Magnetospheric disturbance induced equatorial plasma bubble development and dynamics: A case study in Brazilian sector

M. A. Abdu,[1] I. S. Batista,[1] H. Takahashi,[1] J. MacDougall,[2] J. H. Sobral,[1]
A. F. Medeiros,[3] and N. B. Trivedi[1]

Received 4 October 2002; revised 22 September 2003; accepted 3 October 2003; published 23 December 2003.

[1] Equatorial ionospheric plasma bubble irregularity development and dynamics during the major magnetospheric storm of 26 August 1998 are investigated using the data collected by a multistation and multi-instrument diagnostic network operated at equatorial and low latitude sites in Brazil, and auroral electrojet activity (AU/AL), IMF, and D_{st} indices. A magnetospheric disturbance onset in the morning of 26 August 1998 was initiated by a solar wind shock and associated IMF Bz polarity reversals and ssc that were soon followed by a succession of substorm-like auroral electrojet (AE) intensifications and D_{st} development. An IMF Bz southward turning and associated AE intensifications in the Brazilian dusk sector produced intense prompt penetration eastward electric field that caused large F region vertical drift and consequently the developments of intense postsunset equatorial anomaly and a series of intense plasma bubbles, the latter event lasting the entire night, as observed by digital ionosondes at São Luís (2.33°S, 315.8°E, dip angle: −.5°) and Fortaleza (3.9°S, 321.55°W, dip angle: −9°) and an all-sky imager, two scanning photometers, and a Digisonde at the low-latitude site Cachoeira Paulista (22.6°S, 315°E; dip angle: −28°). A notable aspect of the dynamics of the bubbles was their initially very low eastward drift velocity which turned into steadily increasing westward velocity that lasted till early morning hours. The results show for the first time a relationship between the zonal drift velocities of optically observed large-scale bubbles (tens to hundreds of kilometers) and that of the smaller scale (kilometer sizes) structures as observed by a digital ionosonde. The results point to the dominant role of a disturbance dynamo associated westward thermospheric wind to maintain the plasma irregularity drift increasingly westward going into postmidnight hours. As an important finding, the results further show that significant contribution to the westward plasma bubble irregularity drift, normally attributed to disturbance dynamo effect, could arise from prompt penetration disturbance zonal electric field, in the course of a disturbance sequence lasting several hours. Such effect is attributed to Hall electric field arising from the primary disturbance zonal electric field, under enhanced nighttime ionospheric conductivities produced possibly by storm associated particle precipitation, in the Brazilian longitude sector in agreement with recent evidences [*Abdu et al.*, 1998b]. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2439 Ionosphere: Ionospheric irregularities; 2435 Ionosphere: Ionospheric disturbances; 2437 Ionosphere: Ionospheric dynamics; 2455 Ionosphere: Particle precipitation; *KEYWORDS:* electric fields, equatorial ionosphere, ionospheric disturbances, ionospheric irregularities, particle precipitation, ionosphere/atmosphere interaction

Citation: Abdu, M. A., I. S. Batista, H. Takahashi, J. MacDougall, J. H. Sobral, A. F. Medeiros, and N. B. Trivedi, Magnetospheric disturbance induced equatorial plasma bubble development and dynamics: A case study in Brazilian sector, *J. Geophys. Res.*, *108*(A12), 1449, doi:10.1029/2002JA009721, 2003.

1. Introduction

[2] The equatorial ionosphere-thermosphere system is known to undergo significant modifications during magnetospheric disturbances. They arise from (1) prompt penetration of magnetospheric electric fields to equatorial latitudes under varying phases of a disturbance sequence, (2) delayed electric field due to disturbance dynamo arising from a perturbed thermospheric global circulation system driven by

[1]Instituto Nacional de Pesquisas Espaciais (INPE), São José dos Campos, São Paulo, Brazil.
[2]University of Western Ontario, Department of Physics and Astronomy, London, Ontario, Canada.
[3]Universidade Federal da Paraiba, Campina Grande, Paraiba, Brazil.

0148-0227/03/2002JA009721

storm energy input and the resulting Joule heating of the high-latitude I-T (ionosphere-thermosphere) system, and (3) disturbance thermospheric winds at low latitudes associated with item 2. The prompt penetration electric fields could arise from the different storm phases: interplanetary magnetic field polarity changes, sudden storm commencements, direct penetration of interplanetary electric field, the DP 2 fluctuations, substorm onset, growth and recovery phases (that is, increases and decreases in polar cap potential drop), and ring current development and decay [see, e.g., *Abdu et al.*, 1995, 1998a; *Fejer and Scherliess*, 1995; *Gonzales et al.*, 1983; *Kelley et al.*, 2003; *Kikuchi et al.*, 1996; *Sastri et al.*, 2002; *Sobral et al.*, 1997]. Depending upon the specific storm phase, the duration of these "transient" events could last from a few minutes to a few hours. On the other hand, the disturbance dynamo electric field that occurs with several hours of time delay with respect to the magnetospheric disturbance onset [*Blanc and Richmond*, 1980] could last much longer, of the order of a day or more [*Abdu et al.*, 1997; *Scherliess and Fejer*, 1997]. Similar durations could apply also to the disturbance associated thermospheric winds [*Abdu et al.*, 1995, 1997].

[3] For isolated and short duration magnetospheric disturbances the different phases of the response features can be rather clearly identified, while such identification is a complex task for disturbances of longer duration for which superimposed response phases could occur. Specific studies have focused attention on the key parameters, such as electric field, plasma drift, wind or one of the major phenomena of the equatorial ionosphere [*Abdu et al.*, 1991, 1998a, 1998b; *S. Basu et al.*, 2001; *Fejer and Scherliess*, 1997; *Forbes et al.*, 1995]. Ionospheric response from space weather perspective has recently been addressed by *Su. Basu et al.* [2001].

[4] Plasma bubble irregularity development and evolution under disturbance electric fields and winds are of particular interest in the context of improving our understanding of the circumstances of their occurrences under predictable geophysical and space weather conditions. Regarding disturbance electric fields, much of the investigations conducted so far concern zonal electric field, that is, vertical plasma drift [see, e.g., *Fejer*, 1997], whereas limited studies have been conducted on the disturbance behavior of vertical electric field, that is, zonal plasma drift [*Abdu et al.*, 1985, 1998b; *S. Basu et al.*, 2001]. F region plasma/bubble irregularity zonal drifts measured by spaced receivers have been used as reliable indicator of the background plasma drift [*Abdu et al.*, 1985; *Valladares et al.*, 1996]. Also little-known are the features of perturbed thermospheric wind in their meridional and zonal components that are known to influence the conditions of plasma bubble development and dynamics. Regarding the nighttime zonal plasma drift, while it is driven mainly by thermospheric wind dynamo electric field of the F region that is decoupled from the E region, its responses under disturbed conditions could be conditioned by disturbance thermospheric wind as well as by externally imposed disturbance electric field possibly coupled with enhanced/modified nighttime E layer conductivity, as we shall be discussing in this paper.

[5] A recent study by *Abdu et al.* [1998b] on drift velocities measured by a digital ionosonde over Fortaleza showed that fluctuations in vertical plasma irregularity drift under magnetically disturbed conditions were anticorrelated with those in the zonal drift (that is, an upward drift perturbation was associated with a westward drift perturbation). Such correlation was explained as resulting from the role of a Hall electric field produced by the externally imposed (prompt penetration) zonal electric field, under enhanced nighttime E layer conductivity, such as that associated with enhanced particle precipitation in the South Atlantic Magnetic Anomaly region. Other sources, such as sporadic E layers that could contribute to the field line integrated conductivities, could also influence the generation the Hall electric field. Further evidence in support of such processes will be presented in this paper. A case study is presented here of the evolution and dynamics of a plasma bubble event that was initiated by prompt penetration of magnetospheric electric field to equatorial ionosphere that was under the influence of disturbance dynamo. The initial slow eastward drift of the bubbles turned to steadily increasing westward drift which prevailed through the rest of the night. This result provides evidence on the possible role of a disturbance westward thermospheric wind on the dynamics of the plasma bubbles. Fluctuating drift superposed on a mean westward drift is suggested to indicate the role of a Hall electric field produced by a fluctuating primary zonal disturbance electric field originating from the AE activity. The study is based on simultaneous data collected by a Digisonde located at the magnetic equatorial station São Luís (SL), a CADI (Canadian Digital Ionosonde) and a magnetometer located at Fortaleza (Fz), and a Digisonde, a 630 nm all-sky imager and two angular scan 630 nm photometers all operated at the low latitude location Cachoeira Paulista (CP).

