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Low and mid-latitude ionospheric electric fields during the January 1984 GISMOS campaign

Bela G. Fejer, Utah State University
M. C. Kelley
C. Senior
O. de la Beaujardiere
J. A. Holt, et al.

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This paper examines in detail the electrical coupling between the high-, middle-, and low-latitude ionospheres during January 1984, using interplanetary and high-latitude electric field and current data together with F region plasma drift measurements from the EISCAT, Sondre Stromfjord, Millstone Hill, Saint-Santin, Arecibo, and Jicamarca radars. We study the penetration of both the zonal and meridional electric field components of high-latitude origin into the low-latitude and equatorial ionosphere. 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 Maisushita, 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]; Alcaydé 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-
latitude electric fields and currents. These observations are then compared in detail with numerical studies of global electric fields.

2. ELECTRIC FIELD RESULTS

In this section we present the electric field measurements made by the EISCAT, Sondre Stromfjord, Millstone Hill, Saint-Santin, Arecibo, and Jicamarca radars, and also some ionosonde and magnetic field data obtained during the January 1984 GISMOS campaign. We study most closely the equatorial, middle-latitude, and low-latitude results, but will also introduce the high-latitude electric and magnetic field data to determine their effects on the electric field perturbations (relative to the quiet-time values) at lower latitudes.

2.1. Radar Operating Modes

During this campaign, extensive incoherent scatter radar measurements were performed [e.g., de la Beaujardiere et al., 1987a,b] in the F region (between about 200 and 500 km in altitude). We will discuss only the cross-field ion plasma drift measurements which are related to the perpendicular component of the ionospheric electric field through \( E = B \times V_d / B \).

The EISCAT radar (69.6° N, 19.2° W) operated with the CP3 mode elevation scans in the magnetic meridian with a time resolution of 30 min, and a latitudinal coverage from 61° to 72° invariant latitude [Alcyadé et al., 1986; Senior and Blanc, 1987]. The Sondre Stromfjord radar (67.0° N, 51.0° W) measurements were made between about 68° and 80° invariant latitude with a cycle time resolution of about 17 min [de la Beaujardiere et al., 1987a]. The operating mode consisted of measurements at nine fixed positions followed by a continuous elevation scan from north to south in the magnetic meridian. The Millstone Hill radar (42.6° N, 71.5° W) was operated on an 180° azimuthal scan at an elevation of 4° [Holt et al., 1984, 1985] covering the invariant latitudes between 55° and 65° with a time resolution of about 30 min. The Arecibo radar (18° N, 67° W; magnetic dip 50° N) scanned in azimuth over 360° at a fixed elevation of about 75°, with a cycle time of about 16 min [e.g., Behnke and Harper, 1973]. The Arecibo drift measurements assume constant and spatially uniform drifts over the whole scan. The Saint-Santin radar (44.6° N, 2.2° E) measured only the zonal component of the F region plasma drift in an invariant latitude of 44° [e.g., Blanc and Amayenc, 1979]. The Jicamarca radar (12.0° S, 76.9° W; magnetic dip 2° N) was pointed perpendicular to the Earth’s magnetic field and measured only the F region vertical plasma drift [Woodman, 1970].

2.2. Equatorial Observations and the Relationship With the IMF and High-Latitude Convection Measurements

The equatorial plasma drift measurements at Jicamarca provide a very accurate measure of the ionospheric electric fields when the radar beam is pointed perpendicular to the Earth’s magnetic field in the F region. Over Jicamarca an upward plasma drift of 40 m/s corresponds to an eastward electric field of about 1 mV/m. The accuracy of these measurements is about 2 m/s, corresponding to a zonal electric field of about 0.05 mV/m, and the integration time is typically 5 min [e.g., Woodman, 1970]. The high accuracy is also a result of the small geophysical noise level on the vertical velocity component [Gonzales et al., 1983]. The variation of this electric field component with magnetic activity has been studied so extensively that a considerable knowledge base exists [Fejer et al., 1979; Gonzales et al., 1979; 1983; Kelley et al., 1979; Fejer, 1981, 1986; Spiro et al., 1988]. We therefore concentrate first on the equatorial zonal electric field measurements.

