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Equatorial Electric Fields During Magnetically Disturbed Conditions
1. The Effect of the Interplanetary Magnetic Field

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Radar measurements of E and F region drift velocities have been used to look for correlations between changes in equatorial electric fields and the interplanetary magnetic field (IMF). The east-west component of the IMF appears to be unimportant, but the north-south component has some effect; rapid reversals from south to north are sometimes correlated with reversals of the equatorial east-west electric field during both daytime and nighttime. This is not always true, however; the IMF may reverse without any apparent effect at the equator. Furthermore, large equatorial field perturbations are sometimes observed when the IMF B_z is large and southward but not varying drastically. In this latter case the equatorial perturbations start nearly simultaneously with the onset of auroral substorms, while in the previous case they usually correlate with the onset of the substorm recovery phase. These observations indicate that the IMF does not affect the equatorial electric fields directly. Rather, it is changes in the magnetospheric electric fields and the auroral zone electric field and conductivity distribution (which may or may not be triggered by IMF changes) which alter the worldwide ionospheric current flow and electric field pattern, of which the equatorial observations are an indication.

INTRODUCTION

During magnetically disturbed periods, significant perturbations occur at equatorial as well as higher latitudes. Possible correlations between the equatorial magnetic field variations and those at middle and high latitudes have been investigated by *Onwumechili and Ogbuehi* [1962], *Nishida* [1968, 1971], *Onwumechili et al.* [1973], and others. The equatorial magnetic effects are due partly to magnetospheric ring currents and partly to changes in the equatorial electric fields associated with perturbations in the worldwide E region current system. With radar measurements the latter can be monitored directly and separated from ring current effects [e.g., *Cohen and Bowles*, 1963; *Farley and Balsley*, 1973; *Fejer et al.*, 1976; *Carter et al.*, 1976]. The east-west electric field which drives the equatorial electrojet current is also responsible for the F region vertical drift, which can be measured accurately with the large 50 MHz radar at the Jicamarca Radar Observatory in Peru [*Woodman and Hagfors*, 1969].

The magnetospheric phenomena which directly affect the ionosphere at high latitudes are ultimately driven by the solar wind, some aspects of which can be monitored by observing the interplanetary magnetic field (IMF). The relationship between the IMF and high latitude geomagnetic phenomena has received considerable attention in recent years [e.g., *Arnoldy*, 1971; *Burch*, 1974; *Nishida*, 1975; *Mishin*, 1977; *Caan et al.*, 1977; *Burke et al.*, 1979]. Possible connections between the IMF and current systems extending down to low latitudes have been considered by *Nishida* [1968, 1971], *Nishida and Kokubun* [1971], *Matsushita and Balsley* [1973], *Rastogi and Chandra* [1974], *Rastogi and Patel* [1975], *Matsushita* [1975], *Patel* [1978], and *Blanc* [1978]. A comprehensive review of previous studies of the effect of the IMF on the equatorial ionosphere has been published by *Matsushita* [1977].

Some of these papers [e.g., *Rastogi and Patel*, 1975; *Patel*, 1978] suggest that there is a close correlation between electric

field reversals at the equator and south-to-north reversals of the vertical component of the IMF. The purpose of this paper is to investigate this possible relationship in more detail, using radar data from Jicamarca. We find that there is no simple one-to-one correspondence between changes, even large changes, in the IMF and in the equatorial east-west electric field. Examples of good correlation can be found, but so can many counterexamples. Detailed case studies and possible mechanisms for the equatorial perturbations and their relationship to magnetospheric convection are presented in a companion paper [*Gonzales et al.*, 1979].

A third paper in this series [*Fejer et al.*, 1979] discusses variations with season and solar cycle in the quiet day equatorial electric field. The normal quiet day vertical F region drift is upward during the day and downward at night with the morning reversal occurring at 0600–0800 and the evening reversal at 1700–2100. However, the behavior near the evening reversal, especially, may be complicated and there is often a pronounced pre-reversal enhancement in the upward drift.

