A Theoretical Study Of The High Latitude *F* Region's Response To Magnetospheric Storm Inputs

J. J. SOJKA AND R. W. SCHUNK

Center for Atmospheric and Space Sciences, Utah State University, Logan, Utah 84322

The response of the polar ionosphere to magnetospheric storm inputs was modeled. During the storm the two major processes that couple the *F* region to the magnetosphere, namely the electric field distribution and the particle precipitation from the magnetosphere, undergo drastic modification on relatively short *F* region time scales. These time-dependent changes are not simply related to the *F* region storm time dependent changes. The lower *F* region responds on a time scale of only minutes to the storm associated changes in the auroral precipitating electron flux, owing to the dominance of chemistry production-loss mechanisms over transport processes. At higher altitudes in the vicinity of $h_m F_2$, the chemistry is balanced by both plasma diffusion along field lines and horizontal plasma convection, which acts to prolong the effect of the storm for many hours after it has ceased. The peak density responds only slowly to increased precipitation and may not reach its maximum enhanced value until over an hour after the storm main precipitation has passed. However, the *F* region peak can be drastically altered on a time scale of minutes if large vertical transport velocities are associated with the storm electric field distribution. In the topside ionosphere the density variations are not correlated with the morphology of the storm auroral precipitation or the temporal variation of the storm electric field pattern. Time delays of up to 3 or 4 hours occur at high altitudes for 'peak' densities to be reached after a storm, and the subsequent recovery is on the order of 5 hours. These long delays at altitudes above 400 km reflect the long time constants associated with plasma diffusion from low altitudes, where the plasma is created, to high altitudes.

1. INTRODUCTION

During the past few years, we have developed a comprehensive model of the convecting high-latitude ionosphere in order to determine the extent to which various chemical and transport processes affect the ion composition and electron density at *F* region altitudes [cf. *Schunk and Raitt*, 1980; *Sojka et al.*, 1981a, b; *Schunk and Sojka*, 1982a]. Our numerical model produces time-dependent, three-dimensional ion density distributions for the ions NO^+ , O_2^+ , N_2^+ , O^+ , N^+ , and He^+ . The model takes account of diffusion, thermospheric winds, electrodynamic drifts, polar wind escape, energy dependent chemical reactions, magnetic storm induced neutral composition changes, and ion production due to solar EUV radiation and energetic particle precipitation.

In an initial application of this model, we studied the high-latitude *F* region for winter, solar minimum, and low geomagnetic activity conditions [*Sojka et al.*, 1981a, b]. In a subsequent study [*Sojka et al.*, 1981c], we compared the response of the winter *F* region to both weak and strong plasma convection. For strong convection, we also studied the seasonal variations of the high-latitude ionosphere [*Sojka et al.*, 1982a]. One of the important results that emerged from these studies was that high-latitude ionospheric features, such as the 'main trough,' the 'ionization hole,' the 'tongue of ionization,' and the 'aurorally produced ionization peaks,' are a natural consequence of the competition between the various chemical and transport processes known to be operating in the high-latitude ionosphere. We also found that these

features display a marked variation with season, convection pattern, and universal time (UT).

In the studies described above, the cross-tail magnetospheric electric potential was assumed to be constant, and the time dependence was a consequence of the relative motion between the geomagnetic and geographic poles. As the plasma convection pattern rotates about the geographic pole, the high latitude ionosphere moves toward and then away from the sun, producing a UT variation in the photoionization rate. In this study, we considered a more complicated time-dependent situation in that we modelled the response of the high-latitude *F* region to magnetospheric storm inputs. The magnetospheric storm inputs that we varied were the extent of the auroral oval, the precipitating electron energy flux, and the plasma convection pattern. For convenience, in this paper the time-dependent variation of these magnetospheric storm inputs will simply be referred to as the 'storm.'

2. STORM DEPENDENT IONOSPHERIC MODEL

The complete description of our high-latitude ionospheric model is given elsewhere [*Schunk and Raitt*, 1980; *Sojka et al.*, 1981a, b; *Schunk and Sojka*, 1982a] and will not be repeated here. Briefly, we follow a field tube of plasma as it convects through a moving neutral atmosphere. Altitude profiles of the ion temperature and densities are obtained by solving the appropriate continuity, momentum and energy equations including numerous high-latitude processes. These equations are solved over the altitude range from 120 to 800 km, with chemical equilibrium at 120 km and zero plasma flow at 800 km being the lower and upper boundary conditions, respectively. By following many field tubes of plasma we can

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construct a time-dependent three-dimensional model of the high-latitude ionosphere.

