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Vertical Motions of the Midlatitude F_2 Layer during Magnetospheric Substorms

C. G. PARK

Radioscience Laboratory, Stanford University
Stanford, California 94305

C.-I. MENG

Space Sciences Laboratory, University of California, Berkeley 94720

Ground-based ionosonde records from midlatitude stations during winter nights are used to study vertical motions of the F_2 layer associated with magnetospheric substorms. The results show that during substorms the F_2 layer is lifted upward in the pre-midnight sector and pushed downward in the post-midnight sector. These motions are interpreted in terms of **E**×**B** drifts, the electric field being eastward on the eveningside and westward on the morningside. The results emphasize the importance of substorm effects on the midlatitude F region and the potential of ground-based HF sounding techniques in studying magnetospheric substorms.

In recent years a great deal of emphasis has been placed on measuring electric fields in the ionosphere and the magnetosphere. Various techniques that have been used include probes flown on rockets [*Mozer and Bruston*, 1967; *Aggson*, 1969], satellites [*Maynard and Heppner*, 1970; *Gurnett*, 1970], and balloons [*Mozer and Serlin*, 1969], drift measurements of whistler ducts [*Carpenter*, 1970*a*] and barium clouds [*Haerendel and Lüst*, 1970; *Wescott et al.*, 1970], incoherent backscatter radar [*Balsey and Woodman*, 1969; *Behnke*, 1970], and satellite measurements of energetic particles [*Winckler*, 1970]. Although only limited observations have been made to date because of experimental difficulties and the limited applicability of the techniques, preliminary results do emphasize the importance of electric fields in magnetospheric and ionospheric dynamics.

Of particular interest in magnetospheric physics is the global distribution of electric fields associated with magnetospheric substorms. There is evidence that substorm electric fields are important not only in auroral latitudes, but also in middle and low latitudes. For example, whistler results showed that substorm electric fields of ~0.5 mv/m penetrate deep within the plasmasphere [*Carpenter and Stone*, 1967; *Carpenter*, 1970*b*; *Park and Carpenter*, 1970]. In the ionosphere the height of the F_2 layer has been known to change considerably during geomagnetic disturbances, and a number of authors have attributed this effect to electromagnetic drift [*Martyn*, 1953; *Kamiyama*, 1956; *Maeda and Sato*, 1959; *Kohl*, 1960; *Becker et al.*, 1965; *Rüster*, 1965, 1969; *Bullen*, 1969; *Evans*, 1970; *VanZandt et al.*, 1971; *Park*, 1971]. Unfortunately, no systematic study has yet been made of the response of the F_2 layer to isolated magnetospheric substorms. The present study was initiated to make detailed observations of the F_2-layer motions during isolated substorms. The results show that during winter nights substorm-associated motions are clearly indicated in ground-based ionosonde records and that a network of sounders can provide much information about the morphology of substorm electric fields that are thought to be responsible for the F_2-layer motions. In this paper we report our initial results for geomagnetic midlatitudes.

The substorms discussed are isolated and weak enough in intensity for appreciable magnetic bays to occur only near the midnight portion of the auroral oval. (The maximum value of the 3-hour Kp index during the events reported here ranges from 2+ to 4+.) These ionospheric substorms (*Akasofu* [1968] suggested this term for ionospheric disturbances associated with magnetospheric substorms) should be distinguished from much more severe and prolonged ionospheric storms that last for several days and apparently involve significant changes in the neutral atmosphere [e.g., *Obayashi and Matuura*, 1970]. It is hoped that detailed studies of ionospheric substorms will shed new light on classical ionospheric storm phenomena, much as the concept of the magnetospheric substorm has helped in studies of geomagnetic storms [*Akasofu*, 1968].

