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Effects of intense storms and substorms on the equatorial ionosphere/thermosphere system in the American sector from ground-based and satellite data

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Abstract. Equatorial ionospheric responses to magnetospheric storm/substorm-associated electric fields are investigated for a few intense events of the equinoctial months of solar maximum years 1978–1979. All the magnetic storms considered here are the result of the transit at Earth of interplanetary magnetic clouds. The interplanetary magnetic field data B_z from the ISEE 3 satellite, the auroral electrojet activity index AE, and the ring current index Dst are used as indicators of the disturbed magnetospheric conditions, and the ionospheric response features are analyzed using the F layer critical parameters $h'F$, $h'F_3$, h_pF_2, and f_oF_2. Focus is given to identify, when a large number of sequential substorms occurs, (1) the responses to prompt penetration electric field (from individual substorm events) as different from the delayed effect from the disturbance dynamo electric field and (2) the verification of local time dependences of the disturbance electric field polarity as predicted from the existing theoretical models. We have found evidence of near-midnight polarity reversal of prompt penetration disturbance electric field during the course of a developing substorm. Evidence is provided also on the near-midnight polarity reversal for the disturbance dynamo electric field. The prereversal enhancement electric field at sunset, produced by the F layer dynamo, is found to undergo drastic day-to-day variations in the course of a disturbed interval. However, the competing influences of the prompt versus delayed electric fields after a series of substorms could result at times in partial, or even complete, cancellation of the effects, so that the prereversal enhancement in the vertical drift could appear unaffected by the disturbances. There are indications that the disturbance dynamo electric field effects on the equatorial ionosphere last for one more day past the end of the substorm recovery.

1. Introduction

Magnetospheric disturbance electric fields penetrate to low latitudes where they significantly modify the ionospheric electrodynamics normally driven by tidal winds. The ionospheric responses to the disturbance electric fields have been studied using radars, magnetometers, and ionosondes over equatorial and low-latitude regions [*Gonzales et al.*, 1979, 1983; *Fejer*, 1981, 1986; *Kamide*, 1988; *Abdu et al.*, 1988, 1995; *Sastri et al.*, 1992; *Somayajulu et al.*, 1987]. Disturbances are more often observed in the zonal rather than in the vertical electric field, and consequently, drastic modifications are observed in the F layer vertical plasma drift, layer height and densities, spread F/plasma bubble irregularity generation, and the equatorial electrojet processes. Two broad types of disturbance electric fields could account for the observed major responses: (1) a direct penetration of magnetospheric electric fields (often referred to as penetration electric fields) associated with storm sudden commencements and substorm (asymmetric ring current) development/decay processes [*Kikuchi*, 1986; *Gonzales et al.*, 1983; *Fejer et al.*, 1990; *Abdu et al.*, 1995] and (2) a disturbance dynamo electric field produced by changes in the thermospheric circulation, originating from energy deposition in high latitudes, that follow with time delays of a few hours with respect to the prompt electric field of item (1) [*Blanc and Richmond*, 1980; *Fejer et al.*, 1995; *Fesen et al.*, 1989; *Abdu*, 1996; *Emery et al.*, 1996]. Besides the effects from the disturbance electric field responses 1 and 2 the equatorial ionosphere also undergoes significant alteration from modification of the thermospheric dynamics imposed by disturbance dynamo winds that accompany the delayed effects of response 2 [*Abdu et al.*, 1995].

We now have a broad understanding of the ionosphere response features under the action of these different disturbance sources vis-à-vis the magnetospheric storm/substorm conditions and their control by changes in solar wind and interplanetary magnetic field patterns. For example, a southward turning of the interplanetary magnetic field B_z that marks enhanced magnetospheric convection and onset of an auroral

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substorm produces a dawn-to-dusk electric field (i.e., eastward/westward on the day/night sides) in the equatorial ionosphere. After a typical duration of one to several hours, the substorm is terminated by a northward turning of B_z with associated decrease of the convection electric field when a dusk-to-dawn electric field is established. Local time dependences of the penetration electric field initial response features predicted by theoretical models corresponding to a given increase/decrease in the polar cap potential drop [*Senior and Blanc.*, 1984; *Spiro et al.*, 1988] or a field-aligned current intensity [*Tsunomura and Araki*, 1984] have been found to be in reasonable agreement (as far as the polarity of the disturbance electric field is concerned) with observational results. According to these different models the initial time zonal electric fields resulting from a sudden increase in the polar cap potential drop by 100 kV present eastward polarity from ~0600 to ~2300 LT and westward polarity during the remaining hours. The local time of the transition of westward to eastward polarity varies from ~0600 to ~0800 LT in these models, and the opposite transition varies from ~2200 to ~2300 LT [see *Fejer et al.*, 1990]. Recent analysis using equatorial F layer heights as an indicator of the disturbance electric field [*Abdu et al.*, 1988] and asymmetric ring current indices [*Abdu et al.*, 1995] has provided additional aspects of agreement with theory as far as the local time dependence of the disturbance electric field polarity is concerned. However, the questions concerning the intensity and duration of the disturbance electric field that are controlled by different factors such as the time constants of the decay/formation of the shielding charges in the inner magnetosphere, auroral zone conductivity, etc. [*Vasyliunas*, 1975; *Kelley et al.*, 1979; *Gonzales et al.*, 1983] have not yet been satisfactorily answered. Attempts to explain the larger duration and intensities of the equatorial electric fields by the fossil wind mechanism as done in the convection model by *Spiro et al.* [1988] have met with partial success, and they remain as important questions to be addressed. Another important question concerns that of unambiguous identification of the effects to be expected as a function of local time for a given magnetospheric disturbance occurring as an isolated event immediately prior to the observed effect, as different from superimposed delayed effects when a series of disturbances occur in the hours preceding the observed effect, coupled with varying degrees of ring current development. In other words, it is important to understand the response features that depend upon the immediate past history of the magnetospheric-interplanetary disturbance conditions. This question has been very briefly addressed in our recent studies [see, e.g., *Abdu et al.*, 1995].

