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 10 Tepley, C.A.
 10 Burnside, R.
 10 Abdu, Mangalathayil Ali
 10 Sobral, Jose Humberto Andrade
 10 Woodman, R.F.
 10 Kamide, Y.
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the global convection models reproduce a number of characteristics of low-latitude and equatorial electric fields associated with changes in the polar cap potential drop. In addition, we highlight several areas where there is still substantial disagreement between the electric field data and the theoretical results.

88 ELECTRIC FIELDS

88 MAGNETOSPHERE-IONOSPHERE COUPLING

88 IONOSPHERIC DISTURBANCES

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Low- and Mid-Latitude Ionospheric Electric Fields During the January 1984 GISMOS Campaign

B. G. FEJER,¹ M. C. KELLEY,² C. SENIOR,³ O. DE LA BEAUJARDIERE,⁴
J. A. HOLT,⁵ C. A. TEPLY,⁶ R. BURNSIDE,⁶ M. A. ABDU,⁷
J. H. A. SOBRAL,⁷ R. F. WOODMAN,⁸ Y. KAMIDE,⁹
AND R. LEPPING¹⁰

This paper examines in detail the electrical coupling between the high-, middle-, and low-latitude ionospheres during January 17–19, 1984, using interplanetary and high-latitude magnetic field data together with *F* region plasma drift measurements from the EISCAT, Sondre Stromfjord, Millstone Hill, Saint-Santin, Arecibo, and Jicamarca incoherent scatter radars. We study the penetration of both the zonal and meridional electric field components of high-latitude origin into the low-latitude and the equatorial ionospheres. In the dusk sector, a large perturbation of the zonal equatorial electric field was observed in the absence of similar changes at low and middle latitudes in the same longitudinal sector. The observations in the postmidnight sector are used to compare the longitudinal variation of the zonal perturbation electric field with predictions made from global convection models. Our results show that the meridional electric field perturbations are considerably more attenuated with decreasing latitude than the zonal fluctuations. As a result, we conclude that variations in the meridional electric field at low latitudes are largely due to dynamo effects. These observations are used to show that the global convection models reproduce a number of characteristics of low-latitude and equatorial electric fields associated with changes in the polar cap potential drop. In addition, we highlight several areas where there is still substantial disagreement between the electric field data and the theoretical results.

1. INTRODUCTION

There is now extensive evidence that during periods of strong geomagnetic activity the middle- and low-latitude electric fields and currents can depart appreciably from their quiet-day patterns, which are driven by tidal winds. The effects of high-latitude current systems at lower latitudes include (1) simultaneous electric field perturbations over a large range of latitudes and longitudes [e.g., Nishida, 1968; Blanc, 1978, 1983; Gonzales *et al.*, 1979, 1983; Kelley *et al.*, 1979; Reddy *et al.*, 1979; Wand and Evans, 1981; Fejer, 1981, 1986; Somayajulu *et al.*, 1987] and (2) wind disturbances which have latitude-dependent time delays and create (3) storm time dynamo electric fields [e.g., Blanc and Richmond, 1980; Fejer *et al.*, 1983].

Large-scale magnetospheric electric fields imposed on the high-latitude ionosphere [e.g., Kamide, 1988] can be transmitted almost instantly to the middle, low, and equatorial regions through the Earth-ionosphere waveguide [e.g., Kikuchi *et al.*, 1978]. Incoherent scatter radar observations have been used extensively to determine the average electric field patterns at middle and low latitudes for different levels of magnetic activity [e.g., Blanc, 1983; Wand and Evans, 1981; Ganguly *et al.*, 1987], and to measure the extent of the magnetospheric electric field effects on the plasmasphere [e.g., Blanc, 1978; Gonzales *et al.*, 1979, 1983; Fejer, 1986; Earle and Kelley, 1987]. Several numerical studies have examined the global distribution of ionospheric electric fields and currents during both geomagnetically quiet and disturbed conditions by solving the continuity equation for a two-dimensional spherical shell for given high-latitude potential or current distributions, and for different longitude- and latitude-dependent ionospheric conductivities [e.g., Nopper and Carovillano, 1978; Kamide and Matsushita, 1981; Takeda and Maeda, 1982; Tsunomura and Araki, 1984; Senior and Blanc, 1987; Spiro *et al.*, 1988].