OBSERVATIONS

Figure 1 shows the location of the midlatitude ionosonde stations (Wallops Island, Stanford, and Point Arguello) and auroral-latitude magnetic observatories (Great Whale River, Meanook, and College) used in this study. Magnetograms from the auroral-latitude stations were used to identify magnetospheric substorms, and the earliest sign of magnetic disturbance was taken as the substorm 'onset.' (Magnetograms from Leirvogur, Iceland, were also consulted, although they are not shown in the illustrations.) It is sometimes impossible to determine the onset time precisely because of the gradual commencement of the disturbance or because several substorms overlap in time (see Figure 7). The ionosonde records were scaled for the F-layer virtual height $h'F$ at an appropriate fixed frequency (1.6–2.0 MHz). This frequency was selected for each station and each event so that the ionogram traces were clearly visible and essentially horizontal near the frequency of measurement. In some instances true height analysis was performed to obtain the bottomside $N(h)$ profile.

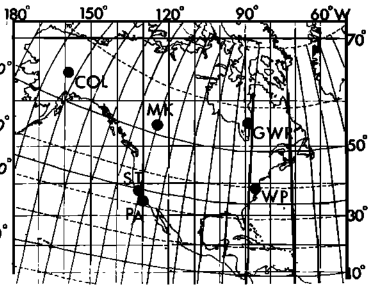

Fig. 1. Map of North America showing the location of ionosonde stations, Wallops Island (WP), Stanford (ST), and Point Arguello (PA), and magnetic observatories, Great Whale River (GWR), Meanook (MK), and College (COL). Geomagnetic latitudes are shown at left and geographic latitudes at right.

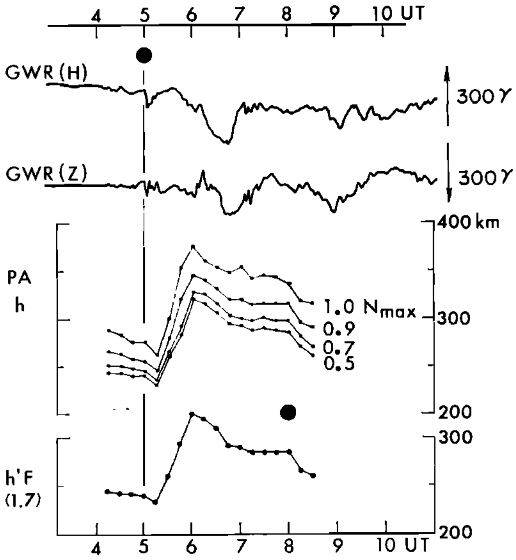

Fig. 2. Example of the F_2-layer motion at Point Arguello during a substorm on December 25, 1966. At the top are transcriptions of H- and Z-component magnetograms from Great Whale River. The vertical line at 0500 UT indicates the time of substorm 'onset' as defined in the text. In the middle are contours of constant normalized electron concentration obtained from bottomside ionograms. At the bottom is a plot of the F-layer virtual height at 1.7 MHz. The large dots indicate local standard midnight.

Figure 2 shows an example of F_2-layer motion during a substorm on December 25, 1966. The H- and Z-component magnetograms at Great Whale River are shown at the top, the arrows indicating the scale and the direction of increasing magnitude. A substorm onset occurs at 0500 UT as indicated by the vertical line. The large dots indicate local standard midnight at the observing stations. In the middle of the figure are plotted true heights of the F layer over Point Arguello at the peak electron concentration and at constant fractions of the peak concentration. The bottom plot shows $h'F$ over Point Arguello measured at 1.7 MHz. A sudden and large upward motion of the F layer starting at 0515 UT (2115 Lst) is interpreted as the effect of an eastward electric field associated with the substorm. The apparent time delay of

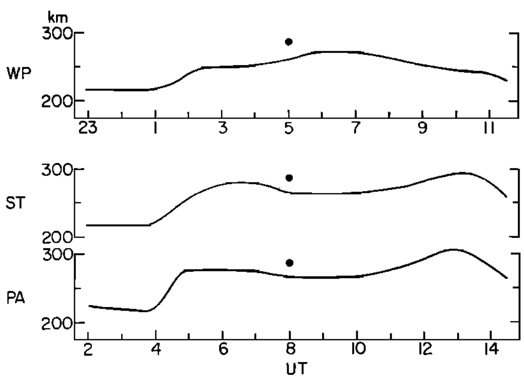

Fig. 3. Plot of the average quiet time behavior of the *F*-layer virtual height (measured at 1.6 MHz) over Wallops Island, Stanford, and Point Arguello for the period November 1968 to January 1969. The horizontal scales represent universal time, and local standard midnight is indicated by dots.