In any initial attempt to model the effects of a magnetospheric storm on the *F* region ionosphere, it is essential that the resulting *F* region trends can be clearly related to the magnetospheric storm inputs. Hence, for this theoretical study, we assumed that the two major storm inputs are (1) the changing magnetospheric convection electric field on a time scale of about an hour and (2) the changing precipitation energy fluxes, again on a time scale of about an hour. Consequently, all other storm variations will be regarded as higher-order and will be neglected, except for the variation of the auroral oval size. Such storm variations include neutral wind changes, neutral atmosphere density, temperature and composition changes, changes in currents and conductivities, and small scale spatial and temporal changes in the magnetospheric electric field and precipitation flux. In neglecting these higher-order variations, we have 'idealized' or 'simplified' the degree of complexity associated with the magnetospheric storm, but we should be able to establish the *F* region's response to the two important mechanisms that we considered.

The storm variations of the magnetospheric convection electric field and the precipitation energy flux are only weakly coupled. Indeed, the dependence of the magnetospheric electric field and precipitation energy flux on activity indices is poorly understood [Reiff *et al.*, 1981; Spiro *et al.*, 1982]. Hence, we will only consider the zeroth-order variations of these two parameters with *Kp* and *AE*, respectively. Studies of the precipitation energy flux reveal a relatively higher degree of symmetry about the noon-midnight meridians [Spiro *et al.*, 1982] than does the magnetospheric convection electric field [Heppner, 1977]. Hence, in order to allow for a wide range of energy fluxes and electric field strengths during a storm we have deliberately chosen two opposite cases of coupling between the electric field and precipitation energy flux in the dawn and dusk sectors. By choosing a dusk enhanced magnetospheric storm electric field pattern and a dawn-dusk symmetric precipitation energy flux, we obtain high electric field strengths combined with high precipitation energy fluxes in the dusk sector, while in the dawn sector the electric fields are weak and the precipitation energy fluxes are high.

The situation we considered was a magnetospheric storm of a few hours duration. The storm perturbs the quiet time ionosphere, and then the ionosphere relaxes back to a quiet time situation. The effects of the storm are manifested in time-dependent changes to the magnetospheric convection electric field, the auroral oval size, and the auroral particle precipitation flux. The calculations were performed for winter solstice and solar maximum conditions.

Figure 1 shows the variation of the magnetic index *Kp* as a function of time for our idealized magnetospheric storm. For the first hour of the study *Kp* was held at a prestorm value of 0.07. This was followed by a storm growth phase of one hour, during which time the *Kp* index increased linearly to a value of 5. The storm main phase lasted 1.5 hours, after which the *Kp* index decreased linearly to its prestorm value of 0.07. The

recovery phase lasted 3 hours. The model study was then continued for an additional 7.5 hours in order to allow the *F* region ionosphere sufficient time to relax back to a quiet time situation.

Our magnetospheric convection model uses the *Kp* index to determine the cross polar cap potential drop and the asymmetry in the dawn-dusk cells. In our previous studies, we used 20 kV and 90 kV as representative of quiet time and storm main phase cross-tail potentials, respectively. We adopted these values and associated a *Kp* of 0.07 with the quiet time potential and a *Kp* of 5 with the storm main phase potential, and we interpolated linearly for intermediate values. Our quiet time model has two symmetric convection cells ($\phi_{\text{dawn}} = 10$ kV, $\phi_{\text{dusk}} = -10$ kV); whereas the storm main phase model has an enhanced convection cell in the dusk sector ($\phi_{\text{dawn}} = 15$ kV, $\phi_{\text{dusk}} = -75$ kV); the convection in the dawn cell is only slightly stronger than that for the pre-storm case. The asymmetry of the dusk cell was assumed to vary linearly with *Kp* from pre-storm to storm main phase conditions. At latitudes equatorward of the polar cap boundary, the electrostatic potential diminishes as the inverse of the fourth power of sine colatitude. During the storm main phase the polar cap boundary expands to a radius of 16.3° , from a prestorm radius of 14.8° . The polar cap is centered a few degrees (2° to 4°) equatorward of the magnetic pole on the midnight magnetic meridian.

The auroral precipitation energy flux is clearly storm-dependent; we used the empirical results of Spiro *et al.* [1982] to model this dependence. The energy flux displays a systematic variation with the auroral index *AE*, which was varied from a prestorm value of 65 to a main phase value of 600. Thus, we were able to allow our auroral precipitating energy flux to vary during the storm.

In Figure 2 we exhibit the inherent differences between the quiet time convection model (panel A) and the storm main phase model (panel B). Each figure shows the same 9 plasma flux tubes followed for a period of 36 hours in a magnetic latitude-MLT coordinate system. All nine trajectories were started on the dawn-dusk meridian. For the quiet-time model (panel A), three trajectories are corotational, i.e., plasma flux tubes following the three most

Fig. 1. Variation of *Kp* as a function of time for our idealized magnetic storm. The storm growth phase lasts for 1 hour, the main phase lasts for 1.5 hours, and the recovery phase lasts for 3 hours.

