Aftereffects of Isolated Magnetospheric Substorm Activity on the Mid-Latitude Ionosphere: Localized Depressions in *F* Layer Electron Densities

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Ground-based ionosonde data from a global network of about 100 stations have been used to study ionospheric disturbances at mid-latitudes associated with isolated magnetospheric substorm activity. The results of four case studies during solstice periods are presented here. In each case, pronounced (~10–30%) depressions in f_oF_2 developed in a limited longitude sector in the summer hemisphere and lasted for about 1 day. The region of depressed f_oF_2 appears as a tongue extending from the auroral zone down to about 20° geomagnetic latitude and corotating with the earth. This region is found to have been on the dayside of the earth while the causative substorm activity was in progress. It is suggested that these depressions are caused by changes in thermospheric composition and that the primary heat source for the thermospheric disturbance is Joule heating in the dayside polar cusp region.

INTRODUCTION

One of the most prominent features of ionospheric storms in middle latitudes is a widespread depression in *F* region densities that lasts for several days during and immediately following the main phase of a geomagnetic storm [e.g., *Martyn*, 1953; *Obayashi*, 1964; *Sato*, 1968; *Mendillo*, 1971]. This is commonly referred to as the negative phase of ionospheric storms and is usually most conspicuous during sunlit hours. Recent satellite observations show that such depressions are directly related to changes in thermospheric composition, in particular, to changes in the ratio of O to N_2 densities [*Prölss and von Zahn*, 1974; *Prölss et al.*, 1975; *Trinks et al.*, 1975]. The production and loss rates of O^+ ions in the *F* region are proportional to O and N_2 densities, respectively, and so a decrease in the ratio $n(O)/n(N_2)$ results in reduced O^+ ion and electron densities. Quantitative discussion of these effects can be found in a number of theoretical papers, including those by *Rüster* [1971], *Chandra and Stubbe* [1971], and *Park and Banks* [1975].

It is generally accepted that auroral heating is an important energy source for the thermosphere and that it has a strong influence on the dynamics of the thermosphere on a global scale [e.g., *Cole*, 1962, 1971; *Volland and Mayr*, 1971]. One of the consequences of this heating is the large-scale changes in neutral composition mentioned above [see also *Taeusch et al.*, 1971]. A number of workers who considered this problem theoretically predicted such composition changes as a result of upwelling of heated gas, rich in N_2, which then spreads to lower latitudes through horizontal transport [*Mayr and Volland*, 1972; *Hays et al.*, 1973; *Bates*, 1974; *Heaps and Megill*, 1975]. Their work may form a theoretical basis for understanding and modeling this important dynamical process when experimental facts about the heat source and the resulting disturbance are firmly established.

In this paper we present the results of several case studies in which isolated magnetospheric substorm activity was followed by significant depressions in f_oF_2 that persisted for about 1 day or longer. These substorm-induced depressions are observed only in certain localized areas but are otherwise similar in many respects to the negative phase of major worldwide ionospheric storms. It is reasonable to believe that in both cases the depressions are caused by the same mechanism, namely, changes in thermospheric composition. We hope that detailed studies of isolated substorm effects in the ionosphere will lead to a better understanding of both ionospheric and thermospheric storm phenomena. For example, we shall see in the next section that interesting relationships exist between the location of the depressed area and the time of substorm activity. These relationships provide important clues regarding thermospheric heat input.

In addition to the long-lasting density depressions just mentioned a variety of other effects (electrodynamic drift, changes in neutral wind, traveling ionospheric disturbances, plasma influx from the plasmasphere, etc.) may be present during and up to several hours after the end of substorm activity. These effects, however, are beyond the scope of this paper. In our case studies we will examine the global distribution of Δf_oF_2 long after all transient and short-term effects have died away.

Our strategy is to look first for simple isolated magnetospheric substorms monitored by ground-based auroral latitude magnetometers. An ideal substorm, lasting for not more than a few hours, would be preceded and followed by at least 24 hours of no activity, yet it should be sufficiently energetic to produce clearly identifiable effects in the ionosphere. Such ideal cases are extremely rare in nature, but a systematic search through several years' data produced a number of events that allowed useful studies to be made. The next section describes the results of these case studies.

OBSERVATIONS

In this section we present the results of four case studies. The auroral electrojet (*AE*) index [*Davis and Sugiura*, 1966; *Allen and Kroehl*, 1975] will be used as an indicator of magnetospheric substorm activity. The ionospheric data used are the hourly values of f_oF_2 from a worldwide network of stations numbering close to 100. Some of these stations that appear in the forthcoming illustrations are listed in Table 1.