2. Results

[6] An ssc, associated with IMF Bz changes, marked the onset of a magnetic disturbances at ~0650 UT on 26 August 1998, as shown by its signatures in the AU/AL indices, the D_{st} indices, and the local magnetogram H component in Figure 1. The disturbance evolution during the following 30 hours is shown in this figure. The H component is for the Eusébio site (3.9°S, 321.15°E, dip angle: −9°), close to Fortaleza. The 4-min resolution IMF B_z component measured by the ACE spacecraft located at L1 point is plotted with a time delay of 36 min, which corresponds to the estimated convection delay from ACE to the magnetosphere at the measured solar wind speed of ~700 km/s. A B_z southward turning at ~0945 UT (indicted by the vertical line 1), seems to be responsible for a series of substorms and the main phase D_{st} decrease that started at ~1000 UT (second and fourth panels). The equatorial electrojet was almost totally inhibited on this day, as indicated by the H-component variations over Huancayo as well as by the absence of any 50 MHz VHF backscatter radar echoes from electrojet over São Luís (2.33°S, 315.8°E, dip angle: −0.5°) (not shown here). The F layer vertical drift (V_z), obtained from the Digisonde over São Luís, as the mean of d(hF)/dt values calculated from 3 to 9 MHz, is presented in the third panel of Figure 1. It shows large increase in its postsunset

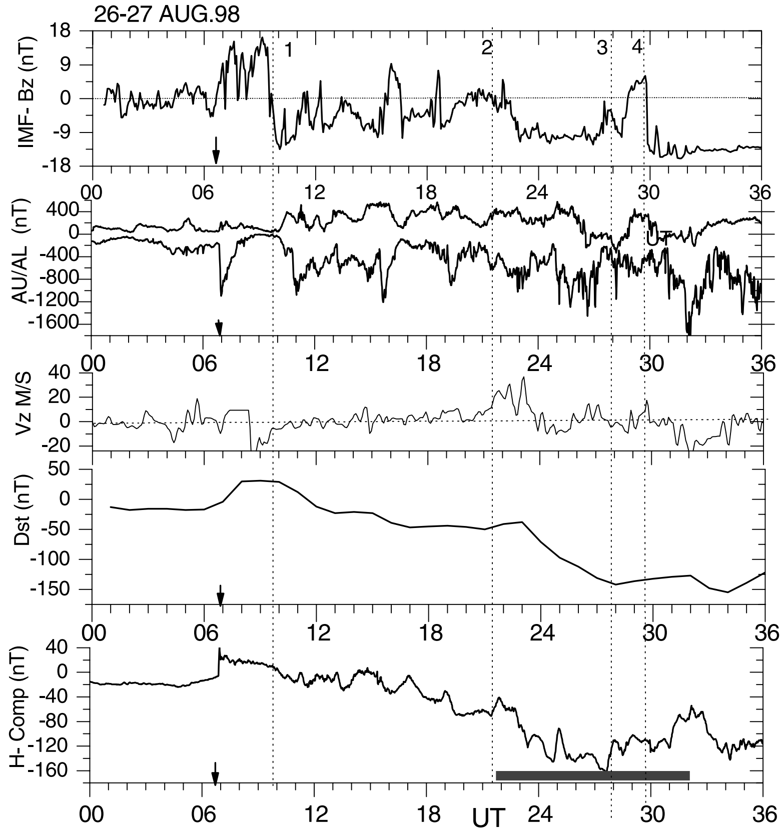

Figure 1. The panels in descending order show the disturbance sequences in the IMF Bz, auroral activity indices AU/AL, the F region vertical drift calculated as d(hF)/dt (here presented as the mean values corresponding to the sounding frequencies covering 3–9 MHz), the D_{st}, and local magnetic field H component variation during 26–27 August 1998. The onsets of an ssc at ~0650 UT with the associated signatures in the IMF B_z and AU/AL are indicated. The shaded bar (bottom panel) represents the plasma bubble observation period (interval starting with the equatorial F layer uplift) reported here. The dotted vertical lines indicate (line 1) the first major B_z southward turning that preceded the major AE events, (line 2) the B_z southward turning that seems to have caused the evening PP eastward electric field, (line 3) a minor southward increase of B_z, and (line 4) a major B_z southward turning that seems to have preceded the postmidnight bubble event.

(prereversal) enhancement as compared with the previous evening (Figure 2). (It should be pointed out here that under daytime conditions the d(hF)/dt is not a reliable indicator of vertical plasma drift when the layer height is dominantly controlled by photochemistry). The subsequent nighttime V_z variation is well correlated to the AE activity phases in good agreement with the modeling and observational results [*Fejer and Scherliess*, 1995; *Spiro et al.*, 1988]. Figure 2 shows (in the top and middle panels) plots of plasma frequency isolines obtained from the Digisonde ARTIST (Automatic Real Time Ionogram Scaling and True height) software and (in the bottom panel) the f_0F2 and h_mF2 variations over São Luís and Cachoeira Paulista. The lower section of the top panel shows the V_z variation over São Luís (the same as in Figure 1). A comparison of the f_0F2 variations at the two stations shows that the daytime equatorial ionization anomaly (EIA) which was well developed on 25 August (a relatively quiet day) is almost totally inhibited on the 26th except for a short duration f_0F2 enhancement over CP around 1500 UT which appears to be caused by a surge of intense equatorward wind [*Pincheira et al.*, 2002], as inferred from the notable F layer height increase at this time over CP that was absent over SL. The presence of a westward electric field responsible for the EIA inhibition during much of the daytime (0700–1400 LT or 1000–1700 UT)) of 26 August is evident from the lower heights of the plasma frequency isolines over São Luís as compared with their values of 25 August (top panel).

[7] An enhancement in eastward electric field in the form of F layer height increase is evident from ~1700 UT onward on 26 August (in comparison to 25 August) over São Luís in Figure 2 (top panel). Then a significant intensification in the eastward electric field occurred in the dusk sector, starting at ~2130 UT (1830 LT), which seems to follow an IMF Bz southward turning and associated AU/AL increase indicated by the dotted line 2 in Figure 1. This large increase of F layer height due to disturbance eastward electric field in the dusk sector is similar to such effects previously reported by *Batista et al.* [1991] and *Abdu et al.* [1995]. This was promptly followed by a strong intensification of the EIA as seen in

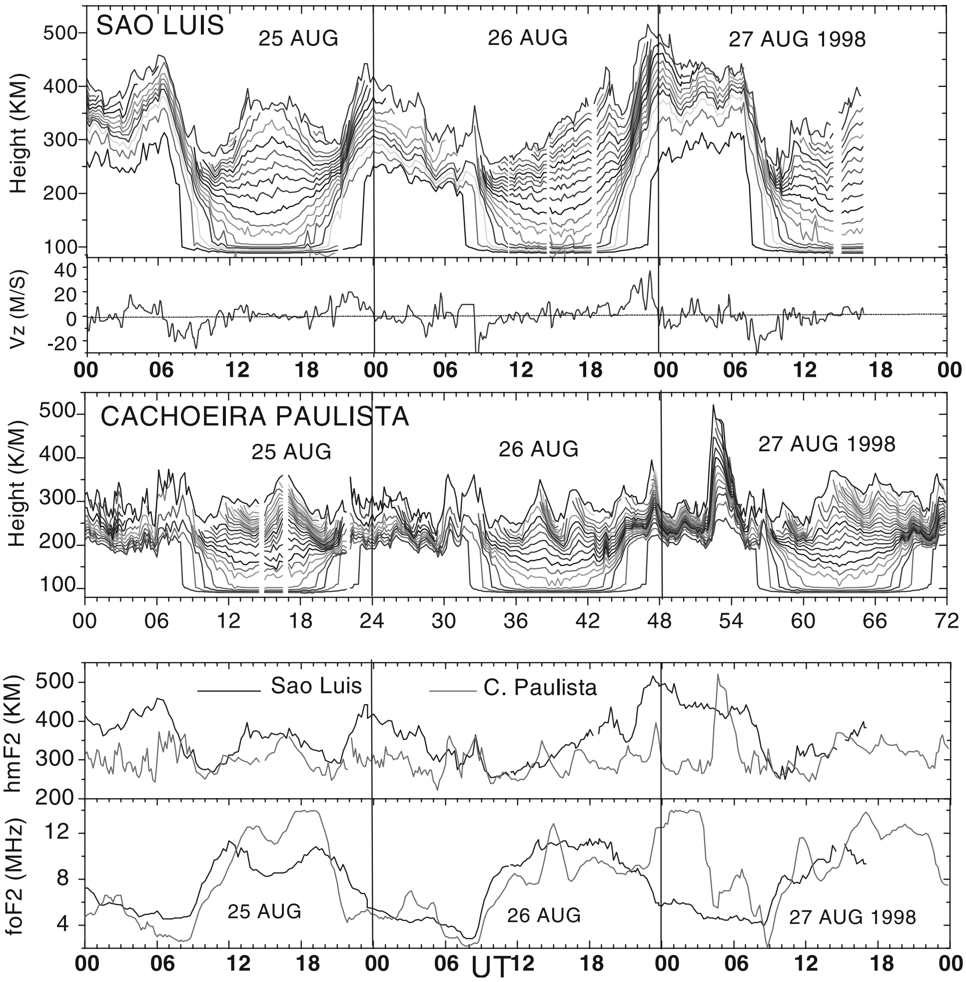

Figure 2. The iso lines of plasma frequencies starting at 1 MHz and increasing in steps of 0.5 MHz up to the height of the F layer peak electron density (hmF2, also shown), and the F region vertical drift (as in Figure 1) over São Luís (top panel), the iso lines of plasma frequencies and hmF2 over Cachoeira Paulista (middle panel), and the h_mF2 (repeated) and the F layer peak electron density represented by f_0F2 over the same two locations (the bottom panel). See color version of this figure in the HTML.

