GLOBAL SCALE, PHYSICAL MODELS OF THE F REGION
IONOSPHERE

J. J. Sojka
Center for Atmospheric and Space Sciences
Utah State University, Logan

Abstract. During the last decade, ionospheric F region modeling has reached an accurate climatological level. We now have global computer models of the F region which simulate the interactions between physical processes in the ionosphere. Because of their complexity, these climatological models are confined to modern day supercomputers. This review focuses on the development and verification of these physical ionospheric models. Such models are distinct from local models, steady state models, and empirical models of the ionosphere, which are, to their conception, unable to represent physically the range of F region variability or storm dynamics. This review examines the limitations of the physical models, which are at the present time mainly associated with inputs to the ionospheric system. Of these, the magnetospheric electric field and auroral precipitation are by far the most dominant and yet the least well-defined dynamic inputs. Several developments are currently under way which could well lead to meteorological modeling capabilities in the next decade. For this the use of higher-resolution inputs, both temporal and spatial (for example, auroral imagery), is critical. Coupling the ionospheric models with thermospheric and magnetospheric models will lead to self-consistency and probably a predictive capability. Coupling to thermospheric models is currently under way; however, coupling with the magnetosphere must await the development of a magnetospheric model.

1. INTRODUCTION

The F region is the terrestrial plasma environment between an altitude of 120 and 800 km. Since Marconi’s earliest trans-Atlantic wireless communication experiments, it has been realized that the F region plays a major role in these over-the-horizon communications; and its variability is a communication engineer’s nightmare. Manned space vehicles and many satellites operate in this low Earth orbit (LEO) environment. However, this F region environment is not benign. The plasma develops electrical sheaths around all objects; these sheaths are not always negligible. Large objects (e.g., space stations, solar collectors, etc.) will develop large electric potentials, tens to thousands of volts, as they move through the Earth’s magnetic field. Such voltages in conjunction with the plasma sheath are a potential hazard to both humans and electronic components on these spacecrafts.

The F region is bounded by the E region below and the exosphere above, and together these three regions form the terrestrial ionosphere. In turn, it is now realized that the ionosphere together with the atmosphere and magnetosphere forms a larger-scale coupled system. This magnetosphere-ionosphere-atmosphere system is strongly coupled via electric fields, particle precipitation, field-aligned currents, heat flows, and frictional interactions. Although it has been well established that the magnetosphere-ionosphere-atmosphere system is strongly coupled, that

Copyright 1989 by the American Geophysical Union.

Reviews of Geophysics, 27, 3 / August 1989
pages 371–403
Paper number 89RG01346

8755-1209/89/89RG-01346 $05.00

• 371 •
2. \textit{F} \textit{Region Model}

At present, there are several numerical models available for different ionospheric phenomena, including auroral models \cite{Roble and Rees, 1977}, \textit{E} region current conductivity models \cite{Matsushita and Xu, 1982; Kamide et al., 1986}, high-latitude models \cite{Knudsen et al., 1977; Watkins, 1978; Schunk and Raitt, 1980; Sojka et al., 1981a}, mid-latitude models \cite{Roble, 1975; Quegan et al., 1982}, equatorial models \cite{Sterling et al., 1969; Anderson, 1981} a global model \cite{Sojka and Schunk, 1985a}, and coupled thermospheric-ionospheric models \cite{Fuller-Rowell et al., 1987; Roble et al., 1987}.

In this section an overview of the Utah State University (USU) time-dependent ionosphere model \cite{Schunk and Walker, 1973; Schunk and Raitt, 1980; Sojka et al., 1981a; Sojka and Schunk, 1985a} is given in order to show both the theoretical and the modeling attributes of physical \textit{F} region models. The methodology used in solving the \textit{F} region is a Lagrangian framework for the solution of the transport equations; i.e., transport equations are solved along a magnetic plasma flux tube while the flux tube convects in the ionosphere. Other techniques can be used, but this method was adopted because of its simplicity and its physical attributes. In the \textit{F} region ionosphere the plasma is very strongly tied to a flux tube while normal to this direction the flux tube experiences an \( \mathbf{E} \times \mathbf{B} \) plasma drift. Hence in a coordinate frame drifting at the \( \mathbf{E} \times \mathbf{B} \) velocity, the transport equations need only be solved along the flux tube. The validity of this scheme has been shown by Schunk \cite{1988}.

Figure 1 shows the \textit{F} region ionosphere sandwiched between two planes representing its lower and upper boundaries. In the midnight cross section, three magnetic field lines (heavy solid lines) and their plasma flux tubes are shown. At high latitudes the plasma flux tube is almost vertical because of the small dip angle of the magnetic field. This plasma flux tube convects along electric field equipotentials as indicated by arrow \( V_1 \). At high latitudes this \( V_1 \) velocity depends upon the magnetospheric electric field and a corotational electric field. At mid-latitudes the plasma flux tube corotates as indicated by arrow \( V_2 \). Here the field line is significantly more inclined, and its upper boundary is less dependent upon the magnetosphere. Finally, at equatorial latitudes the plasma flux tube no longer has an upper magnetospheric boundary. Its convection, arrow \( V_3 \), is complex because of the equatorial dynamo electric field present in the \( E-F \) regions. In each of these three regions the inputs to the model are quite different.

\textbf{Figure 1}. A schematic view of the \textit{F} region ionosphere bounded below (120 km) and above (800 km) extending from the north pole to the magnetic equator. The imposed magnetospheric electric fields and auroral oval are shown as contoured curves and stippled regions, respectively. A midnight cross section reveals the direction of motion of a high-latitude (\( V_1 \)), mid-latitude (\( V_2 \)), and equatorial (\( V_3 \)) plasma flux tube.
The USU ionospheric model was initially developed as a mid-latitude, multi-ion (NO⁺, O₂⁺, N₂⁺, and O⁺) model by Schunk and Walker [1973]. The time-dependent ion continuity and momentum equations were solved as a function of altitude for a corotating plasma flux tube including diurnal variations and all relevant E and F region processes. This model was extended to include high-latitude effects due to convection electric fields and particle precipitation by Schunk et al. [1975, 1976]. A further extension of the model to include the minor ions N⁺ and He⁺, an updated photochemical scheme, and the mass spectrometer/incoherent scatter (MSIS) atmospheric model is described by Schunk and Raitt [1980]. The plasma convection and particle precipitation models are described by Sojka et al. [1981a, b]. More recently, the ionospheric model has been extended by Schunk and Sojka [1982a] to include ion thermal conduction, diffusion thermal heat flow, and the electron energy equation of Schunk et al. [1986]. The incorporation of the Sterling et al. [1969] equatorial ionospheric model and the various improvements to this model are described by Sojka and Schunk [1985a]. This development resulted in a global F region modeling capability.

The USU Time-Dependent Ionospheric Model (TDIM) is a computer model which numerically solves the F region continuity and momentum equations for ions and the F region energy equation for both ions and electrons. Figure 2 schematically shows how these equations depend upon other regions of space. In this schematic figure and in the TDIM formulation, no coupling with these other regions is implied. The other regions are purely time-dependent inputs to the TDIM. At present the TDIM, as well as other large-scale models, tends to use smooth inputs. In this context, smooth implies that the input is represented by a statistical average model; i.e., the solar spectrum is a single spectrum whose intensity varies with the F10.7 index; the neutral atmosphere is the MSIS model; the auroral oval is an empirical statistical oval, etc. Tables 1a, b, and 1c indicate how empirical models are used as inputs to the continuity, momentum, and energy equations in the TDIM formulation. These equations define the physical processes in the F region. As indicated by the tables, these equations are strongly coupled. For details of the theoretical development of the USU TDIM, see the recent review by Schunk [1988].

Table 1a pertains to the continuity equation. In the TDIM the ions of interest are three major ions (NO⁺, O₂⁺, and O⁺) and three minor ions (N₂⁺, N⁺, and He⁺). The plasma production input is obtained from three sources: solar EUV, auroral precipitation, and solar resonantly scattered radiation. The latter is important in the dark F region in the absence of auroral production. In these regions it represents the F region bottomside maintenance process. Plasma loss rates depend not only on recombination processes but also on ion composition changes due to complex chemical reactions. Some of these reactions can be highly temperature dependent, leading to a coupling with the energy equation for both the ions and the electrons. The momentum equation leads to plasma diffusion along magnetic field lines, resulting in plasma composition and density changes.

The momentum equation is split into two distinct parts: plasma transport along the flux tube and the motion of the entire plasma flux tube due to E x B/B² drifts. Table 1b summarizes these two parts. To deduce the overall motion of the plasma flux tube, the magnetic field and the total electric field must be defined. These drifts can also induce the vertical transport of plasma which with the neutral-wind-induced vertical drifts acts with gravity to control diffusion along the plasma flux tube. Both the continuity (density) and the energy (temperature) equations are strongly coupled via the plasma pressure term into the momentum equation. The neutral atmosphere model, because of collisions between the plasma and the neutrals, plays an important role in determining the stress tensor and momentum transfer.