Figure 1 shows the auroral electrojet indices, the north-south component of the IMF measured by the IMP-J satellite, the horizontal component of the magnetic field over Huancayo, Peru (magnetic dip 1.2°N), and the Jicamarca zonal electric fields during a 48-hour period. The Jicamarca data show a large eastward electric field perturbation relative to the quiet-time pattern starting at about 1020 UT on January 18 when \( B_z \) turned sharply northward. Then a very unfortunate data gap occurred, after which \( B_z \) was steadily northward for over three hours. Eastward electric field perturbations are commonly observed in this time sector over Jicamarca following sudden northward IMF changes that occur after about an hour or longer of southward IMF \( B_z \) [e.g., Kelley et al., 1979; Fejer, 1986]. Substorm activity is often curtailed when \( B_z \) turns northward suddenly. Both of these characteristics are exhibited in the 1020–1200 UT period.

The Sondre Stromfjord radar data, shown in Figure 2, and in more detail by de la Beaujardiere et al. [1988], confirm this interpretation. When \( B_z \) turned southward at around 0700 UT, the east-west velocity grew steadily more eastward, indicating a strengthening of the sunward convection in the prenoon auroral oval. At about 1020 UT, when \( B_z \) abruptly turned positive, the convection over Sondre Stromfjord began to decay with roughly a one-hour time constant. The time period during which the southward auroral oval electric field (eastward drift) decreased to zero matches exactly the eastward perturbation at Jicamarca. The event is very much reminiscent of that of April 13, 1978 [Gonzales et al., 1979], in which a northward IMF turning generated a simultaneous "bise-out" in the auroral zone convection in the Alaskan sector and an eastward electric field turning at Jicamarca. The other characteristics of the high-latitude electric field data shown in Figure 2 will be discussed later.
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, an event 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 only say 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; Heeels 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...
by the high-latitude magnetic field indices (see Figure 1), occurred simultaneously over a range of at least 40° in longitude at the equator.

Figure 3 also shows a series of simultaneous perturbations in the Jicamarca plasma drift velocity, the height $h'F$ over Fortaleza, and the magnetic field data from Trivandrum starting at about 0530 UT on January 19. The first perturbation had a small amplitude in the Jicamarca vertical drift data, but is clearly seen in the data from the other two equatorial stations. The large upward drift velocity perturbation over Jicamarca about one hour later (at about 0640 UT) was correlated with a simultaneous decrease in the horizontal component of the magnetic field over Trivandrum which corresponds to a westward electric field perturbation. These data illustrate the local time dependence of the low-latitude electric field perturbations of high-latitude origin [Fejer, 1986]. Note, for example, that the Jicamarca vertical drift perturbations on the nightside between 07 and 08 UT (02-03 LT) had a magnitude of about 50 m/s (corresponding to an eastward electric field of about 1 mV/m). On the other hand, the amplitude of the perturbation on the dayside was less than about one half of the maximum daytime $\Delta H$ amplitude (when the magnetospheric current contribution, indicated by $Dst$, is removed), corresponding to a westward electric field perturbation of less than 0.25 mV/m.

**2.3. Relationship Between the Zonal Electric Field Perturbations at Middle and Low Latitudes**

For clarity, we will discuss the zonal electric field (i.e., upward/northward drifts) and south-ward electric fields (eastward drifts) separately. As mentioned previously, electric field measurements at mid-latitudes were made with the Millstone Hill, Arecibo, and Saint-Santin radars. The Millstone Hill radar also provided the high-latitude ($\Lambda = 64^\circ$) observations shown in Figure 2. We will now compare these measurements with the Jicamarca results.

