔΣ could present significant difference between the western and eastern longitude sectors due to the proximity of the SAMA to the latter. In order to examine the control of the evening E-layer conductivity/density variation on the PRE we carried out a simulation of the vertical drift (PRE) variation using the E- and F-region electrodynamics coupling model by Batista et al. (1986) that was based on the original model of Heelis, et al. (1974). The results are presented in **Fig. 8** (see also, Abdu, et al., 2004). This figure shows in the lower panel the E layer critical frequency (f_oE), (which corresponds to the layer peak density, N_mE), local time variation during daytime as observed over Fortaleza and its extrapolation to possible different nighttime values. Each of these model curves identified as mod1, mod2, etc. in the figure presents different conductivity local time gradient around sunset that produces different amplitudes of the prereversal vertical drift enhancement shown in the upper panel. It can be noticed that the steeper the gradient in foE (that is, E layer Pederson conductivity), in the transition from day to night, the higher the peak amplitude of the evening V_z variation (that is, PRE).

Fig.9 shows a sketch of how an enhanced conductivity distribution, with the conductivity decreasing from a hypothetical location of maximum intensity of *E*-region particle precipitation in southern Brazil, could result in a westward gradient in Σ that can add to the normal ΔΣ across the sunset terminator which also is directed westward. The consequence of the resulting enhanced ΔΣ will be to produce larger PRE according to the model simulation result of Fig.8. Thus a possible enhancement of the conductivity gradient due to quiet time particle precipitation in the SAMA could contribute to an increase of the post sunset V_z in the Brazilian sector. The significantly larger V_z over Brazil as compared to the V_z over Jicamarca of Fig. 7 can be accounted for in this way (see also further considerations on this point in the discussion session).

3.3- Effect of storm associated enhanced conductivities on the post sunset plasma drifts.

During magnetic disturbances intense particle precipitation can cover a wider geographical area. DMSP satellite measurement of energetic particles, at ~840 km, during the great magnetic storm of March 1989, in the South American longitude sector, shows that the geographic region affected by particle precipitation could extend equator-ward up to Fortaleza latitude as shown in **Fig. 10** (Greenspan et al. 1991). Under such conditions the combined effects of magnetospheric electric field penetration to low/equatorial latitudes and the enhanced ionospheric conductivity due to energetic particle precipitation in the SAMA region could cause complex response features of the ionosphere over this region. The disturbance zonal electric field that penetrate to low latitudes could govern the electrodynamics of the equatorial ionospheric responses in two ways: 1- direct effect on vertical plasma drift, by which an eastward electric field occurring at sunset hours could cause uplift of the F-region plasma, that could add to the normal vertical drift due to PRE, thus helping trigger the development of spread F/plasma bubble irregularities even during the season of their normal non occurrence (Abdu, et al., 2003a; Sastri, et al., 1997), or causing a more intense bubble event during the season of its normal occurrence (Abdu, et al., 1988; Hysell, et al.,1990); 2- electric fields, generated by Hall conduction and divergence-free current flow in regions of conductivity spatial gradients due to enhanced particle precipitation, under the action of the primary disturbance (penetrating) electric field (Abdu, et al., 1998; 2003a). As regards the sunset and nighttime effects, while the ionospheric response from the Item 1 can be observed in all longitude sectors, that from the Item 2 should be observable only/mainly in the longitude sector the SAMA. As far as the daytime effects are concerned, the responses arising from conductivity features, similar to that in item 2, but not necessarily caused by particle precipitation, should of course be observable in varying degrees at all longitudes, as are the effects from the item 1.

Figure 11 shows F layer bottom side irregularity vertical drift velocity (middle panel) measured by a digital ionosonde at Fortaleza, during a magnetically disturbed night in November 1994 as represented by the auroral activity indices in the top panel (Abdu, et al., 1998). Oscillations in the vertical drift that are coherent, but somewhat shifted in phase, with the fluctuations in AE index, are out of phase with those in the zonal drift velocity (plotted in the bottom panel). Frequent cases of such "anti correlated" vertical and zonal drift variations have been observed during magnetic disturbances, as shown in some examples of their scatter plots in **Fig.12**. Such an "anti correlation" between the vertical and zonal velocities can be understood based on a simple equation connecting the zonal and vertical electric fields, in which the current divergence effects are ignored for simplicity, and Hall conduction and neutral wind dynamo terms are included (see, Haerendel, et al.1992; Abdu, et al. 1998; 2003a).

$$E_V \cong -B U_{EW}^{P} + E_{EW} \left[\Sigma_H / \Sigma_P \right] \qquad (1)$$

Where, E_{EW} and E_V are the zonal and vertical electric field respectively. The first term on the right side represents neutral wind dynamo, and U_{EW}^{P} is field line integrated conductivity weighted zonal wind. The term inside the bracket is Hall conduction term, with Σ_H and Σ_P representing the field line integrated Hall and Pedersen conductivities. This equation clearly shows that the degree of "anti correlation" between the two velocities is highly dependent on the variability in the neutral wind dynamo. The influence of Hall conduction on daytime F region plasma drifts as observed by Jicamarca Radar has been shown by Fejer and Emmert [2003] for the case of a penetration electric field event associated with a solar wind pressure surge event. Their results are presented in **Fig. 13.** An increase in the solar wind pressure was responsible for penetrating disturbance zonal electric field over equator that caused vertical plasma drift and associated westward plasma drift very similar to the results in Fig. 11 and 12. These results were obtained during daytime over Jicamarca when the ratio Σ_H/ Σ_P is large. Our results over Fortaleza correspond to night conditions when normally (under quiet conditions) the conductivity ratio, Σ_H/ Σ_P, is not sufficient to produce the degree of Hall conduction observed in the results of Fig. 11 and 12. It seems to be clear therefore that an extra ionization and associated conductivity enhancements, due to particle precipitation under magnetic disturbances, should be invoked to explain the large zonal velocity fluctuations that are anti correlated with the vertical drift fluctuations seen in Figs 11 and 12. No cases of "anti correlated" vertical and zonal plasma drifts such as that in Fig. 13 has been reported over Jicamarca under night time conditions. This points to the uniqueness of the night time results over Brazilian longitude sector suggesting that the SAMA associated enhanced night time conductivity was indeed a necessary condition for the generation of vertical electric field /zonal plasma drift perturbations observed during magnetically disturbed conditions.