TABLE 1. Ionosonde Stations

Station	Symbol	Geographic Position	Geomagnetic Position	Difference Between LST and UT, hours
Adak	AD	51.9°N, 183.4°E	47.2°N, 240.0°E	−12
Argentine Islands	AI	65.2°S, 295.7°E	53.7°S, 3.3°E	−4
Athens	AT	38.0°N, 23.6°E	36.6°N, 101.3°E	2
Auckland	AU	37.0°S, 175.0°E	41.3°S, 252.7°E	12
Bogotá	BO	4.5°N, 285.8°E	16.0°N, 354.6°E	−5
Boulder	BL	40.0°N, 254.7°E	48.9°N, 316.4°E	−7
Brisbane	BR	27.5°S, 152.9°E	35.7°S, 226.9°E	10
Budapest	BU	46.7°N, 21.2°E	45.4°N, 102.1°E	1
Campbell Island	CI	52.5°S, 169.2°E	57.3°S, 253.2°E	11
Canberra	CA	35.3°S, 149.0°E	44.0°S, 224.3°E	10
Christchurch	CC	43.6°S, 172.8°E	48.1°S, 252.8°E	12
Churchill	CH	58.8°N, 265.8°E	68.7°N, 322.6°E	−6
Gorky	GK	56.2°N, 44.3°E	50.4°N, 126.7°E	3
Grand Bahama	GB	26.6°N, 281.8°E	37.9°N, 349.6°E	−5
Graz	GZ	47.1°N, 15.5°E	47.0°N, 96.9°E	2
Halley Bay	HB	75.5°S, 333.4°E	65.8°S, 24.3°E	−2
Huancayo	HU	12.0°S, 284.7°E	0.6°S, 353.8°E	−5
Irkutsk	IR	52.5°N, 104.0°E	41.0°N, 174.4°E	7
Kerguelen	KE	49.4°S, 70.3°E	57.4°S, 128.1°E	4
Khabarovsk	KH	48.5°N, 135.1°E	37.8°N, 200.00°E	9
Kiruna	KI	67.8°N, 20.4°E	65.3°N, 115.6°E	1
Leningrad	LG	60.0°N, 30.7°E	56.3°N, 117.4°E	2
Lindau	LI	51.6°N, 10.1°E	52.3°N, 93.9°E	1
Mexico City	MX	19.4°N, 260.3°E	29.2°N, 326.5°E	−6
Moscow	MC	55.5°N, 37.3°E	50.9°N, 120.5°E	2
Mundaring	MD	32.0°S, 116.2°E	43.5°S, 186.1°E	8
Ottawa	OT	45.4°N, 284.1°E	56.8°N, 351.1°E	−5
Point Arguello	PA	35.6°N, 239.4°E	42.2°N, 300.7°E	−8
Provideniya	PR	64.4°N, 186.6°E	59.6°N, 235.7°E	12
Rarotonga	RA	21.2°S, 200.2°E	20.9°S, 273.6°E	−11
Rostov	RO	47.2°N, 39.7°E	42.5°N, 119.2°E	3
Sanae	SA	70.3°S, 357.6°E	63.6°S, 44.1°E	0
Slough	SL	54.5°N, 359.4°E	54.3°N, 83.3°E	0
St. Johns	SJ	47.6°N, 307.3°E	58.5°N, 21.2°E	−4
Sverdlovsk	SV	56.7°N, 61.1°E	48.5°N, 140.7°E	4
Tamanrasset	TT	22.8°N, 5.5°E	25.4°N, 79.5°E	0
Terre Adélie	TA	66.7°S, 140.0°E	75.7°S, 230.9°E	0
Tomsk	TM	56.5°N, 84.9°E	45.9°N, 159.6°E	6
Townsville	TO	19.3°S, 146.7°E	28.5°S, 218.8°E	10
Uppsala	UP	59.8°N, 17.6°E	58.5°N, 105.9°E	1
Wakkanai	WK	45.4°N, 141.7°E	35.3°N, 206.0°E	9
Washington	WA	38.7°N, 282.9°E	50.1°N, 350.1°E	−5
White Sands	WS	32.3°N, 253.5°E	41.1°N, 316.9°E	−7
Winnipeg	WI	49.8°N, 265.6°E	59.9°N, 326.6°E	−6
Woomera	WO	31.0°S, 136.3°E	41.2°S, 209.2°E	9
Yakutsk	YA	62.0°N, 129.6°E	50.9°N, 193.8°E	9
Yuzhno Sakhalinsk	YZ	47.0°N, 143.0°E	37.0°N, 206.9°E	10

June 26, 1965, case. Figure 1*a* shows the *AE* index for June 25 and 26, 1965. The major activity during this period is indicated by a fairly isolated burst of substorms between ~1430 and ~2000 UT on June 25. This is followed by a day of relative calm except for a few minor perturbations. June 23 and 24 were exceptionally quiet days, the *AE* index not exceeding 200 γ at any time.

The ionospheric behavior in this case was discussed earlier in some detail in a slightly different context [*Park,* 1974]. It was reported that the substorm activity of June 25 produced

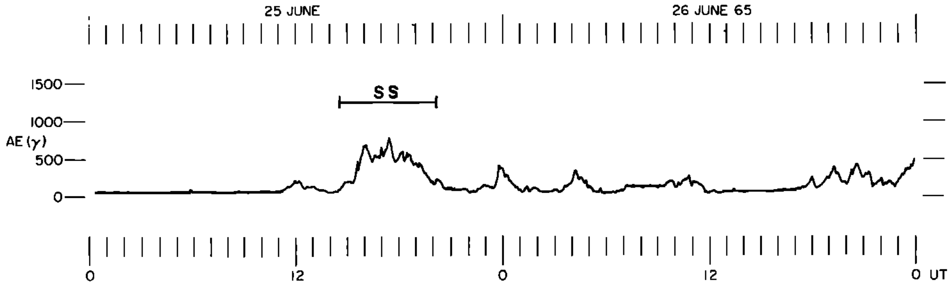

Fig. 1*a*. A plot of the *AE* index for June 25 and 26, 1965.

