Seasonal Variations of the High-Latitude F Region for Strong Convection

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We combined a plasma convection model with an ionospheric-atmospheric composition model in order to study the seasonal variations of the high-latitude F region for strong convection. Our numerical study produced time-dependent, three-dimensional, ion density distributions for the ions NO^+ , O_2^+ , N_2^+ , O^+ , N^+ , and He^+ . We covered the high-latitude ionosphere above 42°N magnetic latitude and at altitudes between 160 and 800 km for a time period of one complete day. From our study we found the following: (1) For strong convection, the high-latitude ionosphere exhibits a significant UT variation both during winter and summer. (2) In general, the electron density is lower in winter than in summer. However, at certain universal times the electron density in the dayside polar cap is larger in winter than in summer owing to the effect of the mid-latitude 'winter anomaly' in combination with strong antisunward convection. (3) In both summer and winter, the major region of low electron density is associated with the main or mid-latitude trough. The trough is deeper and its local time extent is much greater in winter than in summer. (4) Typically, the electron density exhibits a much larger variation with altitude in winter than in summer. (5) The ion composition and molecular/atomic ion transition altitude are highly UT dependent in both summer and winter. (6) The ion composition also displays a significant seasonal variation. However, at a given location the seasonal variation can be opposite at different universal times. (7) High-speed convection cells should display a marked seasonal variation, with a much larger concentration of molecular ions near the F region peak in summer than in winter.

1. INTRODUCTION

Recently, we combined a plasma convection model and an ionospheric-atmospheric composition model in order to study the dynamics of the high-latitude F region. The plasma convection model, which is based on the work of Volland [1978], includes the offset between the geographic and geomagnetic poles, the tendency of plasma to corotate about the geographic pole, and a dawn/dusk magnetospheric electric field mapped to a circular region in the ionosphere about a center offset by 5° in the antisunward direction from the magnetic pole [Meng *et al.*, 1977]. Equatorward of the circle the potential diminishes radially and varies inversely as the fourth power of sine magnetic co-latitude. The ionospheric-atmospheric composition model takes account of solar EUV radiation, energetic particle precipitation, diffusion, thermospheric winds, electrodynamic drifts, energy-dependent chemical reactions, and magnetic storm induced neutral composition changes [cf. Schunk and Raitt, 1980]. For boundary conditions on the ion densities, we equated local production and loss rates at the lower boundary (140 km) and we assumed no flux of ions across our upper boundary (800 km). Earlier studies by Raitt *et al.* [1975] have indicated that a polar wind outflow has a negligible effect on the O^+ density profile at altitudes below 800 km. The complete details concerning the combined plasma convection and ionospheric-atmospheric models are given by Sojka *et al.* [1981a] and are not repeated here.

Our high-latitude F region model produces time-dependent, three-dimensional ion density distributions for the ions NO^+ , O_2^+ , N_2^+ , O^+ , N^+ , and He^+ . Typically, we cover the high-latitude ionosphere above 42°N magnetic latitude and at altitudes between about 160 and 800 km

for one complete day. In an initial application of the model, we studied the high-latitude winter F region at solar minimum for low magnetic activity [Sojka *et al.*, 1981a, b]. The main result we obtained was that high-latitude ionospheric features, such as the 'main trough,' the 'ionization hole,' the 'tongue of ionization,' the 'aurorally produced ionization peaks,' and the 'universal time effects,' 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 obtained good agreement, both qualitatively and quantitatively, between our theoretical predictions and Atmosphere Explorer measurements of the variations of the ion composition with latitude and local time.

In a subsequent study [Sojka *et al.*, 1981c], we modeled the high-latitude winter F region for conditions corresponding to strong plasma convection. In addition, we adopted an asymmetric electric field pattern with a small convection cell in the dawnside polar region. This plasma convection pattern is in contrast to that adopted in our initial study, which corresponded to slow plasma convection with a symmetric electric field pattern. The main conclusion drawn from this study was that the high-latitude ionospheric features, such as the main trough, the aurorally produced ionization peaks, the polar hole, and the tongue of ionization, are evident for strong convection but they are modified in comparison with that found for slow convection. In particular, the tongue of ionization is much more pronounced for strong convection than for weak convection. Also, the polar hole that is associated with quiet geomagnetic activity conditions [Brinton *et al.*, 1978] does not form when the plasma convection is strong, but a new polar hole appears in the polar cap at certain universal times. This new polar hole is associated with large downward electrodynamic plasma drifts. In addition, we found that the main elec-

tron density trough is not as deep for strong convection as that found for weak convection. However, it is still strongly UT dependent.