4. Discusion and conclusions.

Energetic particle precipitation in the SAMA region is a well-established phenomenon. More recent results from the radiation detector on board SAC-C satellite shows the energetic proton flux over SAMA region extending to equatorial latitudes. Further, balloon born X-ray measurements have detected energetic electron precipitation at stratospheric heights during magnetic disturbances (For example, Pinto and Gonzalez, 1986; Jayanthi et al., 1997). The aeronomic effects in terms of enhanced ionization in the E and D region of the ionosphere that are caused by energetic particles of relatively lower energy range (electrons of < 100 keV and protons of a few MeV), are also now well established based on the diverse results presented above. The focus of this paper is on the influence of enhanced particle precipitation in the SAMA on the electro-dynamical processes of the equatorial ionosphere due to the modified ionospheric conductivity distribution resulting from particle precipitation, under quiet as well as disturbed conditions, a field of research which has not received any attention by the scientific community so far. On the other hand, this problem has great impact/implication on the currently important questions of longitudinal/seasonal variability of the equatorial sunset electro dynamics processes and associated spread F/ plasma bubble irregularity development conditions. In this context the significant difference in the amplitude of the PRE between the east and west coast of South America in its monthly mean values calls our special attention. The difference is real and significant since the same technique by similar instruments was used to obtain the vertical drift velocities at the two sites. Any significant/major role of thermospheric zonal wind in the evening hours in causing the observed larger V_{zp} over Sao Luis, as compared to Jicamarca, seems unlikely on the basis of the following reasoning. The two magnetic equatorial stations have different latitudinal separation from the geographic equator (in their respective longitude sectors), Sao Luis at 2.33ºS being closer to it and Jicamarca at 12ºS being farther from it. While this different separation from the geographic equator can cause different seasonal variations in the evening thermospheric zonal wind at the two locations, such difference does not seem to be sufficient to account for the observed difference in the PRE amplitudes. For example, in

March, due to the proximity of the sub solar point to Sao Luis, the evening zonal wind amplitude over here can be larger than over Jicamarca, whereas the (solar radiation dependent) $\Delta\Sigma$ values is larger for the latter station where the solar terminator and the magnetic meridian alignment occurs in this month. We note, in **Fig.07**, that the amplitude of the PRE is larger over Sao Luis during March, which might suggest that an expected larger zonal wind effect over SL might have overcome the expected increase of PRE due to $\Delta\Sigma$ over Jicamarca. The situation reverses in December, when SL goes through larger $\Delta\Sigma$ and Jicamarca can be subjected to larger zonal wind. However, the PRE amplitude over SL is again significantly larger than over Jicamarca (**Fig.07**). This apparent contradiction can be explained if we include an extra $\Delta\Sigma$, with westward increase of conductivity in the eastern sector of Brazil, due to the SAMA induced particle precipitation (as was sketched Fig. 09), that is superposed on the normal sunset $\Delta\Sigma$ which is also westward, so that the net enhanced $\Delta\Sigma$ could be a deciding factor in the generally larger PRE amplitude in all/most of the seasons observed over SL. Further, we may point out that in view of the well-known westward secular drift of the SAMA, one would expect that the difference in the evening vertical drift velocities between the east and west coast of South America, as the present data set shows, should continue to increase in the coming years.

The situation under magnetic disturbances becomes highly complex due to the disturbance magnetocpheric electric fields that penetrate to equatorial latitudes and their interaction with the enhanced conductivity structure of the ionosphere over SAMA. Results presented in Figs 11 and 12 for moderate magnetic disturbances showed that vertical electric field by Hall conduction induced by the interaction of the disturbance zonal electric field with the enhanced conductivity governs the dynamics of the spread F plasma irregularities over Fortaleza (as was explained by Abdu, et al., 1998; 2003a). A possible effect of the enhanced conductivity on the zonal electric field could not be clearly identified in these events. However, it is expected that the divergence-free conditions for the Pederson/Hall current driven by a disturbance primary zonal electric field in regions of large scale conductivity spatial gradients could lead to local generation of enhanced zonal electric field as well. Some evidence for such enhanced zonal electric field seems to be available in the equatorial ionospheric response to very intense storms. An example of ionspheric F layer height responses to the great storm of 13-14 March 1989, at a number of equatorial- low mid latitude stations, distributed at different longitudes of the earth, taken from Abdu, [1994], are presented in **Fig. 14a** (left panel). Here the top panel shows the AE activity index variations during 12, 13 and 14 March and below are shown the virtual height of the F layer base (h'F) for different stations including Fortaleza and Cachoeira Paulista in Brazil, and Dakar and Ouagadougou in West Africa that are approximately 1 hr in local time ahead of the Brazilian stations. Associated with the intense sub storm activity around 21 UT of 13 March, that is, in the evening sector (~18 LT) in Brazil drastic increase in h'F occurred over both Fortaleza and Cachoeira Paulista. As explained by Batista et al. [1991] this corresponded to a penetrating disturbance eastward electric field of > 2mV/m. In fact the F layer disappeared for about 1 hr from the 1000 km height range of the ionograms over Fortaleza and Cachoeira Paulista, and the spectacular height rise had lasted till past local midnight hours. In comparison to this, over the West African stations, also in the evening sector, but some 20º Eastward, only a modest response (smaller height increase) was observed. This appears to be a clear evidence of a strong longitudinal effect, in the equatorial/low latitude response to intense magnetic storms, with significantly enhanced disturbance zonal electric field intensity in the SAMA longitude sector. Another example of what looks like an enhancement of the penetrating zonal electric field in the SAMA longitude sector is shown in Fig. 14b (right panel), taken from Basu, et al. [2001]. DMSP passes over Fortaleza and Ascension Island during the great storm of July 15-16, 2000 are shown in the upper panel. The corresponding latitudinal cuts of ion densities as observed by the F14 and F 15 satellites over Fortaleza and Ascension Island are presented, respectively, in the left and right panels below. The large bite out of the ion densities around the magnetic equator is similar to that observed, also in the evening sector, during the March 1989 storm by the DMSP F8 and F9 satellites, as reported by Greenspan et al [1991], and is caused by the equatorial F-layer uplift to well above the ~840 km DMSP orbits, as a result of the large penetrating eastward disturbance electric field associated with the storm. We note that the width and (probably) the depth of the ion density depletion are significantly larger along the passes over Fortaleza than along those over Ascension Island, located only ~1.5 hour in local time ahead of the former. Basu, et al. [2001] have attributed this difference to the influence of SAMA which is most effective at the longitude of Fortaleza, and decreasing with increasing longitudinal separation from there. Although the DMSP passes over the two stations, in Fig. 14b, are separated by ~1.6 hr in UT, the significant longitudinal difference in the intensity of the disturbance eastward electric field between the two nearby longitudes is very similar to the results in Fig.14a. In the latter case also the F layer height rise (due to penetrating eastward electric field intensity) over Fortaleza was significantly larger than over the West African stations. Thus there are important evidences to the effect that amplification/local generation of electric field takes place in the SAMA region under magnetically disturbed conditions. Further detailed analysis of this problem needs to be undertaken.

The present study leads to the following conclusions: Energetic particle precipitation causing enhanced ionization in the ionosphere is a regular feature over the SAMA, which is responsible for a modified background ionospheric conductivity distribution in the region. Such conductivity spatial distribution seems to modify the conductivity longitudinal/local time gradients at sunset hours to a degree capable of affecting the quiet time sunset electrodynamics processes and hence the development of prereversal electric field enhancement in the evening hours, that is known to control the equatorial spread F/plasma bubble irregularity development conditions. The generally larger evening F-layer vertical drift over the eastern sector as compared to the western sector of South America seems to be caused by the proximity of the SAMA to the former. Significant intensification of particle precipitation and associated enhanced ionization modify drastically the ionosphere over SAMA during magnetospheric disturbances. The electrodynamics processes under such disturbed conditions are controlled by the interaction of disturbance penetrating electric field with the enhanced conductivities and their spatial gradients. As a results, local generation of vertical electric field (zonal plasma drift) seems to takes place during disturbances of moderate intensities. Significant enhancement in zonal electric field (vertical plasma drift) as well seems to occur in the SAMA during intense magnetic storms. Thus the particle precipitation in the SAMA region does seems to play a significant role in the equatorial ionospheric electrodynamics under quiet as well as disturbed conditions. This leads to important questions as to the role of the SAMA in influencing the longitudinal variability of the equatorial spread F and in the equatorial ionospheric response to magnetospheric disturbances. More quantitative studies need to be undertaken towards more detailed answers to these questions.