Detailed measurements of ionospheric electric fields and currents have been made recently during the Incoherent Scatter World Day campaigns. These coordinated studies include observations with the EISCAT (European Incoherent Scatter), Sondre Stromfjord, Millstone Hill, Saint-Santin, Arecibo, and Jicamarca radars and from several other ground-based and in situ probes. The GISMOS (Global Ionospheric Simultaneous Measurements of Substorms) campaign was designed to measure in detail the ionospheric and magnetospheric effects associated with substorms and to provide detailed data sets for testing global thermospheric, ionospheric and magnetospheric models. The instrumentation is described by de la Beaujardiere [1987]. Some of the high-latitude convection electric fields and currents during the January 16–19, 1984 GISMOS campaign have been discussed by de la Beaujardiere *et al.* [1987a,b], Alcayde *et al.* [1986], Senior and Blanc [1987], and Richmond *et al.* [1988]. In this study we concentrate on *F* region plasma drift measurements from incoherent scatter radars to study the relationship between low- and mid-latitude ionospheric electric fields and the high-

¹ Center for Atmospheric and Space Sciences, Utah State University, Logan.

² School of Electrical Engineering, Cornell University, Ithaca, New York.

³ Centre National d'Etudes des Télécommunications/Centre de Recherche en Physique de l'Environnement, St.-Maur des Fosses, France.

⁴ Radio Physics Laboratory, SRI International, Menlo Park, California.

⁵ Haystack Observatory, Massachusetts Institute of Technology, Westford.

⁶ Arecibo Observatory, Arecibo, Puerto Rico.

⁷ Instituto de Pesquisas Espaciais, São Jose dos Campos, São Paulo, Brazil.

⁸ Instituto Geofísico del Perú, Lima.

⁹ Kyoto Sangyo University, Kita-ku, Kyoto, Japan.

¹⁰ Goddard Space Flight Center, Greenbelt, Maryland.

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Fig. 2. Interplanetary and auroral electrojet magnetic field data, and high-latitude eastward and northward F region plasma drifts observed with the EISCAT, Sondre Stromfjord, and Millstone Hill radars during a 48-hour period. The electric field measurements were made at invariant latitudes of 66° , 74° , and 65° , respectively. The small circles indicate local midnight.

The subsequent electric field pattern over Jicamarca shown in Figure 1 closely followed the quiet-time variation up to about 1700 UT on January 18 when, shortly after a southward B_z turning, substorm activity began once again. At this time a small-amplitude westward electric field perturbation was recorded in the Jicamarca data. This effect is seen even more clearly in the Huancayo magnetic field data, which also indicate the presence of a westward electric field perturbation. The Jicamarca electric field perturbation was westward up to about 2400 UT (1900 LT). The westward electric field perturbation relative to the quiet-time pattern during this period might not have been due to the high-latitude substorm activity since there are considerable variations in the quiet-time patterns particularly in the afternoon and evening sectors. In fact, the afternoon electric fields on 17 January (not presented here), which was a quiet day, were also more westward than the quiet-time pattern (smooth curve) shown in Figure 1. Daytime westward electric field perturbations lasting several hours were also present over Jicamarca and Huancayo about 24 hours later. It is important to note that these perturbations (16–24 UT on January 18 and 14–24 UT on January 19) last for many hours. Long-lasting and slowly varying equatorial electric field perturbations have been discussed by Fejer *et al.* [1983] in the context of a disturbance dynamo. Therefore, the rapid variations we see in these data (e.g., 10–12 UT on January 18, 00–02 UT, 06–08 UT, 08–12 UT on January 19) may be due to direct penetration of electric fields while the slow variations are likely due to dynamo effects.