Plate 2. O^+ density contours as a function of magnetic latitude and MLT for selected times at an altitude of 300 km. Note that the density color coding is different from that shown in Plate 1.

Plate 1. O^+ density contours as a function of magnetic latitude and MLT for selected times at an altitude of 160 km. Note that the density contours covers two orders of magnitude.

Plate 3. O^+ density contours as a function of magnetic latitude and MLT for selected times at an altitude of 500 km. Note that the density color coding is different from that shown in Plates 1 and 2.

Fig. 2. Plasma drift trajectories over the polar region viewed in a magnetic latitude-local time frame. These trajectories were calculated with allowance for corotation and a magnetospheric electric field. Panel (a) corresponds to prestorm magnetospheric conditions with a total cross-tail potential of 20 kV, while panel (b) corresponds to the storm main phase conditions for which the total cross-tail potential was 90 kV. The same nine flux tubes, located on the dawn-dusk meridian, were followed for 36 hours to obtain the convection patterns shown. However, since the storm main phase lasts for only 1.5 hours, the plasma flux tubes will only follow short segments of these trajectories.

equatorward trajectories corotate with the earth. For the main phase model (panel B), only plasma following the most equatorward trajectory executes this corotational motion. The influence of the storm main phase convection electric field extends at least 10° more toward the equator than does the quiet time electric field. The dawn cells, highlighted by two closed trajectories on the dawn meridian, are almost identical for panels A and B, whereas the dusk cells are radically different. This shows that the convection electric field in the dawn cell does not change significantly with changes in Kp , whereas the electric field in the dusk cell does change markedly.

Since the storm main phase lasts 1.5 hours, it is evident that the plasma flux tubes only follow small segments of the trajectories shown in Figure 2 during this time. During the buildup and decay phases of the storm, the plasma flux tubes follow trajectories that continually evolve from the quiet time to the storm pattern. Figure 3 shows the actual trajectories traced out by the 9 representative plasma flux tubes during the storm. The

Fig. 3. Actual drift trajectories followed by plasma flux tubes during our storm simulation. We have selected the same nine flux tubes and plotting format as used for Figure 2. These trajectories highlight the evolution of the convection pattern through the storm.

dawn cell trajectories show some dispersion in that changing Kp has caused them to trace out different closed loops. In the dusk sector, the evolution of trajectories is complicated; different line styles have been used to help separate the trajectories. These trajectories appear to overlap each other. However, this is because different trajectories cross the same location at different times, which is a consequence of the storm dependence of the convection electric field. The field tubes of plasma that follow the trajectories inside the dawn and dusk cells complete several loops during the storm. However, the field tubes of plasma that follow the two most equatorward (corotational) trajectories only complete partial loops during the storm.

Not only do the plasma trajectories vary with time during the storm, but so does the local electrodynamic plasma drift. Figure 4 shows contours of the horizontal (upper two panels) and vertical (lower two panels) electrodynamic drift components for pre-storm conditions (left panels) and at the storm main phase (right panels). These drift components were computed for an altitude of 300 km, assuming that the magnetospheric electric field was perpendicular to the geomagnetic field. Comparing pre-storm horizontal drifts (panel A) with the main phase horizontal drifts (panel B) reveals that the largest speed in each panel, 800 m/s for quiet time and 4400 m/s for the main phase, are in approximately the same ratio as the respective cross-tail potential drops, 20 and 90 kV. Also, the pre-storm drifts clearly display two symmetric cells, whereas the main phase drifts show a strongly enhanced dusk cell. This dusk cell is a relatively large region where the plasma drift exceeds 2 km/s.

A comparison of the vertical electrodynamic drifts indicates that the pre-storm (panel C) to main phase (panel D) ratio of the maximum speed is of the order of 1:10. This is significantly different from the ratio of the horizontal speeds and is due to the drastic change in the electric field distribution in going from prestorm to storm conditions. In general, the drifts are upward in the day sector and downward at night, a direct result of the fact that the magnetospheric electric field is everywhere

Fig. 4. Contours of the electrodynamic plasma drift components displayed in the magnetic latitude-MLT frame. The horizontal plasma drift component is shown in panel (a) for prestorm conditions and in panel (b) for the main phase of the storm. The vertical plasma drift component is shown in panel (c) for prestorm conditions and in panel (d) for the main phase of the storm. The contours are labeled in m/s. In panels (c) and (d), upward drifts are positive, while downward drifts are negative.

perpendicular to the magnetic field. The main phase vertical drifts (panel D) reach 110 m/s upward and 130 m/s downward in the dusk convection cell, with there being a relatively short distance between the locations of these maximum vertical drifts. As we will show later, this short distance will have a significant effect on the *F* region ionization.