$\sim$15 min between the substorm onset and the start of the lifting of the ionosphere may be due to the longitudinal separation between the observing stations.

Although the peak electron concentration (not shown in the figure) and the shape of the layer (as indicated by the separation between contours of constant normalized concentration) change during the substorm, *h'F* appears to be a good indicator of the motions of the *F* layer. This has been found to be true for the midlatitude nighttime *F* layer in all the substorm periods studied to date. We therefore show only *h'F* for some of the cases presented below. It should be remembered, however, that small changes in *h'F* can result from changes in the shape of the layer while the height of the peak concentration remains constant.

The rest of the examples come from December 1968. As an indication of the quiettime behavior of the F_2 layer over the three ionosonde stations, Figure 3 shows the average behavior of *h'F* measured at 1.6 MHz during 5–8 of the quietest nights in November and December 1968 and January 1969. The quiet nights were chosen so that the maximum 3-hour *Kp* index did not exceed 1+. The horizontal scales represent universal time, and local standard midnight is indicated by the dots.

Figure 4 illustrates the effects of substorms when local time at the observing ionosonde is past midnight. The format is similar to that of Figure 2, but in this case only *h'F* is shown. The arrow for the *D*-component magnetogram shows the direction of increasing eastward field. When the first substorm occurs near 0900 UT, *h'F* at Point Arguello decreases, apparently because of a westward electric field. As the substorm subsides, *h'F* recovers to the quiettime level (compare with Figure 3), but the second substorm starting at 1200 UT causes *h'F* to decrease again.

Figure 5 shows two isolated substorms, one occurring at Wallops Island before local midnight and the second after midnight. Both true height contours and *h'F* at Wallops Island are plotted in the format of Figure 2. It is clear that the F_2 layer is lifted up during the first substorm in pre-midnight hours and is pushed down during the second substorm in post-midnight hours; this lifting up and pushing down corresponds to the effects of an eastward and a westward electric field, respectively. Note that the second substorm develops rather gradually; hence its onset time is somewhat arbitrary.

At the bottom of the figure, *h'F* at Stanford shows a sharp decrease during the second sub-

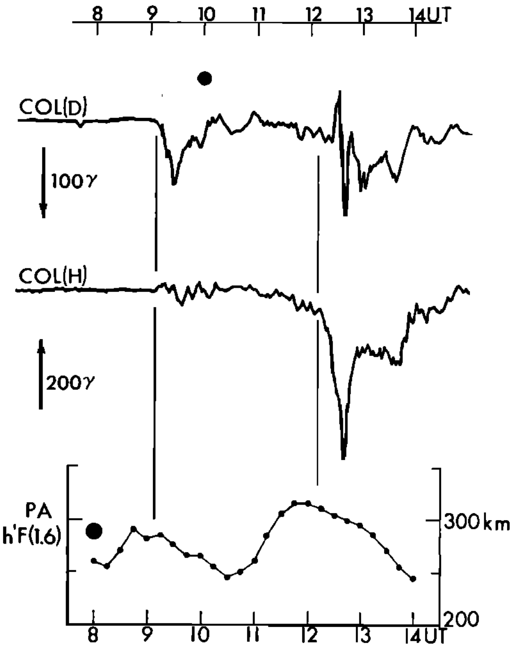

Fig. 4. Example of substorm behavior in the morning sector on December 29, 1968. The format is similar to that of Figure 2.

storm. The similarity between *h'F* curves for Wallops Island and Stanford suggests that a large-scale (>45° in longitude) electric field is involved. During the substorm starting at 0300 UT, there is evidence that the *F* layer over Stanford was lifted by an eastward electric field. The data are not shown in the figure because the effect is somewhat obscured by the diurnal behavior. The diurnal curve for *h'F* at Stanford (Figure 3) shows a rapid increase near 0400 UT, presumably due to recombination and the reversal of neutral wind direction [*Cho and Yeh*, 1970].

In Figure 5 the differences between Meanook and Great Whale River magnetograms can be explained in terms of geographic separation between the two stations and the localized nature of the auroral electrojet [*Akasofu and Meng*, 1967]. This example illustrates why multiple stations must be used in studying substorm effects.