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Conclusions.

Figure Captions:

Fig.1: Shows the geomagnetic field total intensity distribution, represented by iso intensity lines, over the globe, in which the lowest value of the total magnetic field intensity situated in South Brazil defines the position of the center of the SAMA (South Atlantic Magnetic Anomaly) which was located in the South Atlantic several years ago.

Fig. 2: Magnetic declination angles over Peru and Brazil on the map of South America. The declination angle is ~ 21ºW over Fortaleza (FZ), Brazil and ~ 4ºE over Jicamarca (JIC) Peru.

Fig.3: Contours of constant omni directional flux of fission electron, (cm^{-2}sec-1), derived from 0.29 MeV energy for altitudes 320+-45km as observed by COSMOS satellite. Due to the secular westward drift of the SAMA, the region of maximum flux has moved over to Brazilian land mass during the course of years since this measurement was made in the 1960's.

Fig. 4: Variation of the VLF (very low frequency) signal phase, received at Atibaia, SP, (top panel) plotted during an intensely disturbed period of 01- 04 May 1978. The VLF phase represents the reflection height of the VLF signals propagating in earth-ionosphere wave guide, nominally considered to be at 90 km during the night, and 70 km during the day. A decrease (advance) in phase indicates lowering of the VLF reflection height due to ionization increase below the normal reflection height. The dotted curve is a reference phase variation for quiet conditions. The middle panel shows the top frequency ftEs reflected by the sporadic E layer whose plasma frequency is indicated by the blanketing frequency fbEs. The Kp variations are shown in the bottom panel. (Abdu et al., 1981a)

Fig 5: Examples of sporadic E layers over Cachoeira Paulista during a magnetic disturbance in May 1978, showing range spreading, more intense during the night and less so during the day due to ionospheric absorption of the radio waves.(Batista and Abdu, 1977).

Fig. 6: Shows the month versus local time variation of equatorial spread F occurrence (in monthly mean percentage occurrence values) over Cachoeira Paulista that shows a broad summer peak and UHF (1.6 GHz) scintillation occurrences over Huancayo, Peru, that has two equinoctial maxima.

Fig.7: F region vertical drift over Sao Luis (solid line) and Jicamarca (dashed line) obtained from Digisonde data, plotted as monthly mean values representing four months: March 2000, June, September and December 1999.

Fig.8 Results of simulation using an E- F-region electrical coupling model showing that higher local time gradient at sunset in the E layer conductivity produces higher amplitude of the PRE. The curves identified as mod 1 and mod 5 correspond to the lowest conductivity gradient at sunset (lower panel) and therefore the highest PRE amplitude (upper panel).

Fig. 9: A cartoon of the sunset terminator and the possible background ionization/ conductivity pattern in the SAMA. Enhancement of the conductivity gradient due to quiet time precipitation in the SAMA could contribute to increase of the $\Delta\Sigma$ across the sunset terminator to result in enhanced Vz (PRE) in the Brazilian sector.

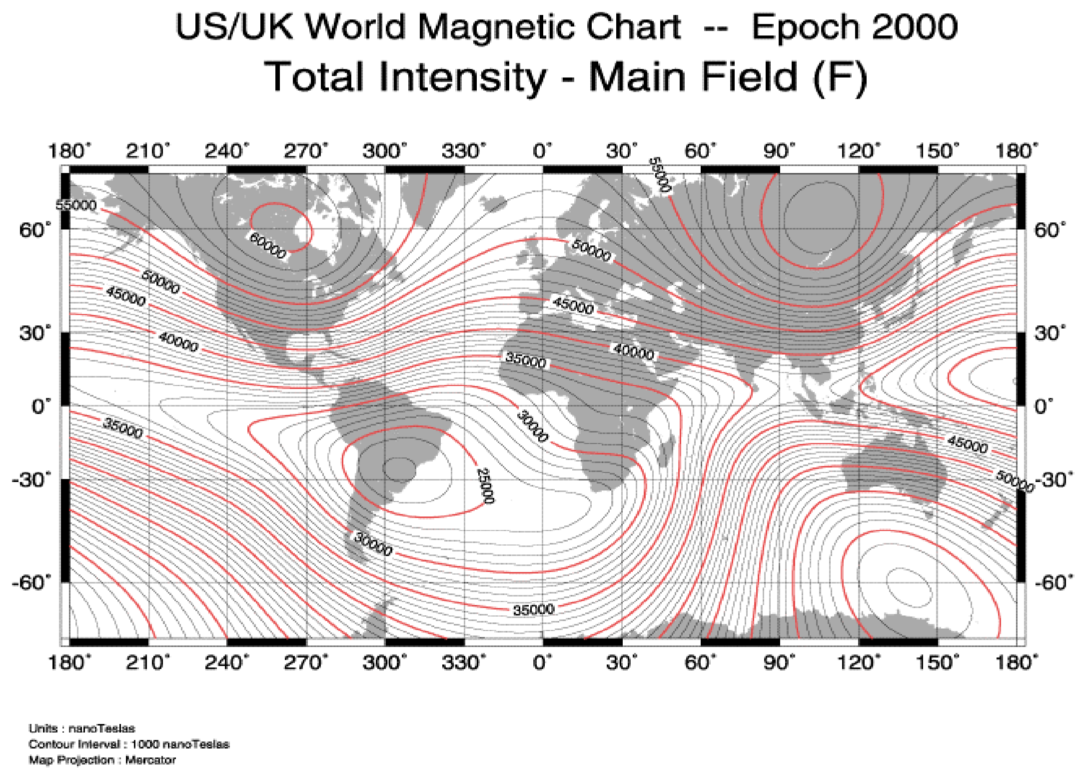
Fig. 10: Distribution of energetic particle flux as observed by the DMSP-9 satellite during the main phase of the March 1989 great storm (from Greenspan et al., 1991).

Fig.11: Vertical and zonal irregularity drift velocities over Fortaleza in the height region of 300 km (lower two panels) during a disturbance period marked by auroral electrojet activity (top panel) which occurred on 20 November, 1994.

Fig.12: Scatter plots of Vz versus Vx for three cases of disturbance electric field events.