In this investigation, we studied the seasonal variations of the high-latitude *F* region for conditions corresponding to strong plasma convection. In section 2, we describe our *F* region model as it pertains to this study. In sections 3, 4, and 5, we discuss the seasonal variations of the electron density, the ion composition, and $N_m F_2$, respectively. Section 6 is devoted to a seasonal comparison of altitude profiles of ion density at selected locations, while in section 7 we summarize our results.

2. *F* REGION MODEL

Our model consists of two main components: a plasma convection model and an ionospheric-atmospheric model [Sojka *et al.*, 1981a]. The model produces time-dependent, three-dimensional ion density distributions for the ions NO^+ , O_2^+ , N_2^+ , O^+ , N^+ , and He^+ . We cover the ionosphere above 42°N magnetic latitude and at altitudes between about 160 and 800 km for one complete day. A number of parameters are required as inputs to our model; the neutral composition, thermospheric wind, neutral temperature, electron temperature, EUV solar radiation spectrum, production due to auroral particle precipitation and resonantly scattered solar radiation, and a magnetospheric electric field. These parameters are used in the calculation of plasma convection, plasma diffusion, and photochemical processes, which in turn yield the ion density distributions. The model can describe different combinations of season, solar cycle, and geomagnetic activity levels. For this study we compared summer and winter ionospheric densities for solar maximum and active magnetospheric conditions. As in our earlier studies, we maintained a constant cross-tail potential for the duration of our calculations (1.4 days).

The magnetospheric electric field is mapped into the ionosphere about the geomagnetic pole, which is offset from the northern geographic pole by 11.5° . In the polar cap region, defined by a circle of radius 18.5° centered on a point 5° anti-sunward of the geomagnetic pole, the electric field equipotentials are aligned sunward. Equatorward of the polar cap, the electric field diminishes and varies inversely as the fourth power of sine co-latitude in the magnetic frame. To simulate active magnetospheric conditions, a total cross-tail magnetospheric potential of 90 kV was selected. In addition, an enhanced dusk cell pattern was adopted. Such an asymmetry in the convection electric field is commonly found in satellite electric field observations [Heppner, 1977] and in incoherent backscatter radar observations (J. Foster, private communication, 1980).

The important aspects associated with the high magnetic activity conditions used in this study, namely convection trajectories, horizontal and vertical convection velocities, and auroral ionization sources, have been extensively discussed by Sojka *et al.* [1981c] and therefore are only briefly discussed here. Trajectories near the center of the enhanced dusk cell circulate in 0.06 days, while the corresponding trajectories in the weak dawn cell take 0.15 days to circulate. The plasma

associated with the stagnation trajectories takes approximately 1.35 days to circulate. Associated with the enhanced convection in the dusk cell are regions where the horizontal convection speed exceeds 2 km/s, while in the adjacent stagnation region speeds below 50 m/s are found over a wide local time sector. In the noon and midnight sectors, plasma convection induces vertical drifts exceeding 50 m/s upward and 60 m/s downward, respectively. These vertical drifts in the evening sector at mid-latitudes are countered by neutral wind induced upward drifts of a comparable magnitude.

The statistical auroral oval associated with a $K_p = 5$ was used to define a region within which an auroral ionization source was present. Outside this oval, the production was set to a suitably low value to simulate the effect of resonantly scattered solar radiation.

The seasonal comparison was made between a model data set for mid-summer and one for mid-winter. For each of these two days, the model was run for approximately 1.4 days to accommodate one complete circulation of the slowest trajectory. Seasonal differences were present in the model inputs in two different ways, the first being the location of the terminator in the polar cap. In mid-summer the polar cap is sunlight for nearly all UT's, while in mid-winter the polar cap is in darkness for nearly all UT's. The second seasonal input is that due to the neutral atmospheric model (MSIS), which gives different neutral density and temperature profiles for summer and winter.

