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Distortions of the Nightside Ionosphere during Magnetospheric Substorms

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Ionosonde records from widely spaced ground stations show that during magnetospheric substorms the F layer is pushed upward in the premidnight local time sector and downward in the postmidnight sector. The area affected probably depends on the substorm intensity, but it may be as large as ~20°–60° in geomagnetic latitude and ~9 hours in local time. These distortions are believed to be caused by eastward electric fields in the evening side and westward fields in the morning side. The inferred ionospheric electric fields do not show close correlation with magnetic perturbations at middle latitudes, thus suggesting that the latter are caused primarily by magnetospheric currents. The F-layer concentrations change as a result of vertical motions of the layer and influx of thermal plasma from the plasmasphere. In one of the cases reported, a thick nocturnal E layer with $f_0E \sim 2.5$ MHz was observed near 60° geomagnetic latitude. This effect is attributed to substorm-induced precipitation of energetic particles.

Magnetospheric substorms are accompanied by electric fields in the magnetosphere and the ionosphere, detectable by various techniques including electrostatic probes [*Mozer*, 1971; *Heppner*, 1972], whistlers [*Carpenter et al.*, 1972], artificial ion clouds [*Haerendel*, 1972; *Wescott et al.*, 1970], ground-based ionosondes [*Park and Meng*, 1971], incoherent scatter radar [*Banks et al.*, 1973], and trapped energetic particles in the magnetosphere [*Winckler*, 1970; *McIlwain*, 1972]. These electric fields penetrate deep within the plasmasphere and have important effects on the dynamical behavior of the coupled magnetosphere-ionosphere system (see a recent review by *Carpenter and Park* [1973]). Recent theoretical results by *Fedder and Banks* [1972] predict strong interactions between convection electric fields and neutral-air winds in the polar region. Similar effects may also be important at middle latitudes. It appears that the magnetosphere, ionosphere, and neutral atmosphere should now be viewed as a closely coupled electrodynamic system, subjected to excitation by substorms with an average frequency of several times a day. Our results show that even moderate substorms involving Kp values of ~2–4 have significant effects on the nightside ionosphere, and that data from a worldwide network of ionosonde stations can provide important information about the electric field distribution in the ionosphere during substorms.

Park and Meng [1971] showed that magnetospheric substorms cause large vertical motions of the midlatitude F layer that are readily identifiable in ground-based ionosonde records, particularly during winter nights. The direction of motion was found to be upward in premidnight hours and downward in postmidnight hours. These motions were interpreted in terms of $\mathbf{E} \times \mathbf{B}$ drifts, caused by an eastward electric field in the evening sector and a westward field in the morning sector with a transition near midnight. In the present study, simultaneous ionosonde records from widely spaced stations are used to examine the spatial extent of such effects. Our strategy is to study selected substorms that are simple and isolated, yet sufficiently intense to produce clearly identifiable effects on ionosonde records. In the next section, we present the results of three case studies. They will illustrate the merits of this approach as well as some of the difficulties one usually encounters in substorm

TABLE 1. Coordinates of Ionosonde Stations and Magnetic Observatories

		Geographic, deg		Geomagnetic, deg	
Station	Symbol	Lat. N	Long. E	Lat. N	Long. E
Adak	AD	51.9	183.4	47.2	240.0
Akita	AL	39.7	140.1	29.5	205.5
Boulder	BC	40.0	254.7	48.9	316.4
Churchill	CH	58 8	265.9	68.7	322.8
College	CO	64.9	212.2	64.6	256.5
Fredericksburg	FG	38.2	282.6	49.6	349.8
Grand Bahamas	GB	26.6	281.8	37.9	349.6
Great Whale River	GWR	55.3	282.2	66.6	347.4
Huancayo	HU	−12.0	284.7	−0 6	353.8
Kakioka	KA	36.2	140.2	26.0	206.0
Leirvogur	LE	64.2	328.3	70.2	71.0
Manila	MN	14.7	121.1	3.4	189.8
Meanook	MK	54 6	246.7	61.8	301.0
Mexico City	MX	19.4	260.3	29.2	326.5
Okinawa	OK	26.3	127.8	15.3	195.6
Ottawa	OT	45.4	284.1	56.8	351.1
Point Arguello	PA	35.6	239 4	42.2	300.7
Stanford	ST	37.4	237.8	43.6	298.5
Tashkent	TK	41.3	69.3	32.4	143.7
Tokyo	TO	35.7	139.5	25.4	205.4
Wallops Island	WP	37.9	284.5	49.3	352.1
White Sands	WS	32.3	253.5	41.1	316.9
Winnipeg	WI	49.8	265.6	59.9	326.6
Yamagawa	YG	31.2	130.6	20.3	197.8

research. The results show that the substorm-associated vertical motions of the F layer occur simultaneously over most of the nightside, thus lending further support to the electric field interpretation.

OBSERVATIONS AND INTERPRETATIONS

The ionosonde stations and magnetic observatories used in this study are listed in Table 1 along with their symbols and coordinates. Figure 1 is a map showing the location of the ionosonde stations.

Magnetograms from auroral latitude stations were used to identify isolated substorm activity. In this study, the substorm 'onset' is defined as the earliest sign of geomagnetic bay disturbance identified from available auroral zone magnetograms. However, it should be noted that the onset of a substorm is usually difficult to identify because of its gradual development or because of inadequate data coverage in the auroral zone and the polar region. The onset defined here is related to the breakup of the auroral substorm [*Akasofu and Snyder*, 1972].