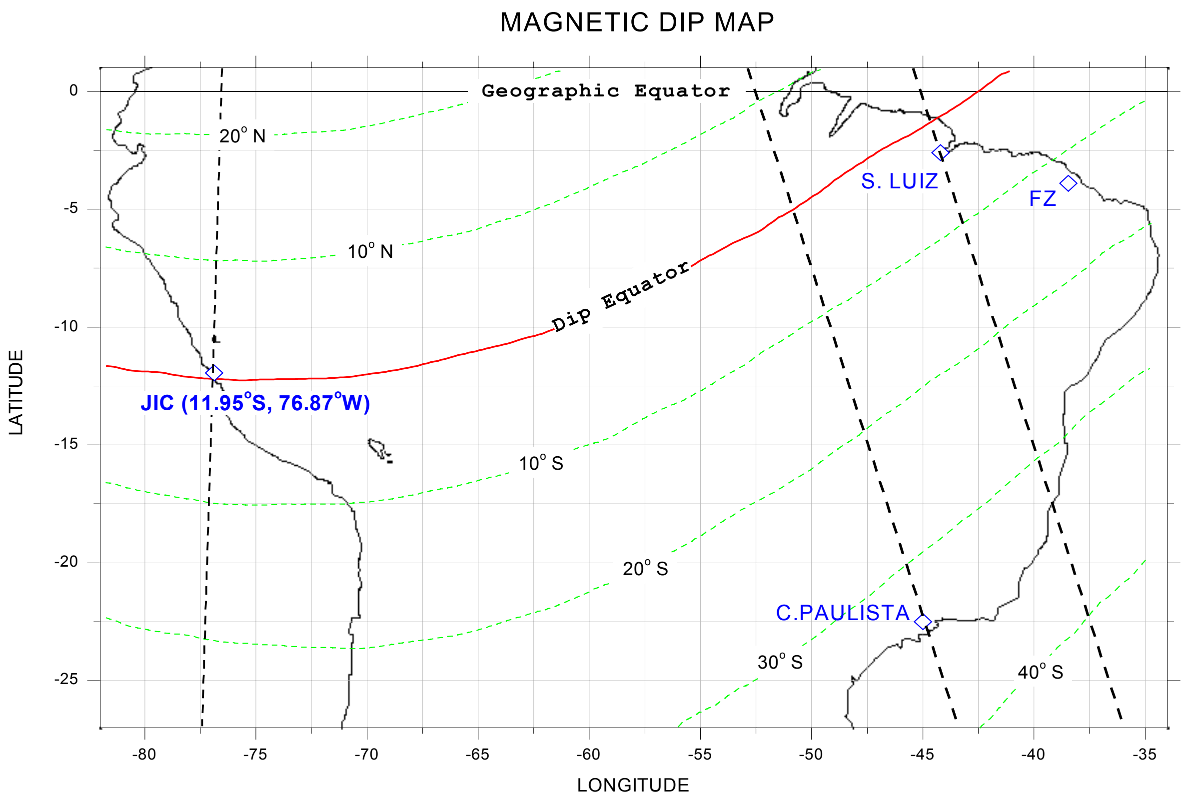
Fig.13: IMF, north-south magnetic field component and solar wind dynamic pressure measured by the WIND satellite and shifted by 23 min and Jicamarca horizontal magnetic field and plasma drifts observations near 1730 UT, on Oct 19 1998.

Fig.14: Shows the h'F variations over longitudinally distributed stations during the greats storm of March 89 (left panel) and the DMSP ion densities on the passes in the Atlantic sector between Brazil and Africa during the great storm of July 2000 (right panel).



US/UK World Magnetic Chart -- Epoch 2000
Total Intensity - Main Field (F)
180° 210° 240° 270° 300° 330° 0° 30° 60° 90° 120° 150° 180°
60° 30° 0° -30° -60°
55000
60000
50000
45000
40000
35000
30000
25000
Units : nanoTeslas
Contour Interval : 1000 nanoTeslas
Map Projection : Mercator

Fig. 1



MAGNETIC DIP MAP
Geographic Equator
Dip Equator
20° N
10° N
10° S
20° S
30° S
40° S
S. LUIZ
FZ
C.PAULISTA
JIC (11.95°S, 76.87°W)
LATITUDE
LONGITUDE
0
-5
-10
-15
-20
-25
-80
-75
-70
-65
-60
-55
-50
-45
-40
-35

Fig. 2

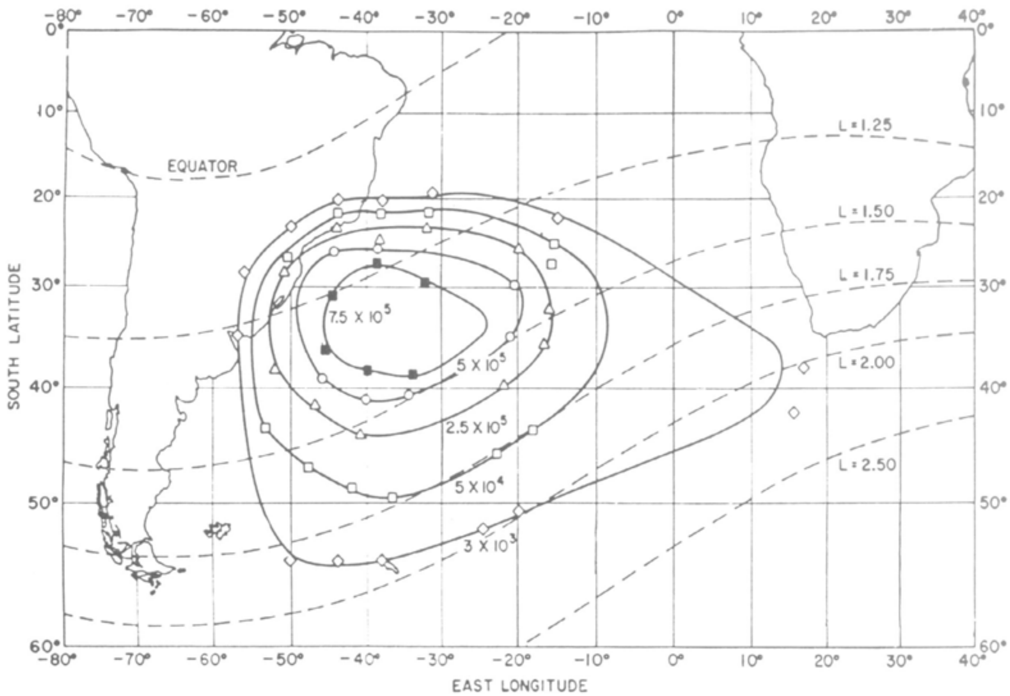
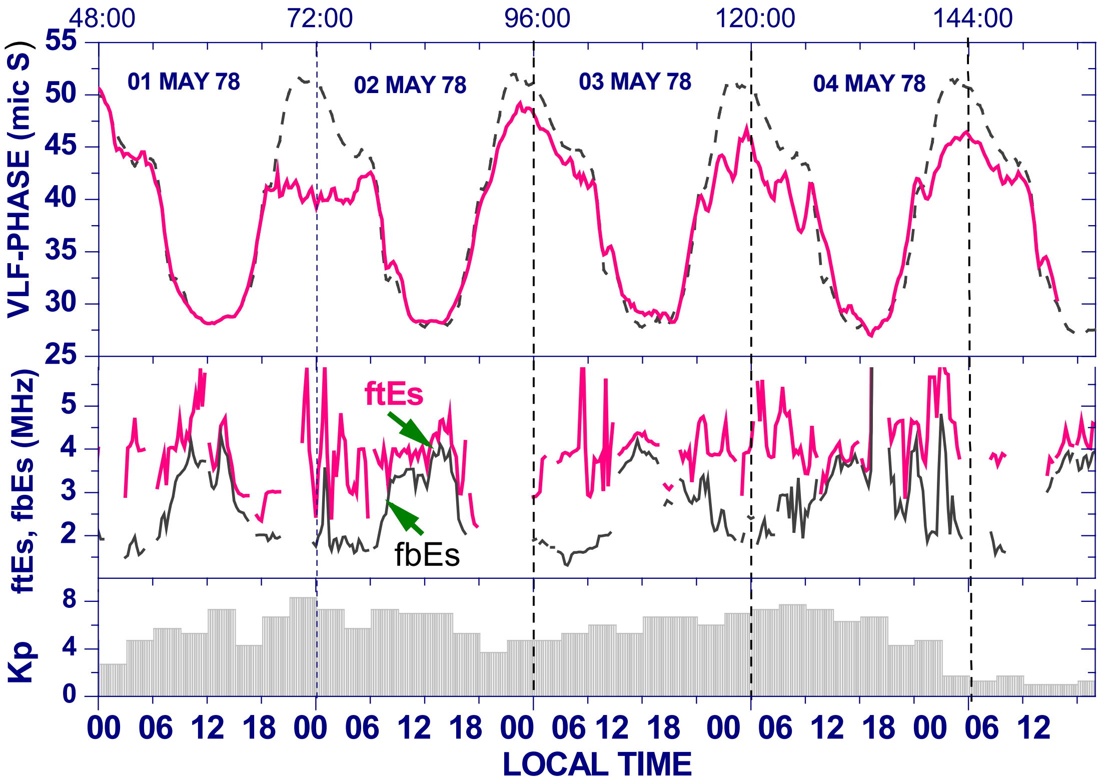