Figure 6 represents a relatively complex situation. The magnetograms indicate continuous activity throughout the period shown, and the event near 1000 UT is not an isolated substorm as in earlier cases. Nevertheless, it is clear that the ionosphere is pushed downward at both Stanford and Point Arguello during the substorm, the behavior again corresponding to the effects of a westward electric field in the morning sector. As the substorm subsides near 1200 UT, *h'F* starts to recover. The fluctuations in *h'F* before 1000 may be associated with low-level magnetic activity. Open circles are used

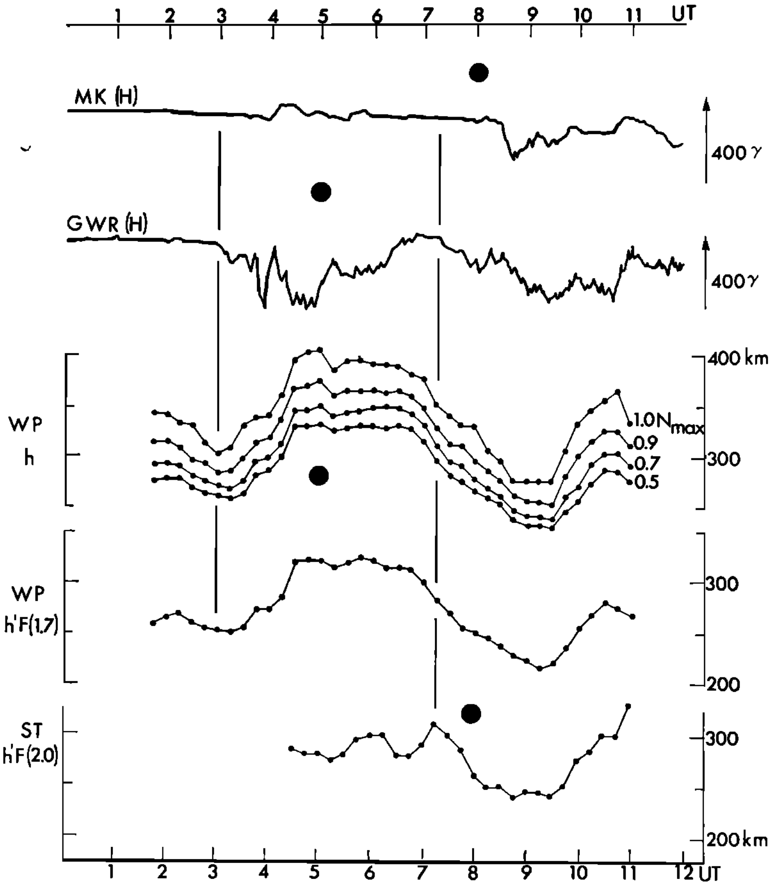

Fig. 5. Example of two isolated substorms on December 3, 1968, showing different ionospheric responses in the evening and the morning sector. The format is similar to that of Figure 2.

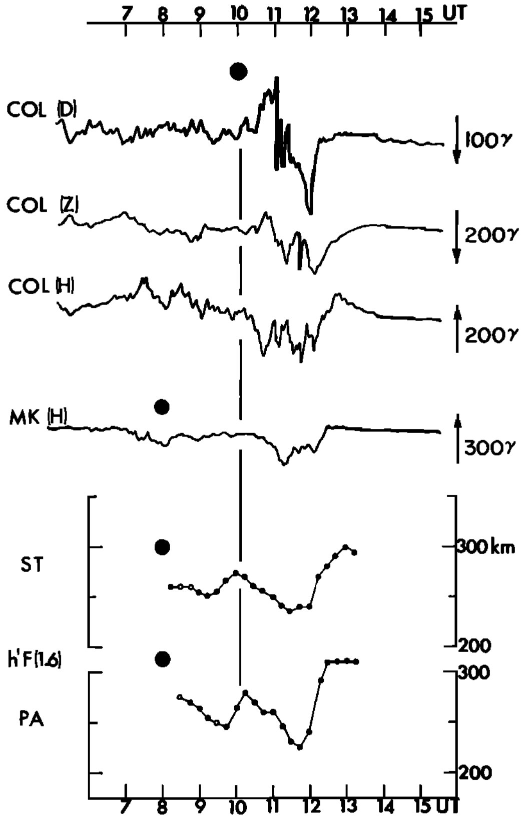

Fig. 6. Example of a substorm on December 10, 1968, superimposed on continuous low-level activity. The format is similar to that of Figure 2.

for several *h'F* data points measured at frequencies between 1.7 and 1.8 MHz when the *F*-layer trace does not extend to 1.6 MHz.