A very large eastward electric field perturbation was observed over Jicamarca at about 00 UT on January 19 coincident with the onset of substorm activity as indicated by the auroral magnetograms. This eastward electric field

perturbation ceased suddenly at about 0040 UT as B_z turned northward, and at the same time as the AE index decreased. Very large and longer-lasting eastward electric field perturbations were also seen in the postmidnight sector later on the same night. For isolated substorms these postmidnight equatorial perturbations are almost always associated with sudden northward B_z turnings and with onsets of substorm recovery phases. However, the relationship between the Jicamarca electric field perturbations and changes in the high-latitude ionosphere between about 0640–1200 UT is not clear since IMF data from the IMP-J satellite were not available for most of this period. The prenoon (12–17 UT) drifts on January 19 were fairly close to the quiet-time values but, as noted above, the afternoon drifts were clearly below the quiet-time pattern. The sudden impulses observed on the Huancayo magnetometer data at about 1800 UT on January 18 and at 1600 UT on January 19 are essentially absent on the electric field data. It seems unlikely that this absence is due entirely to the averaging of the electric field data; it is more likely that the magnetometer responded to a magnetospheric current system not mirrored in the ionospheric currents.

Although the IMF data are very spotty, we have some help from the high-latitude incoherent scatter radar data in Figure 2. The period of transition in B_z from north to south, followed by seven hours of average B_z southward (16–24 UT on January 18), has been studied in some detail by *de la Beaujardiere et al.* [1987a,b, 1988]. They show that the reversal in the meridional field at Sondre Stromfjord at 1800 UT was due to the equatorward motion of the convection reversal, not to a change in the electric field (convection) intensity. It corresponds to the time when, directly overhead of Sondre Stromfjord, the sun-ward convection shifted to antisunward without any significant change in the magnitude of convection. (The convection had intensified earlier at about 1600 UT.) Indeed, no large perturbation in the low-latitude electric field was observed. On the other hand, the event observed at Jicamarca near 00 UT on January 19 is somewhat mysterious. It begins at the time of a substorm onset and ends with a sharp B_z northward excursion. Unfortunately the IMF data end abruptly at this time. We can say only that the period during which the AE index was large ended shortly thereafter but it is not clear whether the end was triggered by B_z or whether it was related to processes internal to the magnetosphere and associated with substorm activity. The high-latitude electric fields decayed within an hour or so of midnight UT but were more or less unchanged during that period.

Figure 3 shows the Jicamarca (12.0° S, 76.9° W, magnetic dip 2° N) vertical plasma drifts, the variation of $h'F$ (virtual height of the bottomside F layer) over Fortaleza, Brazil (38° W, 4° S, magnetic dip 3.5° S), the horizontal magnetic field data over Trivandrum, India (1° S, 146.4° E, geomagnetic), and the Dst index during the most active 24-hour period of this campaign. Bittencourt and Abdu [1981] have shown that near the geomagnetic equator, when $h'F$ is above about 300 km, the temporal variation of this parameter provides a good measure of the vertical plasma drift velocity (i.e., of the zonal electric field). The typical rise in $h'F$, starting at about 2000 UT (1700 LT over Fortaleza), corresponds to the prereversal enhancement of the upward plasma drift [e.g., Woodman, 1970; Fejer, 1981] which is driven by F region dynamo electric fields [e.g., Rishbeth, 1971; Heelis *et al.*, 1974]. The enhancement ended at about 2200 UT since $h'F$ was virtually constant for two hours. The westward electric fields observed over Jicamarca in the afternoon sector did not extend as far as Fortaleza, about 40° east of Jicamarca, as is usually the case for disturbance dynamo electric field effects [e.g., Fejer *et al.*, 1983; Fejer, 1986]. The large eastward electric field perturbation starting at about 2330–2400 UT over Jicamarca was well correlated with the sudden rise in $h'F$ at Fortaleza. Therefore, this eastward electric field perturbation, which started with the onset of substorm activity, as indicated

perturbations were also inferred from the Fortaleza and Trivandrum data during this period (see Figure 3). Only two other latitudinal studies of this type exist [Gonzales *et al.*, 1979; Gonzales *et al.*, 1983]. They present three events with large eastward perturbations observed at Jicamarca simultaneous with changes at either Millstone Hill (April 13–14, 1978) or at Arecibo (October 10–11, 1980).