In the present paper we further investigate the above mentioned issues by analyzing the equatorial-low-latitude ionospheric responses in the Brazilian longitude sector for a few intense magnetic storms, with peak values of the ring current index $Dst < -100$ nT, that occurred during equinoctial months of the high solar activity years 1978–1979. Magnetospheric and interplanetary processes associated with the storms reported here were previously reported by *González and Tsurutani* [1987], *González et al.* [1989], and *Tsurutani et al.* [1988]. All magnetic storms considered here are the result of the transit at Earth of interplanetary magnetic clouds (see *Zhang and Burlaga* [1988] and *Lockwood et al.* [1991] for details of the causative magnetic clouds) which are structures in the ecliptic solar wind, wherein the magnetic cloud field B is larger than average and changes direction smoothly from a large northern (southward) direction to a southern (northward) direction across the structure [*Burlaga et al.*, 1981; *Klein and Burlaga*, 1982]. The magnetic clouds are considered interplanetary signatures of solar coronal mass ejections (CME) [*Burlaga et al.*, 1982; *Marubashi*, 1986; *Wilson and Hildner*, 1984]. The present work thus aims at a study of the coupling between interplanetary, magnetospheric, and ionospheric variabilities.

Interplanetary magnetic field B_z, auroral electrojet activity index AE, and the ring current index Dst are used as indicators of the storm/substorm conditions, and the ionospheric effects are investigated using the F layer critical parameters $h'F$ (the virtual height of the F layer base), $h'F_3$ (the virtual height at the plasma frequency of 3 MHz), h_pF_2 (the height of the maximum electron density assuming a parabolic shape for the F layer peak, which is easily deduced from ionograms as representative of the true height of the F layer peak, h_mF_2), and f_oF_2 (which is a measure of the peak density of the F_2 layer, N_mF_2). The magnetic storms analyzed are those of August 28–29, 1978; September 28–30, 1978; March 28–30, 1979; April 2–4, 1979; and September 17–19, 1979. It may be pointed out that the use of ionosonde F layer parameters as indicators of the substorm effects have more sensitivity during sunset, night, and morning hours than during daytime hours. This is because of the photoionization that could significantly counteract changes in the height imposed by the disturbance electric field when such electric fields vary slower than the timescales for the recombination and diffusion processes. Significant daytime effects were observed, however, under the severely disturbed conditions that marked the storm events studied here.

2. Results

In the following, we will present case studies of the response features for each of the storm events. The cases presented are not, however, in chronological sequence of their occurrences. We have tried to specify a cause-effect relationship mainly using substorm events as the immediate cause and the corresponding F region response as the effect. In literature the definition of a substorm has not always been unique. Magnetospheric physicists distinguish between convection increases driven directly by southward interplanetary magnetic field (IMF) B_z, sometimes called "convection bays," and spontaneous increase of the aurora and westward auroral electrojet around midnight, which they call "true substorm." Here we define a substorm event as being represented by a rapid increase in the auroral electrojet (AE) activity index that lasts generally for around one to a few hours before it decays rapidly. Most of the individual substorm events discussed in this paper have their onsets preceded by an IMF B_z southward turning and an abrupt ending following a northward turning, or a decrease in the southward component of the IMF.

2.1. August 26–29, 1978

The parameters B_z, Dst, and AE for this storm interval are plotted versus local time (for 45°W longitude) in Figure 1, together with the F layer critical parameters. This disturbed interval, consisting of a series of substorms of varying duration, was preceded by fairly quiet conditions (for most of the day of August 26) until the onset of a brief northward B_z at ~2300 LT, which was immediately followed by southward turning of B_z that triggered the first substorm of the series. The ionospheric response to this first substorm, which was rather weak, was seen as a decrease in $h'F$ and $h'F_3$ lasting until ~0200 LT,