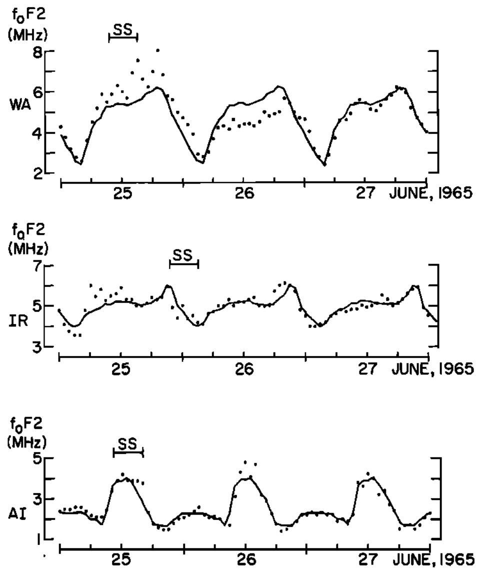

Fig. 1*b*. Plots of the F_2 layer critical frequency versus LST for June 25-27, 1965, at Washington, Irkutsk, and Argentine Islands. The solid curves represent the monthly median behavior. The horizontal bars marked SS refer to the substorm period indicated in Figure 1*a*.

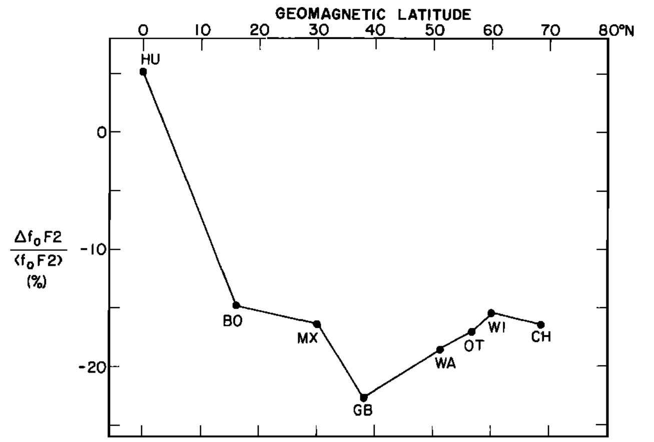

Fig 1*d*. A plot similar to Figure 1*c* but showing latitudinal variations in f_oF_2 perturbations near the Washington meridian.

large *F* region disturbances over North America that were similar in many respects to the major ionospheric storm 10 days earlier. The latter was caused by a major geomagnetic storm whose main phase started near 1000 UT on June 15 and lasted for ~2.5 days. An important difference, however, was the fact that the June 25 disturbance was confined to North America, whereas the June 15 storm was worldwide.

Figure 1*b* shows plots of f_oF_2 versus local standard time (LST) at three selected stations, Washington (top), Irkutsk (middle), and Argentine Islands (bottom). The dots are hourly values, and the solid curves represent the monthly median behavior. The substorm period, 1430-2000 UT, is indicated by horizontal bars. Washington shows significant enhancements in f_oF_2 on June 25, followed by a ~20% depression throughout the daylight hours on June 26. It is this long-lasting negative phase that we wish to examine in detail in this paper. Note that this negative phase persists through a magnetically quiet period, long after any electrodynamic, gravity wave, or other transient effects would be expected to have died away. In contrast to the Washington data, no sign of disturbance is apparent at Irkutsk, which is close to Washington in geomagnetic latitude but 180° away in longitude, or at Argentine Islands, located near the conjugate point of Washington. Apparently, the disturbance observed at Washington occurred in a localized area, and we wish to map this disturbed area using f_oF_2 data from a worldwide ionosonde network.

The data look complicated at first glance because they show strong longitudinal dependence of Δf_oF_2 in addition to LST and UT variations. However, the long-lasting nature of the negative Δf_oF_2 phase makes it possible to identify local time and longitudinal variations separately. Local time variations appear to be directly related to solar illumination, the decrease being much more pronounced when the disturbed ionosphere is sunlit (see the top panel of Figure 1*b*). Thus we arrive at a picture of a disturbed region, limited in longitudinal extent, more or less corotating with the earth, and experiencing local time variations as it moves into and out of sunlight. The UT variations are due to the slow recovery of the disturbed region, which takes more than 1 day.

Figure 1*c* is a plot of Δf_oF_2 at local noon at a number of mid-latitude stations on June 26. The data have been smoothed somewhat by taking the average of hourly values at 1100, 1200, and 1300 LST. The vertical scale is the percentage deviation from the monthly median. All the stations in the figure lie between 40°N and 60°N geomagnetic latitude. The difference between LST and UT ranges from +9 hours at Yakutsk to −12 hour at Adak. Thus this figure represents longitudinal variations of Δf_oF_2 during the period 0300-2400 UT on June 26. The percent depression has a maximum value of −18.5% at Washington and falls off to half that value at ~30°W and ~120°W.