As mentioned above, the Arecibo and Millstone Hill data were averaged for about 1 hour in Figure 4. The Arecibo data show typically large fluctuations, making the unambiguous evaluation of the electric field perturbations of high-latitude origin quite difficult. This is particularly the case in the postmidnight period, where there is large variability in the plasma drifts even during relatively quiet conditions. For example, very large northward velocities were observed at about 0300 LT (0700 UT) on January 17 (not shown here), at a time when only modest activity was observed at high and equatorial latitudes. Earle and Kelley [1987] have pointed out that gravity wave activity may provide a source of electric fields with periods of a few hours which compete with geomagnetic sources.

To summarize, the results shown here indicate that the electric field perturbations observed at the equator in the postmidnight sector and associated with the onset of substorm recovery phases, possibly triggered by sudden northward B_z turnings, are associated with similar changes at low and mid latitudes, at least for the same meridional sector. The latitudinal variation of these zonal electric field perturbations will be examined later. In the evening sector, there seems to be no mid- and low-latitude zonal electric field perturbation associated with the eastward electric field changes, observed at the equator in the American sector during a time of a large increase in substorm activity, followed quickly by a rapid recovery.

2.4. Meridional Electric Fields

The latitudinal variation of meridional electric fields has not been studied in detail so far. Figure 5 shows the zonal plasma drifts (north-south electric fields) during the January period for Millstone Hill, Saint-Santin, and Arecibo. Zonal plasma drifts were not measured over Jicamarca during this period. However, it is well known that the equatorial zonal plasma drifts (vertical electric fields) are considerably less affected by magnetic activity than the vertical plasma drifts [Woodman, 1972; Fejer *et al.*, 1981, 1985; Gonzales *et al.*, 1983]. Conversely, this velocity component was measured over Saint-Santin using the procedure described by Blanc and Amayenc [1979]. The smooth curves correspond to the quiet-time empirical curves for $K_p = 0$ at Millstone Hill [Wand and Evans, 1981] and for $K_p \leq 2+$ for Saint-Santin [Blanc and Amayenc, 1979].

Figure 5 shows the clear predominance of westward drift velocity perturbations. At Millstone Hill, the observations are below the average curve for nearly the entire two-day period. This is particularly surprising for January 18 when the largest K_p values were $2+$ during 18–21 UT and $3+$ during 21–24 UT. According to the empirical model of Wand and Evans [1981] for winter, a southward electric field perturbation of about 6 mV/m at about 23 UT would be typical of a period of $K_p \sim 5$. With only a brief exception, the Arecibo and Saint-Santin measurements were also westward relative to the quiet curves. The exception was a Saint-Santin observation of a large eastward electric field perturbation between about 16 and 20 UT on January 18, which had no counterpart in the American sector. The Saint-Santin and Millstone Hill observations were discussed in detail by Senior and Blanc [1987].

The Millstone Hill and Arecibo zonal drift for the entire three-day period is shown in Figure 6. Note that the daily variation in the Arecibo westward drift did not change

Fig. 5. Interplanetary and auroral magnetic field data and southward ionospheric electric field data at four different latitudes. The smooth curves denote the quiet-time average variations, and the small circles indicate local midnight.

Fig. 6. Eastward F region drift velocity for Millstone Hill ($A = 55^\circ$) and Arecibo ($A = 33^\circ$).

appreciably during this entire period even though there were large variations in the Millstone Hill drifts, particularly near the dusk sector (2000–2400 UT). This suggests that the low-latitude zonal plasma drifts were primarily due to thermospheric dynamo electric fields rather than to the penetration of meridional electric fields from high latitudes. The Arecibo zonal drift measurements during January 17–19 are shown in a common plot in Figure 7. Of these three days, January 18 was the quietest and January 19 was the most disturbed. Notice that the main effect of the increased magnetic activity seems to be the occurrence of increased

result of the daytime conductivity enhancement. Conductivity effects are also responsible for most of the differences in the electric field amplitudes obtained by the different models. In particular, the very small eastward electric fields in the dusk sector in the RCM pattern are a result of the very large assumed values for the field-line integrated Pedersen conductivity, which has the effect of shorting out the equatorial electric field perturbations. The model electric field patterns shown in Figure 8 show that in the evening sector the smallest eastward electric fields are given by the Senior-Blanc model. As time evolves after the sudden increase in the polar cap potential drop, this initial electric field response decays as a result of the readjustment of the shielding currents in the inner magnetosphere. The time constant for this shielding effect varies from about 10 min. to 1 hour, depending on the plasma sheet temperatures. For a sudden decrease, not increase, in the polar cap potential drop, the electric field perturbations would have the opposite signs, that is, westward in the dayside and eveningside and eastward in the morningside. To compare the electric field perturbations with the model results shown in Figure 8, we need to examine initially the time variation of the polar cap potential drop.