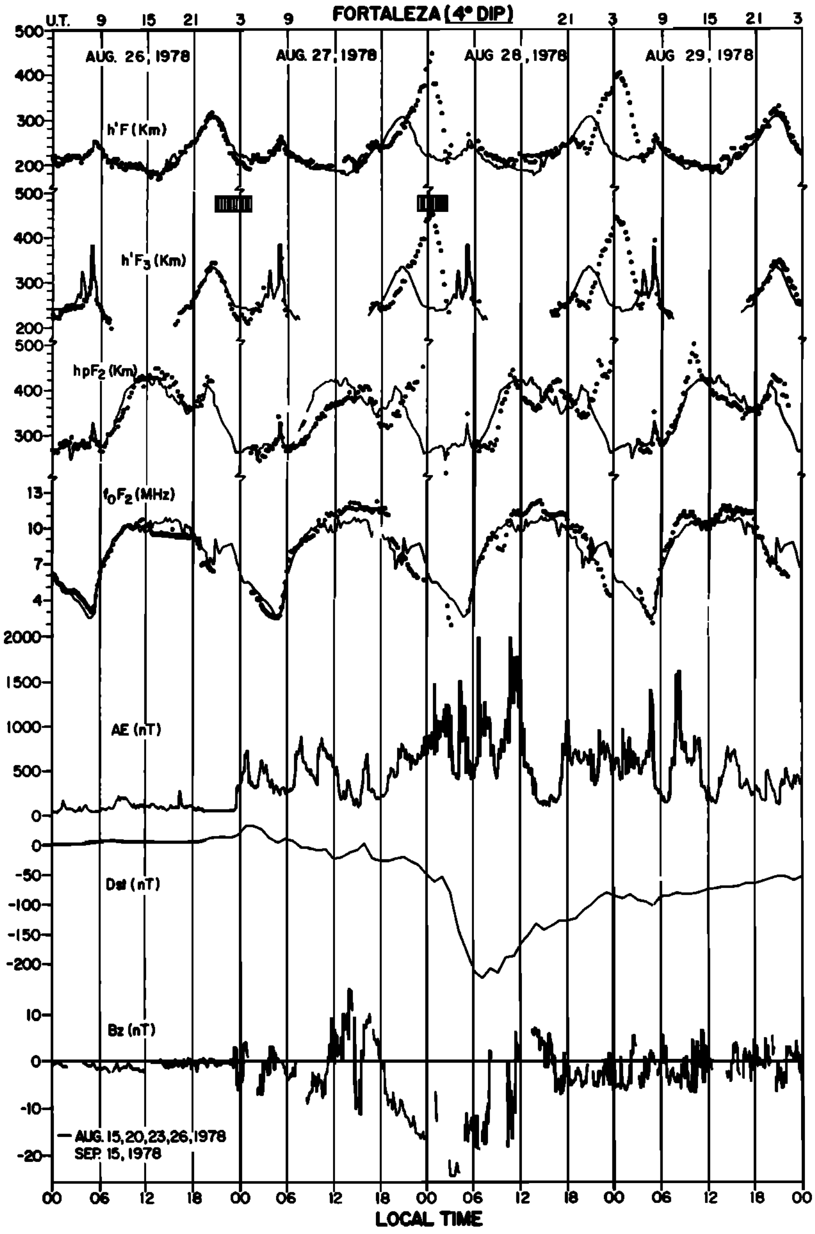

Figure 1. Ionospheric, magnetospheric, and geomagnetic parameters during August 26–29, 1978. Solid lines of ionospheric parameters are average values during the set of quiet days indicated in the bottom left. The horizontal shaded bands denote spread F occurrence. The F layer critical parameters are as follows: $h'F$, the virtual height of the base of the F layer; $h'F_3$, the virtual height at the plasma frequency of 3 MHz; hpF_2, the height of the maximum electron density assuming a parabolic shape for the F layer peak representative of the true height of the F layer peak, h_mF_2; and f_oF_2, the peak plasma frequency of the F_2 layer. Dots represent experimental data. The B_z data were provided by the ISEE 3 satellite.

with no further detectable effect until 0700 LT. Two substorms of nearly the same duration were then produced by corresponding B_z southward excursions (around 0700 LT and an increase in B_z southward component around 0930 LT) whose net effect was seen as a significant decrease of the parameter h_pF_2, indicating a westward electric field disturbance that lasted until ~1500 LT (the effect of a westward electric field in $h'F/h'F_3$ is rather difficult to detect because of the dominating recombination effect at lower heights). The substorm, triggered by a major abrupt B_z southward and northward excursion, seems to be responsible for an increase in h_pF_2 around 1500 LT on August 27 (indicating disturbance electric field of eastward polarity), which soon started to decrease around 1700 LT (also seen in $h'F$) in association with the recovery (at 1630 LT) of the substorm (the relationship between the B_z polarity and the AE growth and decay is not totally decipherable for this case, however). The important point is that these last decreases of h_pF_2, $h'F$, and $h'F_3$ continued until after 1800 LT when their quiet time pattern (solid line) was subjected to the prereversal eastward electric field enhancement [*Woodman*, 1970; *Fejer et al.*, 1979; *Abdu et al.*, 1981]. Thus a substorm recovery seems to produce, in this case, an inhibition of the well-known prereversal electric enhancement near sunset. However, this response feature is likely to have some contribution also from a disturbance dynamo electric field arising from the series of substorms that preceded it [*Abdu et al.*, 1995]. A major response feature that followed and persisted until around 0030 LT on August 28 is the significant rise of the F layer seen in all three height parameters. The start of this height rise at ~1900 LT coincided with that of a substorm triggered by a B_z southward turning of large amplitude, which lasted until 0800 LT in the morning of August 28. The Dst main phase development of this storm also occurred during this southward B_z interval of the cloud. The average vertical velocity of the F layer was ~15 m s^{-1}, representing an eastward disturbance electric field of ~0.3 m V m^{-1}, that lasted until 0030 LT. It is significant to note that while the substorm was still growing in intensity with the AE index steadily increasing past midnight, the F layer drift reversed with a downward velocity of ~60 m s^{-1} (i.e., a westward electric field of ~1.2 m V m^{-1}) until a temporary decrease in the B_z south just earlier to 0300 LT (not clearly observable because of data discontinuity) terminated this substorm. The polarity reversal near midnight, clearly observed in this case, is in good agreement with theoretical model predictions for initial time zonal electric field, resulting from a sudden increase in the polar cap potential drop which characterizes a substorm onset situation [*Senior and Blanc*, 1984; *Tsunomura and Araki*, 1984; *Spiro et al.*, 1988]. However, the zonal electric field observed here is of significantly longer duration (~9 hours) in contrast with the shorter duration (of the order of 1 hour) predicted by the theory of *Spiro et al.* [1988]. The longer duration of the disturbance electric field in the present case might also be caused, besides the possible effect of the fossil wind discussed *Spiro et al.* [1988], by the fact that the substorm intensity showed a steady increase until its termination in the early morning hours. In any case, the equatorial electric field reversal near midnight, arising from a steady and long-duration substorm growth discussed here, is the first evidence of its kind in support of the different theoretical predictions on the question of the polarity local time dependence. The height variation pattern on the night of August 27–28 is almost exactly repeated on the next night, August 28–29. In this case, however, the driving electric fields were significantly weaker, as can be judged from the $dh'F/dt$ values (which is a measure of the vertical drift as shown by *Abdu et al.* [1981] and *Bittencourt and Abdu* [1981]). These weaker electric fields are probably associated with weaker and irregular AE activity that prevailed for the duration of this height variation. This height variation pattern seems to reinforce the evidence for the midnight polarity reversal of the disturbance electric field such as that provided by the similar height variation pattern of the previous night.