Figure 1*d* shows the latitudinal profile of Δf_oF_2 near the Washington meridian. Again, each data point is an average of the hourly values at 1100, 1200, and 1300 LST. The percent depression remains nearly constant down to ~15° geomagnetic latitude.

As was pointed out earlier, a similar depression was not observed in the southern hemisphere.

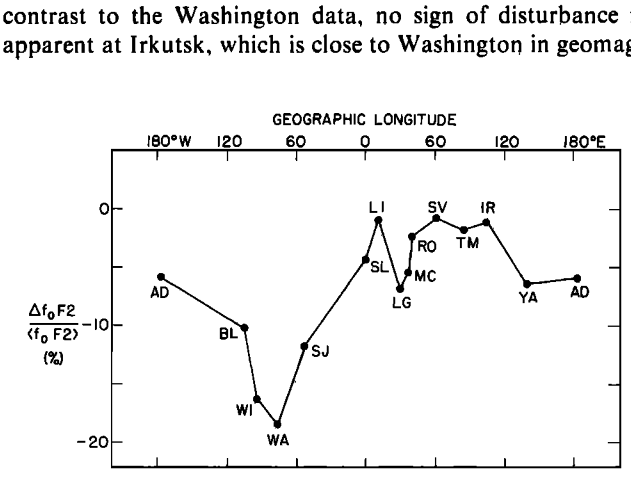

Fig. 1*c*. A plot showing longitudinal variations in f_oF_2 perturbations at middle-latitude stations. The ordinate is the percentage deviation of f_oF_2 from the monthly median, and each data point represents an average over the hourly values at 1100, 1200, and 1300 LST on June 26, 1965. The station symbols are listed in Table 1.

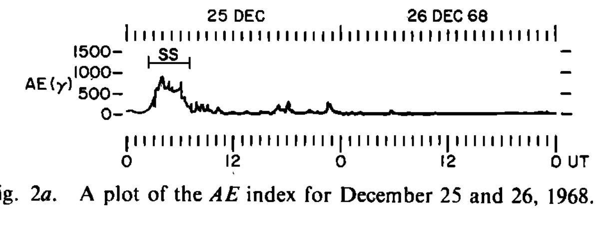

Fig. 2*a*. A plot of the *AE* index for December 25 and 26, 1968.

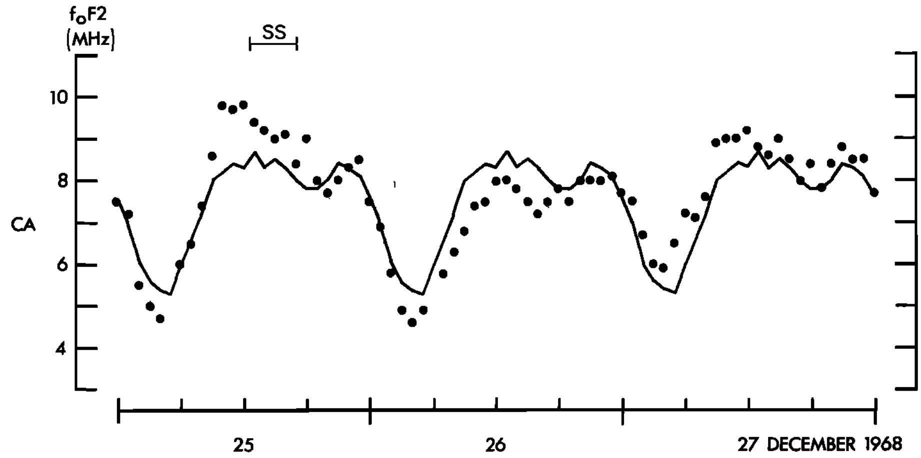

Fig. 2*b*. A plot of f_oF_2 versus LST at Canberra in the same format as that in Figure 1*b*.

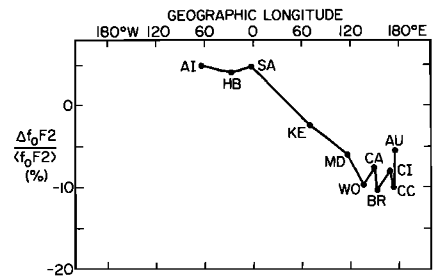

Fig. 2*c*. A plot showing longitudinal variations in f_oF_2 perturbations at local noon on December 26, 1968. The format is the same as that in Figure 1*c*.

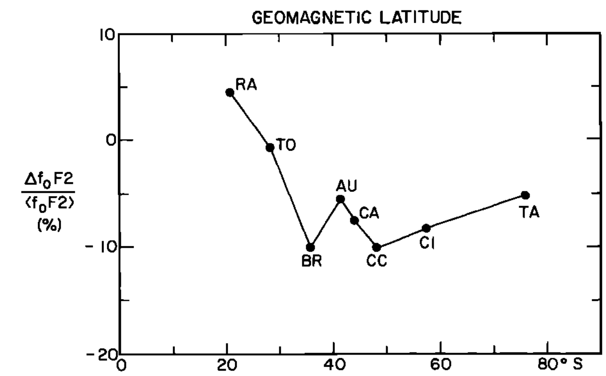

Fig. 2*d*. A plot similar to Figure 2*c* but showing latitudinal variations in f_oF_2 perturbations near the Canberra meridian.