The effect of strong downward drifts in regions devoid of ionization sources is to cause a rapid decay of the *F* region. However, in the dusk cell where the large downward drifts occur, the neutral wind, which predominantly flows antisunward over the polar cap, induces an upward ion drift, which acts to cancel the downward electromagnetic drift. At the equatorward edge of the dusk convection cell, the wind-induced upward ionization drift exceeds the downward electromagnetic drift, and therefore, acts as a nocturnal maintenance process for the mid-latitude ionosphere. The neutral wind pattern that we adopted is discussed by Sojka *et al.* [1981a]. This wind model consists of an altitude independent wind blowing from 1300 LT over the pole to 0100 LT with a speed of 200 m/s. The speed diminishes as the cosine of longitude from 0100 LT at other local times.

Figure 5 highlights the difference between the prestorm (panel A) and main phase (panel B) auroral precipitation fluxes. In both panels the precipitating energy flux is represented by contours in a magnetic latitude-MLT plot, with $AE \cong 65$ for panel A and $AE \cong 600$ for panel B. These contours, which show the statistical distribution of the

precipitating electron energy flux into the northern polar region, were obtained from an empirical model developed by Spiro *et al.* [1982]. The empirical model is based on Atmosphere Explorer satellite data.

During pre-storm conditions the auroral oval is approximately sub-visual with energy fluxes below $0.4 \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. For both cases, the precipitating auroral electrons have their highest energy fluxes in the night sector. For our calculations of auroral ionization rates, we assumed that the precipitating auroral energy spectral shape did not depend on position or time. We adopted a characteristic auroral arc spectrum with a peak energy of 4 keV [see Knudsen *et al.*, 1977]. During the storm, as Kp and consequently AE changed, we varied the energy flux by interpolating smoothly between the average fluxes for the AE ranges obtained by Spiro *et al.* [1982].

3. *F* REGION RESPONSE TO A MAGNETIC STORM

The initial polar *F* region ion densities at the start of the storm were obtained from our storm independent, UT model [cf. Sojka *et al.*, 1981a, b]. This model was run for 36 hours for the appropriate pre-storm solar and geophysical conditions. Starting at a UT of zero hours, a total of 2,304 plasma flux tubes were followed for 14.5 hours through the storm cycle shown in Figure 1. The integration time steps varied from a few seconds to no more than 4 minutes, depending on the local electric field distribution. These time steps were also chosen to ensure

Fig. 5. Contours of the auroral precipitating electron energy flux in the magnetic latitude-MLT frame. Panel (a) corresponds to prestorm conditions, while panel (b) corresponds to main phase of the storm. The contours are labeled in $\text{erg cm}^{-2}, \text{s}^{-1} \text{sr}^{-1}$.

that at fixed UT times each flux tube had appropriate altitude profiles of the ion densities. The altitude profiles were binned into 3° magnetic latitude and 1 hour magnetic local time regions for each of the selected UT times. Those UT time intervals were typically 1/2 hour apart, but during the growth and recovery phase of the storm they were 15 min apart. Since our study lasted 14.5 hours, we obtained 37 sets of *F* region ion distributions. Each set consisted of 5 ion species (NO^+ , O_2^+ , N_2^+ , O^+ , and N^+), the density of each ion being stored at 20-km intervals between 120 and 800 km. The data sets cover the polar region poleward of 42° magnetic latitude.

Because of the need to compare density distributions at many times during the storm, a rectangular rather than polar diagram format will be used; the rectangular plots can be fitted together more conveniently. In Figure 6 we show three such rectangular panels to highlight the important parameters relevant to the major ionization sources for the storm study. These are the solar zenith angle (left panel), the pre-storm auroral electron energy flux (central panel), and the main phase auroral electron energy flux (right panel). In this display, the auroral precipitation patterns appear radically different from the same data plotted in the dial format of Figure 5. The solar zenith angle indicates that the EUV production source is confined to a region centered about 12 MLT ($\approx$ noon), extending only to about 60° north magnetic latitude at winter solstice (regions of positive cosine of solar zenith angle). From our previous *F* region model studies [Sojka *et al.*, 1981a, b], the lower *F* region (below 200 km) displays density variations that directly correspond to the variations in the ionization production sources. Hence, we expect that the patterns shown in Figure 6 will be reflected in the ion density distributions at different times during the storm at altitudes below 200 km.