EXPERIMENTAL RESULTS

The equatorial east-west electric field can be determined from Doppler radar measurements of either the east-west electrojet electron drift velocity or the vertical F region drift velocity; usually the results are in good agreement. The radar measurement techniques, as well as some of the Jicamarca observations we shall present, have been discussed in various papers [e.g., *Balsley and Woodman*, 1969; *Woodman and Hagfors*, 1969; *Woodman*, 1970; *Balsley*, 1973]. At the equator the ionospheric east-west electric field is typically of the order of 0.5 mV/m and is eastward during the day and westward at night. This value of the field corresponds to an E region electron drift velocity of about 400 m/s and an F region vertical velocity of about 20 m/s.

We have examined the hourly average values of the vertical (B_z) and azimuthal (B_y) components of the IMF during the period from 1967 to 1975, when east-west E region and/or

TABLE 1. Dependence of Hourly Average of Jicamarca Vertical
Drifts on the Interplanetary Magnetic Field

	$B_z(GSM) > 0$	$B_z(GSE) > 0$	$B_y(GSE) > 0$
V	15.8 ± 7.7	15.6 ± 7.6	17.0 ± 7.9
N	74	73	68
	$B_z(GSM) < 0$	$B_z(GSE) < 0$	$B_y(GSE) < 0$
V	18.3 ± 7.3	18.1 ± 6.8	16.4 ± 0.5
N	63	62	70

vertical F region drifts were measured at Jicamarca. In addition, we have examined selected auroral zone magnetograms and the variation of the auroral electrojet indices during periods of large changes in the equatorial electric field and/or in the north-south component (B_z) of the IMF.

The averages of the hourly F region vertical drifts between 1000 and 1400 LT, from March 1968 to December 1971, are shown in Table 1 for positive and negative values of the vertical and azimuthal components of the IMF. Here N denotes the number of samples for each average. The average velocities are essentially unaffected by changes in the azimuthal IMF component, but the north-south component appears to have a slight effect. When B_z is southward $(B_z < 0)$ the average vertical drift is slightly larger than when it is northward $(B_z > 0)$. This result holds true whether the IMF data are expressed in geocentric solar magnetospheric (GSM) or in geocentric solar ecliptic (GSE) coordinates. A more detailed variation of the midday hourly average F region vertical drifts as a function of the corresponding $B_z(GSM)$ hourly values in steps of 2 γ is shown in Figure 1. The average vertical velocities are essentially independent of B_z except for the decrease for large northward IMF values. Even this decrease is no larger than the scatter in the observations about the average values. The data around local midnight show essentially the same results but are more variable and are frequently contaminated by spread F effects.

Although the average effect of the IMF is barely detectable, pronounced and rapid reversals of the IMF vertical component from southward to northward are sometimes clearly associated with large equatorial drift velocity perturbations or even reversals. Figure 2 shows two nighttime examples. On magnetically quiet days the E and F region drifts reverse from
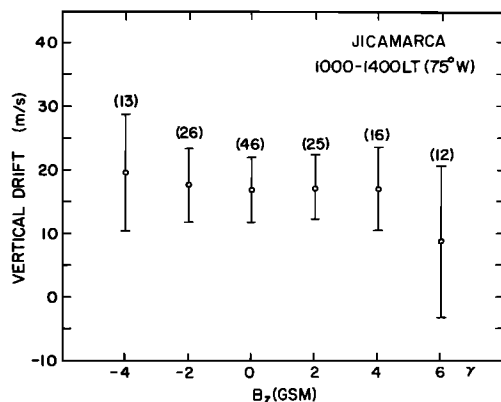

Fig. 1. Variation of the hourly average F region vertical drift velocity (positive upward) with the similarly averaged northward (positive) component of the IMF (in 2 γ increments). The point at -4γ ($+6 \gamma$) is an average of all drifts for $B_z \leq -4 \gamma$ ($\geq +6 \gamma$). The bars indicate measured standard deviations. The number of samples averaged for each point is shown.
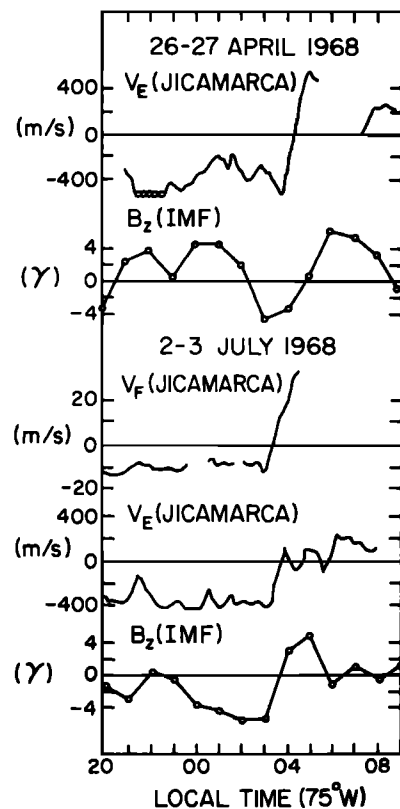