It may be noted that the prereversal enhancement at F layer height sunset is drastically inhibited on August 28. In fact, the $h'F$, $h'F_3$, and h_pF_3 remained lower for a longer duration than on the previous evening. This seems to be a clear indication of a westward electric field of a disturbance dynamo arising from the series of AE activity events that preceded this local time right from the previous day [see *Fejer and Scherliess*, 1995]. The reduced prereversal enhancement can also be produced by the action of a disturbance (westward) zonal wind that attenuates the normal (eastward) zonal wind basically responsible for the generation of the prereversal enhancement electric field (as suggested by *Abdu et al.* [1995]). The disturbance variation of h_pF_2 during the daytime of August 28 that preceded the evening inhibition of the prereversal enhancement is quite interesting. Although the F layer height response to a disturbance electric field is usually difficult to detect during daytime, significant structures in the h_pF_2 variation are registered on this particular day, and especially the large increase in h_pF_2 from 0900 to ~1100 LT seems to be closely associated with a corresponding large increase in the AE index. This is a clear indication that rapid changes in the direct penetration electric field can in fact produce detectable effects in the daytime F layer height, even when the ionosphere is under the influence of a disturbance dynamo electric field as it appears in the present case.

2.2. Events of September 17–19, 1979, and September 28–30, 1978

These two events presented in Figures 2 and 3, have certain common features between them and the results in Figure 1 where the large B_z negative values dominate a major part of the prenoon hours (on August 28, 1978, September 29, 1978, and September 18, 1979) when the Dst development (the main phase) also took place. Also, prior to this situation the first major B_z southward turning had occurred on the previous day at the dusk sector, that is, very close to 1800 LT in all of these events (Figure 1–Figure 3).

Another important point to note is that the B_z southward turning event of September 17, 1979, was preceded by no significant substorm activity (as indicated by only minor fluctuations in the AE index values). On this evening the prereversal electric field enhancement amplitude was higher than the "quiet" day average (solid line). More interestingly, the onset of a substorm at ~1930 LT produced an enhanced vertical drift superimposed on the reversal phase of the evening electric field (indicated by the dashed vertical line at 1930 LT). The vertical drift velocity was ~30 m s^{-1} (i.e., a disturbance eastward electric field of ~0.7 m V m^{-1}). The substorm recovery starting with the abrupt northward B_z turning produced a westward electric field, indicated by the steep decrease of the heights starting at ~2100 LT. Both the eastward electric field enhancement at 1930 LT and the following westward electric field disturbance are in agreement with the predictions by the theoretical models cited above for the sunset sector.

As compared to the event of September 17, the B_z southward enhancement at 1800 LT on September 28 (Figure 3) and the associated substorm were preceded by moderate substorms at least from the previous night, and the prereversal sunset enhancement electric field appears to be weaker with earlier reversal time as compared to the mean pattern (solid curve). This is an indication that the disturbance dynamo electric field and disturbance zonal wind produced by the auroral activity of the preceding hours could be responsible in this case for the inhibition of the sunset electric field enhancement as pointed out by *Abdu et al.* [1995]. However, the electric field at the prereversal enhancement (~1800 LT) does not seem to be significantly influenced by the disturbance dynamo westward electric field. This is because of the superposition of a disturbance eastward electric field produced by a substorm which had its onset just at this local time. Here we have a case of an equilibrium between the opposing disturbance electric field (from a disturbance dynamo which is westward and from a developing substorm which is eastward), so that a net response in the F layer height becomes undetectable. The role of the disturbance electric field and the disturbance zonal wind are further manifested in the significantly weaker sunset electric field on the following day (September 29). The disturbance dynamo electric field seems to be evident even during several hours prior to the evening, as seen in the reduced h_pF_2 values at these hours. As a result, the plasma fountain is inhibited, and consequently, f_oF_2 values over Fortaleza are significantly enhanced as compared to the quiet day values. In fact, reduced h_pF_2 values accompanied by significantly enhanced f_oF_2 values are present during the daytime of September 28, whose cause should be sought in the history of the substorm events extending to the previous day (which is not shown here).