Finally, the energy equation inputs are summarized in Table 1c. This equation is solved separately for the ion O⁺ (the major F region species) and the electrons. In the case
TABLE 1a. Continuity Equation Inputs

<table>
<thead>
<tr>
<th>Term</th>
<th>Process</th>
<th>Model Representation and Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>solar EUV</td>
<td>empirical Solar spectrum (F10.7 index); empirical neutral atmosphere (MSIS) (F10.7 and ( ap ))</td>
</tr>
<tr>
<td></td>
<td>solar resonantly scattered radiation</td>
<td>adopted ionization cross sections</td>
</tr>
<tr>
<td></td>
<td>auroral precipitation</td>
<td>distribution of resonantly scattered radiation; adopted ionization rate profiles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>empirical distribution of precipitating electrons; their flux and energy (statistical models (Kp or ( AE )) or images); adopted semiempirical ionization rate profiles</td>
</tr>
<tr>
<td>Loss</td>
<td>recombination</td>
<td>comprehensive chemistry scheme; ion and electron temperature-dependent reactions (energy equation); neutral atmosphere (MSIS) (F10.7 and ( ap ))</td>
</tr>
<tr>
<td></td>
<td>composition changes</td>
<td>ion chemistry (NO(^+), O(^+), O(^\bullet), N(_2)(^+), N(^\bullet), and He(^+)); temperature-dependent reactions (energy equation); neutral atmosphere (MSIS) (F10.7 and ( ap ))</td>
</tr>
<tr>
<td>Diffusion</td>
<td>transport</td>
<td>momentum equation</td>
</tr>
</tbody>
</table>

TABLE 1b. Momentum Equation Inputs

<table>
<thead>
<tr>
<th>Term</th>
<th>Process</th>
<th>Model Representation and Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>((E \times B)/B^2)</td>
<td>magnetic field (eccentric dipole); empirical magnetospheric electric fields (IMF and ( Kp ) dependent); empirical equatorial dynamo electric field model; corotational electric field in magnetic frame</td>
</tr>
<tr>
<td>transport</td>
<td>induced drifts</td>
<td>vertical component of ((E \times B)/B^2) (same inputs as for horizontal transport); empirical neutral wind model to induce vertical drift.</td>
</tr>
<tr>
<td>Pressure</td>
<td>pressure gradient</td>
<td>ion density and temperature (continuity and energy equations)</td>
</tr>
<tr>
<td>Stress tensor</td>
<td>(E)-induced stress</td>
<td>ion-neutral collision frequencies; neutral atmosphere (MSIS) (F10.7 and ( ap ))</td>
</tr>
<tr>
<td>Momentum transfer</td>
<td>collisions</td>
<td>adopted collision frequencies; neutral atmosphere (MSIS) (F10.7 and ( ap )); neutral wind model; ion temperatures (energy equation)</td>
</tr>
<tr>
<td>Gravity</td>
<td>acceleration</td>
<td>adopted radial inverse square gravitational acceleration</td>
</tr>
</tbody>
</table>

TABLE 1c. Energy Equation Inputs

<table>
<thead>
<tr>
<th>Term</th>
<th>Process</th>
<th>Model Representation and Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat source</td>
<td>volume heating rate</td>
<td>solar heating rate model; semiempirical auroral particle rate model; joule heating, ion-neutral drifts; continuity and momentum equations; neutral atmosphere (MSIS) (F10.7 and ( ap ))</td>
</tr>
<tr>
<td>Heat sinks</td>
<td>volume cooling rate</td>
<td>cooling rates for collisions with electrons, ions, and neutrals (continuity equation); neutral atmosphere (MSIS) (F10.7 and ( ap ))</td>
</tr>
<tr>
<td>Energy exchange</td>
<td>collisions</td>
<td>ion/electron/neutral collision frequencies; ion velocities (momentum equation); neutral wind model; densities (MSIS) (continuity equation)</td>
</tr>
<tr>
<td>Heat flow</td>
<td>heat flow</td>
<td>upper boundary heat flux (&quot;guessed&quot;)</td>
</tr>
<tr>
<td>Pressure</td>
<td>transport</td>
<td>momentum equation</td>
</tr>
<tr>
<td>Stress tensor</td>
<td>transport</td>
<td>momentum equation</td>
</tr>
</tbody>
</table>
of the electrons the role of heat sources, sinks, and heat conduction is important. The description of the sources and sinks involves converting photon and auroral precipitation energy into electron heating rates, solving complex heat loss equations, and obtaining an important but almost unknown topside (magnetospheric) heat flux. For the ion energy equation the topside heat flux is not as important as the effects of joule heating. Since the role of collisions is significant, the neutral atmosphere, the neutral wind, and complex temperature-dependent heat equations are needed. In the case of the electrons, only the continuity equation is important, while for the ions, both the continuity and the momentum equations are important.

Present-day developments in the TDIM formulation focus on the input representation of discrete structures, in particular, high-latitude auroral and plasma structures. Better inputs of both the discrete auroral arcs and the structured electric fields indicated in Figure 2 are being developed. Another development not represented in Figure 2 is a fully coupled neutral atmosphere F region system. The University College, London, and the National Center for Atmospheric Research (NCAR), Boulder, groups have developed such models [Fuller-Rowell et al., 1987; Roble et al., 1987].

3. THEORETICAL MODEL STUDIES

3.1. Low Geomagnetic Activity

During periods of low geomagnetic activity the F region's dependence upon either substorm dynamics or magnetospheric convection and precipitation inputs is minimized. Under these conditions the solar cycle and seasonal dependencies can readily be studied by considering the ionosphere to be in a "quasi steady state" configuration. This assumption allows the freezing of the magnetospheric inputs for periods of more than 24 hours so that the model can achieve a diurnally reproducible pattern.

The first high-latitude F region model study was carried out by Knudsen et al. [1977]. They used the ionospheric model of Schunk and Walker [1973] with appropriate convection and precipitation inputs to simulate the high-latitude ionosphere for winter, medium solar activity, and quiet magnetic conditions. In this study they assumed that the geographic and geomagnetic poles were aligned, thus removing the ionospheric UT dependence. This first study revealed certain high-latitude ionospheric features (see Figure 3). These features are a "tongue" of plasma extending from the local noonside of the Earth across the
polar cap to the nightside, a ridge of ionization produced by auroral electron precipitation, and a deep mid-latitude trough.

Watkins [1978] carried out a high-latitude model study allowing for the offset between the geographic and the geomagnetic poles, which allows for a UT dependence. In this study, Watkins followed trajectories beginning at only two UTs (0530 and 1730 UT). Hence the data sets presented by Watkins contained data from a mixed range of UTs, i.e., they were not snapshots at 0530 and 1730 UT. Consequently, the UT trends inferred were not generally correct. However, the seasonal (solar terminator) trends were mainly correct. This ionospheric model was based upon a single-ion (O+) time-dependent chemistry model.

Sojka et al. [1981a] studied the UT dependence of the high-latitude ionosphere for solar minimum, winter, and quiet geomagnetic activity conditions. They used the ionospheric model of Schunk and Raitt [1980] which itself was an updated version of the model of Schunk and Walker [1973]. Twenty-three high-latitude plasma flux tubes were followed for over 1 day; then each of these trajectories was repeated 12 times starting at 2-hour UT intervals. In this way, enough results were obtained to create UT snapshots. Plate 1 shows \( N_m F_2 \) at 0600 and 1800 UT. This study reproduced the general features of the Knudsen et al. [1977] and Watkins [1978] study; it also showed the UT dependence of these features and addressed several other phenomena. These additional features were sensitivity of nighttime maintenance processes, polar hole, ion composition, and the sensitivity of the collocation of auroral and convection patterns.

The minimum value for the electron density in the mid-latitude trough was shown to be sensitive to nocturnal maintenance processes, such as ion production due to resonantly scattered radiation, ion production due to a small flux of precipitating particles, and a neutral-wind-induced upward ionization drift. Sojka et al. [1981a] also showed that the depth and longitudinal extent of the main trough exhibits a significant UT dependence. The way in which the auroral oval is positioned relative to the plasma convection pattern was found to have an appreciable effect on the MLT extent of the main trough. For example, if the auroral oval is contracted by 2° of magnetic latitude while the plasma convection pattern remains fixed, the extent of the main trough can change by more than 2 hours of MLT (see Figure 4). This highlights a major difficulty in performing detailed modeling of the main trough in that the auroral oval is a region of highly structured precipitation which is represented by a statistical model. Indeed, even today this problem persists in large-scale ionosphere-thermosphere modeling; only in a few cases are auroral images available to define precipitation boundaries with adequate precision. At the same time the convection electric field is only sparsely defined from satellite and incoherent scatter radar observations.

Soyka et al. [1981a] also studied the polar ionization hole and found that its spatial extent, depth, and location are UT dependent. Ion production due to resonantly scattered radiation could maintain the electron density at 300 km in the polar ionization hole at about \( 2 \times 10^5 \) cm\(^{-3} \). However, they also found that the level of ion production in the morning sector of the auroral oval has an appreciable effect on the location and spatial extent of the polar ionization hole.

Because of the competition between the various dynamic and chemical processes, they found that a wide range of ion compositions could occur in the polar F region at different locations and times. The ion composition was the topic of a follow-up study by Sojka et al. [1981b]. By using the sophisticated capabilities of the
Schunk and Raitt [1980] ionospheric model to compute self-consistent NO⁺, O₂⁺, and O⁺ densities, the UT dependence of the mean ion mass was studied. Figure 5 shows this variation as a function of altitude through the important molecular to atomic ion transition region.