The O^+ density over the polar region at 160 km is shown in Plate 1 for 8 times during our storm study. Each of the 8 color panels shows a 'snapshot' in which the O^+ density has been contoured at intervals of 0.3 on a logarithmic scale and color coded to denote the absolute density ranges. The results are presented in a magnetic latitude-MLT frame. A color key in the upper right of Plate 1 shows that the absolute density varies over almost 2 orders of magnitude, from below 10^3 (dark blue) to above 3×10^4 (purple). The upper edge of each color

panel is connected by a line to the corresponding time on the storm profile curve. Panel 1 (the left most panel) corresponds to pre-storm conditions, panel 2 (second from the left) is for a time during the storm growth phase, panel 3 is for the storm main phase, panels 4 and 5 are for times during the storm recovery phase, and panels 6, 7 and 8 are for times during the post storm phase.

On each panel two distinct regions of higher densities are present, namely a band at all local times between 60° and 80° magnetic latitude and a 'spike' about 1200 MLT at low latitudes ($<60^\circ$). The first of these two features is due to the auroral ionization source, while the second is due to the solar EUV ionization source. Both regions have shapes very similar to their respective production sources (see Figure 6). During the 14.5 hours of the study, the solar EUV feature changes; this corresponds to the UT motion of the solar terminator in the magnetic frame and is completely unrelated to the storm variations going on in parallel. In contrast, the density changes in the auroral region are entirely due to the storm dependent changes in the auroral electron precipitation pattern. Pre- and post- storm panels 1, 6, 7, and 8 show identical auroral O^+ densities, with the highest densities in the night sector being below 10^4 cm^{-3} . During the storm, the auroral region O^+ densities increase significantly, and at the storm main phase they exceed $3 \times 10^4 \text{ cm}^{-3}$ over a

Fig. 6. Contours of ionospheric parameters that are relevant to the production of ionization. The left panel shows the cosine of the solar zenith angle; the middle panel shows the prestorm auroral energy flux; and the right panel shows the auroral energy flux during the main phase of the storm.

wide region centered about midnight MLT. Also, during the storm the auroral region of enhanced densities expands, predominantly equatorward by 5° to 6° , again reflecting the storm changes in the auroral production source. The symmetry between the dawn/dusk high density auroral regions is significant, since in these regions the plasma drift properties are highly asymmetric during the storm main phase (see Figure 4). In the dusk cell near midnight, there are strong downward drifts of the order of 100 m/s, and the corresponding horizontal drifts are in excess of 2 km/s. These drifts are approximately 4 times greater than the corresponding dawn sector drifts during the storm main phase. Hence, at 160 km, production and loss processes play the major role in determining the O^+ density, with transport processes being relatively minor. This is consistent with the chemistry time constants, which for our winter solstice and solar maximum conditions, are on the order of only a few minutes at most.

Plate 2 shows the O^+ density distribution at 300 km for 8 selected times during the storm study. These 8 times are identical to those used in Plate 1, as are the coordinates (magnetic latitude and MLT), and the density contouring interval. The absolute densities (see color key on Plate 2) are significantly higher, ranging from $8 \times 10^4 \text{ cm}^{-3}$ (dark blue) to above $2 \times 10^6 \text{ cm}^{-3}$ (purple). These higher densities are a consequence of the altitude, 300 km, being in the vicinity of the *F* region peak. Comparing Plates 1 and 2 shows that at 300 km the simple ionization source regions are no longer readily identified. At low latitudes and about 1200 MLT there still is a region of high density, however it does not show the same UT dependence or LT location as the solar EUV production region present at 160 km. In fact, at 300 km this feature has been spread over a wider area and shifted to a later local time, by approximately 2 hours, owing to the importance of horizontal transport.

At 160 km, the region previously defined as an auroral region can no longer be identified. This region poleward of 60° magnetic latitude now shows relatively little correlation with either the auroral source region (Figure 6) or the storm time profile. Panel 2, taken 30 min into the storm growth phase, shows densities identical to the pre-storm densities in panel 1, yet at 160 km the corresponding panel 2 shows marked density enhancements due to increased auroral precipitation. Panels 6, 7, and 8 of Plate 2, in contrast, are for post-storm times where the auroral production rate is identical to panel 1, and yet the densities in these panels are quite different from each other and those in panel 1.

During the storm itself (panels 2, 3, 4, and 5), a marked density variation is observed. However, unlike the storm disturbance that peaks at a time corresponding to panel 3, the peak densities occur between panels 4 and 5, depending on location. This time lag is of the order of 1 to 2 hours in relation to the time variation of the auroral production source. The symmetry in density patterns about midnight is no longer present, the highest densities are found in the morning sector (see panels 4 and 5), with the densities exceeding $2 \times 10^6 \text{ cm}^{-3}$. In the corresponding evening sector, the densities are at least a factor of 2 lower. This asymmetry is a direct consequence of the differences in plasma transport processes between the two regions (see Figure 4). Even after the storm recovery, the

asymmetry is still present, although now the convection pattern has returned to the quiet-time symmetric pattern. The persistence of this density asymmetry results from the much longer time constants, hours rather than minutes as was the case at 160 km, for the 300 km *F* region to relax to its quiet time situation.