EQUATOR
L = 1.25
L = 1.50
L = 1.75
L = 2.00
L = 2.50
7.5 X 10^5
5 X 10^5
2.5 X 10^5
5 X 10^4
3 X 10^3
SOUTH LATITUDE
EAST LONGITUDE

Fig.3



48:00
72:00
96:00
120:00
144:00
01 MAY 78
02 MAY 78
03 MAY 78
04 MAY 78
VLF-PHASE (mic S)
55
50
45
40
35
30
25
ftEs
fbEs
ftEs, fbEs (MHz)
5
4
3
2
Kp
8
4
0
00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12
LOCAL TIME

Fig.4

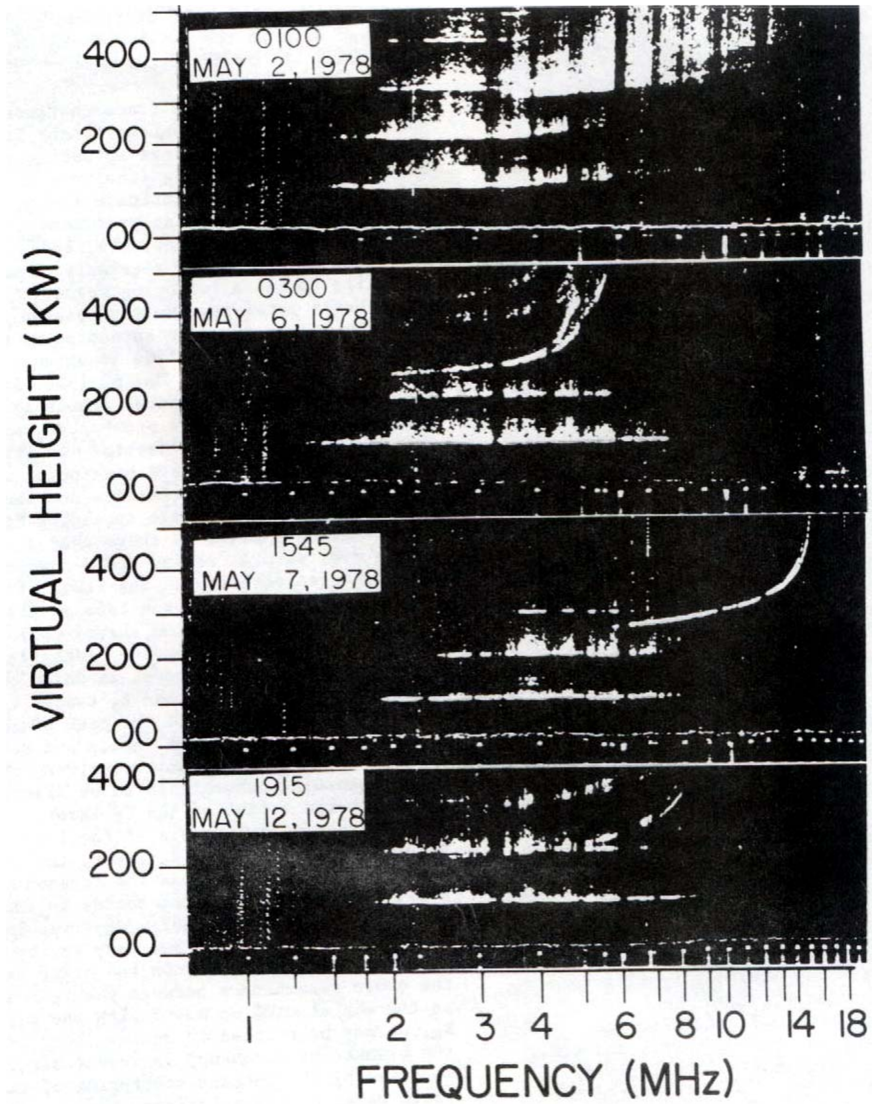
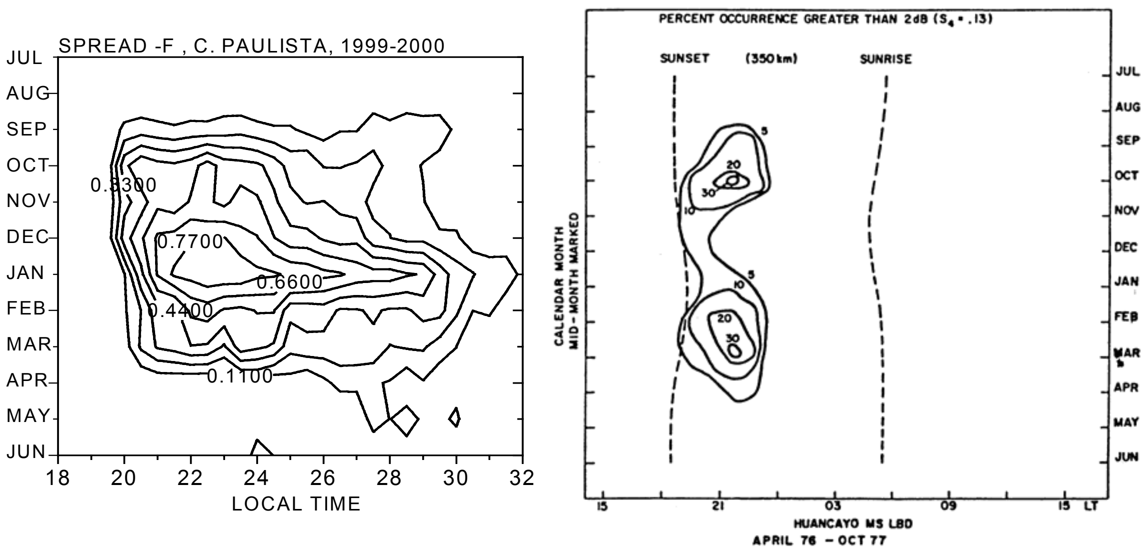

0100
MAY 2, 1978
0300
MAY 6, 1978
1545
MAY 7, 1978
1915
MAY 12, 1978
VIRTUAL HEIGHT (KM)
400
200
00
1
2
3
4
6
8
10
14
18
FREQUENCY (MHz)

Fig. 5



Monthly percentage occurrence contours of scintillations ≥ 2 dB for Huancayo observations of Marisat at 1.54 GHz during April 76 – Oct. 77. The sunset and sunrise times at 350 km altitude are indicated.