Figure 4 shows the variation of the upward/northward plasma drift velocity at Jicamarca, Arecibo, and Millstone Hill, and the high-latitude and interplanetary magnetic field data during a 48-hour period. The Arecibo and Millstone Hill data were averaged for 1 hour and 1.5 hours, respectively, to reduce the statistical fluctuations. The typical error bars for the data from these stations are about 5 m/s and 10 m/s, respectively. The three radars are nearly in the same local time sector. The smooth curves superposed on the Millstone Hill local data correspond to the average empirical quiet-time winter solstice model for $Kp = 0$ [Wand and Evans, 1981], whereas the Arecibo quiet-time pattern corresponds to the local winter average for $Kp \leq 2^+$ [Ganguly et al., 1987]. Over Arecibo and Millstone Hill an eastward electric field of 1 mV/m corresponds to a northward drift, perpendicular to the magnetic field, of about 27 and 20.6 m/s, respectively.

Due to the great degree of variability in the Millstone Hill and Arecibo data sets there are only two periods when something significant can be said. The first is 00-01 UT on January 19 when very large perturbations were seen at Jicamarca and Fortaleza but not over Millstone Hill ($\Lambda = 55^\circ$) or Arecibo. This is significant (and mysterious) since the magnitude and spikelike nature of the event should have made it detectable. No such perturbation was observed even on the original Arecibo data obtained with an integration time of 16 min. The equatorial electric field perturbation occurred during a period of large westward electric field north of Millstone Hill ($\Lambda = 64^\circ$). The other time period worth discussing is 06-10 UT on January 19 when eastward perturbations were detected at Millstone Hill, Arecibo, and Jicamarca. Electric field
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 field perturbations 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 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
important source of meridional electric field perturbations. At low latitudes disturbance dynamo effects seem to be an efficient down to the equatorial ionosphen. The high- and mid-latitude meridional electric field perturbations seem to be driving mechanisms. The zonal electric field perturbations plasma drifts. On these occasions, the shift from eastward to occur when there are large changes in convection and penetrate have different latitudinal and longitudinal dependence and low and equatorial latitudes do not occur simultaneously and hours later than at mid-latitudes, and led to increased westward drifts occurred earlier than during quiet periods. The penetration of high-latitude electric fields to middle and westward drifts at earlier local times in the postmidnight sector. The data shown in Figure 7 are in good agreement with the results by Ganguly et al. [1987] for $2r < Kp < 4$. These authors suggested that disturbance dynamo effects are the main source for meridional electric field perturbations over Arecibo during active periods. Therefore, the amplitudes of meridional electric field perturbations associated with enhancements of the high-latitude ionospheric currents decrease significantly with latitude. At Arecibo these electric field (zonal drift) perturbations have small amplitudes relative to both the quiet-time and the disturbance dynamo values, and at equatorial latitudes these perturbations are usually undetected.

2.5. Summary of Experimental Results

1. As reported before, large zonal electric field perturbations were observed simultaneously over a large range of latitudes and longitudes. The zonal electric field perturbations are westward during the day and eastward at night. The amplitudes are largest in the postmidnight sector when magnetic activity is decreasing.
2. In an entirely new result, a large eastward electric field perturbation observed over Jicamarca and Fortaleza in the dusk sector seemed unrelated to similar changes at higher latitudes, at least in the American sector.
3. Meridional electric field perturbations observed simultaneously at high and middle latitudes as a result of convection electric fields during active periods seem to have very small amplitudes in the low-latitude ionosphere.
4. The main effect of magnetic activity on the zonal plasma drift at low latitudes occurred in the postmidnight sector, a few hours later than at mid-latitudes, and led to increased westward plasma drifts. On these occasions, the shift from eastward to westward drifts occurred earlier than during quiet periods.
5. The zonal and north-south electric field perturbations at low and equatorial latitudes do not occur simultaneously and have different latitudinal and longitudinal dependence and driving mechanisms. The zonal electric field perturbations occur when there are large changes in convection and penetrate efficiently down to the equatorial ionosphere. The high- and mid-latitude meridional electric field perturbations seem to be caused mostly by the penetration of convection electric fields. At low latitudes disturbance dynamo effects seem to be an important source of meridional electric field perturbations.