It is interesting to note that the disturbance dynamo westward electric field continued to be active for at least 24 hours after the conclusion of the causative disturbances in both cases of the disturbance intervals presented in Figures 2 and 3. The inhibition of the sunset electric field of September 29, 1978, is similar to that of September 18, 1979, which was preceded by several hours of substorm activity (Figure 2).

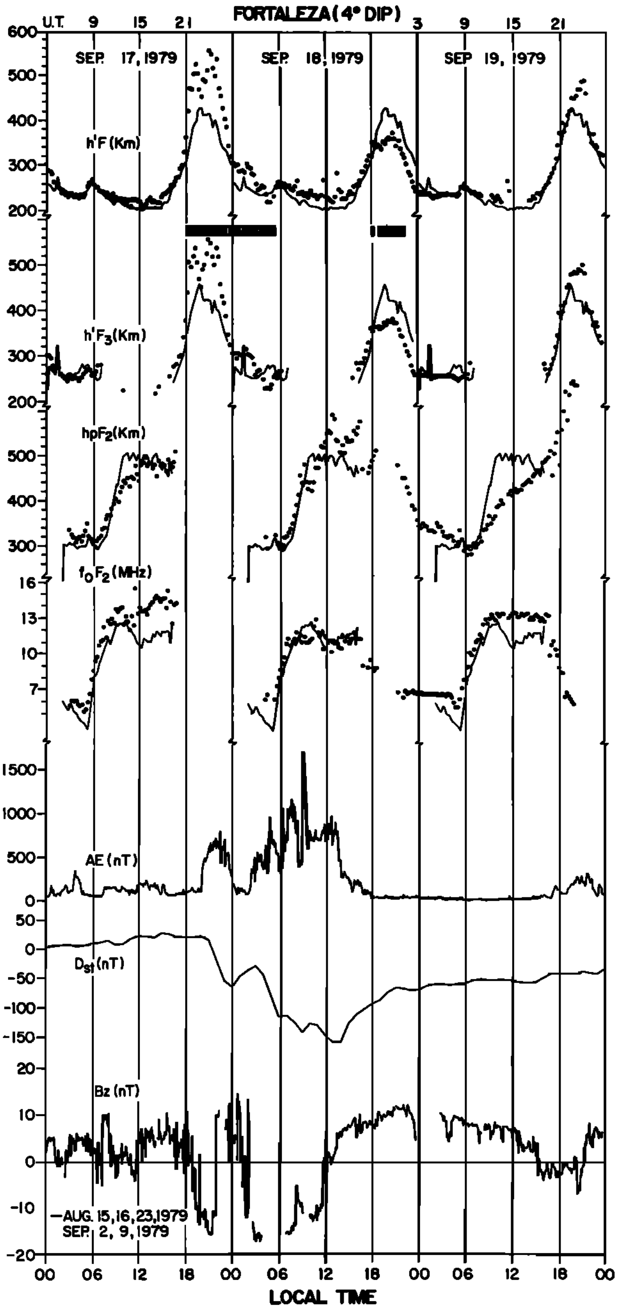

Figure 2. Same as Figure 1, but for September 17–19, 1979.

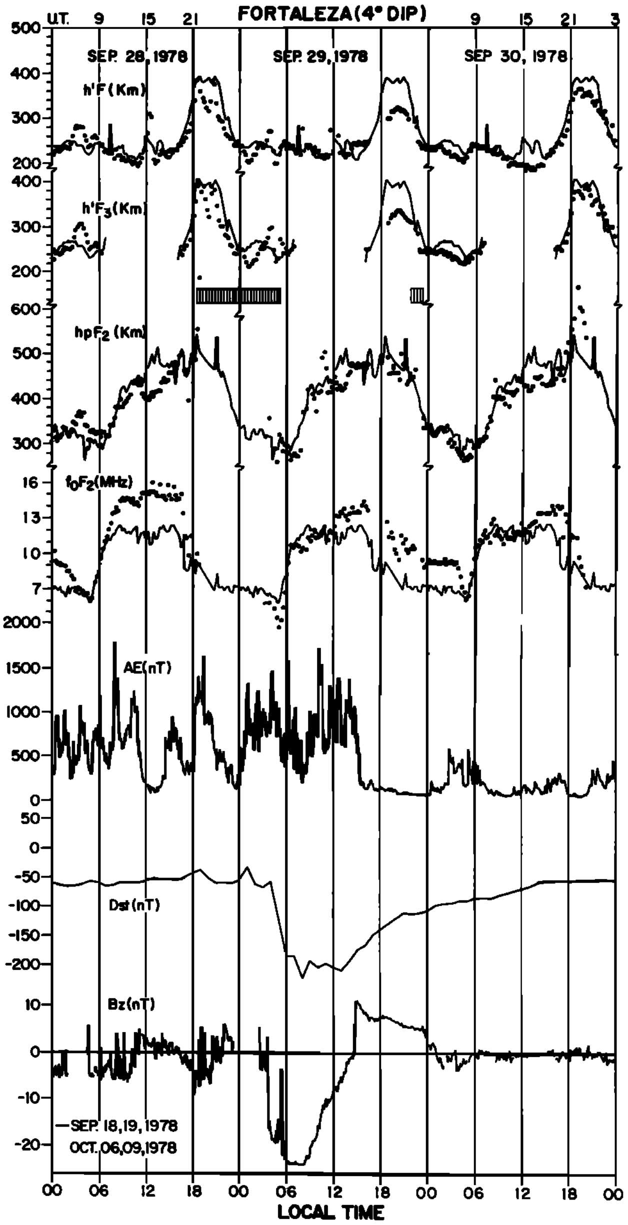

Figure 3. Same as Figure 1, but for September 28–30, 1978.