the large increase of f_0F2 over CP with its decrease over São Luís. (A time delay by $\sim$2 hours in the EIA response to the electric field increase can be noted here as was previously pointed out by *Abdu et al.* [1991]). The enhanced EIA seems to have continued (although with varying intensity) till the morning hours of 27 August under the conditions of repeated AU/AL intensification and associated V_z variation. Although disturbance dynamo electric field is expected to be present throughout this night the correlated variations, with the expected phase relationship, between the V_z and AU/AL would highlight the role of a PP electric field as being an important control factor during the entire period. The F layer heights over Cachoeira Paulista are also highly perturbed on the night of 26–27 August in ways that would suggest the influence of a disturbance meridional wind that is superposed on the effects from disturbance zonal electric field [*Pincheira et al.*, 2002].

[8] It is to be noted that the amplitude of the evening F layer height increase associated with the prereversal eastward electric field enhancement on the day 25 is $\sim$20 m/s which is typical for the month of August and, generally, insufficient to cause generation of spread F irregularities in the Brazilian longitude sector [*Abdu et al.*, 1981a]. In contrast, the increased V_z and the corresponding large F layer height increase of 26 August arise from the superposition, over the background electric field pattern, of the prompt penetration electric field associated with the auroral electrojet intensification, which occurred in the dusk sector [see also *Abdu et al.*, 1995; *Fejer and Scherliess*, 1995]. If a disturbance dynamo effect in suppressing the PRE were present on this evening as is expected [e.g., *Abdu et al.*, 2003], then the observed evening increase of the V_z could be primarily arising from the PP electric field arising from the AE increase that occurred at this time (see Figure 1). The resulting F layer vertical drift velocity that reached $\sim$40 m/s, with the associated height rise, was responsible for the EIA enhancement just discussed above. It was also responsible for the generation of a series of plasma bubbles whose onset was first observed as range spread F in the ionogram at 2200 UT (1900 LT) over the equatorial station São Luís which is shown in Figure 3 (top panel). The subsequent

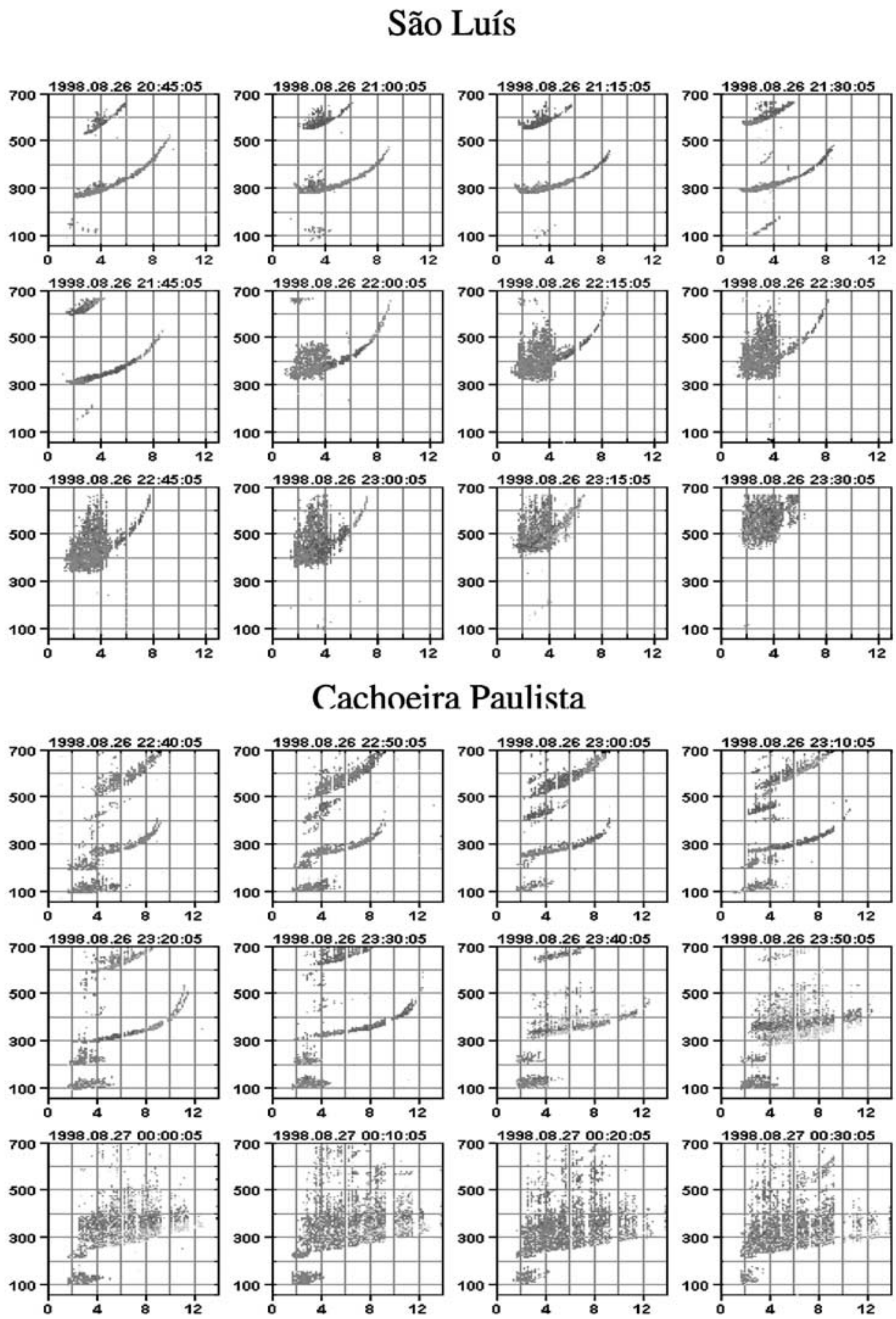

Figure 3. Ionograms over SL and CP showing the range type spread F traces that indicate presence of plasma bubbles over the two locations. The onsets of the bubble event are seen at 2200:05 UT (1900:05 LT) over SL and at 2340:05 UT (2040:05 LT) over CP. See color version of this figure in the HTML.

growth of the bubble is evident in the increasing range spread of the traces observed in the successive ionograms taken at 15-min intervals. The vertical growth of the bubble to apex altitudes (>∼800 km) of the field lines that map the irregularities down to the bottom-side F layer over Cachoeira Paulista is marked by the occurrence of range spread F starting at 2340 UT (2040 LT) in the ionograms taken at 10-min resolution, shown in Figure 3 (bottom panel). The vertical rise velocity for the initial bubbles, based on the time delay in their range spread F manifestation over CP comes out to be approximately 80 m/s, which is within the limits of vertical bubble velocities measured by radars [see, e.g., *Tsunoda*, 1981] and previous ionosonde diagnostics [*Abdu et al.*, 1983]. It is important to note that the bubble development occurred even in the presence of strong sporadic E layers over Cachoeira Paulista that lasted till past midnight [see also *Bowman and Mortimer*, 2003]. Such E_s layers are auroral

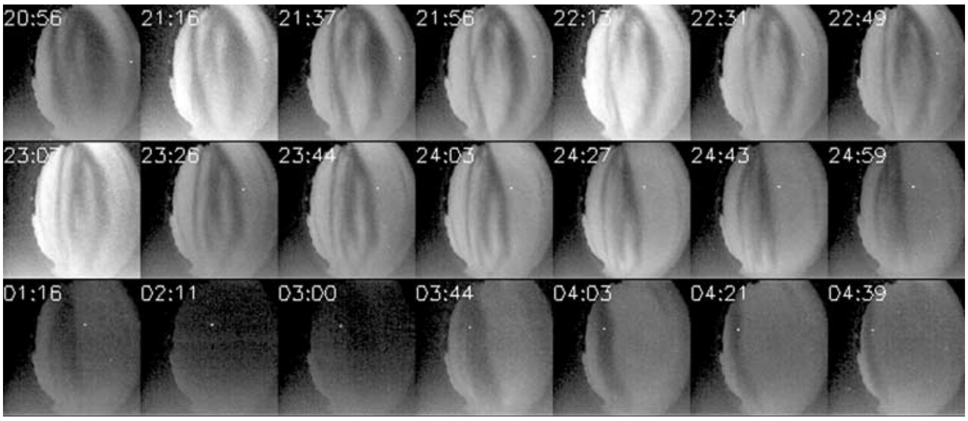

Figure 4. Sequence of 630 nm all-sky images of plasma depletions taken at ∼20 min intervals over CP. The images have the north upward and the east is at left.

type (a-type), showing range-spreading echoes that are known to occur over this location in association with magnetic disturbances. They have been shown to be produced by enhanced particle precipitation in the region of South Atlantic Magnetic Anomaly by *Batista and Abdu* [1977] and *Abdu et al.* [1981a]. We will show that this aspect has important implications on the electrodynamics of the plasma bubble irregularities.