3. SEASONAL VARIATION OF ELECTRON DENSITY

The plasma convection and ionospheric-atmospheric composition models were combined to generate altitude profiles of the various ion species over the area poleward of 42°N magnetic latitude, covering all local times for a 1.4-day period. In order to obtain adequate coverage in three-dimensional space and in universal time, the region of computation was divided up as follows. The altitude profiles consisted of ion densities computed every 4 km from 160 to 800 km. A total of 44 drift trajectories was chosen to give adequate spatial coverage in the high-latitude region, and each trajectory was traversed 12 times, corresponding to 12 different UT starting times, which were separated by 2 hours. Ion density profiles were stored at variable distances around the trajectory such that a typical trajectory at one UT had between 40 and 200 altitude profiles per ion species. The net result of the computations was a data base containing over 20,000 altitude profiles for each of the six ion species considered. The altitude profiles were distributed in magnetic latitude, MLT, and universal time. For convenience of presentation, these three parameters were divided into bins; the bin sizes were 3° for magnetic latitude, 1 hour for MLT, and 2 hours for UT. Additional computational details are given by Sojka *et al.* [1981a].

Figures 1 and 2 show contours of the electron density at 300 km for four universal times for mid-winter and mid-summer, respectively. The four UT's selected correspond to the geographic pole being near the dawn (0100 UT), noon (0700 UT), dusk (1300 UT), and midnight (1900 UT) magnetic meridians. In both figures, each plot is a polar diagram in MLT and magnetic latitude. The elec-

Fig. 1. Contours of the winter electron density at 300 km for four universal times displayed in the magnetic quasi-inertial frame. The gray scaling corresponds to different density levels, as indicated in the key. Magnetic local time (MLT) is indicated by tick marks at hourly intervals, and magnetic latitude is indicated on the vertical scale.

tron density variation is presented as gray scaled contour intervals, with the darkest shades corresponding to the lowest densities. Over the polar region at 300 km, the electron density varies from about 10^4 to 10^6 cm^{-3} in both summer and winter. A particularly evident feature seen in Figures 1 and 2 is the marked UT variation of the electron density. With regard to the seasonal variation, the lowest densities are generally found in winter (Figure 1), where larger areas of dark shading are more evident than in summer (Figure 2). However, there are certain regions where the summer density is lower than the equivalent winter density. These regions and other ionospheric features evident in winter and summer will be compared in the following paragraphs.

In both summer and winter, the major region of low electron density is found in the night sector equatorward of 60° , which is the location of the mid-latitude trough. The lowest densities and largest LT extent of the trough are found in winter (Figure 1). In winter, the terminator lies in the dayside sector at latitudes equatorward of at least 78° (magnetic). At 0700 UT (panel B of Figure 1), the terminator intersects the noon meridian at a latitude of about 55° (magnetic), and the whole polar region is in darkness. For this UT, the winter trough appears to circle the polar cap. In summer, the situation is somewhat different; the terminator intersects the midnight meridian at 68° and therefore most of the polar cap is in sunlight.

As a result, the summer dayside at 7 UT (Figure 2) does not show a continuous region of low densities around the polar cap.

The local time extent of the trough in winter is highly dependent on UT. At 0100 UT the trough is deepest in the morning sector and extends to about 8 MLT, while at 1300 UT the trough is deepest in the dusk sector and extends to about 1600 MLT. In the morning sector the trough remains at latitudes of about 50° , whereas in the late afternoon sector the trough is found at a latitude of between 60° and 62° . In contrast, the summer trough is confined to the late night sector (see Figure 2). At 0100 UT the summer trough extends from about 2100 MLT to 0500 MLT and the density remains above 10^5 cm^{-3} , whereas the equivalent winter trough extends from 1500 MLT to 0900 MLT with densities below $5 \times 10^4 \text{ cm}^{-3}$. For other UT's, the MLT extent of the trough in summer is very similar to that at 0100 UT, although the minimum density is strongly UT dependent. The lowest summer trough densities are below $5 \times 10^4 \text{ cm}^{-3}$ at 1300 UT.

Smaller regions of low electron density are found at certain times in the polar cap. For both winter (Figure 1) and summer (Figure 2), a low density region is present on the midnight meridian near a latitude of 80° and at 0700 and 1300 UT. This density depletion is associated with a region of large downward convection speeds ($\sim 70 \text{ m/s}$), which lies just poleward of the nightside auroral oval. In

Fig. 2. Contours of the summer electron density at 300 km for four universal times displayed in the magnetic quasi-inertial frame. The gray scaling density levels and coordinate system are identical to those shown in Figure 1.

this region the plasma, in addition to displaying a rapid anti-sunward convection with horizontal speeds of between 200 and 600 m/s, also convects downward into the lower ionosphere where the neutral densities and hence recombination rates are much higher. This, combined with the lack of additional ion production, causes the observed density depletion. At magnetic local times in the night sector away from midnight, the vertical downward drifts are significantly smaller, and hence the loss mechanism is less effective. For both winter and summer the depletion is most marked at 0700 UT, which corresponds to the time the terminators are at their most sunward location on the noon-midnight meridian in the magnetic quasi-inertial frame.