Finally, Figure 7 shows a case of continuous auroral-zone magnetic activity with no clearly identifiable individual substorms. The Wallops Island *h'F* data show some undulations, but the motion is generally upward before local midnight and downward after midnight. At $\sim$1000 UT, the magnetic activity ceases, and the ionosphere starts to recover.

Discussion

The previous section showed a close relation on an event to event basis between substorms and vertical motions of the F_2 layer. However, the height of the F_2 layer does not follow magnetic variations in detail, particularly in the later phases of substorms, because the auroral-zone magnetic variations may be caused by variations in electrical conductivity or motions of highly localized electrojet current systems that do not involve comparable variations in large-scale electric fields.

The direction of electric fields and the reversal near local midnight are consistent with other results [*Park and Carpenter,* 1970; *Park,* 1971]. If we assume that the F_2 layer moves essentially with the electromagnetic drift velocity when the layer is at high altitudes (say, $h_mF_2 > 300$ km), electric fields (east-west component) of several millivolts per meter are inferred from the motions reported here. These electric fields are of the same order of magnitude as the substorm electric fields deduced from whistlers [*Carpenter and Stone,* 1967; *Park and Carpenter,* 1970]. To determine electric fields from motions of the F_2 layer in a more quantitative way, it is necessary to solve time-dependent continuity equations including photochemical reactions, ambipolar diffusion, neutral air motions, and protonospheric fluxes. Such an effort is being undertaken. Important information on the neutral atmosphere and various photochemical reaction rates can be obtained from coordinated whistler observations of cross-*L* drifts in the magnetosphere and HF sounding of the underlying ionosphere.

We have presented only winter hemisphere results since substorm effects of the kind reported are not so easily detectable in the summer hemisphere. In summer nighttime the *F* layer decays continuously throughout the night

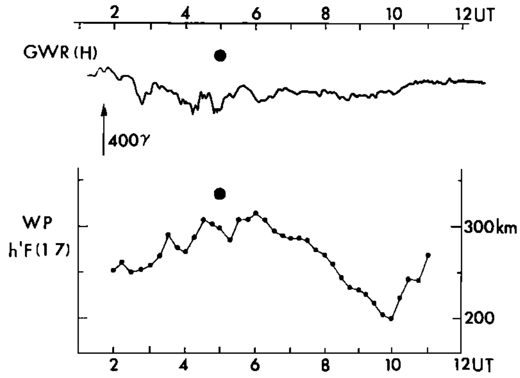

Fig. 7. Example of continuous magnetic activity with no clearly identifiable individual substorm on December 6, 1968. The format is similar to that of Figure 2.

and is controlled primarily by recombination and ambipolar diffusion. Thus, a given electric field may not produce the same observable effects in the two conjugate F regions.

Vertical motions of the F_2 layer are usually accompanied by changes in peak electron concentration and columnar content. There is, however, no simple relationship between the peak concentration N_mF_2 and the height of the peak concentration h_mF_2. For example, a decrease in h_mF_2 is frequently accompanied by an increase in both N_mF_2 and columnar content until h_mF_2 reaches a certain level, but below that level a further decrease in h_mF_2 causes a rapid decay of the F_2 layer. *Park* [1971] showed that this behavior could be explained qualitatively in terms of modulations of protonospheric fluxes by electric fields and height variations of recombination rate.