Figure 9 shows IMF B_z data and two models for the polar cap potential drop. The first one, calculated by Senior and Blanc [1987] and used for their simulation of the high- and mid-latitude convection during January 18–19, 1984, was determined from the IMF data using the empirical formula derived by Reiff and Luhmann [1986]. In this case, the time delay between changes in B_z and in the polar cap potential drop was chosen as 30 min based on the variations in the Dst , AU , and AL indices. The second Φ_0 curve corresponds to the difference between the potential maxima and minima derived by Richmond et al. [1988] for the GISMOS period. They followed the procedure developed by Richmond and Kamide [1988] which relies on simultaneous use of ground-based magnetic field observations, electric fields measured by radars, and conductivities to determine self-consistent electro-dynamical patterns at high latitudes. Upward and downward pointing arrows indicate the starting times of some of the equatorial electric field perturbations either observed at Jicamarca or inferred from the Huancayo, Fortaleza, and Trivandrum data. We will compare these perturbations with the electric field model results taking into account the polar cap potential variations in Figure 9. We should keep in mind that increases (decreases) in the polar cap potential drop should result in eastward (westward) electric field perturbations in the daytime sector and westward (eastward) in the nighttime sector.

Figure 9 shows that the increase in southward B_z starting at about 1630 UT resulted in gradual increases in the polar cap potential drop. This increase in Φ_0 did not produce simultaneous eastward electric field perturbations (see Figure 1). The numerical models suggest that the low-latitude response to a gradual increase in the potential drop over an hour or two is considerably less intense than shown in Figure 8, in agreement with the absence of corresponding electric field perturbations in the equatorial data. In contrast to the usually small effects associated with southward B_z changes and with increases in the polar cap potential drop, even small decreases in the polar cap potential drop associated with large and sudden northward B_z changes often result in large electric field perturbations (eastward during the day and westward at night) at Jicamarca [Gonzales et al., 1979; Fejer et al., 1979; Fejer, 1986]. At present, this asymmetric response of the equatorial electric field to changes in B_z and in the polar cap potential drop remains unexplained. The other major difficulty for the global convection model is the observation of longer-lasting electric field perturbations associated with sudden decreases than with increases in the polar cap potential drop. An example of a long-lasting eastward electric field perturbation is seen in the Jicamarca data starting at 0820 on January 19. Recently, it has been suggested that neutral wind effects might explain this

Fig. 9. North-south component of the interplanetary magnetic field and estimated polar cap potential drop profiles during part of the most active January 1984 GISMOS period. The upward and downward pointing arrows indicate the starting times of equatorial zonal electric field perturbations consistent with increases and decreases in the polar cap potential drop, respectively.

asymmetric response and the long-lasting perturbations associated with sudden decrease in Φ_0 and with sudden northward B_z changes [e.g., Spiro et al., 1988].

The very large eastward electric field perturbation observed at Jicamarca and Fortaleza starting at about 2330–2400 UT (1830–1900 LT) on January 18 (see Figure 3) occurred at nearly the same time as the large decrease in the AL index. Senior and Blanc [1987] pointed out that this intensification of the westward electrojet occurred in the dawn sector following the ring current injection event between 23 and 00 UT. This large eastward electric field perturbation cannot be explained by the convection models as an initial time response to an increase in the polar cap potential drop if we assume the potential drop derived from the solar wind and IMF data by Senior and Blanc [1987], but it would be consistent with the pattern derived by Richmond et al. [1988], which shows a large increase in the polar cap potential drop. These results show the importance of realistic estimates of Φ_0 for model calculations. As mentioned previously, however, this equatorial electric field enhancement was not associated with corresponding effects over Arecibo and Millstone Hill although large westward fields were observed north of Millstone Hill ($\Lambda = 64^\circ$) during this period. The equatorial electric field enhancements stopped very abruptly at about 0040 UT (1940 LT over Jicamarca) at the same time as B_z turned northward and the polar cap potential drop decreased. The Φ_0 derived by Senior and Blanc [1987] and shown in Figure 10 would predict a westward electric field perturbation