December 26, 1968, case. Figure 2*a* shows a plot of the *AE* index for December 25 and 26, 1968. Fairly isolated substorm activity is indicated between ~0230 and ~0700 UT, the maximum *AE* index reaching ~900 γ. This is then followed by an unusually long period of extreme quiet. We will examine the global picture of Δf_oF_2 during this quiet period on December 26. (There were two minor substorms on December 24: one from ~1400 to ~1700 UT and the other from ~2200 to ~2400 UT. However, it appears unlikely to us that these minor substorms could cause the depressions in f_oF_2 described below. Thus we tentatively attribute all the decreases in f_oF_2 observed on December 26 to the substorm activity between ~0230 and ~0700 UT on December 25.)

The ionospheric behavior in this case was similar to that in the June 26, 1965, case, except that the disturbed area was in the southern hemisphere and in a different longitude sector. Figure 2*b* shows f_oF_2 data from Canberra, which was apparently in the middle of the disturbed area. The horizontal bar indicates the substorm period, 0230–0700 UT on December 25.

As occurred in the previous case, f_oF_2 is depressed throughout most of December 26, the first quiet day after the substorm activity. The spatial extent of this depression is illustrated in Figures 2*c* and 2*d* in the same manner as it was in Figures 1*c* and 1*d*. In Figure 2*c* the difference between LST and UT ranges from +12 hours at Auckland to −4 hour at Argentine Islands. Thus the time period covered by this figure is 0000–1600 UT, December 26. The depression penetrates to ~30° geomagnetic latitude but is limited in longitude between ~100°E and ~180°E.

No station in the northern hemisphere reported similar depressions in f_oF_2.

June 18, 1967, case. The *AE* index in Figure 3*a* shows three bursts of substorm activity on June 17, followed by a day of extreme quiet. Ionosonde data on June 18 show a depressed area over Europe, similar to the two previous cases discussed above. Figure 3*b* shows an example from Slough. The three substorm events are marked SS1, 2, and 3. Judging from the intensity of these events, we would naturally suspect that substorm 2 was responsible for most, if not all, of the observed disturbance. However, we cannot rule out the possibility that substorms 1 and 3 also contributed to the total Δf_oF_2. This point will be discussed further in the next section.

Figures 3*c* and 3*d* show, in the same manner as they were shown in Figures 1*c* and 1*d*, longitudinal and latitudinal profiles of Δf_oF_2 at local noon on June 18. All the stations in Figure 3*c* lie between 35°N and 60°N geomagnetic latitude, and all the stations in Figure 3*d* lie within 20° in geographic longitude of Slough. In Figure 3*c* the difference between LST and UT ranges from +12 hours at Provideniya to −7 hour at White Sands, and so the time period covered by this figure is 0000–1900 UT, June 18. The latitudinal profile shows that the depression penetrated to well below 25° geomagnetic latitude, a pronounced peak occurring near 35°N.

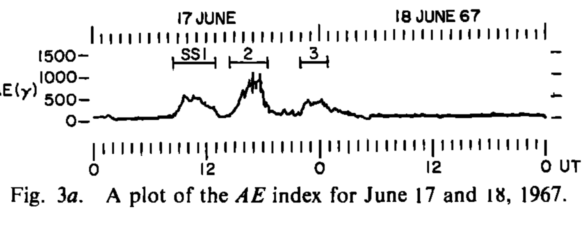

Fig. 3*a*. A plot of the *AE* index for June 17 and 18, 1967.

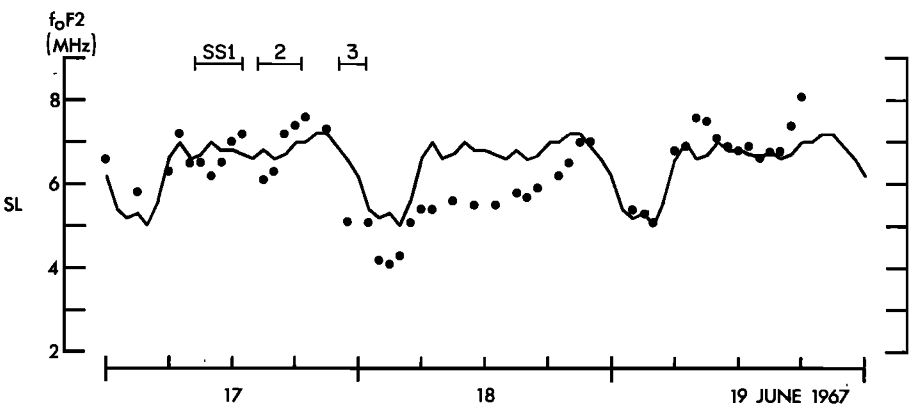

Fig. 3*b*. A plot of f_oF_2 versus LST at Slough in the same format as that in Figure 1*b*

No southern hemisphere station reported similar depressions on June 18.