A light-ion (O⁺ and H⁺) ionospheric model was developed by Quegan et al. [1982]. They considered the same longitudinal range as Sojka et al. [1981a], poleward of 40°. However, the UT dependence of the ionosphere was not considered. Quegan et al. studied the topside diurnal coupling between O⁺ and H⁺ in the mid-latitude trough region. By using a neutral wind model based upon the model results of Roble et al. [1974] and Fuller-Rowell and Rees [1980], they were able to consider the topside dependence upon wind-induced plasma drifts. Figure 6 shows how \( N_m F_2 \), \( h_m F_2 \), O⁺, and H⁺ at 1100 km vary along the noon-midnight meridian for the low solar, equinox, and quiet geomagnetic activity conditions of the Quegan et al. [1982] study. This study includes their adopted neutral wind; its effect can best be seen by the gradual increase in \( h_m F_2 \) in the midnight sector from 240 to 310 km. Comparison of the latitudinal \( h_m F_2 \) variation of Figure 6 with those of Figure 7 confirms the role played by the neutral wind at high latitudes. Quegan et al. obtained the results in Figure 7 by setting the high-latitude neutral wind velocity equal to zero. The mid-latitude wind remained unaltered. The \( h_m F_2 \) along the midnight meridian decreased, although \( N_m F_2 \) did not show a marked change with the exception of the trough. In the trough, marked by the rightmost arrow (PP), \( N_m F_2 \) decreased by almost an order of magnitude in the absence of a wind system. The topside concentrations were found to reflect the behavior of the F layer peak. These findings are consistent with the earlier work of Sojka et al. [1981a].

Sojka and Schunk [1985a] extended their ionospheric modeling to a fully global capability by including an equatorial ionospheric model. The equatorial model followed the work of Sterling et al. [1969] and Anderson [1973]. With the global formulation, Sojka and Schunk [1985a] were able to study the ionosphere's global UT response for the first time. In their initial study they considered solstice conditions for solar maximum and quiet geomagnetic activity. They chose the southern hemisphere in winter to emphasize the larger southern hemisphere geomagnetic-geographic pole separation winter effects.
Figure 5. Contours of mean ion mass at two universal times for each of three altitudes. The mean ion mass is in atomic mass units [from Sojka et al., 1981b].
Figure 6. Calculated variations with invariant latitude of $h_m F_2$, $N_m F_2$, and $O^+$ and $H^+$ concentrations at 1100 km along the 1200–2400 LT meridian. The five lowest latitude data points correspond to the mid-latitude region, while the remainder are high-latitude locations. The arrows labeled "PP" indicate the latitude of the ionospheric projection of the plasmapause [from Quegan et al., 1982].

Figure 7. The same as Figure 6 but with the high-latitude neutral wind set to zero [from Quegan et al., 1982].
Plate 2. Global $N_{F_2}$ values in a magnetic latitude-MLT frame at (left) 0300 UT and (right) 1500 UT [from Sojka and Schunk, 1985a].

Plate 2 shows the Sojka and Schunk global variation of $N_{F_2}$ in the magnetic latitude-MLT frame at (left) 0300 UT and (right) 1500 UT. The highest densities are colored red and reach $\sim 5 \times 10^6$ cm$^{-3}$, while the lowest densities are colored blue, reaching a minimum of $\sim 7 \times 10^3$ cm$^{-3}$. In both panels, $N_{F_2}$ varies over almost 3 orders of magnitude, with the highest densities being associated with the Appleton peaks and the lowest densities occurring in the winter (southern) hemisphere mid-latitude trough. A very marked asymmetry exists between the northern and the southern hemispheres. In the summer hemisphere (north) the densities are higher than in the winter hemisphere and show a relatively small UT variation. In contrast, the UT variation in the winter hemisphere is very marked, with almost an order of magnitude density variation in places. A number of distinct $F$ region features can be seen in Plate 2; these divide the $F$ region into three primary latitudinal regions. The Appleton peaks lie on either side of the magnetic equator at $\sim \pm 0.5$, extending from noon until 0400 MLT. For solstice conditions, these peaks are asymmetric mainly because of the effect of the neutral wind. At mid-latitudes, from 20° to 55°, the most distinct feature is the nocturnal mid-latitude trough. A comparison of the two panels in Plate 2 shows that the mid-latitude trough is strongly UT dependent not only in the winter hemisphere but also in the summer hemisphere. In the winter hemisphere the minimum density is approximately an order of magnitude lower than in the summer hemisphere. The morning local time boundary of this trough shows the seasonal dependence of the terminator. In the two polar regions, poleward of $\sim \pm 60°$, the $F$ region is highly dependent upon magnetospheric processes. Ion production due to auroral precipitation and magnetospheric convection causes the polar cap to appear highly complex in winter. In the summer hemisphere, where the polar cap is sunlit, the auroral precipitation associated with the low geomagnetic activity conditions is insufficient to create a marked density feature.

3.2. High Geomagnetic Activity

The problems associated with studying the $F$ region during high geomagnetic activity are those of specifying auroral precipitation and magnetospheric convection during high activity and to a lesser extent the thermospheric changes. Sojka et al. [1981c] assumed that both of these enhanced inputs could be held constant for a 24-hour period. They studied the ionosphere's response to high activity ($kp = 5$) during winter and solar maximum conditions. To simulate active magnetospheric conditions, they selected a total cross-tail magnetospheric potential of 90 kV. In addition, an enhanced dusk cell convection pattern was adopted which resulted in plasma drifts of almost 2 km s$^{-1}$ in the dusk sector. Their adopted auroral oval corresponded to the $kp = 5$ auroral oval described by Comfort [1972].

Figure 8 shows the Sojka et al. [1981c] contours of the electron density at 300 km for four universal times. The four UTs selected correspond to the geographic pole being near the dawn (0100 UT), noon (0700 UT), dusk (1300 UT), and midnight (1900 UT) magnetic meridians. The
Figure 8. Contours of the electron density at 300 km for four universal times displayed in the magnetic frame. The gray scaling corresponds to different density levels, as indicated in the key [from Sojka et al., 1981c].

Although a polar hole is not expected during active conditions because the transpolar convection is too rapid to allow the plasma to decay to the level of a polar hole, one is found. In Figure 8 there is a region in the polar cap at 0700 UT that contains relatively low electron densities. In contrast to the low geomagnetic activity polar hole, which is due to chemical loss processes acting over a long time period, the high geomagnetic activity polar hole found by...
Sojka et al. resulted from large downward transport velocities that existed in this region. Figure 9 shows how the computed \( h_m F_2 \) varies over the high-latitude ionosphere. This figure shows how the higher electric fields induce upward plasma drifts in the dayside polar cap (\( h_m F_2 \geq 300 \text{ km} \)) while in the nightside polar cap they induce downward drifts (\( h_m F_2 < 300 \text{ km} \)). Sojka et al. discussed how this trend is opposite to that during quiet periods when the neutral-wind-induced vertical drifts are dominant. Equatorward of the midnight auroral oval where the neutral wind again dominates, the plasma is lifted (\( h_m F_2 \geq 350 \text{ km} \)).

Sojka et al. [1981c] also considered the mid-latitude trough in detail. This trough is a region of low electron density situated just equatorward of the nocturnal auroral oval. They found for their input conditions that at 0100 UT the trough was deepest in the morning sector; at 1300 UT it was deeper in the evening sector than in the morning sector; and between these two UTs the trough tended to be more symmetrical about midnight. They contrasted the main trough formed under conditions of strong convection with that for weak convection [Sojka et al., 1981a, b] and found the main differences to be connected with the depth and local time extent at a given UT. In general, the lowest trough densities were found for weak convection; they were about an order of magnitude lower than for strong convection.

Sojka et al. [1982a] followed up their active condition study [Sojka et al., 1981c] with a seasonal study under active geomagnetic conditions. This was for the same winter conditions as in the study of Sojka et al. [1981c] and an equivalent summer study. In Figure 10 the peak electron density \( N_m F_2 \) at 0700 UT is contoured for (left) winter and (right) summer in the magnetic frame. A number of seasonal differences 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 \( 2 \times 10^5 \text{ and } 4 \times 10^5 \text{ cm}^{-3} \). At higher latitudes (above 65°) in the same afternoon sector, the summer densities are again lower in some

---

**Figure 9.** Contours of \( h_m F_2 \) at 1000 UT displayed in the magnetic frame. The contours are labeled in units of kilometers [from Sojka et al., 1981c].

**Figure 10.** Contours of \( N_m F_2 \) for (left) winter and (right) summer conditions at 0700 UT displayed in the magnetic frame. The contours are labeled in units of \( \log_{10} N_m \text{ (cm}^{-3} \) [from Sojka et al., 1982a].
regions than the equivalent winter densities. This feature is the seasonal anomaly. A polar depletion region near the magnetic midnight meridian at about 80° has a lower $N_{eq} F_2$ in winter than in summer. The mid-latitude trough $N_{eq} F_2$ values are lower in winter and also have a larger local time extent. A major ion composition difference is found near the stronger convection cell at dusk; in summer, even at 300 km a large concentration of molecular ions is present, while in winter this region is almost all $O^+$. Another seasonal difference is present in the night sector at 260 km in the region associated with the mid-latitude trough. In winter the trough is populated with a high concentration of molecular ions, whereas in summer the light ion $O^+$ is found to be dominant.