Another region of relatively low polar cap densities is present in summer at all UT's (Figure 2). This low density region lies in the noon-dusk sector poleward of about 65° latitude. No corresponding region of low density is found in the winter (see Figure 1). This summer low density region has an electron density that varies between 10^5 and 2×10^5 cm^{-3} , whereas in winter the electron density exceeds 2×10^5 cm^{-3} in this region. This somewhat anomalously high winter to summer electron density ratio will be discussed more fully later, where it is shown that other regions of anomalously high winter electron densities are present in the dayside polar cap.

The electron density variation with altitude for both

winter (left panel) and summer (right panel) is shown in Figure 3. The electron density is shown at four altitudes (160, 260, 360 and 600 km) for 0900 UT. A magnetic latitude-MLT polar diagram is used to display the electron densities, which are shown as contours of $\log_{10} N_e$ cm^{-3} at 0.5 intervals over the range 3.5 to 5.5. Typically, the winter electron densities show a much larger variation at all altitudes. At 160 km, in both winter and summer, local production and loss processes dominate. At this altitude, the auroral oval is clearly seen as a region of high-electron density that surrounds the pole at latitudes between 60° and 75° . Production due to solar EUV radiation is also evident, as shown by the high electron densities near noon, where the contours lie along the dawn-dusk direction parallel to the terminator. Here a major seasonal difference is evident; in winter, the terminator lies equatorward of the polar cap on the dayside, while in summer, the terminator lies in the night sector. Thus, most of the summer ionosphere at 160 km has densities above 3×10^4 cm^{-3} , whereas most of the winter ionosphere at 160 km is below this density.

At altitudes above 160 km, plasma transport processes rapidly become important. Even at an altitude as low as 260 km, the auroral oval and terminator locations are no longer sharply marked in the density contours. In winter on the dayside (260 km, left panel), the density contours are skewed in a corotational sense away from

Fig. 3. Contours of the electron density at 0900 UT and four altitudes for winter (left column) and summer (right column) conditions displayed in the magnetic quasi-inertial frame. The contours are labeled in units of $\log_{10} N_e$ (cm⁻³).

Fig. 4. Contours of the winter (left panel) and summer (right panel) mean ion mass at 0600 UT for three altitudes. The mean ion mass is in atomic mass units. The contours are plotted in the magnetic quasi-inertial frame.

the terminator's dawn-dusk alignment. A similar skewing is evident in the night sector in summer at 260 km, although to a lesser extent.

It should be noted that our ionospheric model produces a 'winter anomaly', as seen by the higher electron densities in winter than in summer at mid-latitudes in the afternoon sector. In the summer afternoon sector at 260 and 360 km, the electron density lies between 10^5 and $3 \times 10^5 \text{ cm}^{-3}$, whereas in winter there exists a large region where the density is greater than $3 \times 10^5 \text{ cm}^{-3}$. Although the winter anomaly appears to be present only at mid-latitudes in this figure, it is actually present over a wide region of the dayside ionosphere; the contour interval of 0.5 on a $\log_{10}$ scale is too coarse to reveal the full extent of the anomaly. The anomaly is present at all altitudes above 260 km and is most marked at altitudes where the

F region peak is expected, 260 to 400 km. This aspect will be discussed in more detail later where altitude profiles of the ion densities are shown.

4. SEASONAL VARIATION OF ION COMPOSITION

The ion composition in the F region undergoes a major change from 160 km, where the composition is dominated by the molecular ions NO^+ and O_2^+ , to above 300 km, where the atomic O^+ ion is dominant. In a previous study, Sojka *et al.* [1981b] showed that for winter, solar minimum, and quiet geomagnetic conditions, the altitude of the transition from molecular to atomic ions is very UT dependent. In this study, which is for solar maximum and active geomagnetic conditions, we have also found a marked UT variation of the ion com-

Fig. 5. Contours of the winter (left panel) and summer (right panel) mean ion mass at 2000 UT for three altitudes. The mean ion mass is in atomic mass units. The contours are plotted in the magnetic quasi-inertial frame.

position and transition altitude for both summer and winter. As expected, the ion composition also exhibits a significant seasonal variation.