3. DISCUSSION

The penetration of high-latitude electric fields to middle and low latitudes has been examined in a number of theoretical and numerical studies [Wolf, 1970; Nopper and Carovillano, 1978; Nisbet, 1978; Maekawa, 1980; Kamide and Matsushita, 1981; Spiro et al., 1981; 1988; Senior and Blanc, 1984, 1987] based on the convection model approach introduced by Vasyliunas [1970]. The global ionospheric currents and electric fields are obtained by applying either an electrostatic potential drop across the polar cap or field-aligned currents on a two-dimensional (thin shell) ionosphere, with assumed models of ionospheric conductance. In this section we will compare our observations with previous results and with predictions from numerical models.

The models to be examined in more detail here are the Senior-Blanc semiempirical linear convection model [Senior and Blanc, 1984], the Rice University convection model (RCM) [e.g., Wolf et al., 1978; Spiro et al., 1988], and the model described by Tsunomura and Araki [1984]. The Rice model has recently been extended to low latitudes by introducing realistic equatorial boundary conditions and a denser grid at low latitudes, and it has been used to examine neutral wind effects on the low-latitude electric fields [e.g., Spiro et al., 1988]. The work of Tsunomura and Araki [1984] was concerned mainly in explaining the preliminary impulse of geomagnetic sudden commencement. However, similar models, using the field-aligned currents and realistic ionospheric conductivities, have been used by a number of other authors to study the middle- and low-latitude ionospheric ionospheric currents and field-aligned currents on the geomagnetic sudden commencements [e.g., Maeda and Maekawa, 1973; Kamide and Matsushita, 1981].

3.1. Daily Variation of the Perturbation Electric Fields

Figure 8 shows the variations of the equatorial zonal electric fields as a function of local time obtained from the three numerical studies mentioned above. The results from the Senior-Blanc and from the Rice models are the initial response corresponding to a sudden increase in the polar cap potential drop by 100 kV. The pattern from the Tsunomura-Araki model, derived with the assumption that the field-aligned currents do not affect the conductivity in the source region, was obtained by multiplying their electric field response curve by a factor of 10 to correspond to a magnetic field perturbation of 100 nT at the dayside equator. We have also changed the sign of the field pattern derived by Tsunomura and Araki [1984] to be consistent with an increase in the polar cap potential drop.

Figure 8 shows that the three models give essentially the same initial time response for the equatorial electric field resulting from a sudden increase in the polar cap potential drop (or in the high-latitude field-aligned currents) with eastward perturbations in the dayside and eveningside and westward perturbations in the morningside. The eastward electric field perturbations occur over a larger time sector as a
The numerical models suggest that the low-latitude response to potential drop. This increase in \( \Phi_0 \) did not produce simultaneous eastward electric field perturbations (see Figure 1). 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 \( \Phi_s \) 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 potential drop. This increase in \( \Phi_0 \) 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 6, in agreement with the absence of corresponding electric field perturbations in the equatorial data. In contrast to the usually small effects associated with south-ward \( B_z \) 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 asymmetric response and the long-lasting perturbations associated with sudden decrease in \( \Phi_0 \) 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 eastward 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 \( \Phi_0 \) 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 (\( \Lambda = 64^\circ \)). 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 \( \Phi_0 \) derived by Senior and Blanc [1987] and shown in Figure 10 would predict a westward electric field perturbation...
perturbations at the equator are better correlated with changes in the high-latitude current system usually responds with a time lag. Our results indicate that zonal electric field perturbations at the equator are better correlated with changes in the polar cap potential drop than with variations in the ionospheric conductivity. These results illustrate both the progress in the simulation studies and their present limitations. The responses of the electric field to simple changes in the polar cap potential drop are well reproduced by the models. However, this is not the only high-latitude parameter that should have a strong effect on electric field penetration even if we neglect neutral wind effects. Ionospheric conductivity, for example, plays an important role in the amplitude of the electric field perturbations and in the shielding time constant [Jaggi and Wolf, 1973; Siscoe, 1982]. Large longitudinal conductivity gradients in the dusk sector might explain the absence of an eastward electric field perturbation over Millstone Hill and Arecibo at about 2400 UT on January 18. There are other effects such as changes in the radius of the polar cap (corresponding to increase or decrease of the magnetic flux in the tail lobe), and the release of plasma down in the tail occurring in substorms which must also cause electric field penetration effects (R. Wolf, private communication, 1988). These last two effects have not been modeled realistically so far.