We present below the results of three case studies involving relatively well-defined substorms that produced large-scale distortions of the nightside $F2$ layer. Simultaneous ionosonde records from widely spaced stations were used to monitor the changes in the height of the $F2$ layer during these substorms. In some cases, the bottomside electron density profiles were obtained from true height analysis of ionograms. It was found that changes in true height of the $F2$ layer peak (h_mF2) closely follow changes in virtual height ($h'F$) measured at an appropriate fixed frequency. Therefore, in many cases, $h'F$ is used instead of h_mF2 to indicate F-layer motions. When using $h'F$, however, we must make sure that ionogram traces are essentially horizontal near the frequency of measurement and that their low-frequency tails do not indicate significant temporal variations in underlying ionization. Large enhancements in underlying ionization are often observed during substorms at subauroral latitudes, presumably owing to precipitating energetic particles. An example of this is shown later.

Vertical motions of the F layer, as indicated in ionograms, occur almost simultaneously with substorm onset over widely spaced stations. Therefore, these motions are interpreted as being due to $\mathbf{E} \times \mathbf{B}$ drifts involving large-scale electric fields.

DECEMBER 3, 1968, CASE

Summary. This case study involves ionosonde records from Winnipeg, Ottawa, Wallops Island, Boulder, Stanford, White Sands, Grand Bahamas, Mexico City, and Huancayo. These stations are distributed over ~0°–60° in geomagnetic latitude and ~3 hours in local time. There were two periods of relatively isolated substorm activity between 0000 and 1200 UT. The ionosonde stations were in the premidnight local time sector during the first substorm onset and in the morning sector during the second substorm. In association with these two events, the ionograms indicated simultaneous vertical motions of the F layer over all midlatitude stations. The direction of motion was upward in the evening sector and downward in the morning sector, corresponding to an eastward electric field and a westward electric field, respectively. The substorm effects were not clearly identifiable at low-latitude stations (i.e., Mexico City and Huancayo). At middle latitudes, N_mF2 tends to increase when h_mF2 decreases, and vice versa, probably owing to modulations in protonospheric fluxes [*Park*, 1971].

Further details. Figure 2 shows selected magnetograms from 0000–1200 UT on December 3, 1968. The large dots indicate local standard midnight at the observing stations. The Great Whale River magnetogram showed the earliest sign of magnetic activity among all available auroral latitude magnetograms. Accordingly, we used the Great Whale River record to place the substorm onset at ~0300 and ~0715 UT, as indicated by two vertical lines in Figure 2. Notice that these substorms, particularly the second, developed rather gradually at Great Whale River, so there is no unique way of defining the onset time. The magnetograms from Meanook and Fredericksburg also show two bay events, but with some delay. This is because of the localized nature of the substorm current system, and it emphasizes the need for using multiple stations in substorm studies.

The behavior of the F layer over Wallops Island is shown in the lower part of Figure 2. The height of the F layer at the peak electron concentration and at constant fractions of the peak concentration was obtained from true height analysis of ionograms. A comparison of the true height curves with the $h'F$ curve shows that we

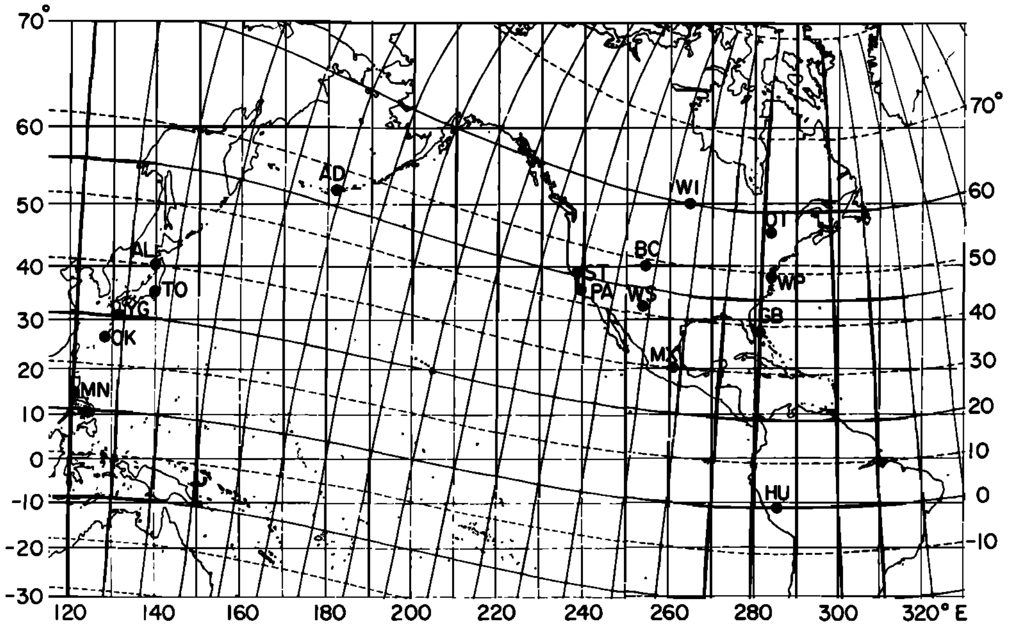

Fig. 1. A map showing the location of ionosonde stations used in this study. Geographic latitudes are shown at left and geomagnetic latitudes at right.