One of the more critical aspects of the active geomagnetic conditions is the significant ion heating in regions of large electric field. A follow-on from the preceding studies was the addition of the complete $F$ region $O^+$ energy equation into the USU high-latitude ionospheric model [Schunk and Sojka, 1982a]. The ion energy model was improved by including thermal conduction and diffusion thermal heat flow terms in the ion energy equation. At low altitudes the ion energy balance is determined by thermal coupling to the neutrals. At intermediate altitudes, coupling to the electrons becomes appreciable and at high altitudes, ion thermal conduction dominates. An electric field produces elevated ion temperatures through frictional interaction between ions and neutrals. Although the heating occurs predominantly at low altitudes, there is an upward flow of heat from the lower ionosphere which acts to raise the ion temperature at high altitudes. Typically meridional electric fields greater than 40 mV m$^{-1}$ cause a change in the temperature $T_i$ that is larger than that due to either solar cycle or seasonal changes.

With the improved high-latitude ionospheric model, Schunk and Sojka [1982a, b] considered the effect of active conditions upon the $O^+$ temperature. Figure 11 (from the Schunk and Sojka [1982a] study) shows contours of the ion temperature in the magnetic frame at 0000 UT for altitudes of 360 and 800 km. The intense $O^+$ heating in the strong dusk convection cell of the polar ionosphere is clearly seen at 360 km, where $T_i$ reaches 3500 K near the center of the cell. At the center of the cell and at lower altitudes (~160 km) the ion temperature reaches 4400 K. This heating, which is a consequence of ion-neutral frictional interactions, is less evident at high altitudes (800 km) with the result that $T_i$ decreases with altitude in the $F$ region in the strong convection cell, which is opposite to the normal $T_i$ variation, i.e., increasing with altitude. Schunk and Sojka referred to this feature as a “hot spot” and found it to be associated with regions where the electric field in strong convection cells exceeds ~40 mV m$^{-1}$.

One of the major difficulties in applying high-latitude $F$ region models during geomagnetically active periods is that of accounting for the effects of storms. These phenomena vary on time scales much less than the 24-hour study periods described above. Locally, their effect upon the convection electric field and auroral precipitation are well documented; however, on the large scale their effect is less well defined. Sojka and Schunk [1983, 1984] addressed this large-scale problem by simulating a time-dependent variation in both the electric field and the auroral precipitation.

By contrasting the $O^+$ variation at 160, 300, and 800 km, Sojka and Schunk [1983] were able to demonstrate the ionosphere’s temporal and spatial response to the simulated storm. Their $O^+$ density over the polar region at 160
Plate 3. O\textsuperscript{+} density contours as a function of magnetic latitude and MLT for selected times at an altitude of 160 km. Note that km is shown in Plate 3 at eight times during this storm study. Each of the eight color panels shows a "snapshot" in which the O\textsuperscript{+} density is 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 top right of Plate 3 shows that the absolute density varies over almost 2 orders of magnitude, from below $10^3$ (dark blue) to above $3 \times 10^4$ (purple). The upper edge of each color panel is connected by a line to its corresponding time on the storm profile curve. Panel 1 (the leftmost panel) corresponds to prestorm 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 poststorm phase. On each panel, two distinct regions of higher densities are found, 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. The density changes in the auroral region are entirely due to the storm-dependent changes in the auroral electron precipitation pattern. Prestorm and poststorm panels 1, 6, 7, and 8 show identical auroral O\textsuperscript{+} densities, with the highest densities in the night sector being below $10^4 \text{ cm}^{-3}$. During the storm the auroral region O\textsuperscript{+} densities increase significantly.

The O\textsuperscript{+} density distribution at 300 km for the same eight selected times during the storm study are shown in Plate 4. The absolute densities (see color key in Plate 4) 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 3 and 4 shows that at 300 km the simple ionization source regions are no longer readily identified. The high-latitude F region (300 km) shows relatively little correlation with either the auroral source region or the storm time profile. Panel 2, taken 30 min into the storm growth phase, shows densities identical to the prestorm densities in panel 1, yet at 160 km the corresponding panel 2 shows marked density enhancements due to the increased auroral precipitation. Panels 6, 7, and 8 of Plate 4, in contrast, are for poststorm times...
where the auroral production rate is identical to that in 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 F region density variation is observed. However, unlike the storm disturbance that peaked 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 1–2 hours in relation to the time variation of the auroral production source. Sojka and Schunk [1983] showed how this lag becomes even more marked above 300 km. Figure 12 shows their computed temporal variation of O\(^+\) at 160, 300, 540, and 800 km at 75° magnetic latitude and 0300 MLT. At higher altitudes, not only is there a time delay in attaining the maximum density but also the temporal variation becomes complex. Indeed, as Figure 12 shows, even at low altitudes (160 km) the topside can affect the bottomside through downward diffusion long after the storm has turned off. By adopting a dusk-enhanced storm convection pattern, Sojka and Schunk [1983] were able to

the density color coding is different from that shown in Plate 3 [from Sojka and Schunk, 1983].

Figure 12. O\(^+\) density versus time at selected altitudes for a magnetic latitude of 75° and an MLT of 0300 [from Sojka and Schunk, 1983].
show how the ionosphere responded to different degrees of activity.

In their follow-up storm study, Sojka and Schunk [1984] concentrated on the ion temperature and ion compositional storm effects. Figure 13 [from Sojka and Schunk, 1984] shows the ion temperature at 600 km for six times during their earlier storm study. At high altitudes the ion density structure is more complicated owing to the effects of horizontal transport which leads to more complicated temperature variations. The temperatures are higher and have a wider dynamic range at high than at low altitudes. During the growth phase ($T = 0130$ hours in Figure 13) the elevated temperatures which had been found in the dawn sector at 340 km are not discernible at 600 km. However, the main phase “hot spot” in the dusk-enhanced convection sector is present. In the dawn sector the main phase, recovery phase, and poststorm phase are all dominated by an equatorward region of elevated ion temperatures that is associated with the topside electron density increase after the storm main phase. As late as 5 hours after the storm main phase this region of elevated ion temperatures covers a wide area of the dawn sector auroral oval (0200–1100 MLT and 60°–70° magnetic latitude). These temperatures are still between 400° and 1000°K hotter than the prestorm temperatures (compare $T = 0830$ and $T = 0030$ in Figure 13), while at this time the ion temperatures at 340 km have returned to within about 100° of their prestorm values.

As expected, Sojka and Schunk [1984] found that the ion composition exhibited a major dawn-dusk asymmetry associated with the storm phase asymmetric convection pattern. With upward drifts reaching $-100$ m s$^{-1}$ in the dusk convection reversal region, they found the molecular-atomic ion transition height being raised to over 250 km, compared to the 215-km prestorm value. In contrast, where the induced drift is downward, in the premidnight convection reversal region, the transition height is lowered from 210 km to below 180 km. These effects are found to follow the storm profile variation. More surprisingly, they found that the nocturnal region of lower transition heights lags behind the recovering auroral precipitation by several hours. This whole region is found
to exhibit an anomalously long recovery time because the storm-enhanced \( \text{O}^+ \) ions at high altitudes take many hours to diffuse downward as the ionosphere adjusts back to prestorm conditions.

The major drawback of the Sojka and Schunk storm studies is the simplicity of the inputs to the model. During dynamic periods the auroral and convection inputs are the dominant inputs. Schunk et al. [1986] extended the TDIM capabilities by including the electron energy equation. By doing so, the ability of the TDIM model to respond to changing electron heat input conditions is greatly enhanced. However, the energy equation requires an upper boundary heat flux which is difficult to define. Figure 14 contrasts contours of electron temperature at 180, 300, and 800 km for (left) no heat flux and (right) a constant downward heat flux of \( 1 \times 10^{10} \text{eV cm}^{-2} \text{s}^{-1} \) from the Schunk et al. [1986] electron temperature paper. At the lowest altitude (180 km) the topside heat flux has no significant effect, while at 300 km, which is somewhat below the \( F \) region peak, and also at 800 km the effect of

![Figure 14. Contours of electron temperature (degrees Kelvin) as a function of magnetic latitude and MLT at three altitudes for 1700 UT. For these calculations the downward electron heat flux through the topside boundary was (right) \( 1 \times 10^{10} \text{eV cm}^{-2} \text{s}^{-1} \) and (left) zero [from Schunk et al., 1986].](image)
the heat flux is marked. The mid-latitude trough temperatures increased from 1000°K to 3400°K at 300 km and from 1000°K to 4400°K at 800 km. In higher density regions, i.e., dayside, the 800-km temperatures increased by $\sim$2000°K. Schunk et al. [1986] showed that electron hot spot features could be masked by the influence of a uniform widely distributed heat flux. The field-aligned current system coupling the magnetospheric-ionospheric system further complicates the electron energy equation [Schunk et al., 1987].