Fig. 10. Initial time responses for a polar cap potential drop of 100 kV obtained by the Senior-Blanc model at the invariant latitude of Millstone Hill and at the equator.

kept in mind when using radar data to study the latitudinal variation of zonal electric field perturbations of high-latitude origin. First, even when observations are made in nearly the same longitudinal sector, not all perturbations are present at all sites. Second, the ratio of electric field perturbations at middle and low or equatorial latitudes is strongly local time dependent.

Several radar studies have shown that high-latitude north-south electric field perturbations are not usually detected at the magnetic equator [e.g., Woodman, 1972; Gonzales *et al.*, 1983; Fejer, 1986]. The variation in the north-south component of magnetospheric electric fields between high and middle latitudes was studied using simultaneous observations from STARE (67°–70° geomagnetic latitude) and Saint-Santin [Mazaudier *et al.*, 1984; 1987]. In the first of these studies, the north-south electric fields inferred from the radar measurements and from ground-based magnetic field data near local noon were compared with the predictions from the Senior-Blanc model. The theoretical results were found to be in good agreement with the experimental profiles provided that conductivities were normalized using the STARE electric field and the corresponding magnetic field data. In this case, the initial time response for the north-south electric fields was estimated to decrease by a factor of about 4.2 between 60° and 40° in excellent agreement with the mapping expected for a constant electric field in the equatorial plane. Mazaudier *et al.* [1984, 1987] pointed out that the east-west electric field component is not very well reproduced by the Senior-Blanc model, at least for the noon time sector. The simulation underestimates the ratio between the zonal and northward components at high latitudes but overestimates it at Saint-Santin.

Kamide and Matsushita [1981] have examined the electrical coupling between high and low latitudes by solving numerically the steady current continuity equation with field-aligned currents and anisotropic conductivities. Their results indicate the north-south electric field perturbations decay more rapidly with latitude in the evening than in the morning sector as a result of the longitudinal asymmetry in gradient of ionospheric conductivity. In the simplest case, for uniform ionospheric conductivities, their computations near subauroral latitudes indicate a decrease in the north-south electric field proportional to $L^{1.4}$. For realistic conductivity distributions, the electric field decrease with latitude is larger in the evening sector than in the morning sector. For a typical substorm the latitudinal variations were found to be proportional to $L^{2.8}$ and $L^{1.8}$, in the evening and morning sectors, respectively. Furthermore, these variations increase with the intensity of the field-aligned currents in the equatorward side of the auroral oval. If we use the Millstone Hill measurements at the two invariant latitudes shown in Figure 6, we get a southward electric field perturbation proportional to about $L^{2.2}$ in the dusk sector. This would give an amplitude of about 1 mV/m at the latitude of Arecibo, which is within the experimental error. These results indicate that the north-south component at middle and low latitudes is smaller than that predicted by the homogeneous conductivity case, in agreement with the computations of Kamide and Matsushita [1981]. From our data, we cannot estimate the latitudinal decrease for the north-south electric field in the morning sector.

Additional studies of the latitudinal variation of the north-south component of the ionospheric electric field were performed by Spiro *et al.* [1981] and Tsunomura and Araki [1984]. The results from these studies cannot be related directly to our observations, but both are consistent with the experimental data and previous theoretical results indicating that the zonal electric field perturbations penetrate more efficiently into the low-latitude ionosphere than the meridional electric fields. However, more detailed simulations are necessary to better understand this electric field mapping process.