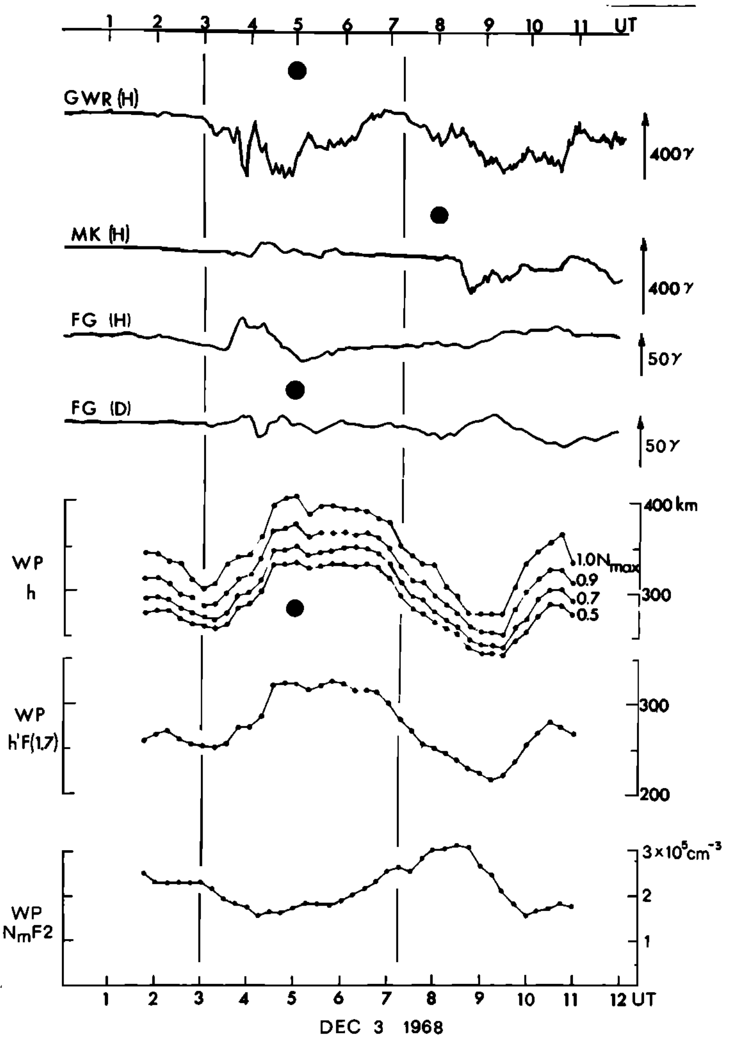

Fig. 2. Geomagnetic and ionospheric data during two substorms on December 3, 1968. The magnetograms are from Great Whale River, Meanook, and Fredericksburg. The arrows indicate the scale and the direction of increasing northward (*H* component) and eastward (*D* component) fields. Plots below show the true height, virtual height at 1.7 MHz, and peak electron concentration of the *F* layer over Wallops Island. Two vertical lines mark the substorm 'onset' as defined in the text, and large dots indicate local standard midnight at each observing station.

can use the latter as a reliable indicator of vertical motions of the *F* layer. During the first substorm, when Wallops Island was in the premidnight local time sector, the *F* layer moved upward by ~100 km. The second substorm, which occurred when the station was in the postmidnight sector, caused a lowering of the *F* layer by ~100 km. This was followed by a recovery starting at ~0930 UT (0430 LST).

Note the lack of correlation between the ionospheric motions and the magnetograms from Fredericksburg, which is only ~180 km from Wallops Island. This lack of close correlation between magnetic variations and apparent ionospheric electric fields gives support to the suggestion that distant magnetospheric currents contribute far more to the magnetic perturbations observed at middle and low latitudes than do overhead ionospheric currents [*Meng and Akasofu*, 1969]. More discussion on this point will follow in the next section. It is clear from this example that one should use auroral oval magnetograms rather than local magnetograms as substorm indicators.

At the bottom of the figure is a plot of the peak electron concentration. An important feature to note here is that N_mF2 does not follow variations in h_mF2 as would be predicted from the height variations of the recombination rate alone. On the contrary, there is a tendency for N_mF2 to increase when h_mF2 decreases, and vice versa. This behavior can be understood in terms of substorm electric fields modulating the downward flow of ionization from the plasmasphere [*Park*, 1971].

Figure 3 shows simultaneous $h'F$ data from nine stations, arranged in the order of decreasing latitude. Large dots indicate local standard midnight at each station. The numbers below station symbols indicate frequencies in MHz for which virtual heights were measured. The tolerance was normally ±0.2 MHz, and small dots are used to indicate data points when the tolerance was ±0.4 MHz. The measurements were made every 15 min at all stations except Mexico City, where the ionosonde was operated on a 30-min schedule.

The $h'F$ data shown in solid curves are to be compared with the quiettime behavior represented by the dashed curves. The quiettime curves for Winnipeg, Ottawa, Boulder, White Sands, Grand Bahamas, and Mexico City have been constructed by taking the mean of hourly $h'F$ values for several magnetically quiet days in December 1968 when the maximum 3-hour *Kp* value did not exceed 2 between 0000 and 1200 UT. For Wallops Island and Stanford, ionograms were scaled every 15 min during 5 to 8 of the quietest nights from November 1968 through January 1969. The maximum *Kp* index did not exceed 1+. For Huancayo, the dashed curve is for December 26, 1968, one of the quietest days of the month with the maximum *Kp* of 1+. At White Sands, Mexico City, and Huancayo, the behavior of $h'F$ on December 3 is similar to the quiettime behavior, and the substorm effects are not clearly identifiable. At other stations the substorm effects are clear: $h'F$ increases during the first substorm when the stations are in premidnight hours and decreases during the second substorm when they are in postmidnight hours. The recovery from the second substorm starts at ~0900 UT. It appears that substorm electric fields extended over at least 3 hours in local time and penetrated to ~40° geomagnetic latitude.