3.3. Ionospheric Features

With the sophistication built into the large-scale $F$ region model the Utah State University group has been able to use the model as a tool to study the generation and behavior of much smaller-scale or localized phenomena in the ionosphere. In this particular application the large-scale models enable quantitative analysis of how one or more input parameters influence ionospheric parameters. These relationships are rarely independent of the other inputs, and consequently, "back of the envelope" calculations and local or steady state chemistry models do not give insight into the phenomena. As an example, Watkins and Richards [1979] carried out an extensive theoretical study of how neutral-wind-induced vertical transport in conjunction with plasma production results in a wide variety of $F$ region profiles. Although this study was carried out with a time-dependent $O^+$ diffusion model, it was severely restricted. In fact, both the winds and the plasma production were arbitrarily "coupled" by being independent inputs turned on and off at will. Consequently, the results are theoretically instructive but are difficult to apply to ionospheric conditions. Sojka and Schunk [1985b] systematically looked at how plasma convection across the polar ionosphere is influenced by neutral winds. Specifically, they were looking for the conditions which could lead to "anomalously" high $h_m F_2$ values. Such high $h_m F_2$ (400–500 km) had been reported by incoherent scatter radar users (J. C. Foster, private communication, 1985). By using the TDIM model, Sojka and Schunk [1985b] were able to infer the solar cycle, seasonal, and geomagnetic activity dependence of the $F$ layer in the polar ionosphere for solar maximum conditions. Specifically, they were able to address the question of how the anomalously high $F$ layers were created. Figure 15 shows two ion density $F$ region profiles with $h_m F_2$ values of $\sim$440 km. These occur for active conditions during solar maximum when winds of the order of 800 m s$^{-1}$ are present. The profiles correspond to a location in the dark midnight sector of the polar cap, a region devoid of auroral production in the simulation. Large $N_F$ $F_2$ densities are associated with fast transpolar convection from a high-density sunlit dayside region.

Figure 15. (Solid curve with circles) midnight $N_F$ profiles at solar maximum, equinox, for fast convection and a neutral wind of 800 m s$^{-1}$. Also shown (solid curve without symbols) is the case of a 160 m s$^{-1}$ neutral wind on the dayside and a 800 m s$^{-1}$ neutral wind on the nightside [from Sojka and Schunk, 1985b].

Alternative suggestions for creating high $h_m F_2$ values have been made. One such suggestion is the precipitation of very soft ($\leq$100 eV) electrons. These would create enhanced densities above $\sim$200 km. Sojka and Schunk [1986] modeled the properties of localized electron density enhancements using the TDIM. They considered a wide range of auroral plasma production profiles and found that the $F$ layer regained its normal $h_m F_2$ within 10–20 min of convecting out of the source region. They were able to show that the often observed $F$ region density structures or "blobs" can readily be accounted for by structure in the auroral precipitation. In sharp contrast to the $h_m F_2$, the relative density enhancements remain for periods as long as 10 hours. The relative enhancement is only removed in regions of large, spatially homogeneous, plasma production (i.e., sunlight or diffuse auroral precipitation). By introducing polar cap arcs, they were able to simulate $F$ region density enhancements similar to those observed in the midnight sector by the incoherent scatter radar.

Ionospheric features associated with the high-latitude model inputs' dependence on the orientation of the interplanetary magnetic field (IMF) were studied by Sojka and Schunk [1987]. They contrasted the "multicell" nature of the convection pattern for northward and southward IMF and strongly negative $B_y$ IMF conditions.
They introduced polar cap Sun-aligned precipitation in the region of sunward polar cap convection. This study shows that for these complex convection patterns, deep polar hole features can develop in the polar cap if the center of a convection cell is devoid of plasma production. Figure 16 shows their modeled $O^+$ distribution at 250 km. These results correspond to solar-maximum winter conditions. During conventional two-cell convection a moderate polar depletion is found in the morning sector (top panel); however, in both the four-cell (middle panel) and the three-cell (bottom panel) cases, exceedingly deep depletions are associated with the center of these cells. Furthermore, in the three-cell case the very high electric fields cause ion heating and subsequent plasma decay in the polar cap afternoon sector.

Schunk and Sojka [1987b] used the TDIM to study the complex time behavior of plasma enhancements as they convect around the high-latitude ionosphere. These complications arise for any ground-based observation because of the plasma flux tube trajectories being driven in a geomagnetic coordinate system. Figure 17 shows how this complexity occurs for even simple two-cell convection. The top panel shows two-cell plasma trajectories in a magnetic frame (local time is magnetic local time). A selected transpolar trajectory is shown as a heavy line. The stippling represents a simple auroral oval. In the middle panel of Figure 17, three circuits of this test trajectory are shown in the solar LT-geographic latitude frame. Not only are these patterns changing with time but how they cross the solar terminator is a UT-dependent function (compare with the winter (W) and summer (S) terminators shown in Figure 17, middle panel) (dashed lines). If the same plasma trajectory is now viewed in the ground geographic latitude-longitude system, the motion is complex (see the bottom panel). Indeed, the same flux tube can cross an observer at different times going in quite different directions. Schunk and Sojka [1987b] showed how a single blob would decay around this test trajectory in both summer and winter. This temporal variation is shown in Figure 18, for both summer (right panel) and winter (left panel). A set of three different initial blob enhancements are used. These enhancements are no enhancement (solid curve), a factor of 10 enhancement (dotted curve), and a factor of 100 enhancement (dashed curve). Even in the presence of auroral precipitation (hatched region in lower part of each panel) and in sunlight (top trace of each panel) the blobs are found to last from 6 to 20 hours. Hence the ground-based observer could well see the same enhanced flux tube reappear hours later and without a knowledge of the complete convection pattern would be unable to recognize it as the same blob. Schunk and Sojka showed how the picture becomes even more complex in the presence of an IMF-dependent convection pattern.
Figure 17. Plasma drift trajectories in different coordinate systems for a two-cell convection pattern with corotation added. (Top) The drift trajectories in a magnetic latitude–MLT reference frame are shown, as well as (middle) the path of a plasma flux tube in the geographic inertial frame for three traversals of the test trajectory. Also shown (middle) are the terminator locations for summer and winter solstice. (Bottom) Finally, the flux tube path in a corotating geographic reference frame is illustrated. Tick marks along the flux tube path show the elapsed time at hourly intervals [from Schunk and Sojka, 1987b].

Figure 18. $N_mF_2$ variation along the test trajectory for three plasma flux tubes in both summer and winter at solar minimum. The solid curve corresponds to the background plasma, while the dotted and dashed curves show the initial O+ density profile multiplied by factors of 10 and 100, respectively. The solar zenith angle variation along the trajectory is shown at the top, and the logarithm to the base 10 of the auroral electron energy flux along the trajectory is shown at the bottom [from Schunk and Sojka, 1987b].

The TDIM can also be used on much finer spatial and temporal scales. Sojka and Schunk [1988] considered the problem of electric field structures on the scales of 10–1000 km superimposed upon the large-scale two-cell polar cap convection. Such structures are the rule, rather than the exception. Figure 19 shows how for three different convection patterns the transpolar $N_mF_2$ varies for eight selected plasma flux tubes. In each panel $\log_{10}(N_mF_2)$ is plotted as a function of the flux tube location along the noon–midnight direction. The origin, $x = 0$, corresponds to crossing the dawn–dusk magnetic meridian, while negative $x$ locations are on the noonside, and positive values are on the nightside. These eight flux tubes are followed across the polar cap, and in all three simulations they end at the same respective location at the same UT time. The top panel shows the variation of $N_mF_2$ for the two-cell pattern. Then the lower two panels show how progressively stronger electric field structures lead to significant spreading or structuring in the $N_mF_2$ values.
Indeed, an entirely different set of initial conditions are needed, since the locations and times at which the trajectories enter the polar cap change as the convection pattern changes. For this exploratory study, Sojka and Schunk used solar maximum winter conditions with only electric field structuring. The question of how precipitation and heat flux structuring would affect the overall results was not considered.

4. IONOSPHERIC MODEL: OBSERVATION COMPARISONS

The problem of comparing ionospheric observations with the calculations of the TDIM, or similar physical models, is nontrivial and yet is a crucial step in verifying the models. First the period of interest must be sufficiently well “documented” such that the appropriate inputs can be defined. Indeed, these inputs must be defined in regions and at times outside the regions for which the comparison is to be made. This is because the $F$ region ionosphere is a convecting system in which the past history is important. In the high-latitude ionosphere with convection speeds of the order of $1 \text{ km s}^{-1}$ and topside time constants of the order of 1 hour this leads to coupling distances of the order of many thousands of kilometers and past histories of many hours. Having the appropriate inputs then leads to the second complication of selecting a subset of the TDIM’s parameters. Models like the TDIM typically create 1–3 million binned density values, for a 24-hour simulation. A higher time resolution storm runs readily double this number. The final problem then comes when the comparison is made and inferences about model-observation shortcomings are attempted. There is no clear “error analysis” procedure for such a complex model; worse still, a single location comparison, whether good or bad, may be quite meaningless on a global scale. Discrepancies can only be discussed in terms of the shortcomings of the model inputs. Only in very rare cases can it be concluded that the inputs are exact and that the shortcomings pertain to new or missing physics. In the following paragraphs a chronological critique of a representative set of large-scale model ionosphere comparisons with observations is given.

4.1. Polar Plasma Transport

Knudsen [1974] described how the high-latitude $F$ region depends heavily upon a convection model, which, unlike mid-latitudes, is not a corotational electric field model. He outlined how a correct set of “inputs” such as an auroral oval to augment solar EUV plasma production and a two-cell convection pattern would lead to the observed polar cap “tongue of ionization.” Knudsen et al. [1977] used the Schunk and Walker [1973] triple-ion model to carry out a numerical simulation of the high-latitude $F$ region. They followed the method described by Knudsen [1974]. The model results were compared with ISIS 2 topside sounder $N_e$ data and Antarctic $N_mF_2$ synoptic data. Favorable agreement was obtained; specifically, they verified the need to use a convecting model for high-latitude studies.