Figure 4 shows contours of the mean ion mass at altitudes of 200, 260, and 300 km for winter (left column) and summer (right column) at 0600 UT. The composition is contoured and labeled in units of atomic mass units (AMU) and is presented in the MLT-magnetic latitude polar diagram previously defined. By comparing the two columns of Figure 4, a marked seasonal difference is noted. A major difference is found near the high convection cell at dusk, where in summer even at 300 km a large concentration of molecular ions is present, whereas in winter this region is almost all O^+ at 300 km. Another seasonal difference is present in the night sector at 260 km in the region associated with the mid-latitude trough. In winter (left column, Figure 4) the trough is populated

with a high concentration of molecular ions, whereas in summer (right column, Figure 4) the light ion O^+ is dominant.

Figure 5 shows the mean ion mass contours of winter (left column) and summer (right column) at the same altitudes but at 2000 UT. A major change has occurred in the composition in going from 0600 UT to 2000 UT; at 260 km the previously described seasonal composition difference in the mid-latitude trough is no longer present. In both winter and summer, the composition at 2000 UT in this region is dominated by atomic O^+ . However, the dusk convection cell still shows a significantly larger concentration of molecular ions in summer than in winter, even at 300 km. At 200 km, the UT difference between Figures 4 and 5 is most marked. At 2000 UT (Figure 5), both winter and summer show marked compositional changes in the night sector mid-latitude trough, while at

Fig. 6. Contours of $N_m F_2$ for winter (left panel) and summer (right panel) conditions at 0700 UT displayed in the magnetic quasi-inertial frame. The contours are labeled in units of $\log_{10} N_e \text{ (cm}^{-3}\text{)}$.

0600 UT the composition is very constant, lying between 26 and 32 AMU. At 2000 UT, the composition in the morning sector at 200 km is mainly O^+ in winter (left bottom panel, Figure 5), whereas in summer (right bottom panel, Figure 5) the composition displays a somewhat higher mean mass, ranging between 17 and 20 AMU. This behavior contrasts strongly with that shown at 6 UT, where the mean ion mass is greater than 23 AMU for both winter and summer (lower panels of Figure 4).

5. SEASONAL VARIATION OF $N_m F_2$

In Figure 6, the peak electron density $N_m F_2$ at 0700 UT is contoured for winter (left panel) and summer (right panel) in the magnetic quasi-inertial frame. The contours are labeled in units of $\log_{10} N_e \text{ cm}^{-3}$. A number of the seasonal differences already discussed are present in the $N_m F_2$ comparison. In the afternoon mid-latitude sector, the winter peak values exceed $4 \times 10^5 \text{ cm}^{-3}$, whereas in summer the density lies between 2×10^5 and $4 \times 10^5 \text{ cm}^{-3}$. At higher latitudes (above 65°) in the same afternoon sector, the summer densities are again lower in some regions than the equivalent winter densities. A polar depletion region near the magnetic midnight meridian at about 80° has a lower $N_m F_2$ in winter than in summer. The mid-latitude trough $N_m F_2$ values are lower in winter and also have a larger local time extent. The winter minimum $N_m F_2$ density is below $5 \times 10^4 \text{ cm}^{-3}$ and occurs between 0600 and 0800 MLT. In summer, on the other hand, the minimum occurs between 2200 and 0100 MLT and is between 5×10^4 and 10^5 cm^{-3} .

6. SEASONAL VARIATION AT SELECTED LOCATIONS

In this section, altitude profiles are presented for selected locations to show the seasonal variations of the NO^+ , O_2^+ , O^+ , and electron densities. The densities are plotted as $\log_{10} N \text{ cm}^{-3}$ in the range 10^2 to 10^6 cm^{-3} over the altitude range from 140 to 800 km. Winter profiles are shown as dashed lines, while solid lines represent summer profiles.