Another feature present at 300 km but not at 160 km is the occurrence of high density regions outside of the ionization production region. High densities occur in the afternoon-evening polar cap and evening-morning sector sub-auroral troughs. In Plate 2 panels 4, 5, 6, and 7, the polar cap (poleward of 80° magnetic latitude) shows enhanced densities many hours after the storm main phase. These high densities have been convected into the polar cap predominantly in the afternoon-evening sector, where during storm activity higher convection drift speeds were present. The persistence of these higher polar cap densities to as late as 8 hours in the study, 4 hours after the main phase, again highlights the long time constants governing the behavior of the *F* region peak density.

Pre-storm troughs are found equatorward of the auroral region in both the evening and morning sectors (see Plate 2, panel 1 dark blue regions equatorward of 70°). The afternoon-evening sector trough appears to extend to a higher latitude; however, during the storm (panels 3 and 4) the morning sector trough extends to the highest latitude and also is nearest to noon. These differences are directly related to the presence of the enhanced convection cell in the dusk sector during the storm. This again shows that near the peak of the *F* region the density variations are much more complex than those present at lower altitudes owing to the greater importance of plasma transport processes. In particular, vertical transport has a marked effect on the *F* region shape. Vertical transport is to some extent responsible for the major asymmetries between the dawn and dusk auroral O^+ density regions that are evident when viewing at a fixed altitude.

Plate 3 shows the O^+ density distribution at 500 km for 8 selected times during the storm study. These 8 times are identical to those used in Plates 1 and 2, as is the layout. However, the density color coding is different owing to the lower densities found at 500 km. The O^+ density ranges from below $2 \times 10^4 \text{ cm}^{-3}$ (dark blue) to above $6 \times 10^5 \text{ cm}^{-3}$ (purple). The 8 panels of Plate 3 show a storm evolution of the O^+ density at 500 km that is somewhat similar to that at 300 km, in that all of the features that were present at 300 km are again present. A dayside low-latitude region of high densities, corresponding to low altitude ionization by solar EUV radiation, is again present. This feature, however, has been shifted to even later local times, by about 3 hours.

A feature not readily evident at 300 km, but which occurs at 500 km, is the nighttime *F* region maintenance at mid-latitudes in the post midnight sector where neutral wind induced upward ion drifts raise the *F* region, and hence increase the O^+ density.

As found at 300 km, the highest densities ($\approx 8 \times 10^5 \text{ cm}^{-3}$) at 500 km occur at auroral latitudes in the dawn sector. However, at this altitude the peak densities appear even later relative to the storm activity (between panels 5 and 6). This is at a time when all storm activity

has virtually ceased and is at least 2.5 hours after the storm main phase. The density ratio between the dusk and dawn auroral sectors is now almost 1:4 in contrast to a ratio of 1:2 at 300 km.

Other features, such as the polar cap density enhancements that occur hours after the storm main phase and the morning-afternoon trough asymmetry are again present. The depth and structure of the troughs relative to their surrounding regions have become more pronounced and different from those at 300 km. These and most of the other differences between the ionospheric evolution at 300 and 500 km are attributable to the increasing importance of both horizontal transport and vertical diffusion with altitude. In fact, even 3.5 hours after all storm activity has ceased (Plate 3, panel 8), the upper *F* region has not relaxed back to its pre-storm condition. At this time there is still a region of enhanced density in the morning sector. In this sector, even during the storm main phase, the convection drift pattern was not significantly changed, which allowed the local buildup of high densities during the time of enhanced auroral precipitation (see panels 3, 4, and 5). The persistence of the high densities reflects the long time constants associated with the decay of the topside ionosphere, of the order of 3-6 hours [cf. Schunk *et al.*, 1976].

Over the whole polar region, the ionosphere exhibits large altitude dependent density variations. In the bottom side *F* region, photochemical processes with time constants of the order of a few minutes dominate; at *F* region peak altitudes, photochemical and transport processes are equally important, with the transport processes being responsible for major morphological changes in the density distribution; and finally, in the topside *F* region transport and diffusion are dominant and the ionosphere becomes relatively sluggish, since the time constant for density changes is of the order of hours.

The strong altitude dependence of the ionospheric response time is illustrated in Figure 7, which shows the temporal evolution of the *F* region density at 3 distinct altitudes during the storm study for a fixed magnetic latitude-MLT location. This location was chosen to lie in the center of the dawn sector high density region at 2 MLT and 63° N magnetic latitude. The O⁺ density for each altitude is plotted as logarithmic values against

Fig. 7. O⁺ density versus time at selected altitudes for a magnetic latitude of 75° N and an MLT of 0300.