4.2. AE Satellites/Molecular Ion Composition Comparison

The first TDIM comparison with observations was made by Sojka et al. [1981b] in which the high-latitude $F$ region molecular composition at 300 km was compared to the observations of Brinton et al. [1978]. The comparison of the NO$^+$ and O$_2^+$ density distributions shows that NO$^+$ is the dominant molecular ion in the “active” oval in most of the 0700–1700 MLT sector and in the morning sector mid-latitude trough. From 0200 to 2000 UT, O$_2^+$ is dominant in the dusk mid-latitude trough region. There were two additional regions where O$_2^+$ dominated (i.e., in the polar cap adjacent to the evening sector poleward oval boundary and in the nonactive oval from 0500 to 0800 MLT). Table 2 summarizes these regions of the polar ionosphere at 300 km, indicating the dominant molecular ion. This table also includes general results of the AE
processes have on the mid-latitude trough and found that production due to a small flux of precipitating particles, both the electron density and the ion composition that was measured by DMSP satellites. Sojka et al. [1981b] studied the extent to which different nocturnal maintenance processes could affect trough results, including production due to resonantly scattered solar radiation, production due to an enhanced level of resonantly scattered solar radiation, production due to a small flux of precipitating particles, and a neutral-wind-induced upward ionization drift. They found that the three latter mechanisms were adequate and adopted the enhanced resonantly scattered radiation mechanism. While this choice provided an adequate description of the major ion (O+) behavior, it appears that in comparison with Brinton et al.'s [1978] observations, the mechanism resulted in an erroneous prediction for the minor ion composition. Sojka et al. [1981b] repeated their earlier study of the effect that nocturnal maintenance processes have on the mid-latitude trough and found that of the mechanisms considered, only a neutral-wind-induced upward ionization drift was capable of producing both the electron density and the ion composition that was measured by Brinton et al. [1978] at 300 km.

4.3. UT Dependence Comparison With Defense Meteorological Satellite Program (DMSP) Satellites

One of the major predictions of the TDIM type of model is the strong UT modulation of the F region. Unfortunately, a single ground station is locked to one particular longitude and is therefore insensitive to this UT modulation. Sojka et al. [1982b] carried out a study using the DMSP F2 and F4 satellites to verify the presence of the UT modulation. These satellites were in polar Sun synchronous orbits at ≈800 km. During a 24-hour period each satellite makes approximately 15 orbits. Unfortunately, these orbits do not lie in exactly the same location in the MLT-invariant latitude frame. However, the model was used to predict the UT-spatial variation for these satellites. The TDIM was run for low geomagnetic activity and solar maximum conditions consistent with the DMSP data period. Sojka et al. [1982b] looked for the lowest observed densities and correlated the UT variation of this with the model densities. By doing so, they were able to show that the modulation was very similar and in phase for the model and observed densities.

4.4. \( N_e \) Comparison With Millstone Hill Observations

The first large-scale high-latitude comparison was made using electron density data from the Millstone Hill incoherent scatter radar and the TDIM by Sojka et al. [1983]. In this study the convection pattern was constrained by the Millstone Hill observations of the F region plasma drift. However, since the radar corotates once in 24 hours, its diurnal plasma drift pattern does not correspond to the instantaneous convection pattern. Hence three separate pairs of convection and auroral models were used for three TDIM simulations to help identify the sensitivity of the modeled densities upon the input convection and auroral model. Plate 5 shows the Millstone Hill diurnal electron density variation at 500 km on October 13 and 14, 1979. The densities are color-coded, with the red region being the largest; they are also plotted in a LT-dip latitude coordinate system. The corresponding TDIM simulations are shown for models A, B, and C in Plates 6a, 6b, and 6c, respectively. A similar color key is adopted, and densities are shown over a similar latitudinal range. From a comparison of these two plates, Sojka et al. [1983] concluded that model B gave best overall agreement and that the model B study with the inclusion of discrete precipitation would match the observed densities.

<table>
<thead>
<tr>
<th>Description of Region</th>
<th>Calculated Variation*</th>
<th>Observed Variation†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active auroral oval</td>
<td>NO⁺</td>
<td>NO⁺</td>
</tr>
<tr>
<td>0700–1700 MLT</td>
<td>NO⁺</td>
<td>NO⁺ (some data gaps)</td>
</tr>
<tr>
<td>Morning sector mid-latitude trough</td>
<td>NO⁺</td>
<td>O⁺</td>
</tr>
<tr>
<td>Dusk sector mid-latitude trough</td>
<td>either NO⁺ or O₂⁺, UT dependent</td>
<td>either NO⁺ or O₂⁺</td>
</tr>
<tr>
<td>Evening sector polar cap adjacent to auroral oval</td>
<td>O₂⁺</td>
<td>O₂⁺</td>
</tr>
<tr>
<td>Dawn sector, nonactive auroral oval</td>
<td>O₂⁺</td>
<td>O₂⁺</td>
</tr>
</tbody>
</table>

*From Sojka et al. [1981b].
†From Brinton et al. [1978].
Plate 5. Electron density variation at 500 km as observed from Millstone Hill over a 24-hour period. The densities are color-coded, with the color key given on the right. The data are presented in a local time-dip latitude coordinate system [from Sojka et al., 1983].

Plate 6. Model electron density variation at 500 km simulated for the Millstone Hill radar. The three panels correspond to the three plasma convection-auroral models. The densities are color-coded, with the key given at the top. The coordinates are MLT and invariant latitude [from Sojka et al., 1983].
4.5. Quiet and Active $N_e$ Comparison With Chatanika Observations

*Murdin et al.* [1984] used high-resolution, but local, Chatanika incoherent scatter radar measurements to contrast quiet and active periods. The data set contained local Chatanika altitude profiles extending from 110 to 460 km, as well as inferred electric field vectors over this altitude range. In addition, the vertically induced drift could be inferred from the data. This gave a crude method of contrasting the neutral wind and electrodynamic mechanisms for inducing vertical drifts. The data set spanned 2 days, which included a relatively quiet day (24 hours) followed by a disturbed day. Figure 20 shows a comparison of model (open circles) and observed (plus signs) electron density profiles for the quiet day at 0930 MLT, (b) 1530 MLT, and (c) 2030 MLT [from Murdin et al., 1984].

Associated with neutral-wind-induced ion drifts are the major mechanisms for the quiet day. At 1530 MLT (Figure 20b) the quiet day observed and modeled profiles are almost identical. In this region (1740 LT), EUV and auroral production is absent and yet $N_mF_2$ has its diurnal peak. This is due to horizontal plasma transport, and hence this profile could not be deduced from local steady state modeling. The model profile for the trough region (Figure 20c) shows excellent agreement with the observed profile. At this location the value of $N_mF_2$ has its lowest diurnal value of about $10^5$ cm$^{-3}$. The value of $h_mF_2$ has increased further from Figure 20b to values near 350 km.

On the disturbed day, *Murdin et al.* [1984] obtained poorer agreement between the model and the observation (Figure 21). In the early afternoon (Figure 21a) the peak densities are similar, but $h_mF_2$ is different by about 60 km. In the early evening sector (Figure 21b) the difference is larger; however, it is in this region that Murdin et al. showed there was highly structured precipitation. This clearly was not contained in the statistical auroral model.

![Figure 20](image_url)  
Figure 20. Comparison of (open circles) model and (plus signs) observed altitude-density profiles for the quiet day at (a) 0930 MLT, (b) 1530 MLT, and (c) 2030 MLT [from Murdin et al., 1984].

![Figure 21](image_url)  
Figure 21. Comparison of (open circles) model and (plus signs) observed altitude-density profiles for the disturbed day at (a) 1330 MLT and (b) 1830 MLT [from Murdin et al., 1984].
4.6. DMSP Observations of the Southern Dayside Trough

The global ionospheric study of Sojka and Schunk [1985a] identified a highly UT-dependent deep dayside trough in the southern hemisphere. This north-south asymmetry was associated with the larger offset between the geographic and the geomagnetic pole in the southern hemisphere. In the southern hemisphere during quiet winter conditions, at about 1400 UT, the dayside terminator does not reach the equatorward edge of the auroral zone. This leads to a dark region devoid of an ionization source, causing low densities. Sojka et al. [1985] used the DMSP F4 satellite to study this southern hemisphere region and verify the phenomenon. Figure 22 shows their model (solid curves) and DMSP F4 (plus signs) ion density at 800 km. The vertical dashed line at -57° geographic latitude indicates a solar zenith angle of 90°, while the downward pointing arrow in each panel indicates a magnetic latitude of -68°. This magnetic latitude was plotted to indicate where the model dayside auroral oval begins, and hence the comparison of the left- and right-hand columns in Figure 22 reveals the extent of the UT effect associated with the oval motion. The upward pointing arrow placed at the top of some graphs corresponded to the in situ determination of this auroral boundary. The left-hand column corresponds to the UTs when a trough was expected and indeed was found. In contrast, the right-hand graphs show model and satellite data lacking this feature.

4.7. N. Comparison With Simultaneous Chatanika and Millstone Hill Observations

In order to better constrain the auroral inputs to the TDIM, Rasmussen et al. [1986] used a multitude of data from satellite, incoherent scatter radars, and a coherent scatter radar. By choosing radar locations widely spaced in longitude, they attempted to avoid a shortcoming of the earlier Sojka et al. [1983] study, that of not observing the inputs over a wide enough range of local times at all UT. Even with this vast array of data it was difficult to make simple statistical models of precipitation, convection, and temperature agree with the inputs. They found, for example, that constraining the auroral oval using the NOAA 6 satellite northern and southern hemisphere precipitation data, assuming symmetry in the oval between the hemispheres, did not produce an adequate description of the auroral oval. In spite of the difficulties in defining suitable inputs, their model-observation comparisons of electron density were very successful.