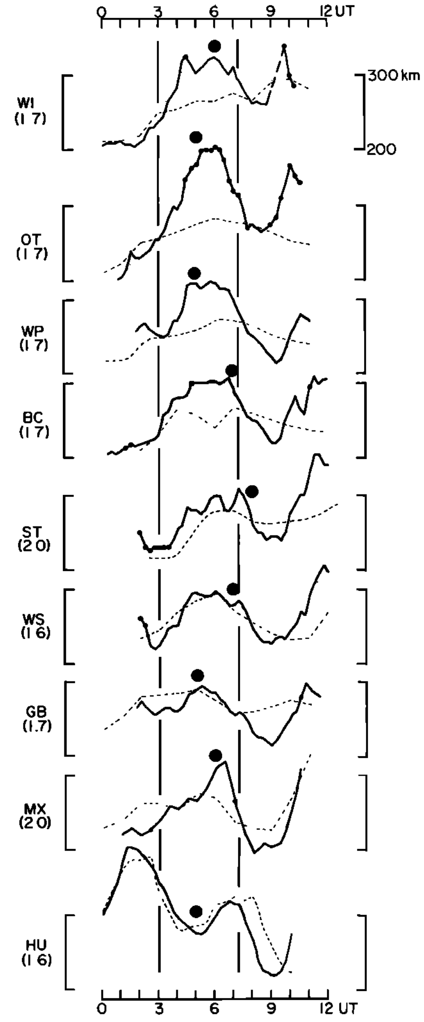

Fig. 3. Plots of $h'F$ over Winnipeg, Ottawa, Wallops Island, Boulder, Stanford, White Sands, Grand Bahamas, Mexico City, and Huancayo during the two substorms of Figure 2. At each station $h'F$ was measured at a fixed frequency ±0.2 MHz. This fixed frequency in MHz is indicated below each station symbol. Small dots are used for $h'F$ measured at the fixed frequency ±0.4 MHz. Dashed curves represent the quiettime behavior (see text).

December 16, 1964, Case

Summary. In this case, the substorm of interest occurred near 1200 UT. The ionosonde stations involved are Adak in the midnight sector, Stanford and Point Arguello in the morning sector, and Akita, Tokyo, Yamagawa, Okinawa, and Manila in the evening sector. Within $\sim$5 min of the substorm onset, Akita, Tokyo, and Yamagawa showed rapid upward motions of the *F* layer, while at the same time Adak, Stanford, and Point Arguello showed rapid downward motions. This again corresponds to an eastward electric field in the evening sector and a westward field in the morning sector, with a transition near midnight. These fields covered $\sim$9 hours in local time and penetrated to $\sim$20° geomagnetic latitude.

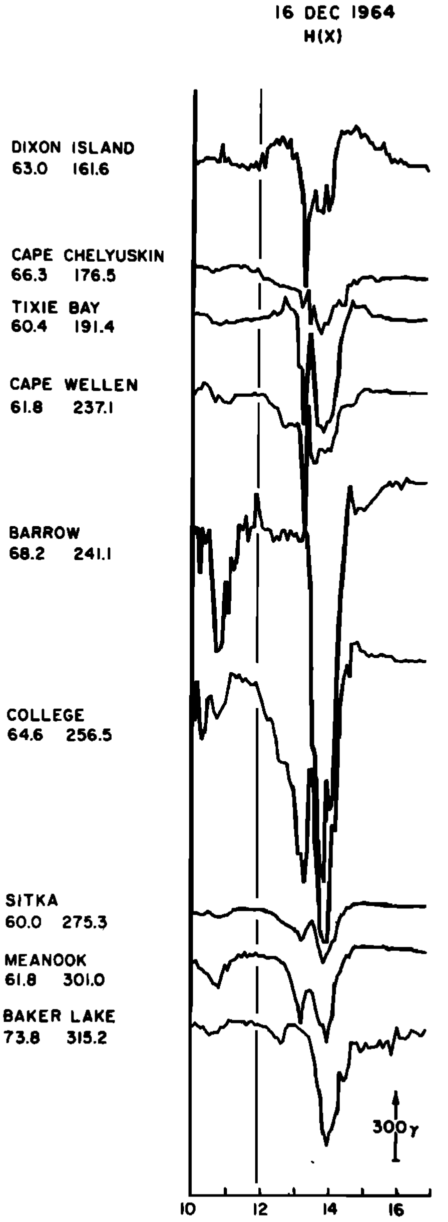

Fig. 4. Auroral latitude magnetograms during an intense substorm activity on December 16, 1964. (From Akasofu and Meng [1969].)

Further details. The auroral latitude magnetograms of this event are shown in Figure 4. Worldwide magnetic variations during this substorm have been analyzed in detail by *Akasofu and Meng* [1969]. The substorm onset is identified at 1155 UT. At some stations the bay activity does not start until $\sim$1 hour later, owing to the localized nature of the auroral electrojet development, as pointed out earlier. This is one of the simplest, yet most intense substorms we have studied to date, with a relatively clear beginning and end. However, even this simple substorm grows in complexity as we examine the details more closely. For example, some stations show two distinct bays, the first one starting at $\sim$1155 UT and the second at $\sim$1350 UT. At other stations, only the second bay is clearly indicated (also, see Figures 6 and 7). It appears that there may have been two overlapping substorms. In spite of these complications, their effects on the ionospheric *F* layer are clearly indicated in ionosonde records.

Figure 5 shows a plot of $h'F$ at Adak, Alaska, during this event. The dots represent $h'F$ measured at 1.6 ± 0.2 MHz and the open circles at 1.6 ± 0.4 MHz. The magnetogram from College, Alaska, is reproduced at the top of the figure. The ionosphere is lowered rapidly within $\sim$5 min of the substorm onset. Because this day was designated a Regular World Day in the geophysical calendar, soundings were made more frequently than the usual 15-min schedule.

Figure 6 shows $h'F$ at Point Arguello and Stanford near 0400 LT at the substorm onset. Both stations show a lowering of the *F* layer immediately following the onset at $\sim$1155 UT and another lowering at $\sim$1350 UT, about the time of the second magnetic bay onset. At the top of the figure are transcriptions of magnetograms from Boulder, Colorado. Only the second substorm is clearly indicated in these magnetograms. There is no close relationship between ionospheric motions and the magnetic variations at middle latitudes.