2.3. Events of March 28–30 and April 2–4, 1979

These two events presented in Figures 4 and 5 are different from the previous ones with respect to the local time intervals of the major B_z southward conditions. For the April event of Figure 5, strong B_z southward conditions (values reaching ~−18 nT) prevailed from around 1200 LT of April 3 when a rapid north-to-south turning of B_z produced the onset of an intense substorm activity at this time. After a discontinuity of the data for several hours (from 2100 to 0300 LT) the B_z index seems to have returned to positive values just before 0600 LT. The associated substorm activity also showed near recovery at this time. A subsequent southward excursion of B_z soon after

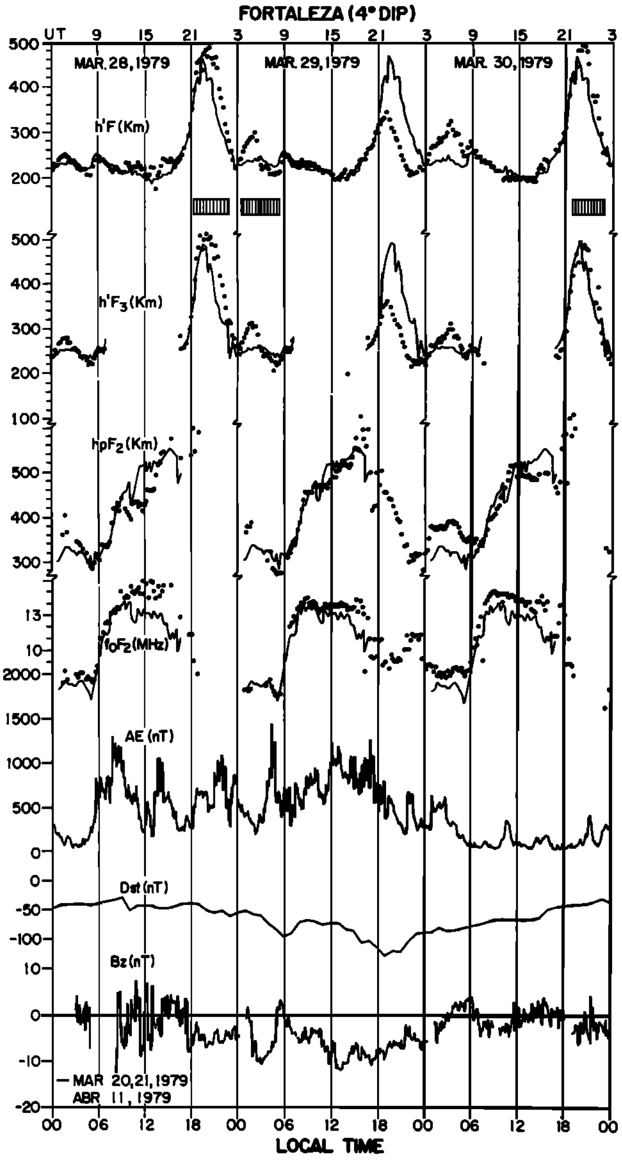

Figure 4. Same as Figure 1, but for March 28–30, 1979.

0600 LT produced a large increase in AE, whose recovery was also marked by the northward turning of B_z. For the March event of Figure 4 the B_z southward conditions prevailed through the night of March 28, the entire day of March 29 (with brief recoveries during the morning hours), and the morning of March 30, but the intensity of B_z was significantly less (−10 nT) than that of the April event.

Regarding the March event, the 1800 LT southward turning of B_z (March 28) that produced a rather weak substorm did not apparently cause any significant addition of eastward electric field to the prereversal enhancement electric field (perhaps there was a cancellation of opposing electric fields from this substorm and from the disturbance dynamo of the preceding substorms). The presence of the disturbance dynamo electric field is evident from the reduced h_pF_2 and increased f_oF_2 during the daytime hours that preceded this evening. The opposing effects of the disturbance dynamo and direct penetration electric field resulted in insignificant alteration in the prereversal F layer height increase observed in this case which is very similar to the case of September 28, 1978, described above with respect to Figure 3. However a second substorm development around 2100 LT did produce enhanced eastward electric field seen as the extended duration/delayed reversal of the evening F layer height enhancements of March 28. The reduced amplitude of the prereversal electric field on March 29 is clear evidence of the action of the disturbance dynamo westward electric field arising from the preceding long interval of substorm activities, as was the case on August 28, 1978 (Figure 1), September 18, 1979 (Figure 2), and September 29, 1978 (Figure 3). It is particularly interesting to note that there is a significant increase in the F layer heights during the postmidnight period that continues until sunrise (0600 LT). Although there is a minor substorm event that developed around 0100 LT, the eastward polarity of the disturbance electric field, inferred from the height increase, does not agree with the convection models which predict postmidnight westward polarity electric field for a substorm development phase. It is