Fig.6

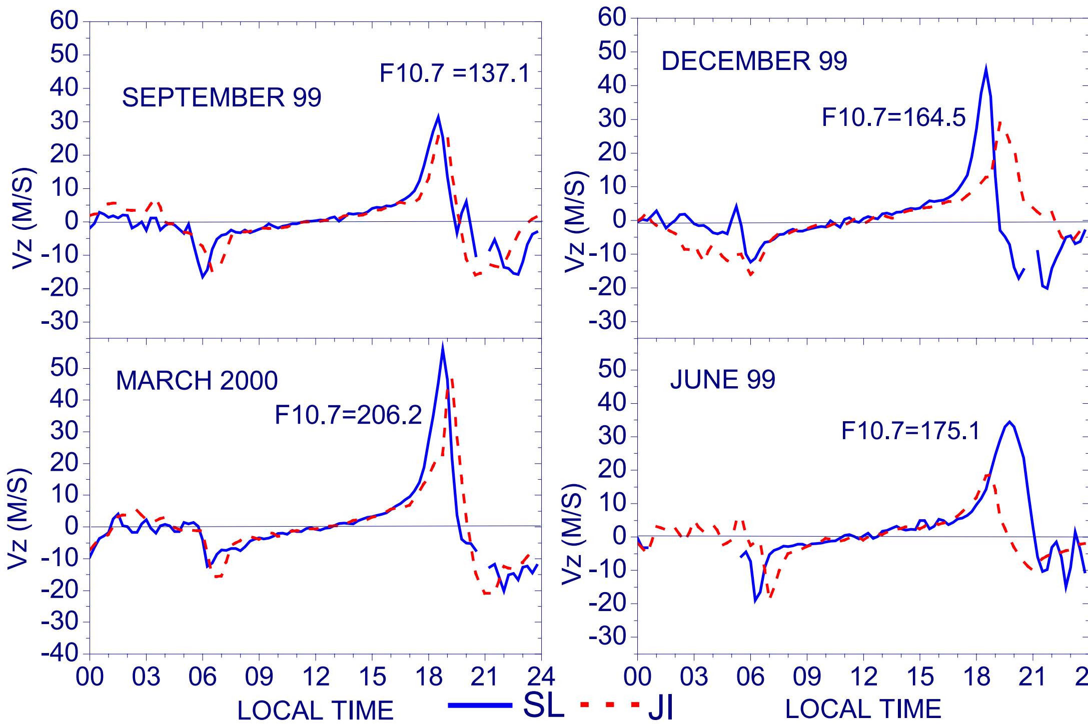

SEPTEMBER 99
F10.7 =137.1
DECEMBER 99
F10.7=164.5
MARCH 2000
F10.7=206.2
JUNE 99
F10.7=175.1
Vz (M/S)
LOCAL TIME
SL
JI

Fig.7

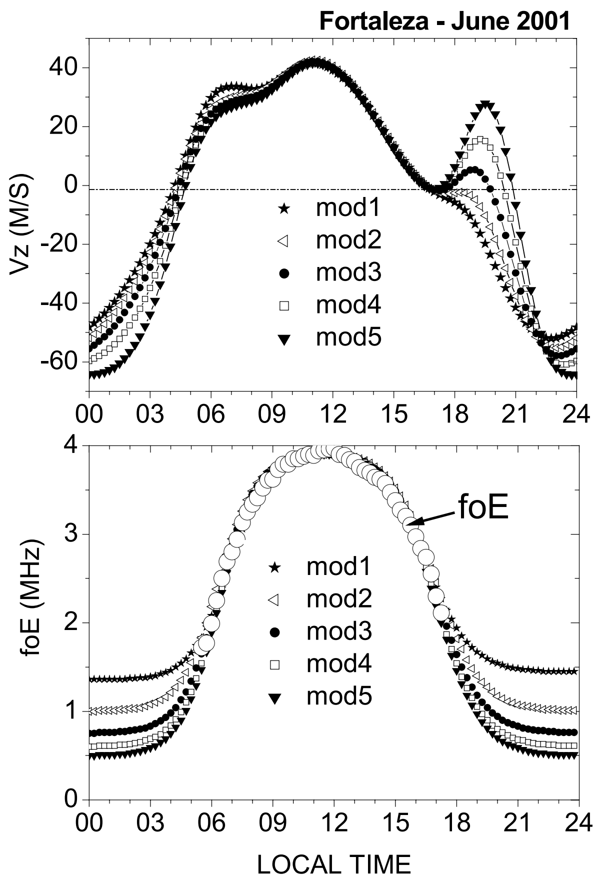

Fortaleza - June 2001
Vz (M/S)
40
20
0
-20
-40
-60
mod1
mod2
mod3
mod4
mod5
00
03
06
09
12
15
18
21
24
foE (MHz)
4
3
2
1
0
foE
mod1
mod2
mod3
mod4
mod5
LOCAL TIME

Fig. 8

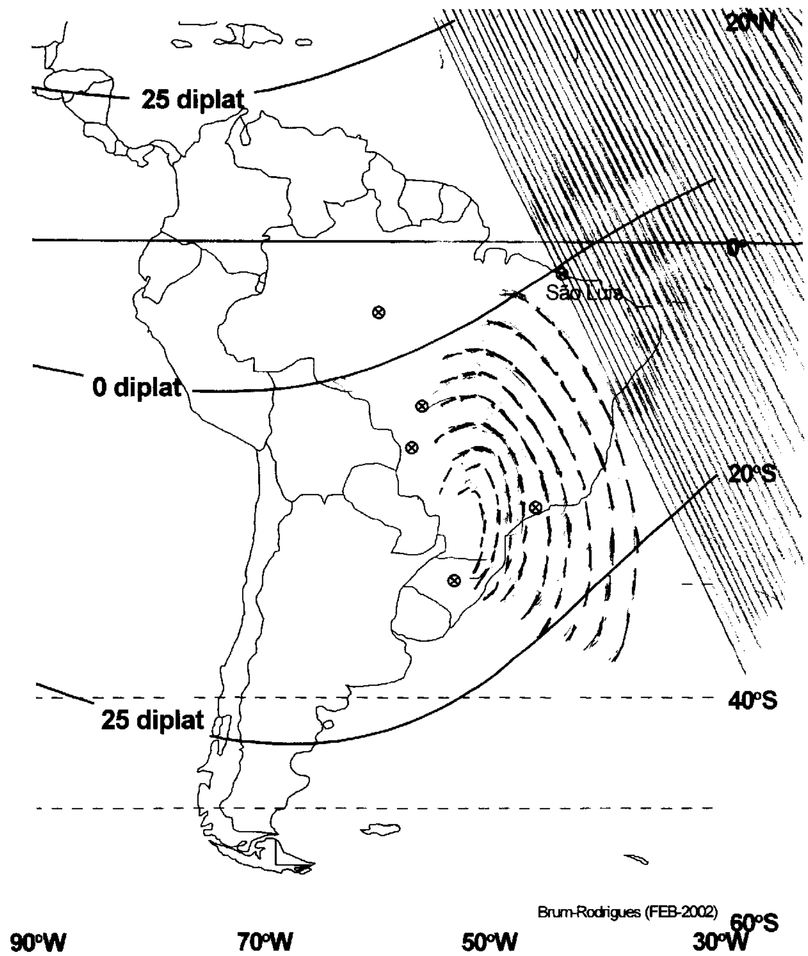

20°W
25 diplat
0°
São Luís
0 diplat
20°S
40°S
25 diplat
Brum-Rodrigues (FEB-2002)
60°S
90°W
70°W
50°W
30°W