Figure 7 shows a rapid upward motion of the F layer in the premidnight sector. The substorm onset at ~1155 UT is marked by a vertical line. The stations are arranged in the order of decreasing latitude starting from Akita at 30° to Manila at 3° geomagnetic latitude. The upward motion is clearly observed at Yamagawa and higher latitude stations. At the top of the figure are magnetograms from Kakioka, which, as in the case of Boulder, show bays associated with only the second substorm. Despite their close proximity, there appears to be no relationship between magnetic perturbations at Kakioka and ionospheric perturbations at Tokyo.

Ionograms from Maui (21°N, 156°W, geographic; 21°N, geomagnetic) and Rarotonga (21°S, 160°W, geographic; 21°S, geomagnetic) have also been examined. The F layer over these South Pacific stations underwent large vertical motions during this night. However, these motions at the two stations were not well correlated and did not appear to be related to substorm activity.

December 25, 1968, Case

Summary. The magnetic records in this case are more complicated than in the previous two cases, because the substorm activity is superimposed on solar-wind-driven oscillations of the magnetosphere. The ionosonde records from Wallops Island, Boulder, and Point Arguello again indicate an eastward electric field in the evening side and a westward electric field in the morning side. Ionograms from Winnipeg during this disturbance show a thick noctural E layer, presumably produced by precipitating energetic particles from the magnetosphere.

Further details. The H-component magnetograms in Figure 8 are from middle- and low-latitude stations covering all local time quadrants. They show an isolated period of disturbance from ~0240 to ~1030 UT. Based on the coherence of magnetic field variations at all stations, it is inferred that these variations were caused by compression and expansion of the entire magnetosphere in response to the variations in solar wind pressure. The auroral latitude magnetograms in Figure 9 also show a relatively isolated period of disturbance from ~0300 UT to ~1030 UT. The solar-wind-driven fluctuations in Figure 8 are not evident in these records, because they are masked by larger perturbations associated with the auroral electrojet. The impulse at ~0240 UT in Figure 8 probably triggered the substorm starting at ~0300 UT. (*Kawasaki et al.* [1971] recently discussed the triggering of substorms by such impulses.)

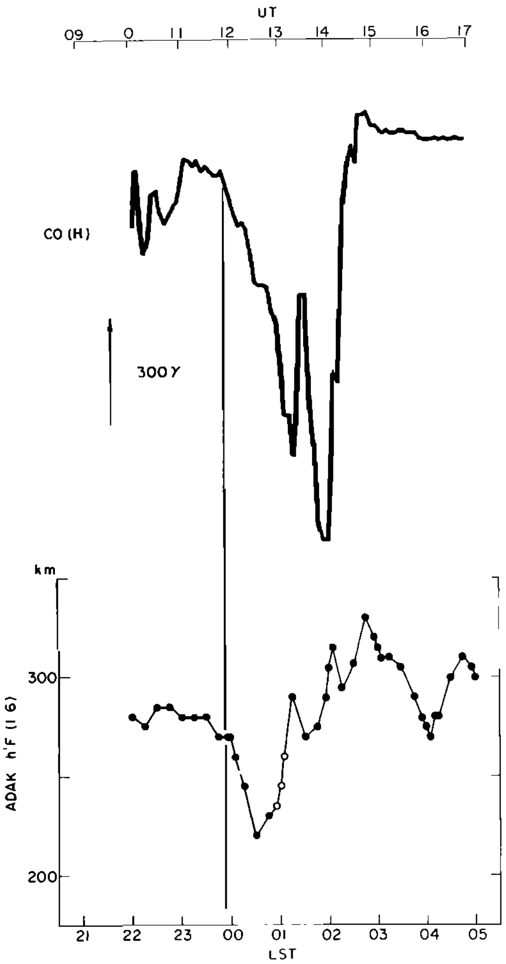

Fig. 5. Plots of $h'F$ at Adak, Alaska, during the substorm of Figure 4. The College magnetogram is reproduced at the top. Solid dots are used for $h'F$ measured at 1.6 ± 0.2 MHz, and open circles indicate $h'F$ measured at 1.6 ± 0.4 MHz.

In Figure 9 the substorm onset near 0300 UT is relatively clear, but at later times interpre-

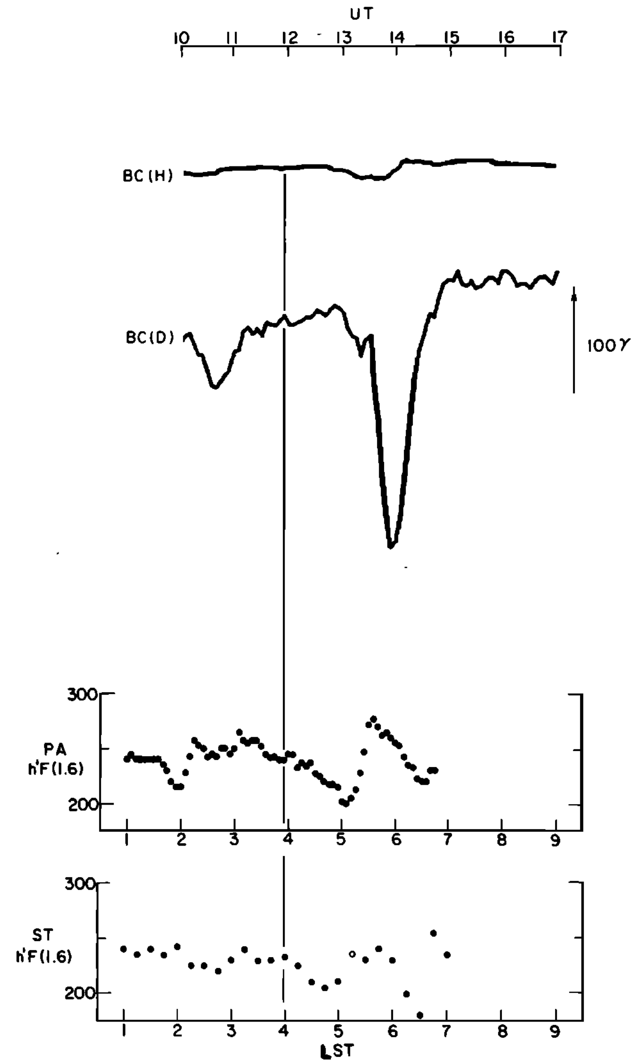

Fig. 6. Plots of *h'F* at Point Arguello and Stanford during the substorm of Figure 4. Magnetograms from Boulder, Colorado, are reproduced at top. The format is similar to Figure 5.