July 15, 1968, case. This case is more complicated than the previous three in terms of both magnetic activity and the resulting ionospheric disturbance. Figure 4*a* shows a 13-hour period of substorm activity from ~1600 UT on July 13 through ~0500 UT on July 14. The peak value of the *AE* index reaches ~1200 γ. This is then followed by a long period of relative quiet through July 15, except for brief activity between ~1700 and ~2000 UT on July 14.

On July 14, some ionosonde stations already showed marked depressions of f_oF_2. However, it is not possible to obtain a global picture of the substorm aftereffects for this day because some stations went through local noon while substorm activity was still in progress. On July 15, magnetic conditions remained relatively quiet throughout the entire day, and so we can obtain a global picture of Δf_oF_2, as we did in the previous three cases. The results, however, are more complicated and difficult to interpret. This is partly due to the fact that by July 15 the ionosphere over some stations was already well on its way to recovery.

Figure 4*b* is a plot of f_oF_2 versus LST at Slough, which appears to be in the middle of the disturbed area. A strong depression persists throughout most of July 14 and 15. Figure 4*c* shows the longitudinal profile of Δf_oF_2 at local noon on July 15. The UT period covered by this plot is from 0000 to 2000 UT, July 15. The strong depression at Boulder appears to reflect real spatial variations, although the picture is somewhat complicated by the fact that the ionosphere over North America was already well into the recovery stage. (The stations between Boulder and Slough showed ~5–10% depression on July 14, while White Sands showed ~37% depression.) It is possible that the depression at Boulder on July 15 is due to the localized effects of the short substorm between ~1700 and ~2000 UT on July 14. Because of these complications, Figure 4*c* cannot be interpreted in terms of longitudinal variations alone. Nevertheless, this case serves to illustrate longitude effects that might be expected following a more typical, i.e., more complicated, magnetic disturbance.

Again, no southern hemisphere stations reported similar depressions in f_oF_2 on either July 14 or July 15.

Relationships between the time of substorm activity and the location of depressed f_oF_2. One common feature clearly revealed in all four cases above is that f_oF_2 depressions are observed only in the summer hemisphere. This strong seasonal asymmetry raises many interesting questions, which will be addressed in the next section.

Next, we want to relate the time of substorm activity to the longitude sector showing negative Δf_oF_2. In determining this sector we arbitrarily place the boundary where the magnitude of Δf_oF_2 falls off to one half of the maximum value. Figure 5 illustrates where in local time these depressed sectors were while substorm activity was in progress. For example, in the June 26, 1965, case the depressed area was between ~30°W and ~120°W (see Figure 1*c*). This area swept through the 0730–1800 local time sector during the substorm period 1430–2000 UT on June 25.

The local time sector traversed by the depressed area in the December 26, 1968, cases is 0930–1900 if we consider only the major substorm activity between ~0230 and ~0700 UT on December 25 and ignore the two minor substorms that occurred late on December 24.

In the June 18, 1967, case there were three bursts of substorm activity, labeled SS1, 2, and 3 in Figure 3*a*. The most

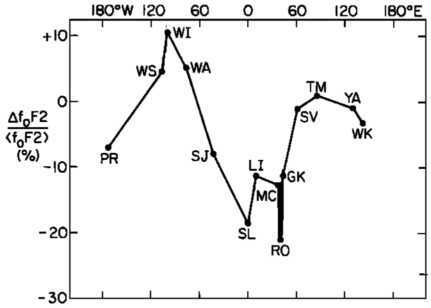

Fig. 3*c*. A plot showing longitudinal variations in f_oF_2 perturbations at local noon on June 18, 1967. The format is the same as that in Figure 1*c*.

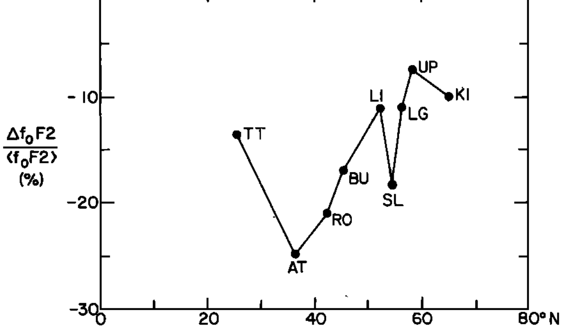

Fig. 3*d*. A plot similar to Figure 3*c* but showing latitudinal variations in f_oF_2 perturbations near the Slough meridian.

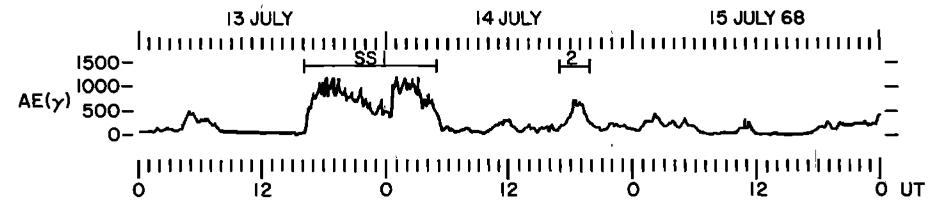

Fig. 4*a*. A plot of the *AE* index for July 13–15, 1968.