[9] An all-sky imager at 630 nm at Cachoeira Paulista operating at a resolution of ∼20 min (that is, one image at every ∼20 min) registered the first airglow depletion signature of these bubbles at 2056 LT, as shown in Figure 4 (wherein the dark patches represent the airglow depletion). The first four images (from 2056 to 2156) show the continuing vertical development of the main bubble structure (the right most depletion), from its ∼1900 LT onset over the equator, that can be verified from the increasing southward extension, with time, of this depletion. On the other hand, a second depletion branching away on the left side of this main one seems to go through a weakening phase (showing retreat towards equator) before its renewed vertical growth which prevailed from 2231 to 2344 LT. In the images after 0116 LT the depletions tend to merge with the low-background airglow intensity. This low airglow intensity was apparently caused by an equatorward wind surge and the resulting large F layer height rise that peaked around 0130 LT (0430 UT) (as can be verified from the plots in Figure 2) which caused low electron density in the emission layer over CP. However, starting from ∼0300 LT (0600 UT) a dominant airglow depletions was again detected which continued through the last image taken at 0439 LT (0739 UT). From an examination of the Digisonde ionograms over São Luís at these times (not shown here) and from the CADI plots (in Figure 7) it is seen that this depletion corresponded to a renewed bubble irregularity development. This bubble development seems to be arising from an IMF Bz southward flip (near 0500 UT) and associated changes in substorm intensity (identified by the vertical line 4 in Figure 1) and the F layer height rise starting around 0200 LT (0500 UT) over Fortaleza (Figure 7) and at São Luís (Figure 2). (It is not clear what is the effect of a brief IMF Bz southward increase and the associated AU/AL intensification identified by the vertical line 3). The vestige of this latter bubble event was visible in the ionograms over São Luís, Fortaleza, and Cachoeira Paulista till sunrise. It may be noted that the airglow depletion patches in the initial images of Figure 4 appeared to be going through very slow eastward motion to stationary state till about 2326 LT after which steadily moving westward, a feature that is better demonstrated in the scanning photometer data to be described below.

[10] Two angular scan 630 nm photometers [*Sobral and Abdu*, 1991] monitored the airglow depletions over Cachoeira Paulista in their two east-west scanning planes, one tilted by 30° toward north and the other toward south of the vertical. Each scan spanning an angular range of ±75° was performed in ∼3 min with a return time of ∼1 min. These scans thus represent two east-west cuts across the depletion images of Figure 4 with a north-south separation of 60 degrees in look angle centered on zenith (which corresponds to a horizontal north-south separation of approximately 500 km at 300 km height). The results are shown in Figure 5 as isointensity plots in east-west scanning angle versus local time format for both the north and south scanning planes. These plots allow us to follow clearly the east-west displacement of the bubbles as a function of local time. The initial longitudinally extended low-intensity patches are perhaps the airglow precursor signatures for the bubble development. Clearly defined bubble type depletions are visible starting at approximately 2050 in the northern and southern scanning planes but with more numerous short living secondary bubbles being present in the northern scanning plane. The smaller ones on the western side of the meridian plane (0° in the figure) as well as the main depletion that developed ∼20° east of the station appear to have a small eastward drift till around 2300 LT. The main depletion then on drifted westward, steadily increasing in velocity. The westward displacement is visible till the depletion merged with the low-airglow background intensity that resulted from an up lift of the layer due to an equatorward wind which occurred around 0130 LT (as stated before). The second bubble event that developed near 0300 LT also drifted west with still larger velocity. Figure 6 presents the local time variation of the

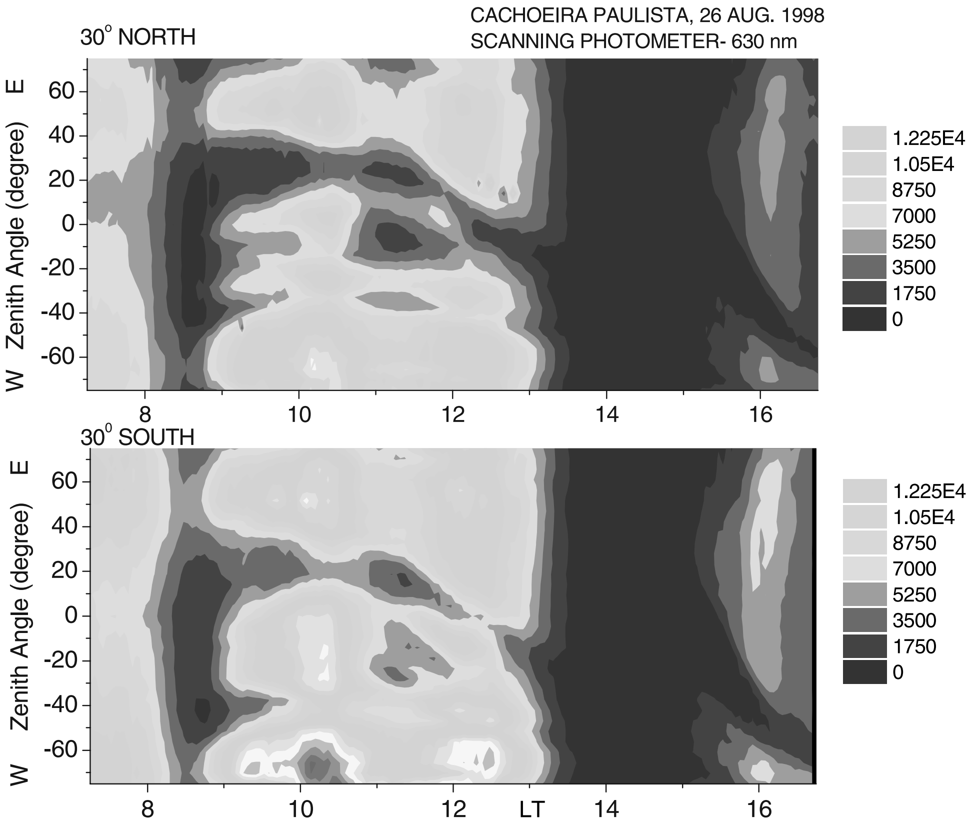

Figure 5. East-west scans of 630 nm airglow intensity as a function of LT, obtained by two angular scanning photometers operated using scanning planes tilted to 30°S and 30°N with respect to vertical. Zonal displacement of the depletions may be noted in the two planes. See color version of this figure in the HTML.

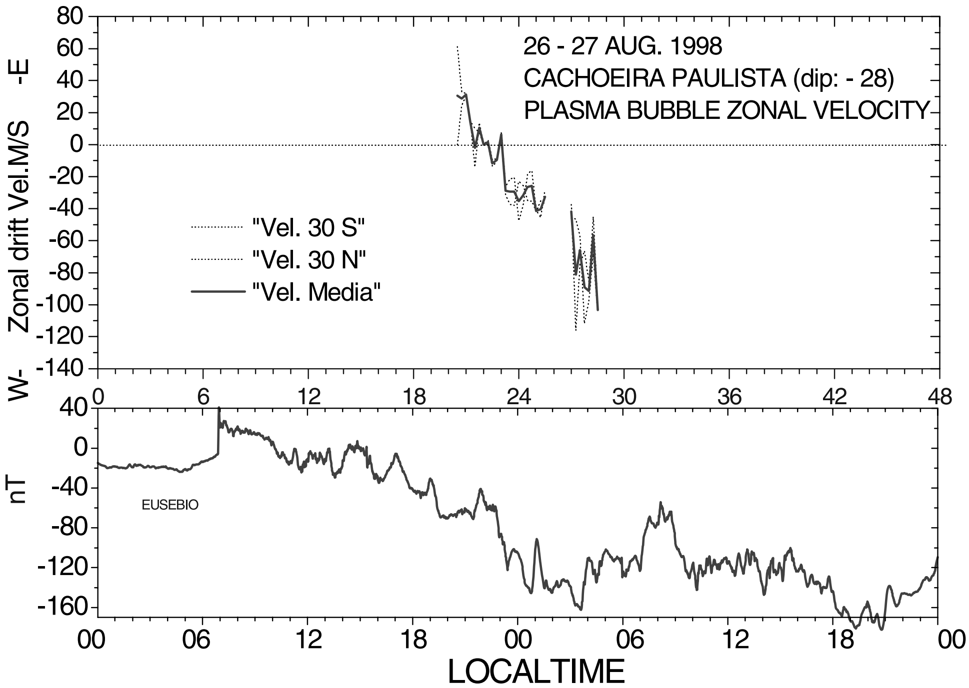

Figure 6. Zonal velocity of the airglow depletions of Figures 4 and 5 plotted versus local time together with the variations in magnetic field H component over Eusebio.

zonal drift velocity of the main depletion, dotted lines showing the north and south plane velocities and the solid line representing their mean values. The progressive increase of the westward velocity of the depletion may be noted. The lower panel of the Figure 6 shows the H-component magnetic field variation over Eusebio. It is interesting to note that there are fluctuations in the zonal bubble velocity that would appear to be related to the fluctuations in the magnetic field. (We will come back to this point).