The results of the present study emphasize the importance of substorms in the midlatitude F region and the need for care in describing magnetic conditions when discussing ionospheric phenomena. In ionospheric research, the 3-hour Kp value of 4 is sometimes used as a demarcation between magnetically 'disturbed' and 'quiet' conditions. As pointed out earlier, the 3-hour Kp value did not exceed 4+ during any of the substorms shown in this paper. (For example, in the case of December 29 (Figure 4), the maximum 3-hour Kp index was only 2+.) Yet these substorms had significant effects in the F_2 layer. Since substorms of comparable intensity occur on the average several times a day, monthly median or average values of ionospheric parameters are influenced by any systematic substorm effects such as lifting of the F_2 layer in the evening sector and depression in the morning sector. A distinction should therefore be made between the monthly median behavior and the 'quiet-time' behavior of the F layer, at least in the winter hemisphere.

A number of authors have reported on anomalous motions of the F_2 layer at lower latitudes, which they attributed to neutral winds [*Behnke*, 1970; *Wright*, 1971; G. Nelson, private communication, 1970] and to equatorial electrojet [*Sato*, 1966]. Anomalous enhancements in nightglow intensity are also known to be closely associated with vertical motions of the F_2 layer [*Brown and Steiger*, 1967; *Gulledge et al.*, 1968; *Nichol*, 1970]. Certain classes of events appear to be limited to narrow latitude ranges [*Bellew and Silverman*, 1966; *Wright*, 1971]. Further correlative studies are needed to learn if and how these phenomena are related to substorm effects observed in midlatitudes.

CONCLUSIONS

Magnetospheric substorms are accompanied by large vertical motions of the nighttime F_2 layer in midlatitudes. The motion is upward in the evening sector and downward in the morning sector, with a transition near midnight. These motions are interpreted in terms of $\mathbf{E}\times\mathbf{B}$ drifts, and the inferred electric fields are eastward in the evening sector and westward in the morning sector. Ground-based HF sounding of the ionosphere can provide a powerful means of studying the electric field distribution associated with magnetospheric substorms.

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REFERENCES

Aggson, T. L., Probe measurements of electric fields in space, in *Atmospheric Emissions*, edited by B. M. McCormac and A. Omholt, p. 305, Van Nostrand Reinhold, New York, 1969.

Akasofu, S.-I., *Polar and Magnetospheric Substorms*, p. 73, D. Reidel, Dordrecht, Netherlands, 1968.

Akasofu, S.-I., and C.-I. Meng, Polar magnetic substorms in the evening sector, *J. Atmos. Terr. Phys., 29,* 1127, 1967.

Balsley, B. B., and R. F. Woodman, On the control of the *F*-region drift velocity by the *E*-region electric field: Experimental evidence, *J. Atmos. Terr. Phys., 31,* 865, 1969.

Becker, W., R. Rüster, and J. Klostermeyer, Experimental results on the dynamics of the *F* region, *Radio Sci., 69D,* 1083, 1965.

Behnke, R. A., Vector measurements of the ion transport velocity with applications to *F*-region dynamics, Ph.D. thesis, Rice Univ., Houston, Texas, 1970.

Bellew, W., and S. Silverman, General behavior of 6300 A [O I] at Sacramento Peak, New Mexico, *Planet. Space Sci., 14,* 407, 1966.

Brown, W. E., and W. R. Steiger, Ionospheric electron content and the [O I] 6300 A nightglow, *Nature, 216,* 47, 1967.

Bullen, J. M., Nighttime decreases in F_2 layer heights at near conjugate stations in low latitudes, *J. Atmos. Terr. Phys., 31,* 827, 1969.

Carpenter, D. L., Remarks on the groundbased whistler method of studying the magnetospheric thermal plasma, *Ann. Geophys., 26,* 363, 1970*a*.

Carpenter, D. L., Whistler evidence of the dynamic behavior of the duskside bulge in the plasmasphere, *J. Geophys. Res., 75,* 3837, 1970*b*.

Carpenter, D. L., and K. Stone, Direct detection by a whistler method of the magnetospheric electric field associated with a polar substorm, *Planet. Space Sci., 15,* 395, 1967.

Cho, H. R., and K. C. Yeh, Neutral winds and the behavior of the ionospheric F_2 region, *Radio Sci., 5,* 881, 1970.