intense of the three substorm bursts was SS2 (having a maximum *AE* index of ~1000 γ), and the local time sector traversed by the depressed area during this event is indicated by the shaded arc in the lower half of Figure 5. If we were to include SS1 (having a maximum *AE* index of ~600 γ) as a part of the causative substorm activity, then the local time coverage that there is much more heating in the sunlit cusp region than in labeled SS1. The third substorm event, SS3, would extend the local time coverage even further, as is indicated by the dashed arc. However, it is very unlikely that SS3 (having a maximum *AE* index of ~400 γ) contributed significantly to the observed depressions in f_oF_2. In our search through several years' data we have not found a case in which an isolated substorm with the maximum *AE* being less than 500 γ produced ionospheric effects of the kind discussed in this paper. This conclusion, however, must be considered tentative until a more systematic study is made of the relationship between the substorm intensity and the resulting ionospheric disturbance.

In studies of this kind a certain amount of ambiguity is unavoidable because it is difficult to find a case involving only one isolated substorm and no other substorm activity that can be suspected of also contributing to the observed effects. Nevertheless, we can see that in all three cases above, the longitude sector that reported negative Δf_oF_2 was on the dayside of the earth while magnetospheric substorm activity was in progress. In the June 18, 1967, case it might be argued that the passage of the disturbed sector throughout the nightside during SS3 was the significant factor. However, this is not a tenable argument, since the Asian sector, which was on the nightside during a more intense activity, SS2, showed no systematic decrease in f_oF_2.

In the July 15, 1968, case, local time discrimination is not possible because of the long duration of the substorm activity (about 13 hours) and also because of the somewhat complex longitudinal behavior of Δf_oF_2. However, the results of this case are consistent with those of the previous cases in that all the stations that showed large negative Δf_oF_2 went through the daytime sector while substorm activity was in progress.

DISCUSSION

It is not possible to study the ionospheric effects of a single elementary magnetospheric substorm because substorms tend to occur in groups and also because the average time interval between substorms is much shorter than the time scale of the associated ionospheric disturbances. However, case studies of relatively simple substorm activity, although they are limited in number, reveal some important clues for understanding ionospheric and thermospheric dynamics.

If we accept that the depressions in f_oF_2 described in the previous section were due to thermospheric composition changes, then a number of observational facts point to enhanced Joule heating in the sunlit polar cusp region as the heat source that produced the thermospheric disturbance. First, a dayside rather than a nightside heat source is suggested because the longitude sectors showing negative Δf_oF_2 were on the dayside during substorm activity. If the disturbance originated in the nightside auroral zone, the disturbed pocket of gas would have had to move about 180° in longitude. The ionospheric data show no evidence of such longitudinal movement.

The strong seasonal asymmetry in observed Δf_oF_2 suggests that there is much more heating in the sunlit cusp region than in the dark cusp region. This in turn implies that the dominant heating mechanism is Joule heating, which should strongly favor the sunlit ionosphere with high electrical conductivity. Heating by precipitating particles is expected to be more symmetrical between conjugate hemispheres.

Finally, we suggest that it is heating at auroral latitudes, not local heating, that causes disturbances at middle latitudes. Measured substorm electric fields in the dayside mid-latitude ionosphere are only a few millivolts per meter [*Carpenter and Seely*, 1976; *Park*, 1976; *Evans*, 1972; *Carpenter and Kirchhoff*, 1975], too weak to produce significant heating. Even if the four particular cases presented here involved unusually large electric fields, local Joule heating at middle latitudes could be ruled out on the basis of the observed seasonal asymmetry in Δf_oF_2. At middle latitudes, where both conjugate ionospheres

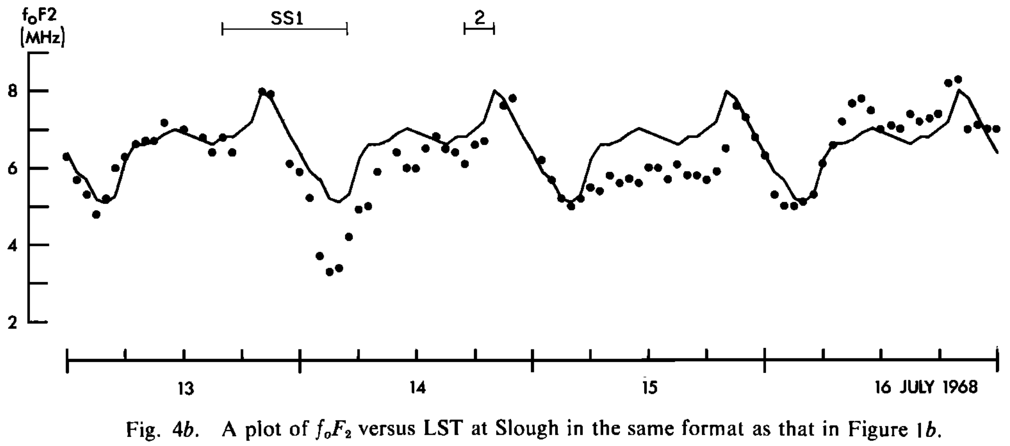

Fig. 4*b*. A plot of f_oF_2 versus LST at Slough in the same format as that in Figure 1*b*.

are sunlit, heating rates should not be very different between the two hemispheres.