Fig.9

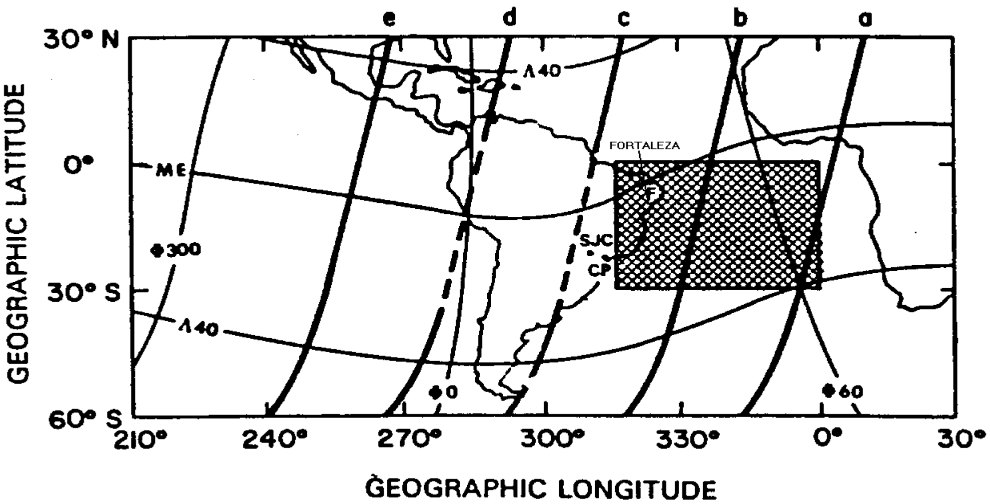
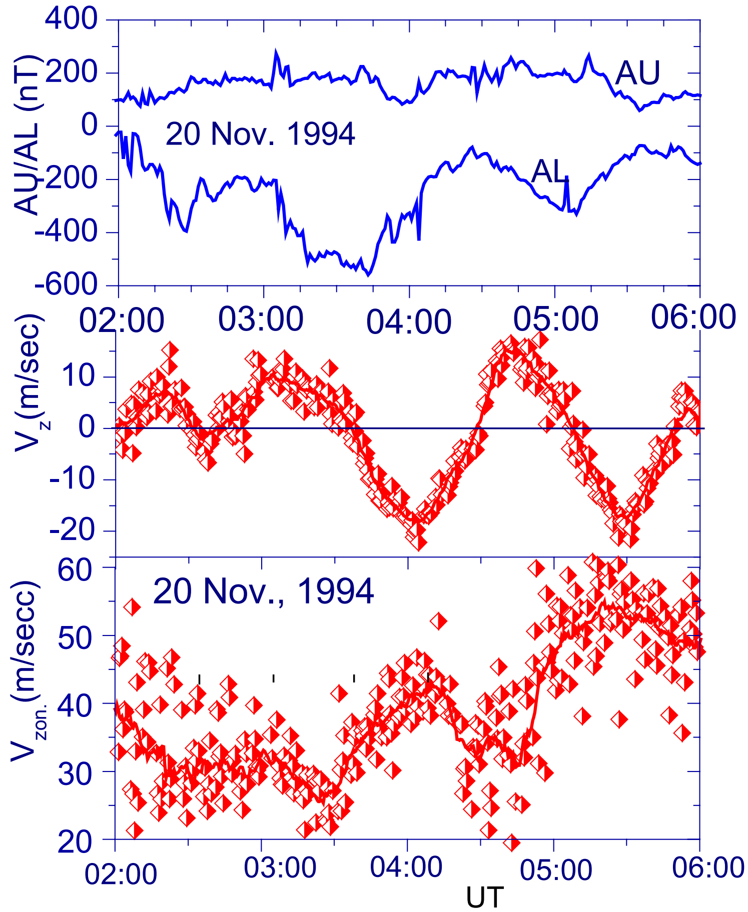

e
d
c
b
a
30° N
0°
30° S
60° S
210°
240°
270°
300°
330°
0°
30°
GEOGRAPHIC LATITUDE
GEOGRAPHIC LONGITUDE
Λ40
ME
Φ300
Λ40
Φ0
Φ60
FORTALEZA
SJC
CP

Fig.10



400
200
0
-200
-400
-600
AU/AL (nT)
20 Nov. 1994
AU
AL
02:00
03:00
04:00
05:00
06:00
V_z(m/sec)
10
0
-10
-20
60
50
40
30
20
$V_{zon.}$(m/secc)
20 Nov., 1994
02:00
03:00
04:00
05:00
06:00
UT