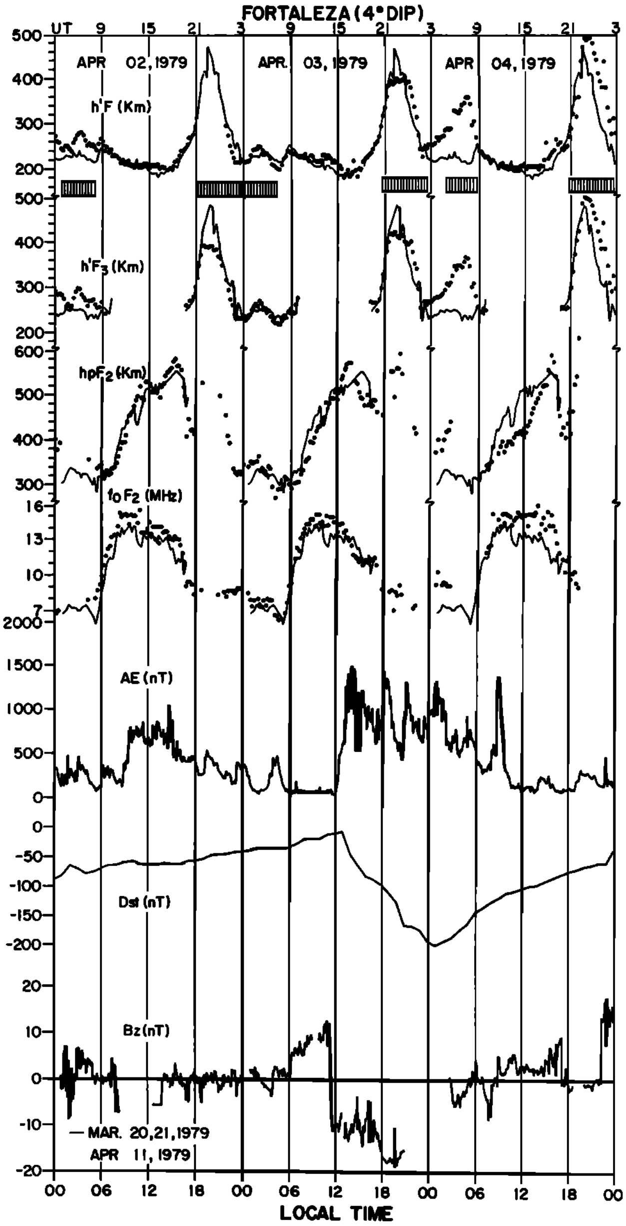

Figure 5. Same as Figure 1, but for April 2–4, 1979.

therefore more likely that the observed height rise in this case could be produced by a disturbance dynamo eastward electric field since a long series of substorm events preceded the night of March 29–30. It should be recalled that the inhibition of the prereversal enhancement that marked the early part of this night indicates the presence of a westward disturbance dynamo electric field [*Fejer and Scherliess*, 1995]. Therefore the sequence of the disturbance height variation on this night provides evidence for the disturbance dynamo electric field polarity reversal from westward (before midnight) to eastward (after midnight). For this case also, the disturbance dynamo westward electric field disturbance continued on to the next day (March 30) as indicated by the reduced h_pF_2 and enhanced f_oF_2 values of this day.

For the April 1979 event (Figure 5) the most significant phase of the storm started with the abrupt southward turning of B_z of large amplitude around 1200 LT on April 3, which was followed by intense substorm activities and ring current development. The midday substorm onset produced an eastward disturbance electric field as indicated by the increase in h_pF_2 values. Its subsequent decrease around 1400 LT corresponds to a westward disturbance electric field produced by the slow recovery of this substorm. These disturbance electric field polarities also agree with the model predictions. Two more substorm enhancements occurred between 1800 and 0000 LT. The recovery of the first of these substorm enhancements seems to have produced a westward disturbance electric field that has terminated the prereversal F layer uplift earlier than the average pattern, but the second substorm onset has produced an eastward disturbance field which caused delay in the evening electric field reversal clearly seen in the $h'F$ and $h'F_3$ pattern and not in h_pF_2, which was discontinuous during that time interval. The height rise registered from midnight to morning hours of April 4 and those of March 30 (Figure 4) seem to be caused mainly by a disturbance dynamo electric field arising from the precedent substorm activities [see also *Fejer and Scherliess*, 1995], as was the case for the morning of March 30, 1979 (Figure 4).

The disturbance dynamo westward electric field is dominant again during the daytime of April 4 as was the case on March 30 (Figure 4) as indicated by the negative deviation of h_pF_2 accompanied by the positive deviation of f_oF_2 that continued until late afternoon hours. Finally, a weak substorm that started at 1900 LT seems to have produced a disturbance electric field around the prereversal enhancement decay phase. The disturbance dynamo electric fields from the disturbances of the preceding intervals seem to have subsided by the time of the onset of this substorm.