tation of these magnetograms in terms of substorm activity becomes more difficult. This is partly due to the reduced size of the auroral oval during this event. The evidence for a shrunken oval is found in auroral photographs as well as in magnetograms. All-sky photographs from College show active auroras in the northern sky at higher latitudes than normal (D. S. Kimball, personal communication, 1972). The fact that Leirvogur and Churchill recorded larger magnetic bays than Great Whale River is another evidence for a shrunken oval (compare the geomagnetic latitude of these stations). It is now known that substorms can occur while the auroral oval is far poleward of its normal location, thus producing no identifiable magnetic signatures at conventional auroral latitude stations [*Akasofu and Snyder*, 1972]. Therefore, the end of magnetic bay activity in Figure 9 does not necessarily signal the end of substorm activity. All-sky photographs from College indicate continued substorm activity until ~1030 UT, although many details are not clear because of incomplete data. The auroral photographs show a bright westward surge in the northern sky at 0647 UT, signaling a development of a new substorm at high latitudes. This substorm did not produce clear signatures on available magnetograms, presumably because the auroral electrojet was too far away from the magnetic observatories.

Figure 10 shows variations of h_mF2 and $h'F$ over Wallops Island, Boulder, and Point Arguello in a format similar to Figure 3. The quiettime $h'F$ curve for Point Arguello was obtained in a similar manner as for Wallops Island and Stanford (see the December 3, 1968, case). The magnetograms from Churchill and Fredericksburg are reproduced at the top of the figure. The F layer moved upward in response to the substorm near 0300 UT when the observing stations were in the premidnight sector. Near 0700 UT, the F layer started to move downward at all stations, which were now in the postmidnight sector. This downward motion was probably caused by a substorm starting at 0647 UT (indicated in auroral photographs but not in magnetograms, as described earlier), but because of the solar-wind-driven perturbations, which occurred during the same period, it is not clear whether the associated electric fields should be attributed entirely to the substorm.

At Boulder and Point Arguello, the F layer was pushed downward until ~1030 UT, about the time when the geomagnetic disturbance ended. At Wallops Island the downward motion stopped about an hour earlier, which is interpreted as a local time effect. During the recovery, the F-layer height increased beyond quiettime levels. Such 'overshoot' is commonly observed when the layer is released from a low altitude.

Vertical motions of the F layer shown in Figure 10 were accompanied by changes in electron concentrations, and the observations at Wallops Island have been reported by *Park* [1971]. A particularly outstanding feature was an increase by a factor of ~2 in the peak electron concentration and columnar content between ~0700 and 0900 UT, while the layer was being lowered. This was explained in terms of enhanced downward flow of thermal plasma from the plasmasphere induced by the lowering of the layer. At Winnipeg, ~10° higher than Wallops Island in geomagnetic latitude, there is evidence for enhanced precipitation of energetic particles associated with the same geomagnetic activity. This is illustrated by a sequence of ionograms in Figure 11. The ionograms at 0200 and 0900 UT

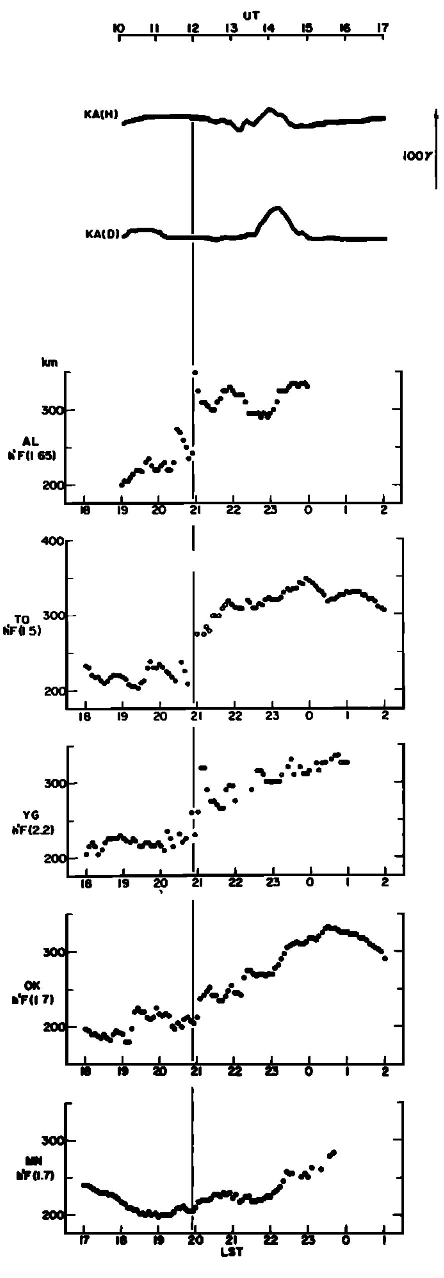

Fig. 7. Plots of $h'F$ at Akita, Tokyo, Yamagawa, Okinawa, and Manila in a format similar to Figure 5 during the substorm of Figure 4. The magnetograms at top are from Kakioka.