Fig. 8. Altitude profiles of electron density of selected times for a magnetic latitude of 78° N and an MLT of 1800.

time for the first 12 hours of the storm study; the storm profile is also schematically shown in this figure. At 160 km the density varies by over an order of magnitude (from 10^3 cm^{-3} to above 10^4 cm^{-3}) in phase with the storm profile. This is no longer the case at 300 km, where the peak density is built up gradually. The buildup continues into the recovery phase of the storm, with the peak density occurring at 5 hr, i.e., 1.5 hours after the storm main phase ended. The decay at 300 km is very gradual and is over a period of at least 6 hours. At 540 km, the peak density occurs at 7 hr, which is 3.5 hours after the end of the storm main phase. During the post storm study, small density variations are present at all altitudes owing to a combination of diffusion, chemistry, and transport processes in the absence of any direct ionization source.

4. VARIATIONS OF $h_m F_2$ DURING A STORM

During the storm, the enhanced convection in the dusk cell produces very large induced vertical drifts (100 m/s). Vertical drifts of this order of magnitude should have a major effect on the shape of the *F* region density profile. Therefore, during the storm not only do the ion densities change due to combinations of enhanced production, diffusion, and horizontal transport, but the shape parameters also change, such as $h_m F_2$ and the topside plasma scale height.

Figure 8 shows the temporal evolution of the electron density altitude profile at a fixed magnetic latitude and MLT during the storm. Altitude profiles are shown at 1/2-hour intervals on a linear density scale from 120 to 500 km. The time evolution of density at fixed altitudes and 20-km intervals is also shown via horizontal lines. Thus, these lines produce a uniform grid in time and altitude of 1/2 hour and 20 km, respectively. The three-dimensional properties of this grid reflect the changing density in the *F* region at a magnetic latitude of 78° N and MLT of 1800.

During the storm main phase, from 2 to 3.5 hr, the lowest altitudes show an increase in density due to enhanced auroral production. At an altitude of 300 km, however, the density decreases during this time, while at higher altitudes the density increases. This behavior is a result of the *F* region peak being raised by more than 60 km during the storm main phase, from 300 km to above

Fig. 9. Contours of $h_m F_2$ in a magnetic latitude-MLT frame. Panel (a) corresponds to prestorm conditions, while panel (b) corresponds to the main phase of the magnetic storm. The contours are labeled in units of kilometers.

360 km. As the storm enters its recovery phase, from 3.5 to 6.5 hours, the vertical transport diminishes and the F peak is lowered. For a period of 2 hours, from 7 to 9 hr, a marked density enhancement is observed in the F region above 200 km. This delayed density enhancement is a result of horizontal transport, which brings the high-density flux tubes to this location.

In contrast to the morning sector F region where a delayed density increase was observed (see Figure 7), in the dusk sector multiple storm signatures are observed. Horizontal transport combined with vertical diffusion and chemistry have relatively long time constants for equilibrium (hours); however, the local effect of an induced vertical drift is to immediately alter the F region shape. Upward drifts raise the peak, while downward drifts lower the peak. A downward drift lowers the F region into a region of higher recombination rates, which acts to decrease $N_m F_2$. Thus, a combination of these processes can result in an apparently anomalous observation; for example, a satellite crossing our model ionosphere at 300 km would observe density decreases during the storm main phase in regions like the one shown in Figure 8. However, satellites at slightly higher altitudes would see density increases. In addition, the second density increase observed between 7 and 9 hr in Figure 8 might be interpreted as the signature of a second storm, which it is not.

Figure 9 shows contours of $h_m F_2$ for both pre-storm (panel A) and storm main phase (panel B) times in a magnetic latitude-MLT frame. The contours are drawn at 20-km intervals and are labelled in kilometers. Before the storm (Figure 9, panel A), $h_m F_2$ for varies between 270 and 370 km. The regions of high $h_m F_2$ are on the nightside and are associated with the induced upward drift caused by the neutral wind. These regions also are found during the storm main phase (see panel B). The bulk of the prestorm polar region has a $h_m F_2$ that is 290 ± 20 km. However, during the main phase this picture changes. Marked decreases and increases are observed in $h_m F_2$ in the evening and afternoon sectors, respectively (panel B). In the afternoon sector the peak is raised to above 350 km, while it is below 250 km in the evening sector. These regions are associated with the enhanced plasma convection in the dusk cell (compare with panel D of Figure 4). In the dawn convection cell on the other

hand, $h_m F_2$ varies by only a few km throughout the storm period owing to the small change in the convection pattern in this sector during the storm.