3. Discussion

[11] The normal spread F season for the Brazilian longitude sector is from September to March with a broad maximum in occurrence centered on December month [*Abdu et al.*, 1981b]. Cases of infrequent range spread F occurrence outside the season of its normal occurrence over Brazil was investigated by *Sastri et al.* [1997], who showed a high probability of their being associated with magnetically disturbed conditions. The event discussed here corresponds to an ESF/plasma bubble occurrence during a period of transition. Based on the statistics on many nights previous to 26 August, it is very unlikely that range spread F and associated plasma depletions on this night would have occurred but for the large uplift of the F layer produced by the superposition of a magnetospheric disturbance eastward electric field on an otherwise low evening prereversal zonal electric field/vertical drift velocity enhancement, typical for this epoch, that was possibly further inhibited by a disturbance dynamo effect. It is interesting to note here that the disturbance electric field induced bubble occurrence (at ~1900 LT) coincided in time with its normal post sunset occurrence.

[12] The range spread F onset time over Cachoeira Paulista is at 2040 LT (2340 UT) in the 10-min resolution ionogram which is close to the first sighting of the airglow depletion in the optical data (Figures 4 and 5). Since the depletions did not show appreciable zonal drift velocity at this early time of its development the time delay for the onset over Cachoeira Paulista with respect to that over São Luís represents the vertical development (rise) velocity, under east-west polarization electric field, of the major depletions. This velocity comes out to be ~80 ms^{-1} as stated before, which is consistent with the southward propagation velocity (or equivalently the vertical velocity in the equatorial plane) of the major depletion edge in the sequence of images from 2056 to 2213 LT in Figure 4.

[13] An important aspect of the ambient conditions of this bubble event is that soon after the onset of the main phase decrease of the H-component (Figure 1), blanketing and auroral type (a-type) sporadic E layers were observed over Cachoeira Paulista. Starting as a weak event in the ionogram at 1730 UT (1430 LT) the Es layer got intensified persisting till ~0400 UT (0100 LT). A part of this E_s layer development sequence can be verified in the inograms in the lower section of Figure 3 (lower panel). It has been shown earlier [*Abdu et al.*, 1981a; *Batista and Abdu*, 1977] that such sporadic E layer occurrence over Cachoeira Paulista under magnetically disturbed conditions could represent enhanced ionization due to particle precipitation in the South Atlantic Magnetic Anomaly (SAMA) region and that its nonoccurrence may not always signify absence of enhanced ionization under disturbed conditions. The enhanced E layer conductivity arising from this extra nighttime ionization could have possibly influenced the rise velocity of bubble on this night. The interaction of the conductivity enhancements and associated spatial gradients produced by the enhanced (and localized) ion production on the bubble electrodynamics, however, appears to be somewhat complicated.

[14] Starting from 5 to 8 hours from the initiation of magnetospheric energy input in the auroral electrojet, which in this case occurred in the morning of 26 August, a disturbance dynamo electric field should be active over low latitudes [*Blanc and Richmond*, 1980; *Fejer and Scherliess*, 1995; *Abdu et al.*, 1997]. This electric field is westward during the day with its reversal to the eastward night time electric field predicted to occur in the evening around 2000–2200 LT [*Blanc and Richmond*, 1980; *Fejer and Scherliess*, 1995]. Although the model calculations by *Blanc and Richmond* [1980] predicts weak intensity for the westward DD field in the evening (before 2000 LT) the observational results from Jicamarca radar by *Fejer and Scherliess* [1995] indicate large fluctuation amplitudes for the disturbance vertical drift, thus suggesting also the possibility of correspondingly large westward DD fields in the evening hours. Such large fluctuation amplitudes, we believe, could be arising from large variability in the amplitude of the disturbance (dynamo associated) westward wind capable of inhibiting the eastward wind-driven prereversal electric field that normally peaks at these hours. Large amplitudes (hundreds of ms^{-1}) of disturbance westward wind at the K_p maximum phase of the 22 March 1979 storm was observed during post sunset hours (2230 LT) over equatorial latitudes from Satellite Electrostatic Triaxial Accelerometer (SETA) Experiment by *Forbes et al.* [1995]. (The velocity was more often eastward at remaining phases of this storm, however). Thus the post sunset eastward E-field enhancement that produced the enhanced EIA and plasma bubble developments does indeed appear to be caused by a PP eastward electric field acting in the presence of opposing influences from a DD electric field (though week in intensity) and associated westward winds. Cases of superposed DD and PP electric fields in which the effect from the former opposes the expected effect from the latter have been previously reported by *Abdu et al.* [1997]. The circumstances here of the superposed occurrence in the dusk sector of the PP electric fields and disturbance dynamo effects appear similar to that reported recently by *S. Basu et al.* [2001].

[15] During quiet conditions the bubble formation occurs due to the evening F layer uplift by the prereversal eastward electric field, which is generated by an eastward thermospheric wind that also drives the ambient plasma eastward, through the F layer dynamo [*Rishbeth*, 1971; *Heelis et al.*, 1974; *Farley et al.*, 1986; *Crain et al.*, 1993; *Eccles*, 1998]. During its initial rapid upward growth the bubble also drifts westward in the reference frame of the eastward drifting ambient plasma, its zonal drift observed in a corotating frame being still eastward [*Tsunoda*, 1981]. With the vertical extension and the weakening of the

vertical polarization field, the bubble zonal drift, as observed from ground, picks up velocity to approach that of the ambient plasma and consequently to that of the driving eastward neutral wind. Thus under normal conditions we expect the bubble drift to present an eastward acceleration during its growth phase to approach the velocity of the ambient plasma and of the background neutral wind which typically peaks around 150 ms^{-1} and 2100 LT [*Fejer et al.*, 1981; *Biondi et al.*, 1991; *Abdu et al.*, 1985; *Sobral and Abdu*, 1991; *Basu et al.*, 1991; *Sahai et al.*, 1992]. Our observation of the depletion zonal velocity (beginning at ~2130 LT in Figures 4–6) seems to have started after the early acceleration phase. The small eastward velocity (~30 m/s) at the beginning of the observation decreased and remained zero till ~2230 LT. The drift then turned westward steadily increasing in velocity till presunrise hours. The course of this velocity variation can be analyzed considering the different possible sources of the vertical electric field, responsible for the ambient plasma zonal drift. The driving vertical electric fields could arise from the following processes: (1) zonal wind; during disturbed conditions, the storm energy input at high latitudes produces a global scale disturbance thermospheric circulation and the action of Coriolis force imparts a westward momentum to this, resulting in westward directed winds gaining importance at middle latitudes [*Blanc and Richmond*, 1980; *Richmond and Lu*, 2000]. The westward winds seem to be present, at times, even at equatorial latitudes as revealed by different types of direct and indirect observations [*Abdu et al.*, 1995; *Forbes et al.*, 1995]. The driving force of such a wind could oppose that of the normal solar thermal tide induced eastward wind, causing a reduced eastward wind or even a net westward wind; (2) vertical Hall electric field arising from disturbance zonal electric field, E_{EW}, (as discussed by *Abdu et al.* [1998b]) consisting of a disturbance dynamo electric field, (E_{EWDD}), and a prompt penetration electric field, (E_{EWPP}), whose polarity is dependent on the auroral substorm phase; (3) divergence of horizontal currents, arising from horizontal (zonal) gradients in E layer/lower F region conductivities, giving rise to vertical electric field, normally (under quiet conditions) important close to dusk hours due to the EEJ current divergence as explained by *Haerendel et al.* [1992]. Under the disturbed circumstances of our present nighttime observations, horizontal gradients in conductivity arising from extra ionization in the SAMA region mentioned above need to be considered instead. In the absence of precise information on the nature of the possible horizontal gradient in the conductivities we will not discuss here the effects from item 3. Instead we will attempt below to identify, based on the measured parameters, the contributions from the items 1 and 2 to the disturbance zonal velocities. Thus the driving vertical electric field can be approximated by the following equation:

$$E_V \cong -B\,U^P_{EW} + E_{EW}[\Sigma_H/\Sigma_P], \qquad (1)$$

where $E_{EW} = E_{EWDD} + E_{EWPP}$. The first term on the right side represents neutral wind dynamo, and U^P_{EW} is field line integrated conductivity weighted zonal wind. The first term inside the bracket is Hall conduction term. Σ_H and Σ_P are field line integrated Hall and Pedersen conductivities [see *Haerendel et al.*, 1992; *Abdu et al.*, 1998b].