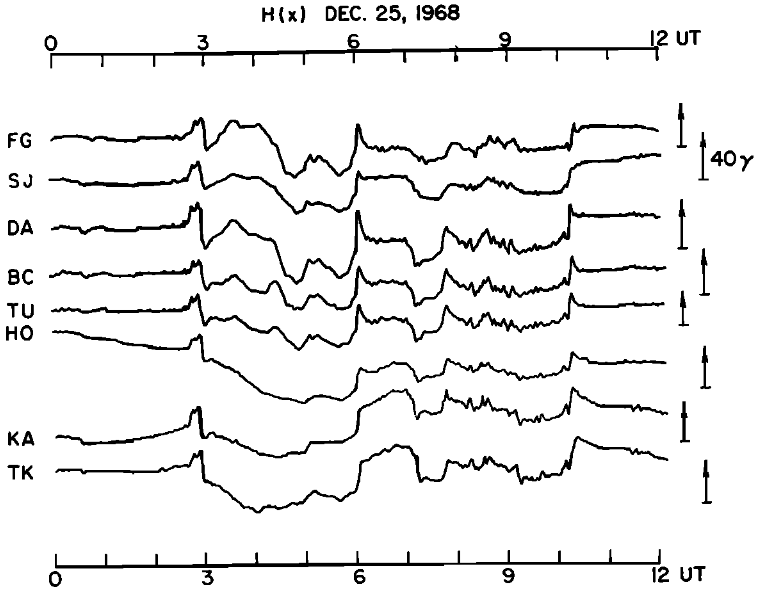

Fig. 8. *H*-component magnetograms showing simultaneous fluctuations at Fredericksburg, San Juan, Dallas, Boulder, Tucson, Honolulu, Kakioka, and Tashkent.

show the normal nighttime *F* layer with little underlying ionization. At intermediate times, the records show a thick *E* layer with $f_0E \cong 2.5$ MHz, which is presumably produced by precipitating energetic particles. Notice also a small increase in f_0F2 between 0300 and 0900 UT, which may be due to an influx of thermal plasma from the magnetosphere.

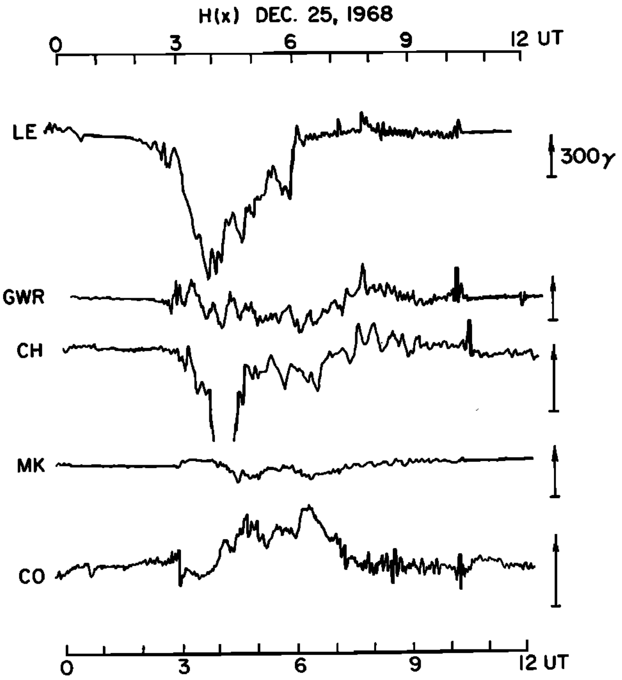

Fig. 9. Auroral latitude magnetograms during the event of Figure 8.

Discussion

In the previous section we emphasized the lack of correlation between inferred ionospheric electric fields and magnetic perturbations at middle latitudes. Similar findings have been reported by *Pushkova et al.* [1972]. *Carpenter and Akasofu* [1972] compared D-component magnetic variations at middle latitudes with east-west electric fields deduced from cross-L drifts of whistler ducts. They also noted certain morphological differences between the two parameters. These results all give qualitative support to the idea that on the nightside, magnetic perturbations at middle and low latitudes are primarily due to currents flowing in the distant magnetosphere rather than to overhead ionospheric currents [*Meng and Akasofu*, 1969; *Akasofu and Meng*, 1969]. A quantitative analysis of this problem will be given elsewhere.

In the examples of the previous section, the response of the nightside ionosphere was clearly indicated in ionosonde records near the substorm onset, and this initial response was interpreted in terms of large-scale electric fields. During later stages of substorms, however, interpretation becomes difficult because of the complexities in the time-dependent behavior of the coupled magnetosphere-ionosphere-neutral atmosphere system. Theoretical studies of this complex system have only recently begun. *Vasyliunas* [1972] considered the penetration of time varying convection electric fields to low latitudes in the presence of ring current particles. *Fedder and Banks* [1972] predicted strong interactions between convection electric fields and neutral-air winds. *Moffett and Murphy* [1973] calculated the effects of electric fields on the ionospheric F layer, including ionization flow into and out of the protonosphere. These effects have yet to be incorporated into a unified model. Experimentally, we need simultaneous observations of atmospheric, ionospheric, and magnetospheric parameters on a global scale.