Evans, J. V., The June 1965 magnetic storm: Millstone Hill observations, *J. Atmos. Terr. Phys., 32,* 1629, 1970.

Gulledge, J. S., D. M. Packer, S. G. Tilford, and J. T. Vanderslice, Intensity profiles of the 6300 A and 5577 A O I lines in the nightglow, *J. Geophys. Res., 73,* 5535, 1968.

Gurnett, D. A., Satellite measurements of DC electric fields in the ionosphere, in *Particles and Fields in the Magnetosphere,* edited by B. M. McCormac, p. 239, D. Reidel, Dordrecht, Netherlands, 1970.

Haerendel, G., and R. Lüst, Electric fields in the ionosphere and magnetosphere, in *Particles and Fields in the Magnetosphere,* edited by B. M. McCormac, p. 213, D. Reidel, Dordrecht, Netherlands, 1970.

Kamiyama, H., Ionospheric changes associated with geomagnetic bays, *Sci. Rep. Res. Inst. Tohoku Univ., Ser. 5, 7,* 125, 1956.

Kohl, H., Movement of the *F*-layer of the ionosphere during bay disturbances of the earth, *Arch. Elek. Übertr., 14,* 169, 1960.

Maeda, K. I., and T. Sato, The *F* region during magnetic storms, *Proc. IRE, 47,* 232, 1959.

Martyn, D. F., The morphology of the ionospheric variations associated with magnetic disturbances, 1, Variations at moderately low latitudes, *Proc. Roy. Soc. London, Ser. A, 218,* 1, 1953.

Maynard, N. C., and J. P. Heppner, Variations in electric fields from polar orbiting satellites, in *Particles and Fields in the Magnetosphere,* edited by B. M. McCormac, p. 247, D. Reidel, Dordrecht, Netherlands, 1970.

Mozer, F. S., and P. Bruston, Electric-field measurements in the auroral ionosphere, *J. Geophys. Res., 72,* 1109, 1967.

Mozer, F. S., and R. Serlin, Magnetospheric electric-field measurements with balloons, *J. Geophys. Res., 74,* 4739, 1969.

Nichol, D. G., The pre-dawn enhancement of λ6300A airglow at higher midlatitudes, *Planet. Space Sci., 18,* 1335, 1970.

Obayashi, T., and N. Matuura, Theoretical model of *F*-region storms, paper presented at Leningrad Symposium on Solar-Terrestrial Physics, Cospar, May 1970.

Park, C. G., Westward electric fields as the cause of nighttime enhancements in electron concentrations in midlatitude *F* region, *J. Geophys. Res., 76,* 4560, 1971.

Park, C. G., and D. L. Carpenter, Whistler evidence of large-scale electron-density irregularities in the plasmasphere, *J. Geophys. Res., 75,* 3825, 1970.

Rüster, R., Height variations of the F_2 layer above Tsumeb during geomagnetic bay disturbances, *J. Atmos. Terr. Phys., 27,* 1229, 1965.

Rüster, R., Theoretical treatment of the dynamical behavior of the *F* region during geomagnetic bay disturbances, *J. Atmos. Terr. Phys., 31,* 765, 1969.

Sato, T., Nighttime abnormal enhancement of ionospheric F_2-region electron density in low and equatorial latitudes, *Rep. Ions. Space Res. Jap., 20,* 150, 1966.

VanZandt, T. E., V. L. Peterson, and A. R. Laird, Electromagnetic drift of the midlatitude F_2 layer during a storm, *J. Geophys. Res., 76,* 278, 1971.

Wescott, E. M., J. D. Stolarik, and J. P. Heppner, Auroral and polar cap electric fields from barium cloud releases, in *Particles and Fields in the Magnetosphere,* edited by B. M. McCormac, p. 229, D. Reidel, Dordrecht, Netherlands, 1970.

Winckler, J. R., The origin and distribution of energetic electrons in the Van Allen radiation belts, in *Particles and Fields in the Magnetosphere,* edited by B. M. McCormac, p. 332, D. Reidel, Dordrecht, Netherlands, 1970.

Wright, J. W., Horizontal drifts accompanying large vertical motions of the nocturnal *F* region, submitted to *Planet. Space Sci.,* 1971.

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