Seasonal anomaly. The left panel of Figure 7 shows

the winter (dashed) and summer (solid) ion and electron density profiles at a latitude of 43° on the 14 MLT meridian. This is in the region where the winter density exceeds the summer density above 200 km, a situation that is commonly referred to as the winter or seasonal anomaly. The F region peak is located at about 300 km for both summer and winter, with the winter density being greater than the summer density by a factor of about 2.4. Below 200 km, the summer densities exceed those of winter. The anomaly is only present in the O^+ ion density, both molecular ions O_2^+ and NO^+ have higher densities in summer.

In the right panel of Figure 7, the seasonal comparison corresponds to a latitude of 73° on the 1400 MLT meridian. At this location the plasma is no longer purely corotating as it was at the mid-latitude location associated with the left panel of Figure 7 but is now moving poleward and westward at speeds between 200 and 600 m/s and with an upward speed approaching 50 m/s [see Sojka *et al.*, 1981c]. The F_2 peak altitude is about 380 km for summer and about 340 km in winter. Additionally, the summer N_e profile does not show a classic F_2 peak signature but, instead, is fairly constant at about a density of $1.5 \times 10^5 \text{ cm}^{-3}$ from 140 to 300 km before increasing slightly to $2 \times 10^5 \text{ cm}^{-3}$ at 380 km, and then decreasing to a density of $6 \times 10^4 \text{ cm}^{-3}$ at 800 km. The seasonal anomaly is again present only in the O^+ density and only at altitudes above 230 km. Near the summer and winter F_2 density peaks, the seasonal anomaly has a winter density which is a factor of between 2 and 2.5 times larger than that in summer.

Dusk high convection cell. Both panels of Figure 8 are associated with the high convection cell and both lie in the auroral oval. The right panel corresponds to a location on the dusk meridian at 74° and the plasma at this location has a horizontal convection speed between 600 and 1000 m/s with almost no upward component. The left panel corresponds to a location of 71° on the dusk meridian, where the horizontal and upward convection speeds are 1600 m/s and 30 m/s, respectively. Both pairs of winter-summer profiles are for the same UT (0500 UT). In the right panel the winter and summer atomic ion and N_e

SEASONAL ANOMALY

Fig. 7. Ion and electron density profiles for winter (dashed curves) and summer (solid curves) conditions for two locations along the 1400 MLT meridian. The left panel corresponds to 43° N magnetic latitude, while the right panel corresponds to 73° N.

profiles are very similar; the F_2 peak lies at about 300 km, and there is a well-defined F region signature. The molecular ions are minor above about 200 km, with the summer densities being somewhat larger than those in winter. In contrast, the left panel of Figure 8 shows a

marked seasonal difference; the F region is quite different from that shown in the right panel and the summer N_e profile is a highly unusual F region profile. The reason for this major difference, both in the seasonal variation at 71° and between the two locations, is the summer/winter

HIGH CONVECTION

Fig. 8. Ion and electron density profiles for winter (dashed curves) and summer (solid curves) conditions for two locations in the dusk convection cell. Both locations are in the auroral oval on the dusk meridian, the left panel at 71° and the right panel at 74°. At the 71° location the horizontal speed is 1600 m/s and the upward speed is 30 m/s, while at the 74° location the horizontal speed is between 600-1000 m/s, and there is a negligibly small upward drift.

LARGE UPWARD CONVECTION

Fig. 9. Ion and electron density profiles for winter (dashed curves) and summer (solid curves) conditions at 0500 UT (left panel) and 1700 UT (right panel). Both panels correspond to the same location; the noon meridian at a magnetic latitude of 79°. This location is characterized by a large upward electrodynamic drift.

change in the neutral atmosphere combined with the relatively large 30 m/s upward drift at 71° but not at 74°. In the presence of the strong upward convection (left panel), the small seasonal difference in the molecular ion density that is shown in the right panel is considerably enhanced. Consequently, the transition altitude at which O⁺ becomes the dominant ion species occurs at 230 km in winter and at 320 km in summer (left panel). Whereas in the case of no upward convection (right panel), this altitude is between 180 and 200 km for winter and summer. In addition to the increase in the transition altitude, the entire F2 layer is raised in the presence of the upward convection. The winter N_e profile (left panel) shows a very broad maximum at about 350 km, while the summer profile is nearly vertical with two maxima, one at 220 km and the other at 410 km. The lower peak corresponds to a region of molecular NO⁺ ion dominance. It is this feature that causes the dusk convection cell to have a large molecular concentration to altitudes as high as 300 km during summer.