The east-west drifts observed with the EISCAT, Scandinavian Twin Auroral Radar Experiment (STARE), Millstone Hill, and Saint-Santin radars during the January 1984 campaign were compared with the predictions of the Senior-Blanc model [Senior and Blanc, 1987]. They showed good agreement at high-latitude stations, but there were some significant disagreements at the middle latitude particularly for the period between about 1800 and 2100 UT where the model predicted a northward electric field of about 3.5 mV/m for Saint-Santin and the observations showed a southward electric field of about 4 mV/m. It was suggested that this disagreement could have been caused by a local electric field source. As mentioned previously, meridional convection electric field perturbations usually do not seem to penetrate efficiently into the low-latitude ionosphere.

3.2. Latitudinal Variation of the Perturbation Electric Fields

Mozer [1970] showed that, assuming a centered dipole geomagnetic field with equipotential field lines, the zonal and meridional ionospheric projections of an electric field independent of the radial distance in the equatorial plane would vary as $L^{3/2}$ and $2L(L-3/4)^{1/2}$, respectively. A similar expression for the latitudinal variation of the electric field was used by Volland [1975]. We use these simple formulas only as a general guide since there is no theoretical reason to expect a uniform electric field in the magnetospheric equatorial plane.

So far, very few model studies have examined the longitudinal variation of perturbation electric fields of magnetospheric origin. Senior and Blanc [1984] calculated the zonal electric field initial time responses at Millstone Hill and at the equator for a sudden increase in the polar cap potential drop of 100 kV. Their results are shown in Figure 10. Here we have used a vertical scale proportional to $L^{3/2}$ so that electric field perturbations following this mapping would have the same amplitudes (say, in centimeters) at different latitudes. No clear latitudinal variation can be determined for the high-latitude stations, partly due to the uncertainty of Millstone Hill and Arecibo measurements. However, the perturbation electric field starting at about 04 UT on January 19 seems to follow the $L^{3/2}$ mapping of Mozer and the calculations of Senior and Blanc [1984] for a sudden decrease in the polar potential drop. Figure 10 shows the latitudinal variation of the electric field magnitude that was observed with a sudden northward $B_z$ turning. Assuming the theoretical mapping shown in Figure 10, the large perturbation shortly after 00 UT on January 19 would correspond to an eastward electric field of about 6 mV/m over Millstone Hill and about 2 mV/m over Arecibo. In spite of the relatively long integration time used by the Millstone Hill radar, an electric field perturbation of this magnitude would have produced a considerably larger effect than that was observed. As mentioned previously, the Arecibo observations were actually made with an integration time of about 16 min and would, therefore, also have detected a much larger effect if this perturbation had occurred overhead.

The results above indicate that two important points must be

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig11.png}
\caption{Zonal electric field perturbations obtained by subtracting the quiet-time patterns from the measured electric field.}
\end{figure}
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 [1977] and the Millstone Hill radar [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 ionospheric conductivities. These 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 L1.4. For realistic conductivity distributions, the electric field decrease with latitude is larger in the morning sector than in the northward sector. For a typical substorm the latitudinal variations were found to be proportional to L2.8 and L1.8, 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 L2.2 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 smaller 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 north-south 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...
electric field perturbations associated with decreases in the polar cap potential drop triggered by sudden northward \( B_z \) changes last considerably longer than those associated with sudden increases in convection. The longitudinal variation in the meridional electric field perturbations particularly at low and equatorial latitudes is not well explained by the models either.

There are also a number of processes that have not been examined in detail as far as the low-latitude electric field perturbations are concerned. They include thermospheric effects, storm-generated electric fields, the effect of gravity waves, of disturbance dynamo electric fields, IMF \( B_y \) effects, longitudinal effects, the relationship between the drift velocity perturbations parallel and perpendicular to the Earth's magnetic field, and others. The extensive experimental and modeling studies using coordinated World Day observations should hopefully provide some clues for these questions.

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REFERENCES