3. Discussion and Conclusions

We have analyzed here the response features of the equatorial ionosphere for five major magnetospheric storms of the equinoctial months of the solar maximum years 1978–1979. These storms can be classified as intense storms having values of $Dst \leq -100$ nT [*González and Tsurutani*, 1987] and are associated with the transit at Earth of interplanetary magnetic clouds. All of them were characterized by occurrences of large numbers of auroral substorms, and in that way the identification of equatorial ionosphere responses is a complex task. Theoretical convection models such as those used by *Spiro et al.* [1988], *Tsunomura and Araki* [1984], *Senior and Blanc* [1984], and *Fejer et al.* [1990] predict low-latitude ionospheric electric fields in response to isolated and "clean" events of auroral substorms. Therefore verification of these model predictions through observational results, attempted in this paper, is relatively less complex only for the first few substorm events in a series of large number of them or for some intense substorms in a series of otherwise very weak events. We have used both of these considerations in our analyses, and the disturbance electric field polarity dependence on the substorm phase as a function of local time is found to be in good agreement with the model prediction. In particular, the disturbance electric field polarity reversal near midnight in response to a given increase or decrease in the polar cap potential drop (corresponding substorm enhancement or recovery phases, respectively) as predicted by the models is confirmed for the first time in our observations of the F layer height response patterns corresponding to a long-duration substorm event in which the substorm development continued on from premidnight to presunrise hours (on the nights of August 27–28 and August 28–29, 1978, of Figure 1). We have also tried to establish the response features to disturbance dynamo electric fields as predicted by the theoretical model of *Blanc and Richmond* [1980]. This has been identified as delayed effects; that is, the response features after a few substorms of the series have already taken place. From this stage onward the response features often represent a net effect of the disturbance dynamo electric field and prompt penetration electric field; in the evening sector especially, effects from disturbance zonal wind add to the scenario as was explained by *Abdu et al.* [1995]. An interesting result concerning the polarity local time dependence of the disturbance dynamo electric field has come out from the present study when during a continuous F layer height disturbance on a given night (March 29–30, 1979, and, to a less degree, April 3–4, 1979), the westward polarity of the electric field before midnight turned eastward after midnight [see also *Abdu et al.*, 1996]. This change of polarity of the disturbance dynamo electric field is in good agreement with the results from statistical analysis of Jicamarca vertical drift data presented by *Fejer and Scherliess* [1995]. In the present study, using reasonably extensive data sets and widely different interplanetary-magnetospheric disturbance conditions, but under limited range of seasonal (equinoctial) and solar activity (maximum) variations, we have succeeded in identifying dominant response features attributable to the two different types of disturbance electric fields and to disturbance zonal winds mentioned above. The main conclusions of this study are the following:

1. Substorm development at sunset sector could produce significant modification in the prereversal enhancement in the vertical drift/F layer height rise, depending upon the storm history of the preceding hours. With quiet magnetospheric conditions approximately preceding a day of the substorm, a large increase in the prereversal vertical drift occurs due to the prompt penetration disturbance eastward electric field adding to the sunset F layer dynamo electric field. Also, inhibition of the vertical drift could result from the substorm recovery phase that produces penetration electric field of westward polarity. When disturbed magnetospheric conditions precede by a few hours to several hours, a substorm development near sunset generally produces a reduction of the vertical drift enhancement (depending upon the intensity of the preceding disturbance). This is caused by the addition of a disturbance dynamo westward electric field to the normal eastward electric field of the evening F layer dynamo. These results are in agreement

with our previous study [*Abdu et al.*, 1995] that utilized asymmetric ring current indices and local magnetograms as indications of the disturbed conditions instead of the AE, Dst, and B_z values used in the present study.

2. A new and rather interesting point in the present set of results is the fact that an eastward electric field arising from a substorm onset near sunset can be canceled partially or totally by a westward electric field produced by disturbance dynamo (or by the opposing influence of a westward disturbance wind discussed by *Abdu et al.* [1995]), so that the net prereversal enhancement in the vertical drift (as judged from the *F* layer height increase near sunset) could appear unaffected by the disturbance conditions (examples are the $h'F$ and $h'F_3$ increases near 1800 LT on September 28, 1978, and March 28, 1979). Local time dependence of the prompt penetration disturbance electric field based on the equatorial *F* layer height response features is in general agreement with the model predictions, especially since experimental evidence is available for the first time to the best of our knowledge from the present study on midnight/near midnight polarity reversal of the disturbance electric field predicted by the different models.

3. The prereversal uplift of the *F* layer (vertical drift produced by the *F* layer dynamo) on the second day of the storm onset is always partially or totally inhibited by either the action of the disturbance dynamo westward electric field or by a westward disturbance wind (as shown by *Abdu et al.* [1995]).

4. The disturbance electric field observed in the evening and daytime having westward polarity is in excellent agreement with the statistical results presented by *Fejer and Scherliess* [1995] following closely the disturbance dynamo pattern of the *Blanc and Richmond* [1980] model. In the present set of results the disturbance dynamo associated eastward electric field manifestations were not clearly identifiable during presunrise hours (except in one case) as were seen in the results of *Fejer and Scherliess* [1995]. This identifying difficulty is most probably because of the superposition of disturbance eastward electric field from the substorm activities that were present during these hours. However, at least one clear case was observed on March 29–30, 1979, of disturbance dynamo electric field polarity reversal from westward (before midnight) to eastward (after midnight).

Further aspects of the low-latitude ionospheric response to diverse conditions of the magnetospheric disturbances are under investigation.

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