Fig. 2. Examples of simultaneous reversals of the equatorial electric field and the IMF B_z at night. The drifts are positive upward (V_F) or westward (V_E). The normal nighttime westward electric field produces a downward F region drift (V_F) and an eastward E region electron drift (V_E). Dots in the E region data indicate a lower bound on the magnitude of the velocity.

eastward to westward and from downward to upward, respectively, at about 0600 LT. The anomalous velocity reversal between 0300 and 0400 on July 3, 1968, has been discussed by *Rastogi and Patel* [1975]. Some additional anomalous drift reversals are shown in Figure 3. It is clear from this figure, however, that not all B_z northward reversals cause significant changes in the equatorial drifts (e.g., the reversal at ~1030 on December 12, 1968), a point we shall return to.

In Figure 4 we again plot the equatorial drift data of April 26-27, 1968, and the variations of the IMF vertical component (now with a time resolution of 2.5 min), and compare these with the auroral electrojet indices AU and AL. The high latitude and IMF data corresponding to this period were discussed by *Caan et al.* [1977], who have presented other examples in which auroral substorms associated with periods of southward IMF abruptly ceased, coincident with permanent IMF northward recoveries. Most of the anomalous drift reversals at the equator associated with northward IMF turnings were indeed coincident with the onset of substorm recovery phases. Examples are the reversals of July 3, 1968; March 6, 1969; and others shown in *Gonzales et al.* [1979]. An additional one is shown in Figure 5. In this last case, the drift measurements at Jicamarca unfortunately were made only after 1200 LT, by which time the drift velocity had already been drastically perturbed from its normally positive daytime value. The sudden change in drift velocity at about 1300 LT is a recovery from the perturbation and should not be confused with the nighttime velocity jumps in Figures 2 and 4 which
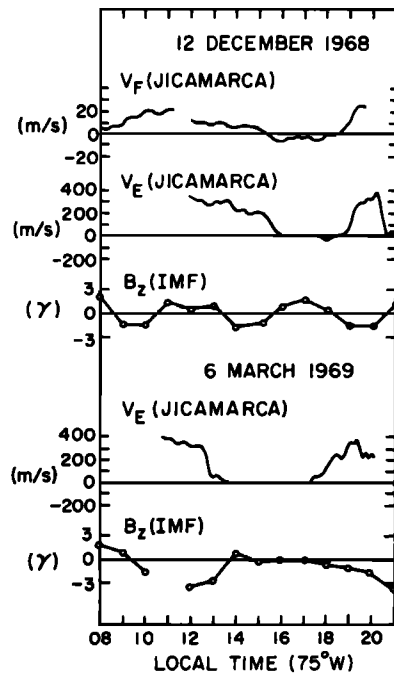
Fig. 3. Examples of daytime electric field reversals associated with reversals of B_z to northward. E region data cannot be obtained when the electric field reverses during the day.
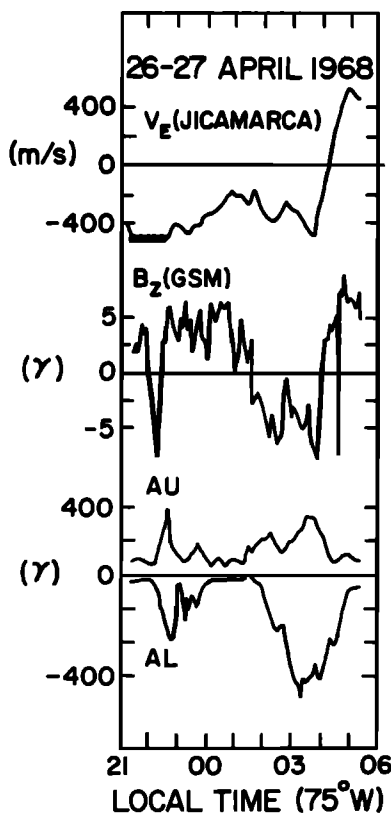