The seasonal comparison in regions where large vertical and horizontal plasma drifts are present is further complicated by the motion of the winter terminator and manifests itself as a seasonal dependence that is also UT dependent. In Figure 9, density profiles are shown for two UT's on the noon magnetic meridian at a latitude of 79°. The left panel of Figure 9 shows the profiles at 0500 UT, while the right panel shows the profiles at 1700 UT. For both times the horizontal convection speed is between 200 and 600 m/s, and the upward speed is about 40 m/s. The F2 peak for all the N_e profiles is at about 360 km. At 1700 UT (right panel), the winter F2 densities exceed the summer densities by a factor of about 4.0, while at 0500 UT the summer densities exceed the winter densities by a factor of about 1.5. This reversal, or UT dependence of

the seasonal anomaly, is due to the fact that the winter location at 1700 UT (right panel of Figure 9) becomes partially sunlit.

Polar depletion. Figure 10 shows the winter (dashed) and summer (solid) electron and ion density profiles at a

Fig. 10. Ion and electron density profiles for winter (dashed curves) and summer (solid curves) conditions for a location in the polar depletion region. The location is on the midnight magnetic meridian at 76°, and the time is 0900 UT.

Fig. 11. Ion and electron density profiles for winter (dashed curves) and summer (solid curves) conditions for a location in the mid-latitude trough. The location is on the 2200 MLT meridian at 50° , and the time is 2100 UT.

location of 76° on the midnight meridian at 0900 UT. This location lies in the polar depletion region where downward convection speeds of the order of 50 m/s are present. Both the molecular and atomic ion densities are higher in summer than in winter; however, the densities are somewhat lower than those already presented. The altitude of the peak F2 density is below 300 km in winter (280 km), while in summer it is at 300 km. These peak altitudes are also lower than previously presented and are a consequence of the downward convection lowering the F region into a region of greater recombination rates. In this polar depletion region there is a marked UT effect (see earlier discussion in section 3); however, the UT effect manifests itself only as a change in electron density, with the profile retaining its shape.

Mid-latitude trough. Ion and electron densities in the mid-latitude trough are shown in Figure 11. Here, summer and winter profiles at 2100 UT are shown for a location of 50° on the 2200 MLT meridian. As in the polar depletion region, the summer densities exceed the winter values; however, a marked difference is present in the profile shapes in comparison with those in the polar depletion region. This difference manifests itself in two forms: the F2 peak is much higher at about 360 km, and below the peak and the density falls sharply to values below 10^4 cm^{-3} over a relatively small altitude range. The altitude difference is simply due to the lack of a downward plasma drift in the trough. A downward drift acts as a source of fresh plasma for the region of high recombination rates below the peak; hence, in the absence of this downward drift, a large hole develops in the lower F region (see Figure 11). A noteworthy consequence of this sharp drop

in density below the F peak is that a satellite measuring density would not detect this strong density gradient and would either see a deep trough or a shallow trough, depending on its altitude. In the polar depletion region this is also true, but to a much lesser extent (see Figure 10).

7. SUMMARY

We combined a plasma convection model with an ionospheric-atmospheric composition model in order to study the seasonal variations of the high-latitude F region for geomagnetic conditions leading to strong convection. The details of our time-dependent atmospheric-ionospheric composition model, including ion chemistry and transport equations, are given by Schunk and Raitt [1980], while the details concerning the combined plasma convection and ionospheric-atmospheric models are given by Sojka *et al.* [1981a]. In a model calculation, a field tube of plasma is followed as it moves along a convection trajectory through a moving neutral atmosphere. Altitude profiles of the ion densities are obtained by solving the appropriate continuity, momentum, and energy equations including numerous high-latitude processes. The result of following many field tubes of plasma is a time-dependent, three-dimensional, ion density distribution for each of the ions NO^+ , O_2^+ , N_2^+ , O^+ , N^+ , and He^+ . The high-latitude ionosphere above 42°N magnetic latitude and at altitudes between 160–800 km was covered for one complete day by using the strong convection model discussed by Sojka *et al.* [1981c].