3.3. Thermospheric Effects

Blanc and Richmond [1980] showed that changes in the global thermospheric circulation from storm-time Joule heating can result in significant changes in the middle- and low-latitude ionospheric electric fields. The occurrence of disturbance dynamo electric field effects with a latitude-dependent time delay of a few hours or more [Blanc and Richmond, 1980] has been detected at middle, low, and equatorial latitudes [Blanc, 1983; Fejer *et al.*, 1983; Mazaudier *et al.*, 1985; Ganguly *et al.*, 1987]. The mid- and low-latitude electric fields predicted by the disturbance dynamo model are poleward at all local times [Blanc and Richmond, 1980]. On the other hand, at very low latitudes the daytime drifts have a small equatorward component. Disturbance dynamo zonal electric fields are westward during the day and eastward at night, that is, have the same sign as the perturbation electric fields associated with a decrease in convection. As a result, it is often difficult to separate the electric field perturbations due to these two processes. Although we have not done a detailed study of disturbance dynamo effects in this paper, it is possible that this mechanism was responsible for the slowly varying departures from the quiet-time patterns over both Arecibo and Jicamarca. For example, this explanation is consistent with Jicamarca zonal electric field data between about 18–22 UT on January 18 and 17–23 UT on January 19, and also with the large postmidnight Arecibo westward drifts.

4. CONCLUSIONS

We have examined an extensive data set of ionospheric electric field measurements that show very clear examples of the perturbation of the mid-latitude, low-latitude, and equatorial electric field associated with the high-latitude current systems. The equatorial observations, which have excellent time resolution, confirmed that the zonal electric field perturbations driving the F region vertical plasma drifts and the equatorial electrojet occur simultaneously on a global scale. These IMF-driven processes affect simultaneously the high-, middle-, and low-latitude ionosphere. As reported previously, we have seen that the largest zonal electric field perturbations occur in the midnight-dawn sector. We also show that large eastward electric field perturbations can occur in the equatorial region over a longitudinal range of at least 40° with no corresponding signatures in the same longitudinal sector at middle and low latitudes. The low and equatorial ionospheres are considerably better shielded from meridional electric field perturbations than from zonal electric field fluctuations. The low-latitude meridional component is probably also affected by disturbance dynamo processes.

We have compared in detail our data with results from a number of global convection models. However, there are great difficulties that make this comparison far from trivial. From the experimental aspect these are, for example, the separation of magnetospheric electric field effects from the (quiet or disturbance) dynamo variation, the accuracy, the relatively long integration times, and the absence of significant longitudinal coverage from the middle- and low-latitude data. On the other hand, the model inputs such as the polar cap potential drop, ionospheric conductivities, etc., are highly idealized. Nevertheless, the numerical models can explain several aspects of the data. They predict the correct daily variation of the electric field perturbations for increases and decreases in the polar cap potential drop, and the occurrence of the largest low-latitude zonal electric field perturbations in the midnight-dawn sector. The latitudinal variation of the zonal electric field perturbations is also in reasonably good agreement with the observations. The models cannot explain the highly asymmetric response of the zonal electric field perturbations to sudden increases and decreases in the potential drop. It is also not completely clear why the equatorial zonal

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- M. A. Abdu and J. H. A. Sobral, INPE, Cp 515, 12200 São José dos Campos, São Paulo, Brazil.
- R. Burnside and C. A. Tepley, Arecibo Observatory, P. O. Box 995, Arecibo, PR 00613.
- O. de la Beaujardiere, Radio Physics Laboratory, SRI International, 333 Ravenswood Ave., Menlo Park, CA 94025.
- B. G. Fejer, CASS, Utah State University, Logan, UT 84322-4405.
- J. A. Holt, Haystack Observatory, Massachusetts Institute of Technology, Westford, MA 01886.
- Y. Kamide, Faculty of Science, Kyoto Sangyo University, Kamigamo, Kita-ku, Kyoto 603, Japan.
- M. C. Kelley, School of Electrical Engineering, Cornell University, Ithaca, NY 14853.
- R. Lepping, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.
- C. Senior, CNET/CRPE, 4, Avenue de Neptune, F-94107 St.-Maur des Fosses, CEDEX, France.
- R. F. Woodman, Instituto Geofísico del Peru, Apartado 374, Lima 100, Peru.

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