Fig. 4. Comparison between equatorial data, IMF measurements made with a time resolution of 2.5 min, and the auroral indices AU and AL. Note that the equatorial field reversal is well correlated with substorm recovery.
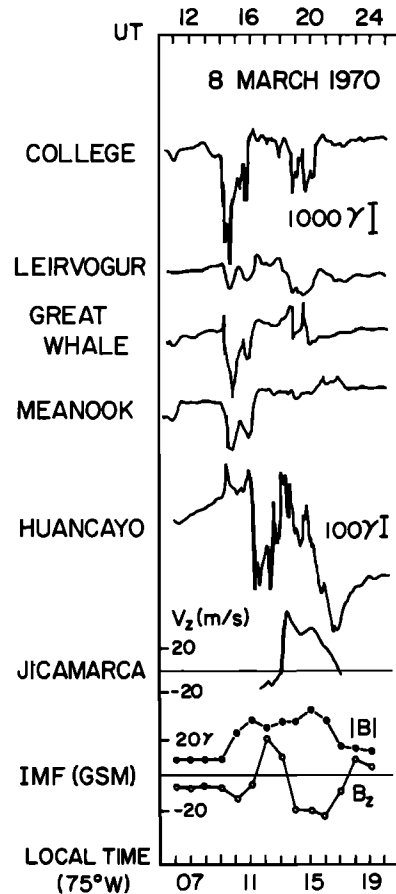

Fig. 5. Example of a daytime equatorial electric field reversal associated with a substorm recovery. Note particularly the Huancayo data. Unfortunately, the Jicamarca observations began after the reversal had occurred. (Here V_z is the upward F region drift which is normally positive during the day.)

appear to be similar but are not. The large variations in the Huancayo magnetogram beginning at about 1100 LT are a better indication in this case of the strong perturbation in the equatorial electric field.

Figure 6 shows additional examples of drift velocity observations and the corresponding IMF data during two strongly disturbed periods. On August 9, 1972, the equatorial drift reversals occurred when B_z was weakly southward, and on October 31 to November 1 the reversals took place during a period of large and steady southward B_z. The equatorial electric field (drift) perturbations shown in Figure 6 started nearly simultaneously with onsets of auroral substorms. This point is discussed in detail in a companion paper [Gonzales et al., 1979].

Large changes in B_z sometimes fail to produce any significant effect on the equatorial ionospheric drifts. Some examples of different relationships between B_z (GSM) and the equatorial drifts are shown in Figures 7 and 8. The large increase in the northward B_z component at about 1600 on March 23–24, 1971, did not affect the ionospheric drift; neither did the northward turnings of May 13 and 22, 1971. In the latter two cases, however, the amplitudes of the B_z variations were relatively small. Two large changes in B_z occurred on June 11–12, 1975 (Figure 8, bottom panel). The daytime perturbations just after noon produced no change in the F region vertical drift, but the northward B_z turning at about 0300 on June 12, 1975, seems to be associated with the large re-
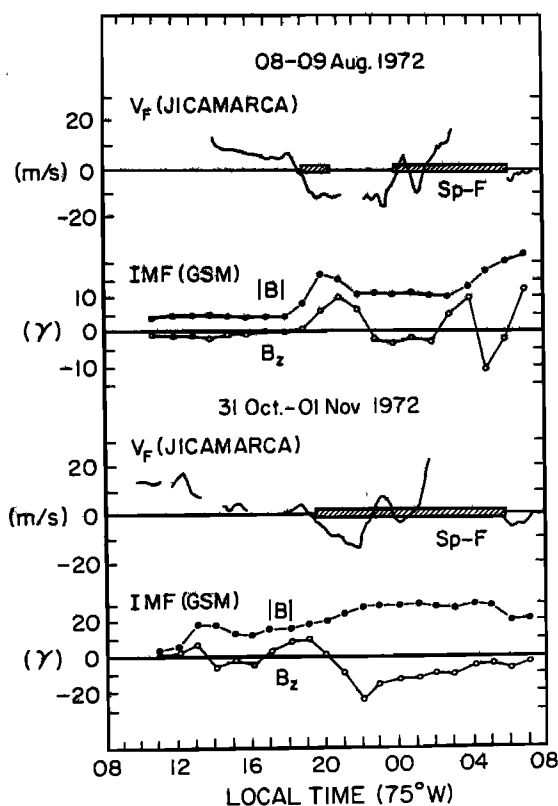
Fig. 6. Examples of equatorial electric field reversals during strongly disturbed conditions. There is little evidence for a detailed correlation with the IMF.