For our study we found the following:

1. The high-latitude ionosphere exhibits a significant UT variation both during the winter and summer.
2. In general, the electron density at high-latitudes is lower in winter than in summer. However, there are certain high-latitude regions where the summer electron density is lower than the winter electron density. For example, at certain universal times the electron density in the dayside polar cap is larger in winter than in summer. This situation results because at mid to high latitudes our ionospheric model produces a 'winter anomaly'; i.e., $N_m F_2$ is greater in winter than in summer. Even though most of the polar cap is in darkness in winter, these higher winter densities do not have sufficient time to decay as they convect across the dayside polar cap owing to our strong convection model. The net result is that the electron density in the dayside polar cap can be larger in winter than in summer. In this regard it should be noted that such a situation should not occur for weak convection because of the much longer transit times.
3. In both summer and winter, the major region of low electron density is associated with the 'main' or 'mid-latitude' trough. The trough is deeper, and its local time extent much greater in winter than in summer. However, the depth and local time extent are UT dependent in both summer and winter.
4. Typically, the electron density exhibits a much larger variation with altitude in winter than in summer. In summer, there are regions where the electron density is nearly constant with altitude over a several hundred kilometer altitude range.

5. The ion composition and molecular/atomic ion transition altitude are highly UT dependent in both summer and winter.

6. As expected, the ion composition exhibits a significant seasonal variation. However, at a given location the seasonal variation can be opposite at different universal times.

7. High convection cells should display a marked seasonal variation, with a much larger concentration of molecular ions near the *F* region peak in summer than in winter.

8. The 'winter anomaly' that occurs in the dayside polar cap is present only in the O^+ ion density, both NO^+ and O_2^+ have higher densities in summer than in winter in this region.

9. For our adopted convection pattern, a polar hole appears in the nightside polar cap as a result of a large, downward, electrodynamic plasma drift. This polar hole appears in both summer and winter, but the molecular and atomic ion densities are higher in summer than in winter. Also, in both summer and winter the electron density in the polar hole displays a marked UT variation.

Watkins [1978] studied the seasonal variation of the electron density at an altitude of 300 km in the polar ionosphere for quiet geomagnetic conditions, i.e., for weak convection. The winter electron densities calculated by Watkins were low and varied by about a factor of 10 over the polar cap, while the summer electron densities were high and displayed only a small gradient from day to night. The variations in density that we obtained in summer for strong convection are in contrast to those obtained by Watkins for weak convection, with the main difference being related to the greater importance of horizontal and vertical transport in our model. With regard to the mid-latitude trough, Watkins found little seasonal variation in the depth or latitude of the trough, the predominant seasonal change being the longitudinal extent of the trough. For strong convection, we have found that the depth and latitude of the trough can also exhibit an appreciable seasonal variation.

At this time, it is not possible to do a detailed comparison between predicted and observed seasonal variations of *F* region plasma densities owing to the lack of comprehensive averaged data sets organized in a manner to present the spatial variation over the whole polar region as a function of universal time. The averaged data sets are needed to reduce the effects of substorms, which are not included in our model. The organization of the data with respect to both location and UT are required because the predicted seasonal variation is strongly dependent on these parameters. At a given location, the seasonal variation can be opposite at different universal times, and at a given UT the seasonal variation can be opposite at different locations. However, we believe that the large seasonal variations that are predicted by the model are reasons to pursue comparisons with suitably binned and averaged experimental data from either in-situ or ground-based measurements, and we hope the required data sets will be available in the near future.

Although detailed comparisons are not possible at this time, the predicted seasonal variations of the large-scale ionospheric features are supported by the available measurements. The model predicts generally lower electron densities in winter than in summer, and this is what

is typically observed at high latitudes [cf. Foster et al., 1981]. On the other hand, the model produces a 'winter anomaly' at mid-latitudes ($N_m F_2$ is greater in winter than in summer), in agreement with the observations [cf. Banks and Kockarts, 1973]. Also, the model predicts that in both summer and winter the major region of low electron density is associated with the 'main' trough and that the trough is deeper and its local time extent much greater in winter than in summer. All of these features are in agreement with the observations [Muldrew, 1965; Liszka, 1965; Feinblum and Horan, 1973; Tulunay and Sayers, 1971].

Acknowledgments. This research was supported by Air Force contract USAF/ESD F19628-79-C0025, NASA grant NAGW-77, and NSF grant ATM80-15497 to Utah State University. The computer modeling effort was supported by the National Center for Atmospheric Research, which is sponsored by the National Science Foundation.

The Editor thanks H. C. Brinton and J. M. Straus for their assistance in evaluating this paper.

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(Received July 23, 1981;
revised September 24, 1981;
accepted September 25, 1981.)