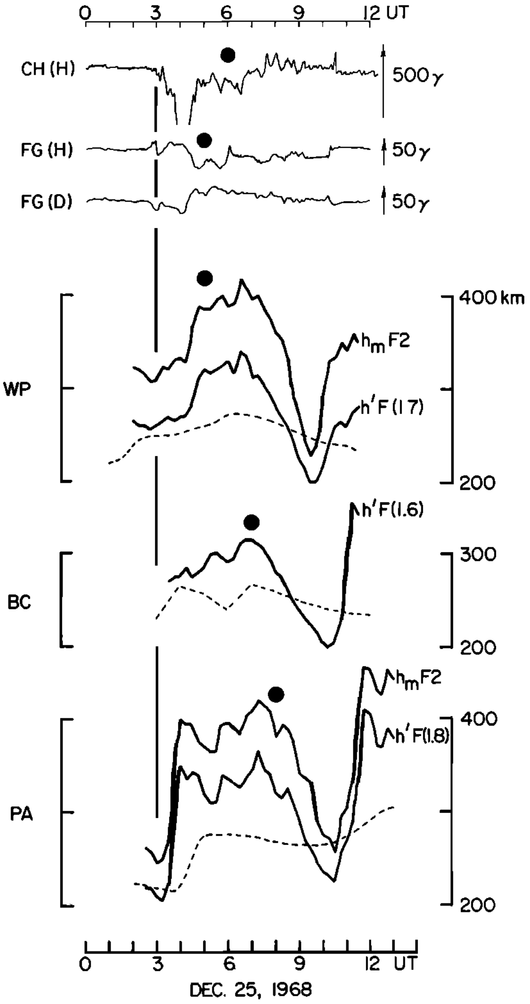

Fig. 10. Plots of h_mF2 and $h'F$ at Wallops Island, Boulder, and Point Arguello during the geomagnetic disturbance of Figures 8 and 9. Magnetograms from Churchill and Fredericksburg are reproduced at the top.

Conclusions

Magnetospheric substorms cause significant distortions of the nightside ionosphere between ~2000 and 0500 LT meridians and between ~20° and 60° geomagnetic latitude. The distortion of the midlatitude F layer is believed to be caused by an eastward electric field pushing the layer upward in the premidnight local time sector and a westward electric field pushing it downward in the postmidnight sector. The inferred ionospheric electric fields are not closely correlated with magnetic perturbations in middle latitudes, thus suggesting that the latter involve sources other than overhead ionospheric currents. The F-layer concentrations are affected by vertical motions of the layer and influx of thermal plasma from the plasmasphere. These effects diminish with decreasing geomagnetic latitude. At subauroral latitudes (~60° geomagnetic latitude), a thick nocturnal E layer may be produced by precipitating energetic particles.

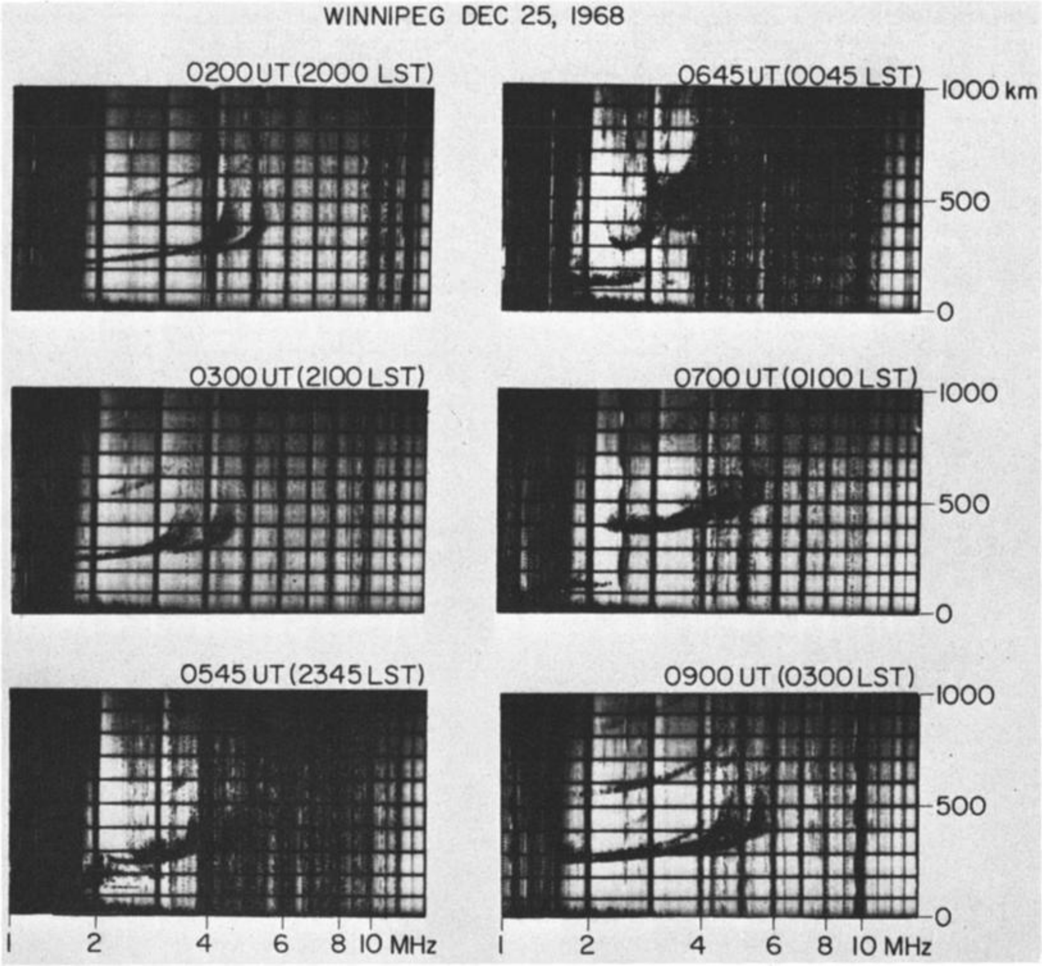

Fig. 11. A sequence of ionograms from Winnipeg illustrating the development of a thick nocturnal E layer during the geomagnetic disturbance of Figures 8 and 9.

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