The comparisons with predictions at 278 and 350 km were good in regions where sunlight dominates production. In regions of decreasing sunlight their predicted and observed trough densities and locations were similar. Also, the formation of the mid-latitude trough had a distinct UT

Figure 22. (Plus signs) Measured and (solid curves) modeled ion densities along satellite tracks plotted as a function of geographic latitude for July 23–27, 1979, average Kp = 3. [from Sojka et al., 1985].
dependence which was evident in both the radar data and the model predictions. However, a comparison at 65° latitude of the $h_m F_2$ diurnal variation was poorer. This they concluded could be due to several processes, including those associated with auroral precipitation, neutral winds, or the convection electric field. Without more precise input data they concluded that it would be difficult to fully understand the discrepancy in $h_m F_2$.

4.8. $f_0 F_2$ Comparison With Halley Bay and Siple Data

The Halley Bay and Siple stations are both located in the southern hemisphere and are normally under the mid-latitude trough. Under geomagnetically quiet conditions they are ideally located to track the trough and study its UT dependence. At both stations there are similar NOAA type HF sounding radars. Berkey et al. [1987] used this unique combination of southern hemisphere data to carry out a comparison of the TDIM with the radar observations. During sunlit winter conditions, reasonably good agreement was obtained for $h_m F_2$ and $N_m F_2$. In darkness they found Halley Bay $N_m F_2$ values to be 20% lower than at Siple, which was consistent with the model UT variation. In summer, both stations were sunlit; under these conditions they concluded that data-model differences in $h_m F_2$ were sensitively dependent upon the adopted neutral wind pattern. This southern hemisphere mid-latitude trough study shows that the hemispheric differences in UT control of the ionosphere predicted by the model can be found in high-resolution data sets.

4.9. Limits on Vertically Induced Drifts

Sica et al. [1988] used the TDIM in a distinctly different way. Smith et al. [1985] using the European Incoherent Scatter Radar (EISCAT) and a ground-based Fabry-Perot spectrometer observed downward ion drifts between 250 and 500 m s⁻¹. These persistent large induced drifts had not been reported before. Sica et al. [1988] used the TDIM in an effort to understand the ionospheric consequences of such a strong downward drift. In their TDIM study they attempted to induce these large ion drifts by the conventional neutral wind and electrodynamic mechanisms. While keeping consistent with other known parameters available from the Smith et al. [1985] study, they were able to reproduce the $h_m F_2$ and $N_m F_2$ observations. However, they were not able to reproduce the thinness of the $F_2$ layer. This latter constraint prevented the TDIM study from matching the data.

4.10. $N_e, T_e, and T_i$ Comparison With Chatanika and Millstone Hill Data

Rasmussen et al. [1988] carried out an energy balance comparison in which both modeled $T_e$ and $T_i$ were compared with the incoherent scatter radar observations at Millstone Hill and Chatanika. As pointed out earlier, the problem in solving the electron energy equation lies in determining what topside heat flux to use. Since Chatanika lies in the auroral zone where this input is expected to be important, Rasmussen et al. [1988] had to use the radar data to try to verify that the adopted heat flux was reasonable. Although the radar data base above 400 km was not extensive, they were able to show that their adopted heat flux was consistent with the observations at Chatanika. Using the TDIM, they coupled the plasma density with the ion and electron temperatures in the simulation. Figure 23 shows the modeled (solid curve) and observed (circles) electron temperature (left-hand column) and electron density (right-hand column) at three altitudes during the 24-hour period. The agreement is excellent. Rasmussen et al. [1988] did show, however, that there was still some ambiguity in deducing the appropriate volume heating rates, even in sunlight. This problem was further compounded when it was found that at Millstone Hill a somewhat different volume heating rate leads to a better agreement. Figure 24 shows the modeled (solid curve) and observed (circles) electron temperature and electron density at Millstone Hill. Again, the agreement appears good, but at low altitudes (195 km) the electron temperatures are somewhat different. This is the altitude range in which Rasmussen et al. found the strongest sensitivity to the volume heating rates.

4.11. Argentine Islands $f_0 F_2$ Comparison

A problem common to all of these studies is that of deciding how representative the particular data period is of the ionosphere’s solar cycle, seasonal, diurnal, or geomagnetic activity dependence. To what extent has the model simulated the true ionosphere, rather than just obtaining agreement with a limited data set? One way to address this question is to use a large enough data base spanning enough of these conditions to restrict the input freedom of the model. Clearly, this implies that a major data extraction and reduction study needs to be undertaken. Wrenn et al. [1987] carried out such a study for ionosonde critical frequency data from the southern hemisphere mid-latitude station Argentine Islands. They employed a new analysis procedure to deduce the monthly geomagnetic quiet day curves over an entire year and repeated this procedure for four ranges of solar activity from solar minimum to solar maximum.

Sojka et al. [1988] used this data base to carry out an extensive solar cycle, seasonal, and diurnal check of the TDIM. Because of the mid-latitude location of the ionosonde the model did not need to have either an auroral oval or a magnetospheric convection model. This was especially the case for quiet geomagnetic activity. Their study used a solar-cycle-dependent solar EUV flux, a neutral atmosphere model, seasonal and diurnal variation of these parameters, and a neutral-wind-induced vertical drift. This latter parameter was the least constrained of the inputs. Figure 25 shows the solar minimum diurnal and
Figure 23. Comparison of the model density and temperature predictions with Chatanika measurements at 65° (±1°) and at three different altitudes: (top) 440 km, (middle) 325 km, and (bottom) 175 km. Electron temperatures are compared in the left column, and electron densities in the right column. The model results are plotted as a solid curve, and the radar measurements are plotted as solid circles [from Rasmussen et al., 1988].

seasonal comparison obtained by Sojka et al. [1988]. Each panel corresponds to the observed $f_F$ (solid curve) and the modeled $f_F$ (vertical bars) as a function of LT from 0 to 24 hours. Both the model and the observations were found to exhibit not only the same overall seasonal trend but also a diurnal trend. They used the same neutral wind description for all 12 months. In the austral summer, November to February, this leads to a minimum $f_F$ at noon and a maximum around midnight, while the reverse is the case during austral winter (April to August). Figure 26 is identical to Figure 25 except that now the comparison is being made for solar maximum. Again, Sojka et al. [1988] found very good agreement in both the seasonal and the diurnal variation. This study showed that the basic TDIM model was able to reproduce the ionospheric variations over a complete range of solar cycle, seasonal, and diurnal variation for at least one mid-latitude location. Their main free parameter was the vertically induced drift.
5. RECENT DEVELOPMENTS

There are two distinct developments under way which will have a significant effect on modeling of the ionosphere. Both relate to how well the inputs to the ionospheric model can be defined. The first is associated with the neutral atmosphere, while the second relates to determining more precisely the magnetospheric precipitation input.

The ionosphere and thermosphere are strongly coupled. Ionospheric models like the TDIM use an empirical representation of the neutral atmosphere (i.e., MSIS). Recently, Fuller-Rowell et al. [1987] have developed a coupled model of both the high-latitude ionosphere and the thermosphere. By doing so, they deduce self-consistently the neutral temperature, density, composition, and wind to be used in the ionosphere. Their model contains a “Eulerian” thermospheric model and a “Lagrangian” high-latitude ionospheric model. They have carried out an initial simulation for solar maximum, winter solstice, and moderate magnetic activity conditions. The results obtained from this coupled model are, in general, consistent with earlier ionospheric model results. In addition, they find that polar cap troughs can be formed in the summer hemisphere from composition changes in the thermosphere caused by geomagnetic effects. Roble et al.
Figure 25. Comparison of the (solid curves) observed and (vertical bars) modeled $f_0F_2$ for Argentine Islands during quiet activity and low solar flux ($F_{10.7}$ cm radio flux from 50 to 100 x $10^{-22}$ W m$^{-2}$). The lower and upper ends of the base correspond to modeled $f_0F_2$ values at $F_{10.7}$ of 50 x $10^{-22}$ W m$^{-2}$ and 100 x $10^{-22}$ W m$^{-2}$ [from Sojka et al., 1988].

Figure 26. Similar $f_0F_2$ comparison as in Figure 25 except the solar conditions are high, with $F_{10.7}$ cm radio flux from 200 to 150 x $10^{-22}$ W m$^{-2}$. The lower and upper ends of the bars correspond to modeled $f_0F_2$ values at $F_{10.7}$ of 200 x $10^{-22}$ W m$^{-2}$ and 250 x $10^{-22}$ W m$^{-2}$ [from Sojka et al., 1988].

[1987] have also developed a coupled ionospheric and thermospheric model. However, their initial approach was to consider global mean properties of the thermosphere-ionosphere. On the basis of these initial findings, this work is being incorporated into a coupled thermosphere-ionosphere thermospheric general circulation model (TGCM). Both of these model developments have been necessitated by the need to include realistic ionospheric effects in high-latitude thermospheric studies, especially during active conditions. The degree to which the ionospheric simulation is improved still awaits detailed studies using these coupled ionospheric-thermospheric models.