Fig. 11

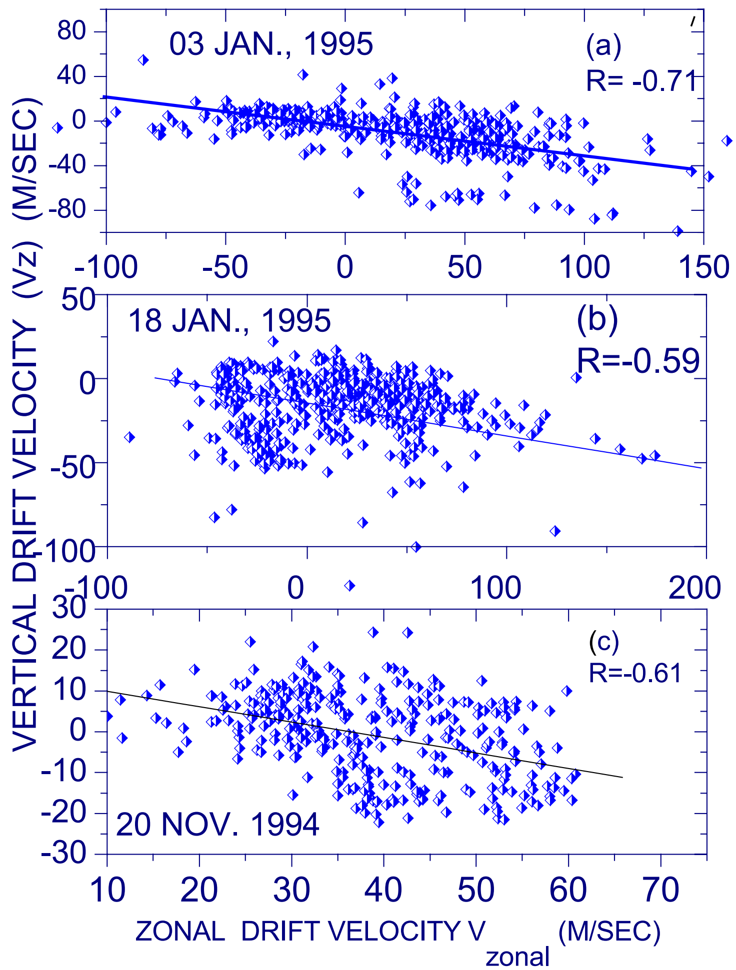
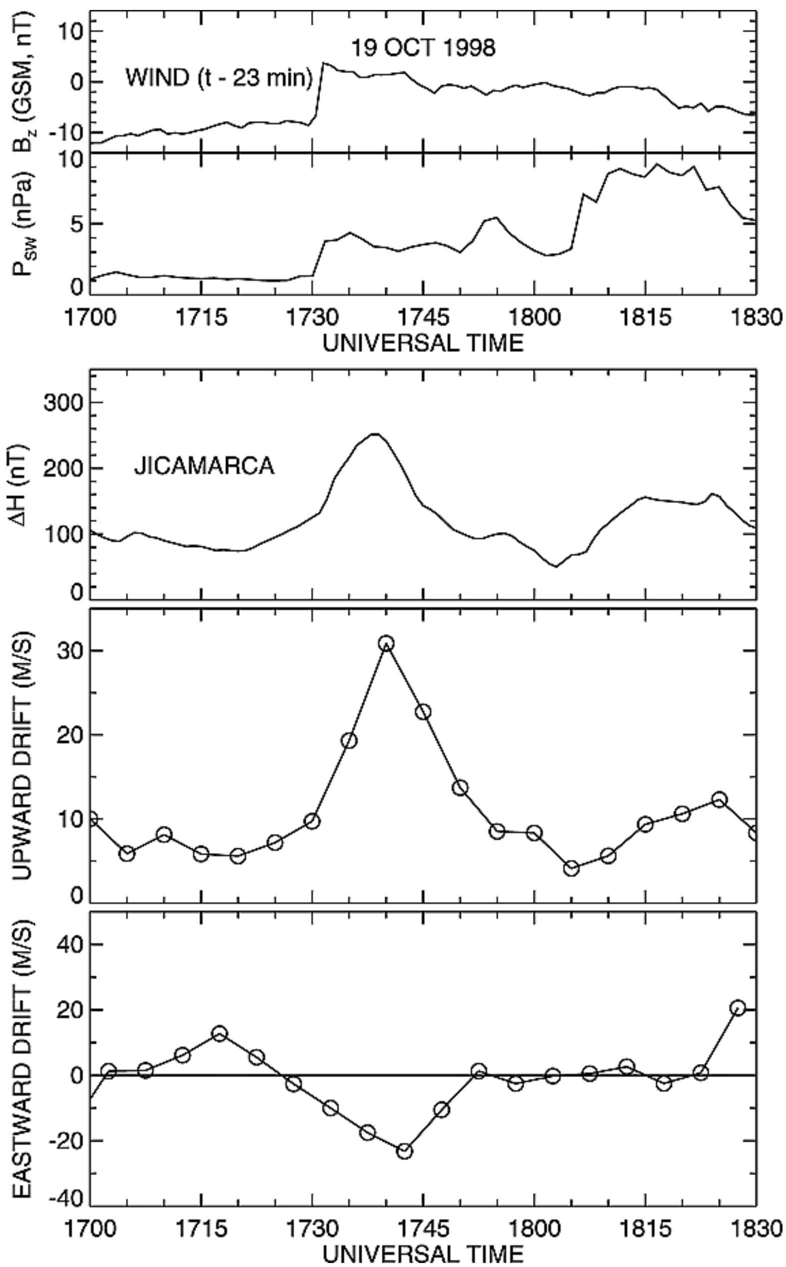
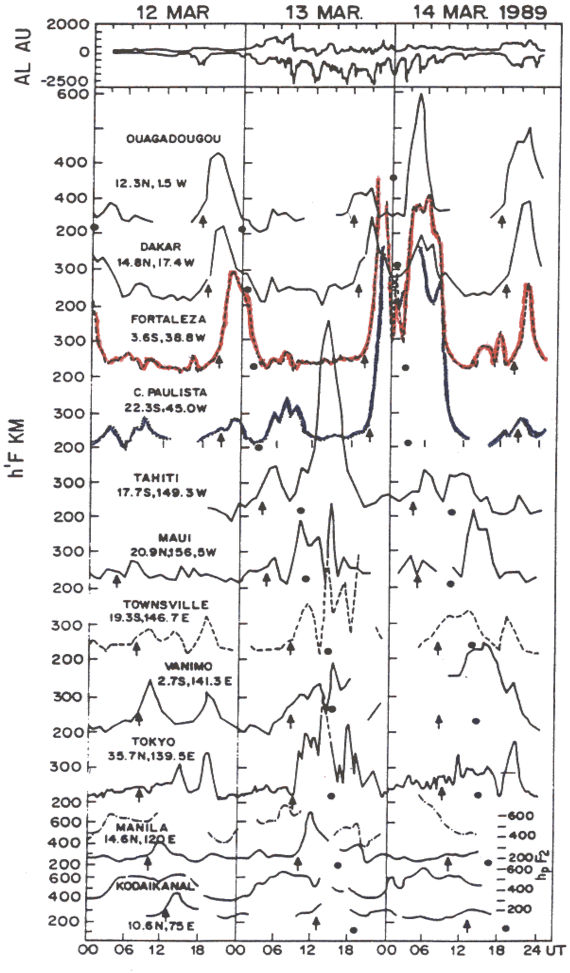

03 JAN., 1995
(a)
R= -0.71
18 JAN., 1995
(b)
R=-0.59
(c)
R=-0.61
20 NOV. 1994
VERTICAL DRIFT VELOCITY (Vz) (M/SEC)
ZONAL DRIFT VELOCITY V zonal (M/SEC)

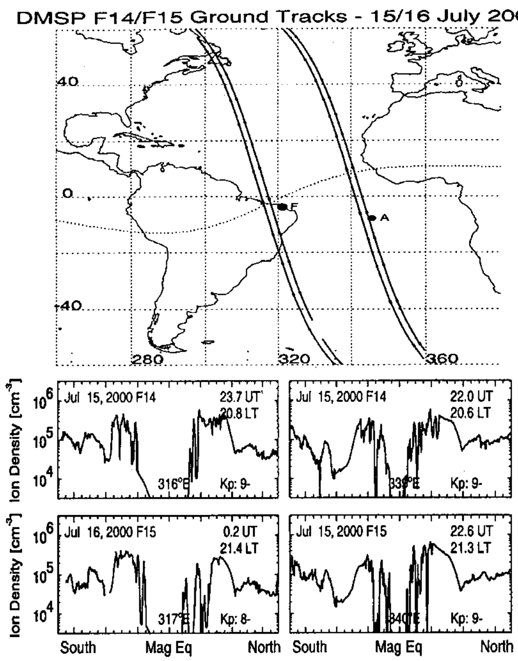
Fig. 12



19 OCT 1998
WIND (t - 23 min)
B_z (GSM, nT)
P_{SW} (nPa)
UNIVERSAL TIME
JICAMARCA
ΔH (nT)
UPWARD DRIFT (M/S)
EASTWARD DRIFT (M/S)
UNIVERSAL TIME

Fig. 13





The top panel illustrates two pairs of DMSP F14 and F15 satellite orbits near Fortaleza, Brazil (F) and Ascension Island (A) on July 15-16, 2000. The bottom left panel shows the ion-density variation as a function of magnetic latitude recorded by DMSP F14 and F15 satellites near Fortaleza. The bottom right panels show the ion density variations recorded by the DMSP satellites near Ascension Island.

Fig. 14