versal of the drift that occurred shortly afterward. In contrast, however, the large drift reversal at 2100 on June 11 occurred during a period of southward and relatively constant IMF. The occurrence of spread F during the night of June 11-12 makes the drift measurements somewhat less reliable than usual, but they seem to be adequate for our purpose.
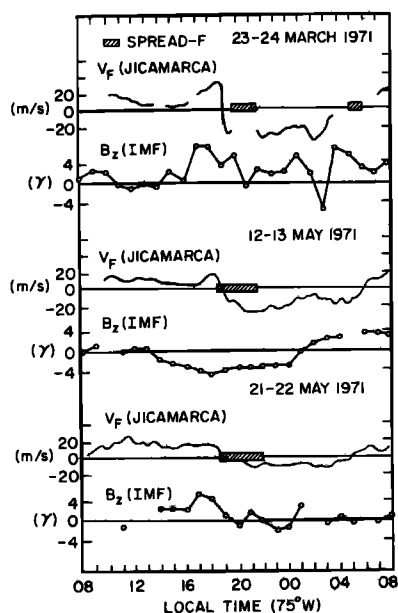

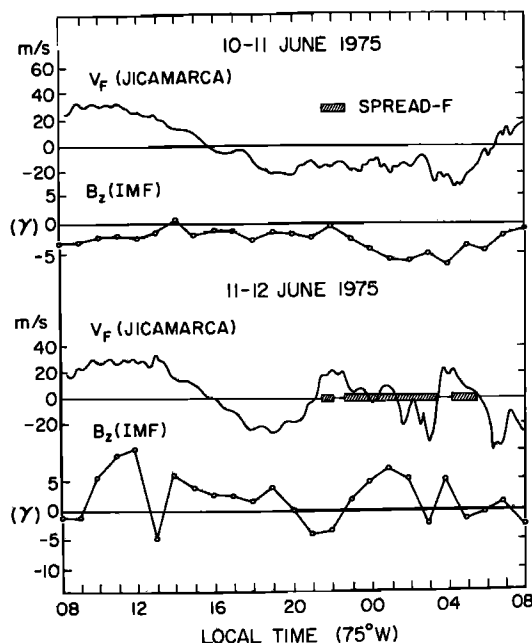Fig. 7. Further examples of simultaneous observations of the IMF and equatorial drifts.

Fig. 8. Additional comparisons. Note the contrast between daytime and nighttime data on June 11-12.

DISCUSSION

Let us first summarize the observations.

1. The average equatorial E region east-west and F region vertical drifts (i.e., the east-west electric field in the E and F regions) show little if any dependence on the IMF, even though temporary perturbations may be correlated.

2. Large perturbations in the equatorial east-west electric field are frequently nearly simultaneous with pronounced northward turnings of the IMF, as suggested by Rastogi and Patel [1975] and Patel [1978], if the northward turning persists for at least 2 hours. However, there are many counter examples.

3. The equatorial electric field perturbations usually occur at the onset of a substorm in the auroral zone or at the onset of a substorm recovery phase, but not both. The first case is associated with periods of southward IMF while the second is usually associated with large northward IMF recoveries following periods of an hour or more of southward B_z. The equatorial electric field perturbations are always in the opposite direction to the normal Sq electric field.