[16] On the night of 26–27 August, the eastward bubble zonal velocity that was already small from the start of the observation at ~2030 LT (2330 UT) rapidly decreased to zero and turned westward increasing in velocity thereafter (Figure 6). The initial decreasing feature of the velocity coincides in time with a decrease of eastward electric field followed by westward field till ~2300 LT (~0200 UT) as seen in Figures 1 and 2. As per the second (Hall conduction) term on the right side of equation (1), this electric field variation should have caused an eastward increase (or a westward decrease) of the zonal velocity. The result in Figure 6 showing an exactly opposite variation in the net zonal velocity could therefore point to the dominant role of a westward disturbance wind (the first term on the right side of equation (1)) in suppressing the effect from a normally eastward blowing wind at these times. (In fact a larger westward wind forcing than it appears to show seems to be implicit in the net observed zonal drift). The steady increase of the westward velocity that characterized the rest of the night could imply (1) a correspondingly steady increase of the driving westward disturbance wind. Such an effect could as well be brought about by the normally expected steady decrease in the driving force of the eastward wind (expected to prevail at these local times) even if the driving westward disturbance wind remained nearly constant during this period. (2) The observed increase of the westward velocity could also involve a Hall drift contribution from an eastward DD electric field expected to be present at these night hours. However, the presence of such a DD electric field is not identifiable in the observed zonal electric field variation that is dominated by AE associated PP electric field variations (see Figures 1 and 2). For the sake of brevity of the discussion, although we recognize its possible importance, we will not be considering further the role of a DD zonal electric field in the observed zonal drift variations. Thus we consider the possibility 1 to be a more likely scenario. In this case the westward wind should correspond at least to a forcing required to produce an amplitude of the order of 100–150 ms^{-1} for the normal eastward wind to be nearly cancelled out during the early hours of the observation (when the eastward velocity was ≤30 m/s). As mentioned earlier, large amplitudes (hundreds of m/s) of cross track westward wind have been observed in sun synchronous (2030 LT) satellite orbits in the equatorial region by *Forbes et al.* [1995] that were associated with large K_p increases. Thus the present observation (that is, based on the bubble irregularity zonal drift measurement) seems to show, though indirectly, that magnetic disturbance associated thermospheric westward wind lasting throughout the night could attain amplitudes matching at least that of the quiet time thermospheric eastward wind.

[17] The variable amplitude of the PP disturbance zonal electric field (vertical drift) that persisted till the morning hours of the 27th (as seen in Figures 1 and 2) could be imposing correspondingly fluctuating Hall electric field induced zonal drift as we shall discus below. An idea of the amplitude of such fluctuation could be obtained from knowledge of the variations in the ratio Σ_H/Σ_P. Under

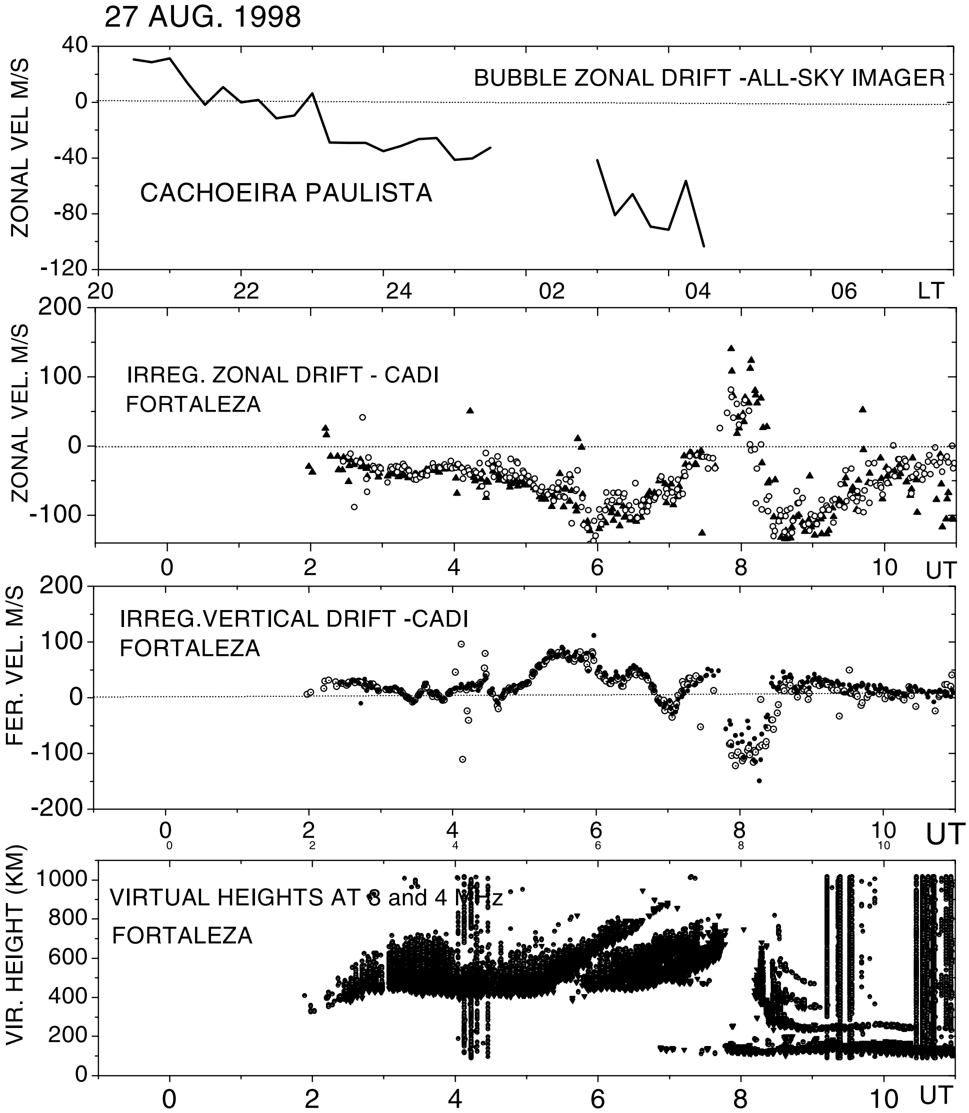

Figure 7. The zonal velocity of the depletions as per Figure 6 (top panel) compared with the irregularity zonal drift (second panel) and vertical drift (third panel) and the virtual heights (bottom panel) at 3 and 4 MHz as observed by a CADI (Canadian Digital Ionosonde) operated at Fortaleza.

normal conditions nighttime values of this ratio are expected to be significantly smaller than its typical value of ~2 for 1900 LT calculated by *Haerendel et al.* [1992]. However, enhanced E layer ionization by magnetic disturbance induced particle precipitation in the SAMA region, as indicated by the presence of the significantly intense sporadic E layers (of a-type) that were present during the night of 26–27, could cause significant increase in this ratio as explained by *Abdu et al.* [1998b]. Fluctuations around unity of this ratio can be easily accounted for using reasonable assumption on the intensity of the extra ionization suggested by the observed E_s layers.