If the disturbance starts at auroral latitudes and spreads to middle latitudes, one may expect to see evidence for equatorward propagation of the disturbance in ionospheric data. However, this is difficult to verify experimentally for several reasons. The first negative value of Δf_oF_2 usually occurs when we might still expect transient effects such as traveling ionospheric disturbances, so that it cannot be unambiguously interpreted as the arrival of a composition perturbation. Another reason is that if this spreading occurs at night, the ionosphere may be under the strong influence of the overlying magnetosphere and may not be very sensitive to thermospheric composition changes [*Park and Banks*, 1974, 1975]. Latitudinal motions of the plasmapause and its influence on the ionosphere add to the complexity.

The conclusion that we reached here regarding the location of the heat source is in agreement with other results. Incoherent scatter radar observations at Chatanika, Alaska, show that the maximum Joule heating occurs in the dayside cusp region (P. M. Banks, private communication, 1975). *Davies* [1974*a*, *b*] analyzed the onset times of large ionospheric storms at many stations and concluded that the data are consistent with a disturbance source near the dayside cusp region.

It should be emphasized that for the purpose of this study we deliberately searched for simple cases involving relatively isolated substorm activity. These cases are by no means representative of typical substorm effects. In more typical cases, geomagnetic activity and the resulting ionospheric disturbances would be much more complicated.

An important question that needs further investigation is the quantitative relationship between substorm intensity (or duration) and the resulting ionospheric disturbance. There are many small substorms that produce no clearly identifiable effects in the mid-latitude *F* region. Also, there are many substorms that are comparable to or even larger than the substorms discussed in this paper but that do not produce similar depressions in f_oF_2. The complete lack of conjugacy in Δf_oF_2 reported here may be due to the fact that we selected substorms of only moderate intensity. During severe storms the winter hemisphere also shows negative Δf_oF_2, although the magnitude is less than that in the summer hemisphere [e.g., *Martyn*, 1953]. We suspect that the winter thermosphere is also susceptible to similar disturbances due to auroral heating when the substorm intensity and duration exceed certain levels. However, we do not know what these levels are.

If the dominant heat source for thermospheric disturbances is on the dayside of the earth, as we suggested, then the *AE* index may not be a good parameter to use for correlation,

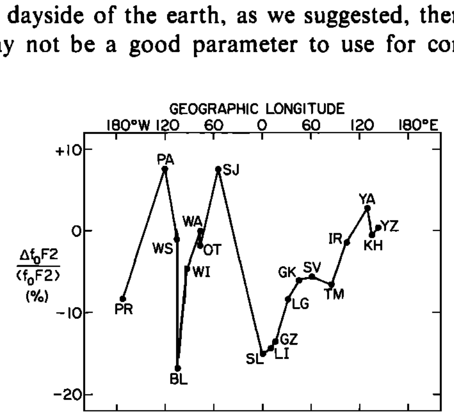

Fig. 4*c*. A plot showing longitudinal variations in f_oF_2 perturbations at local noon on July 15, 1968. The format is the same as that in Figure 1*c*.

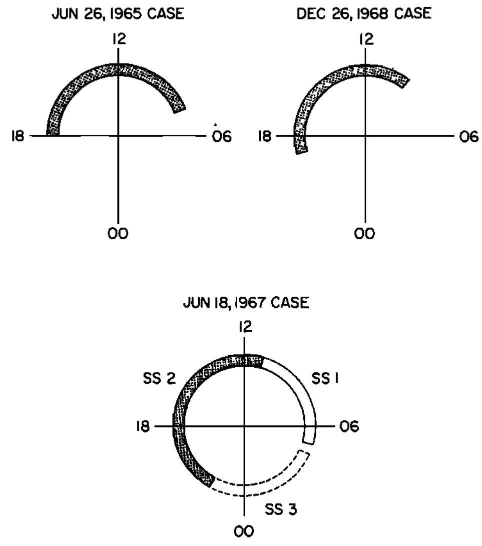

Fig. 5. Sketches illustrating the local time sectors occupied by the region of depressed f_oF_2 during substorm activity. See the text for details.

since it is primarily an indicator of auroral electrojet activity on the nightside. Perhaps we need a different magnetospheric index for correlations with thermospheric and ionospheric dynamics.

Another important question that remains unanswered is what happens to the winter-summer asymmetry in Δf_oF_2 when we approach equinoxes.

CONCLUSIONS

We have examined the behavior of f_oF_2 at some 100 stations following isolated magnetospheric substorm activity of moderate intensity. The four cases examined here occurred during solstice periods. Following each substorm activity, pronounced depressions in f_oF_2 developed in a limited longitude sector in the summer hemisphere and lasted for 1 day or more. The depressed area appears as a tongue extending from auroral latitudes down to ~20° geomagnetic latitude and corotating with the earth in a longitude sector that was on the dayside of the earth while the substorm activity was in progress. These depressions are believed to be caused by changes in thermospheric composition similar to the changes observed by the Esro 4 satellite during large magnetic storms. The location of the depressed f_oF_2 following isolated substorms suggests that the primary heat source for thermospheric disturbance is Joule heating in the sunlit polar cusp region.

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