The second development area focuses upon efforts to improve the magnetosphere precipitation input to the models. At present an empirical auroral model is used for this input. This has no structure or storm dependence built into it. As pointed out in earlier sections, this is the major obstacle to carrying out detailed ionospheric or thermospheric model studies. For the past few years an effort has
been made to use the Dynamics Explorer A satellite global auroral images to define the auroral oval. Craven and Frank [1987] have demonstrated how these images can be used to give detailed spatial and temporal variations of the auroral oval during storm periods. Sojka et al. [1989] have used such images to define the entire northern auroral oval over a 3-hour storm period. The images are used to deduce the precipitating energy flux, auroral boundaries to $\sim 100$ km resolution, and a time resolution of 12 min. In their initial study, Sojka et al. [1989] show how sensitive the ionosphere is to auroral structures.

6. CONCLUSION

This review has focused on the development and role of physical models of the high-latitude (and global) $F$ region. In this region the ionosphere is highly dependent upon the magnetospheric inputs: magnetospheric electric field, auroral precipitation, and electron heat flux. These inputs are only known in an empirical sense or in the case of an electron heat flux are almost unknown, and yet they control the high-latitude ionosphere [Raitt et al., 1981; Schunk and Sojka, 1987a; Sojka and Schunk, 1987]. This review complements several earlier reviews, specifically, ionospheric theory [Schunk, 1988], ionospheric electron temperature [Schunk and Nagy, 1978], stable auroral red (SAR) arcs [Rees and Roble, 1975], equatorial models [Anderson, 1981], topside light ions [Moffet and Quegan, 1983], and empirical physical models [Schunk and Szuszczewicz, 1988].

Five physical models of the high-latitude ionosphere have been developed to date. Their relative merits are contrasted in Table 3. Two of these models are not in current use (i.e., Knudsen’s and Watkins’ models). The Sheffield-University College, London (UCL) and NCAR models are each part of a coupled ionosphere-thermosphere model. Most of this review has dealt with the USU TDIM which has been specifically developed to tackle $F$ region problems. All three of the current models require large amounts of time on supercomputers (i.e., hours on a CRAY XMP). In addition, as the review has pointed out, extensive preparation of inputs is needed to obtain meaningful data sets for comparison with observations.

At high latitudes, reasonably good agreement between the model and the observations is possible provided that the inputs are sufficiently constrained. Under these conditions the current models contain the zero-order and possibly first-order physics. The studies have not revealed missing or inappropriate mechanisms in the models. Tables 4 and 5 summarize the relative order of importance of inputs to the high-latitude models during quiet and active geomagnetic conditions, respectively. In this instance the order of importance is defined as the most sensitive ionospheric input which is also the least defined. Hence the two tables order the weakness in modeling the high-latitude ionosphere. During quiet geomagnetic

### TABLE 3. High-Latitude $F$ Region Physical Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Extent</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knudsen</td>
<td>coupled multi-ion*</td>
<td>high latitude</td>
<td>one study, 1977</td>
</tr>
<tr>
<td>Watkins</td>
<td>single ion, chemistry†</td>
<td>high latitude</td>
<td>one study, 1979</td>
</tr>
<tr>
<td>USU TDIM</td>
<td>coupled multi-ion and</td>
<td>global</td>
<td>variety of $F$ region</td>
</tr>
<tr>
<td></td>
<td>energy equations</td>
<td></td>
<td>studies</td>
</tr>
<tr>
<td>Sheffield-UCL</td>
<td>coupled multi-ion</td>
<td>high latitude</td>
<td>coupled with UCL TGCM</td>
</tr>
<tr>
<td>NCAR</td>
<td>multi-ion‡</td>
<td>global</td>
<td>part of NCAR TGCM</td>
</tr>
</tbody>
</table>

*Coupled multi-ion formulation of molecular and atomic ion chemistry and diffusion.  
†Single-ion formulation for O$^+$ with only chemistry.  
‡Molecular ion chemistry and O$^+$ chemistry and diffusion.

### TABLE 4. Criticality of Inputs During Quiet Geomagnetic Activity

<table>
<thead>
<tr>
<th>Input Region</th>
<th>Zero-Order Input</th>
<th>First-Order Input</th>
<th>Higher-Order Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetosphere</td>
<td>convection E field</td>
<td>ion and polar cap precipitation</td>
<td>electron heat flux</td>
</tr>
<tr>
<td>Magnetosphere</td>
<td>auroral precipitation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetosphere</td>
<td>wind</td>
<td>density, temperature</td>
<td>composition</td>
</tr>
<tr>
<td>Thermosphere</td>
<td></td>
<td>absolute EUV spectrum</td>
<td></td>
</tr>
</tbody>
</table>
periods the physical model can reproduce observations with relatively little "tweaking" of the inputs. This is reflected in Table 4, where no zero-order input problems are listed.

This is not the case during geomagnetically disturbed periods. Neither the dynamics nor the structure of the magnetospheric inputs are well known on a global scale. Consequently, in Table 5 both the magnetospheric E field and the auroral precipitation are treated as zero-order problems. At present these two inputs present a hurdle in achieving a predictive F region capability. During disturbed periods, especially in the auroral oval, the possibility exists for significant changes in the neutral composition. Such effects could have dramatic consequences for the plasma chemistry, eventually leading to rapid changes in the plasma density and composition. The enhanced magnetospheric heat input for the electrons is at present ill defined, although the indications are that it is important.

Only by close interaction between the modeling and the observational community will the definition of magnetospheric inputs be improved upon. The extent of observations leading to global patterns of both the magnetospheric electric field and the precipitation will have to be extended. Alternatively, a breakthrough in our understanding of the magnetosphere as a single system is needed. Problems associated with the supercomputing facilities needed by these models are potentially overcome by use of parallel-processing computers. The F region system is an ideal problem for parallel-processing technology because of the lack of coupling between plasma flux tubes. This technological step may also lead to a real-time ionospheric modeling capability. The capability of ionospheric weather modeling would be a major advance from the present-day state of climate modeling [Schunk and Sojka, 1988].

### Glossary

**Appleton peaks**: two regions of enhanced plasma density located symmetrically about the magnetic equator between magnetic latitudes of 10° and 20° in the afternoon and night local time sector.

**B**: the inherent terrestrial magnetic field.

**Bottomside**: the plasma region lying beneath the altitude of the F region peak density.

**Convection**: the motion of ionospheric plasma under the \( E \times B \) mechanism.

**Corotation**: the tendency for the F region plasma to diurnally rotate with the Earth.

**EUV**: the extreme ultraviolet range of the solar electromagnetic spectrum.

**Flux tube**: a hypothetical envelope containing the F region plasma whose gyrocenters make up a magnetic field line.

\( f_{\text{F}_2} \): the plasma frequency associated with the peak in the F region density profile.

**F10.7 index**: solar flux measured at a wavelength of 10.7 cm, expressed in units of \( 10^{-22} \text{ W m}^{-2} \).

**Hot spot**: a region in which the ionospheric ion temperatures have become enhanced by the presence of a large electric field.

**h\(_{\text{F}_2} \)**: the altitude of the peak electron density in an F region profile.

**IMF**: interplanetary magnetic field of solar origin.

**IMF (B\(_z\))**: the component of the IMF perpendicular to the Earth’s magnetic axis and perpendicular to the Sun-Earth direction.

**N\(_{\text{F}_2} \)**: the maximum electron density in an F region altitude profile.

**Main phase**: the period of maximum disturbance during a magnetic storm.

**Main trough (mid-latitude trough)**: a region of depleted plasma equatorward of the auroral region in the dark local time sector.

**MLT**: magnetic local time.

**Neutral wind**: the neutral gas flow in the F region; it is mainly horizontal and constant with altitude between 200 and 800 km.

**Polar hole**: a region located poleward of the auroral region (in darkness) where the plasma density is lower than elsewhere in the polar cap.

**Seasonal anomaly**: a region near noon at both mid-latitude and high latitudes for which winter peak densities exceed the corresponding summer peak densities in the F region.

**Tongue of ionization**: an extended region of high plasma densities extending from the noon auroral region into the polar cap predominantly in an antisunward direction.

**Topside**: the plasma region located above the altitude of the F region density peak.

**UT (diurnal)**: a cyclic pattern of F region variability with a 24-hour period which is related to the offset between the geographic rotational axis and the magnetic field axis. In the case of zero offset the UT effect is removed, but residual diurnal effects still exist.

### Table 5: Criticality of Inputs During Disturbed Geomagnetic Activity

<table>
<thead>
<tr>
<th>Input Region</th>
<th>Zero-Order Input</th>
<th>First-Order Input</th>
<th>Higher-Order Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetosphere</td>
<td>convection E field</td>
<td>E field structure</td>
<td>density, temperature</td>
</tr>
<tr>
<td>Magnetosphere</td>
<td>auroral precipitation</td>
<td>arc structure</td>
<td>absolute EUV spectrum</td>
</tr>
<tr>
<td>Thermosphere</td>
<td>electron heat flux</td>
<td>wind composition</td>
<td></td>
</tr>
<tr>
<td>Thermosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sun</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ACKNOWLEDGMENTS. This research was supported by NASA grants NAGW77 and NAGW-1547 and AFOSR contract F49620-86-C-0109 to Utah State University.

REFERENCES


---

J. J. Sojka, Center for Atmospheric and Space Sciences, Utah State University, Logan, UT 84322.