[18] What appears to be the most convincing indication of the effect of Hall electric field, produced by prompt penetration of magnetospheric zonal electric field, is provided by the results in Figure 7. This figure shows in the top panel the zonal drift of the plasma depletions (the mean velocity of Figure 6), the irregularity zonal and vertical drifts (middle two panels) and the virtual heights at 3 and 4 MHz (bottom panel), as measured over Fortaleza by a CADI. The CADI utilizes the Doppler spectra of the echoes received by spaced receivers to determine the zonal velocity [*Grant et al.*, 1995]. (The discontinuity of data till ~0200 UT is due to some interference in the CADI reception). The zonal drift is observed to be steadily westward till ~0700 UT in optical data as well as in the CADI results, which demonstrates that the plasma bubble and associated irregularity westward drifts extend from ~300 km (over Fortaleza) up to ~800 km (corresponding to the CP F-layer field line apex height) over the equatorial region. This result shows for the first time a relationship between the zonal drift velocities of the optically observed large-scale bubbles (tens to hundreds of kilometers) and that of the smaller scale (kilometer sizes) structures as observed here by CADI, and the fact of their representing different height domains might suggest an approximate height structure for the ambient plasma zonal velocity. A notable aspect of the CADI drift velocities is that the fluctuations in the

zonal and vertical drifts are nearly anti correlated as is evident till ~0700 LT (1000 UT). (The drift results after 0500 LT (0800 UT) could be influenced somewhat by the occurrence of an E_s layer over Fortaleza followed by sunrise effects, although the anticorrelation between the drift velocities still appears to be present). Such anticorrelation between the vertical and zonal velocities could arise from the Hall conduction term of equation (1) as was shown by *Abdu et al.* [1998b] (and probably also from the integrated conductivity zonal gradient) based on a few case studies. The fluctuations in these velocities seem to be related with those in the AE indices in Figures 1, although such correlation (in present results) is less clear than in some previous case study results presented by *Abdu et al.* [1998b]. In any case, the CADI drift results of Figure 7 provide an evidence that the westward plasma bubble irregularity drift, that occurs after a delay (>5–8 hours) from an auroral disturbance onset, could in fact contain a significant fluctuating component of zonal drift arising from disturbance zonal electric field, besides what looks like a steady/steadily increasing drift arising dominantly from a disturbance westward wind. In the present example the fluctuating zonal drift seems to arise from prompt penetration electric field associated with the AE activity of the post midnight hours.

[19] The airglow depletions starting at ~0300 LT (0600 UT) seen in Figures 4 and 5 that represent newly developed bubble event was caused by the F layer uplift starting near 0200 LT (0500 UT), as seen in the 3 and 4 MHz plasma frequency plots of CADI, over Fortaleza presented in the bottom panel of Figure 7a (as well as over SL in Figure 2). While the optical depletions of these bubbles showed their westward velocity increasing with time, the smaller (kilometer size) structures observed by the CADI presented a decrease in the westward velocity, after 0600 UT. This could be due to the fact of the Hall drift dominating the lower height region sampled by the CADI at these times. As explained in the work of *Abdu et al.* [1998b], the effects from Hall conduction (and perhaps the conductivity spatial gradients) that contributes to the zonal velocity fluctuations, could be helped by enhanced night time ionization produced by sources such as particle precipitation in the south Atlantic Magnetic Anomaly (SAMA) region [*Greenspan et al.*, 1991; *Batista and Abdu*, 1977; *Abdu et al.*, 1981a] and possibly from the presence of sporadic E layers not necessarily associated with particle precipitation. In the present case, however, as pointed out earlier, sporadic E layers presumably produced by enhanced particle precipitation was present during most of the night. It is possible that ionospheric conductivity modification under magnetic storm conditions could occur even at longitude sectors outside that of SAMA. It may be argued that a fluctuating zonal wind could by itself produce a corresponding fluctuation in the observed zonal drift. However, it should be noted that such a fluctuation of zonal drift is unlikely to produce anticorrelated vertical drift fluctuations such as are observed in the present case.

4. Conclusions

[20] A case study using multi-instrument and multistation diagnostics has been presented of plasma bubble irregularity initiation and development under magnetically disturbed condition during a season of its less frequent occurrence. The bubble event was initiated by prompt penetration to equatorial latitude of magnetospheric electric field associated with substorm intensifications in the dusk sector, when a disturbance dynamo is also expected to be active. The onset and development of the plasma depletions were monitored concurrently at magnetic equatorial and low-latitude locations. The vertical rise velocity of a developing bubble calculated from the time delay in the corresponding range spread F occurrence sequences in equatorial and low-latitude ionograms was found to be in agreement with that obtained from the poleward (southward) displacement of the airglow depletion edges as observed in an all-sky optical imager. This result confirmed our previous contention based on statistical analysis that the range spread F events observed in the ionograms over a low-latitude station, such as Cachoeira Paulista, does represent signatures of vertically extended plasma bubbles over the equator. The effect of sustained AE activity in the day sector was, in general, to inhibit the equatorial anomaly development during daytime. However equatorward neutral wind surges, possibly arising from specific substorm intensification, could cause significant density and height enhancements over the EIA crest location. The penetration electric field of eastward polarity, associated with the IMF Bz southward turning and the AE activity in the dusk sector, was strong enough at equatorial latitude to cause the development of an intense equatorial ionization anomaly that persisted for most of the night. The PP eastward electric field also initiated plasma bubble generation, under the competing influences of disturbance dynamo acting against the normal F layer dynamo responsible for the pre reversal eastward electric field at these hours. The bubble zonal drift velocity that usually traces ambient plasma drift, and hence roughly the thermospheric wind velocity (which is normally eastward at night), was found to be initially eastward (but with significantly reduced velocity) and soon turning westward. The dominantly westward plasma flow of the disturbed night was clearly brought out by the zonal drift of a postmidnight bubble that was also initiated by an eastward PP electric field originating from a southward flip of the IMF Bz. Westward velocities steadily increasing towards pre sunrise hours were observed in the topside (bubble structure) as well as in bottomside (smaller-scale structure) plasma irregularities. During the postmidnight hours the westward drift velocities appeared to contain significant fluctuation component arising from the fluctuating PP electric field associated with the ongoing AE activity. The zonal and vertical velocities of the smaller scale structures (<kilometers) showed anti correlated fluctuations (that is, the vertical upward drift perturbations being associated with westward drift perturbations) which suggested the role of Hall electric field as their possible cause, in agreement with our previous findings. The auroral type sporadic E layers that were present during much of the night suggested the presence of enhanced particle precipitation in the SAMA region with the resulting enhanced conductivity providing the source of Hall electric field that can be induced by a primary disturbance zonal PP electric field. This point, first suggested in our previous study [*Abdu et al.*, 1998b], is further supported by the present results. A quantitative evaluation of the contributions from different sources is made difficult

because of the simultaneous presence of different driving forces that control the bubble zonal velocity. However, work is being pursued further to better quantify these results using model values for the different control parameters such as enhanced nighttime E layer conductivity, disturbance electric field, and winds.

[21] **Acknowledgments.** This work was supported by the São Paulo State Foundation for the promotion of research (FAPESP) through the project 99/00437-0. The authors also thank the CNPq (Conselho Nacional de Pesquisa e Desenvolvimento) for support through the process 520185/95-1 (SU). The ACE interplanatary magnetic field (IMF) and solar wind data were kindly provided by N. Ness of Bertole Research Institute and D. J. McComas at Southwest Research Institute.

[22] Arthur Richmond thanks Gerhard Haerendel and J. Hanumath Sastri for their assistance in evaluating this paper.

References

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

Abdu, M. A., J. A. Bittencourt, and I. S. Batista, Magnetic declination control of the equatorial F region dynamo field development and spread-F, *J. Geophys. Res.*, *86*, 11,443–11,446, 1981b.

Abdu, M. A., R. T. de Medeiros, J. H. A. Sobral, and J. A. Bittencourt, Spread F plasma bubble vertical rise velocities determined from spaced ionosonde observations, *J. Geophys. Res.*, *88*, 9197–9204, 1983.

Abdu, M. A., I. S. Batista, J. H. A. Sobral, E. R. de Paula, and I. J. Kantor, Equatorial ionospheric plasma bubble irregularity occurrence and zonal velocity under quiet and disturbed conditions from polarimeter observation, *J. Geophys. Res.*, *90*, 9921–9928, 1985.

Abdu, M. A., J. H. A. Sobral, E. R. de Paula, and I. S. Batista, Magnetospheric disturbance effects on the Equatorial Ionization Anomaly (EIA): An overview, *J. Atmos. Terr. Phys.*, *53*, 757–771, 1991.

Abdu, M. A., I. S. Batista, G. O. Walker, J. H. A. Sobral, N. B. Trivedi, and E. R. de Paula, Equatorial ionospheric electric field during magnetospheric disturbances: Local time/longitude dependences from recent EITS campaigns, *J. Atmos. Terr. Phys.*, *57*, 1065–1083, 1995.

Abdu, M. A., J. H. Sastri, J. MacDougall, I. S. Batista, and J. H. A. Sobral, Equatorial disturbance dynamo electric field longitudinal structure and spread F: A case study from GUARA/EITS campaign, *Geophys. Res. Lett.*, *24*, 1707–1710, 1997.

Abdu, M. A., J. H. Sastri, H. Luhr, H. Tachihara, N. B. Trivedi, and J. H. A. Sobral, DP2 electric field fluctuations in the dusk-side dip equatorial ionosphere, *Geophys. Res. Lett.*, *25*, 1511–1514, 1998a.