5. CONCLUSION

We modelled the response of the high-latitude F region to an idealized magnetospheric storm. During the storm, the spatial extent of the auroral oval, the intensity of the precipitating auroral electron energy flux, and the plasma convection pattern were varied with time. Temporal variations in the precipitating electron energy flux produced variations in the ionization rates, and hence, ion densities. Variations in the plasma convection pattern produced changes in both the vertical and horizontal electrodynamic drift components. A change in the vertical drift affects both $N_m F_2$ and $h_m F_2$, while a change in the horizontal convection speed alters the time a plasma flux tube spends in a given region and produces a change in the ion temperature via ion-neutral frictional heating. In turn, a change in the ion temperature affects the ion chemical reaction rates and the topside plasma scale height. In general, the various high-latitude processes compete in a complicated manner.

One of the more important results to emerge from our storm study is that the ionospheric response time is a strong function of altitude. At low altitudes (< 200 km), photochemical processes dominate and the time constant for density variations is of the order of minutes. As a consequence, the temporal changes in the density during the storm track, the changes in the ionization production rates, and the spatial boundaries of the different production sources are clearly visible. However, as altitude increases, the importance of both horizontal plasma convection and field-aligned plasma diffusion increases. As transport processes become more important, the ionosphere responds more slowly to auroral ionization sources. Consequently, near and above the F region peak, the density variations are not correlated with the morphology of the storm auroral precipitation or the temporal variation of the storm electric field pattern. The upper F region may not feel the full effect of the storm until after the storm activity has ceased.

Because the photochemical and transport processes compete in a complicated manner and because the ionospheric response time is a strong function of altitude, the unambiguous interpretation of F region density variations observed from just one geographic location or at just one altitude may be exceedingly difficult. For

example, if the vertical component of the electrodynamic drift changes during a storm, the high-latitude ionosphere may appear to develop deep troughs or large density enhancements if the ionospheric response to the storm is viewed at one altitude. However, all that may be happening is an increase or decrease in $h_m F_2$ at different locations in response to changes in the vertical drift, with perhaps only small changes in $N_m F_2$. Therefore, it appears that simultaneous observations from several locations are required to determine unambiguously the response of the high-latitude ionosphere to a magnetic storm.

We have compared our earlier non-storm model predictions with observations whenever possible. We compared plasma convection patterns predicted by our model with those observed concurrently at Chatanika, Alaska, and Millstone Hill, Massachusetts [Sojka *et al.*, 1980]. The two radar facilities observed different diurnal patterns of horizontal plasma convection velocities even though the measurements covered by approximately the same range of magnetic latitudes, a feature predicted by the convection model.

For solar minimum, winter and low geomagnetic activity conditions, we have compared the electron density and ion compositional variations that we obtained from our model with the Atmosphere Explorer (AE-C) satellite data presented by Brinton *et al.* [1978], and generally good quantitative agreement was obtained between theory and measurement [Sojka *et al.*, 1981a, b]. However, the AE data were not organized with respect to universal time (UT), and therefore, the large UT variation of electron density that our model predicts, which results from the displacement between the geomagnetic and geographic poles, could not be tested. To remedy this situation, we used the sun synchronous (fixed LT) nature and high time resolution of the ion density measurements from the DMSP F2 and F4 satellites to study the UT dependence of the high latitude ion density at 800 km [Sojka *et al.*, 1982b]. Both the long-term variation of the ion density on a time scale of days and the orbit by orbit variations at the same geomagnetic location in the northern (winter) hemisphere for the magnetically quiet time period chosen show good qualitative agreement with the UT dependence predicted by our theoretical model for similar geophysical conditions. We have also compared our predicted diurnal variations of plasma convection velocities and electron densities with specific measurements made at Millstone Hill on a geomagnetically moderately active day near equinox [paper in preparation] and again good agreement was obtained between theory and measurement. Also, for the same day our model predictions of the ion temperature morphology are in good agreement with that observed at Millstone Hill [Schunk and Sojka, 1982b].

In this study, our goal was to determine the response of the high-latitude *F* region to the two main magnetospheric storm inputs. As we have shown, the *F* region is very sensitive to changes in both the magnetospheric electric field distribution and the precipitation energy flux, and in quite different ways. In addition, we have shown from previous theoretical studies and from comparisons with observations that the *F* region exhibits a marked UT dependence. Because of these complications, a meaningful comparison between model predictions and observations for storm conditions requires data from

several ground-based sites and satellites, not only of the *F* region parameters as a function of time and location but also of the temporal characteristics of both the magnetospheric electric field and the precipitation energy flux during the storm. Unfortunately, at the present time the existing data are far too incomplete to warrant a comparison between model predictions and observations of storm characteristics. However, our storm study has helped define the required measurements for a meaningful comparison between theory and observations, and we are currently involved in collaborative efforts with experimental groups to obtain these data.

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