4. Some large northward changes in the IMF vertical component produce no significant effect on the equatorial electric field. This is frequently the case when B_z has been southward for only a short period (an hour or less) prior to turning northward.

Some of the effects just summarized have been discussed by others. Regarding point 1, Rastogi and Chandra [1974] studied east-west (not vertical) equatorial F region drifts at Thumba and found a rather strong dependence of the average values on B_z. They concluded that an increase in the southward component of B_z causes a decrease in the normal (east-west) Sq equatorial electric field, a result which is also referred to in Matsushita's [1977] review. There are insufficient Jicamarca measurements of east-west F region drift for a thorough study, but we must point out that the conclusions of Rastogi and Chandra cannot be supported by their own observations. East-west equatorial F region drifts are determined by the ver-

tical electric field in the F region, which maps along the magnetic field lines into the north-south electric field in the E region at higher latitudes.

We have already mentioned in point 2 the work of Rastogi and Patel [1975] and Patel [1978]. They suggest that strong IMF reversals from southward to northward impose an electric field on the ionosphere opposite to the normal Sq field, thereby decreasing or even reversing the normal ionospheric drift direction. This induced electric field is $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$, where V is the velocity of the solar wind and B is the IMF in the solar ecliptic plane. We have just seen, however, that although large northward IMF turnings are sometimes associated with large velocity (electric field) perturbations in the equatorial region, there are many exceptions; turnings can occur without equatorial drift perturbations and vice versa. Kane [1978] has found a similar lack of clear correlations between IMF northward turnings and the occurrence of counterelectrojet (daytime reversals of the equatorial electrojet).

The equatorial drift reversals associated with large IMF northward turnings are frequently (over 60% of the cases) nearly simultaneous with the onset of substorm recovery phases in the auroral zone. Caan et al. [1977] have shown that auroral negative bays cease abruptly coincident with permanent northward recoveries in the IMF after periods of steady southward B_z for 2 hours or more. Our results (point 3) show that when the equatorial field perturbations are coincident with IMF northward recoveries and the substorm recovery phase, there are usually no detectable effects associated with the onset of the substorms.

A possible explanation for many of these observations has been proposed by Kelley et al. [1979], who discuss the penetration into the ionosphere of perturbations in the magnetospheric electric field associated with convection. Polarization charges in the inner magnetosphere [Vasyliunas, 1972; Wolf, 1975] tend to shield the low latitude ionosphere from this field, but the time constant for the build up of these charges may be long (~several hours). The idea, then, is that changes in B_z will result in low latitude effects only insofar as the changes alter the magnetospheric convection electric fields and these alterations are too rapid to be balanced by shielding changes. On the other hand, very short lived changes in B_z (≤1 hour) presumably will not cause major changes in the convection. Hence the correlation seems to be best on a time scale of a few hours (although we have not made a quantitative study of this point). This model has some similarity to the ideas of Rastogi and Patel [1975] but is significantly different in that the behavior of the shielding charges play a major role.

Blanc [1978] discussed the extension of magnetospheric convection toward low latitudes, during a period of large (5 γ or more) southward B_z, using mid-latitude F region drift measurements over San Santin. The ionospheric drifts in this case were closely related in intensity to the negative excursions of $d(Dst)/dt$. This relationship between the ring current and the anomalous electric field perturbations also holds for the equatorial case, as is discussed in detail in a companion paper [Gonzales et al., 1979].

CONCLUSIONS

The relationship between the equatorial east-west electric field and the north-south component of the IMF is complex. Pronounced reversals of the IMF to northward are sometimes coincident with equatorial field reversals and the onset of au-

roral substorm recovery, but sometimes not. Such a reversal of the IMF may produce no perceptible change in the equatorial electric field. Furthermore, during magnetically disturbed periods, anomalous equatorial drift reversals are sometimes observed when the IMF is steady and southward, in which case the reversals are usually coincident with the onset of an auroral substorm. In other words, the equatorial effects are not directly related to the IMF, but rather are the result of changes in magnetospheric convection and high latitude substorm phenomena which may (or may not) be triggered by changes in the IMF.

The average value of the equatorial east-west electric field is affected only slightly by the north-south component of the IMF and not at all by the east-west component.

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