Abdu, M. A., P. T. Jayachandran, J. MacDougall, J. F. Cecile, and J. H. A. Sobral, Equatorial F region zonal plasma irregularity drifts under magnetospheric disturbances, *Geophys. Res. Lett.*, *25*, 4137–4140, 1998b.

Abdu, M. A., J. MacDougall, I. S. Batista, J. H. A. Sobral, and P. T. Jaychandran, Equatorial evening prereversal electric field enhancement and sporadic E layer disruption: A manifestation of E and F region coupling, *J. Geophys. Res.*, *108*(A6), 1254, doi:10.1029/2002JA009285, 2003.

Basu, S., et al., Zonal irregularity drifts and neutral winds measured near the magnetic equator in Peru, *J. Atmos. Terr. Phys.*, *53*, 743–755, 1991.

Basu, S., Su. Basu, K. M. Groves, H.-C. Yeh, S.-Y. Su, F. J. Rich, P. J. Sultan, and M. J. Keskinen, Response of the equatorial ionosphere in the South Atlantic region to the great magnetic storm of July 15, 2000, *Geophys. Res. Lett.*, *28*, 3577–3580, 2001.

Basu, Su., et al., Ionospheric effects of major magnetic storms during the International Space Weather Period of September and October 1999: GPS observations, VHF/UHF scintillations, and in situ density structures at middle and equatorial latitudes, *J. Geophys. Res.*, *106*, 30,389–30,413, 2001.

Batista, I. S., and M. A. Abdu, Magnetic storm associated delayed sporadic E layer enhancement in the Brazilian Geomagnetic Anomaly, *J. Geophys. Res.*, *82*, 4777–4783, 1977.

Batista, I. S., E. R. de Paula, M. A. Abdu, and N. B. Trivedi, Ionospheric effects of the 13 March 1989 magnetic storm at low latitudes, *J. Geophys. Res.*, *96*, 13,943–13,952, 1991.

Biondi, M. A., et al., Equatorial thermospheric wind changes during the solar-cycle measurements at Arequipa, Peru, from 1983 to 1990, *J. Geophys. Res.*, *96*, 15,917–15,930, 1991.

Blanc, M., and A. D. Richmond, The ionospheric disturbance dynamo, *J. Geophys. Res.*, *85*, 1669–1699, 1980.

Bowman, G. G., and I. K. Mortimer, Spread-*F*/Sporadic *E* coupling at Chung-Li, especially for postsunset periods of sunspot maximum years, *J. Geophys. Res.*, *108*(A4), 1148, doi:10.1029/2002JA009541, 2003.

Crain, D. J., R. Heelis, G. J. Bailey, and A. D. Richmond, Low latitude plasma drifts from a simulation of the global atmosphere dynamo, *J. Geophys. Res.*, *98*, 6039–6046, 1993.

Eccles, J. V., Modeling investigation of the evening prereversal enhancement of the zonal electric field in the equatorial ionosphere, *J. Geophys. Res.*, *103*, 26,709, 1998.

Farley, D. T., E. Bonelli, B. G. Fejer, and M. F. Larsen, The prereversal enhancement of the zonal electric field in the equatorial ionosphere, *J. Geophys. Res.*, *91*, 13,723–13,728, 1986.

Fejer, B. G., The electrodynamics of the low latitude ionosphere: Recent results and future challenges, *J. Atmos. Sol. Terr. Phys.*, *59*, 1465–1482, 1997.

Fejer, B. G., and L. Scherliess, Time dependent response of equatorial ionospheric electric fields to magnetospheric disturbances, *Geophys. Res. Lett.*, *22*, 851–854, 1995.

Fejer, B. G., et al., F-region East-West drifts at Jicamarca, *J. Geophys. Res.*, *86*, 215–218, 1981.

Forbes, J. M., R. G. Roble, and F. A. Marcos, Equatorial penetration of magnetic disturbance effects in the thermosphere and ionosphere, *J. Atmos. Sol. Terr. Phys.*, *57*, 1085–1093, 1995.

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. Ruohoniemi, W. A. Bristow, G. J. Sofko, J. A. Koehler, D. Danskin, and D. André, Comparison of plasma flow velocities determined by the ionosonde Doppler drift technique, SuperDARN 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 storm of March 1989, *J. Geophys. Res.*, *96*, 13,931–13,942, 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.

Heelis, R. A., P. C. Kendall, R. J. Moffet, D. W. Windle, and H. Rishbeth, Electrical coupling of the E- and F- region and its effects on the F-region drifts and winds, *Planet. Space Sci.*, *22*, 743–756, 1974.

Kelley, M. C., J. J. Makela, J. L. Chau, and M. J. Nicolls, Penetration of the solar wind electric field into the magnetosphere/ionosphere system, *Geophys. Res. Lett.*, *30*, 1158–1161, 2003.

Kikuchi, T., H. Luhr, T. Kitamura, O. Saka, and K. Schlegal, Direct penetration of the polar electric field to the equator during a DP 2 events detected by the Auroral and equatorial magnetometer chains and the EISCAT radar, *J. Geophys. Res.*, *101*, 17,161–17,173, 1996.

Pincheira, X. T., M. A. Abdu, I. S. Batista, and P. G. Richards, An investigation of ionospheric responses, and disturbance thermospheric winds, during magnetic storms over South American sector, *J. Geophys. Res.*, *107*(A11), 1379, doi:10.1029/2001JA000263, 2002.

Richmond, A. D., and G. Lu, Upper-atmospheric effects of magnetic storms: A brief tutorial, *J. Atmos. Sol. Terr. Phys.*, *62*, 1115–1127, 2000.

Rishbeth, H., Polarization fields produced by winds in the equatorial F region, *Planet. Space Sci.*, *19*, 357–369, 1971.

Sahai, Y., H. Takahashi, P. R. Fagundes, B. R. Clemesha, N. R. Texeira, and J. A. Bittencourt, Observation of thermospheric neutral winds at 23°S, *Planet. Space Sci.*, *40*, 767–773, 1992.

Sastri, J. H., M. A. Abdu, I. S. Batista, and J. H. A. Sobral, Onset conditions of equatorial (range) spread F at Fortaleza, Brazil, during the June solstice, *J. Geophys. Res.*, *102*, 24,013–24,021, 1997.

Sastri, J. H., K. Niranjan, and K. S. V. Subbarao, Response of the equatorial ionosphere in the Indian (midnight) sector to the severe magnetic storm of July 15, 2000, *Geophys. Res. Lett.*, *29*(13), 1651, doi:10.1029/2002GL015133, 2002.

Scherliess, L., and B. G. Fejer, Strom time dependence of equatorial disturbance dynamo zonal electric field, *J. Geophys. Res.*, *102*, 24,037, 1997.

Sobral, J. H. A., and M. A. Abdu, Solar activity effects on equatorial plasma bubble zonal velocity and its latitude gradient as measured by airglow scanning photometers, *J. Atmos. Terr. Phys.*, *53*, 729–742, 1991.

Sobral, J. H. A., M. A. Abdu, W. D. Gonzalez, B. T. Tsurutani, I. S. Batista, and C. de Gonzalez, Effects of intense storms and substorms on the equatorial ionosphere/thermosphere system in the American sector form ground-based and satellite data, *J. Geophys. Res.*, *102*, 14,305–14,313, 1997.

Spiro, R. W., R. A. Wilf, and B. G. Fejer, Penetration of high latitude electric field effects to low latitudes during SUNDIAL 1984, *Ann. Geophys.*, *6*, 39, 1988.

Tsunoda, R. T., Time evolution and dynamics of equatorial backscatter plumes: 1. Growth phase, *J. Geophys. Res.*, *86*, 139–149, 1981.

Valladares, C. E., R. Sheehan, S. Basu, H. Kuenzler, and J. Espinoza, The multi-instrument studies of equatorial thermosphere aeronomy scintillation system: Climatology of zonal drifts, *J. Geophys. Res.*, *101*, 26,839–26,850, 1996.

M. A. Abdu, I. S. Batista, J. H. Sobral, H. Takahashi, and N. B. Trivedi, Instituto Nacional de Pesquisas Espacias (INPE), Avenida dos Astronautas 1758, C. P. 515, 12245970 São José dos Campos, São Paulo, Brazil. (abdu@dae.inpe.br; inez@dae.inpe.br; sobral@dae.inpe.br; hisao@laser.inpe.br; trivedi@lacesm.usfm.br)

J. MacDougall, Department of Electrical Engineering, University of Western Ontario, 1155 Richmond Street, London, Ontario, Canada N6A 5B9. (jamacdoug@uwo.ca)

A. F. Medeiros, Departamento de Física, Centro de Ciências e Tecnologia, Universidade Federal da Paraiba, Av. Aprígio Veloso, 882, Bodocongó, Campina Grande, Paraiba 58109-79, Brazil. (afragoso@df.ufpb.br)