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Lie Zhu  
Utah State University

Robert W. Schunk  
Utah State University

Jan Josef Sojka  
Utah State University

M. David  
Utah State University

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Model study of ionospheric dynamics during a substorm

L. Zhu, R. W. Schunk, J. J. Sojka, and M. David
Center for Atmospheric and Space Science, Utah State University, Logan

Abstract. A global substorm electrodynamic model and a global ionospheric model were coupled in order to study ionospheric dynamics during substorms, with the focus on small-scale substorm electrodynamic and plasma structures. The simulation results show that in the expansion phase, structured precipitation and channeled field-aligned currents quickly develop in the substorm onset region. The Hall and Pedersen conductance ratio in the region increases significantly, and the magnetospheric field-aligned currents are mainly closed by highly structured Hall currents. Correspondingly, the plasma in the ionosphere also undergoes significant changes during a substorm and is highly structured in both the horizontal and vertical directions. In the substorm onset region, there are spatially separated small-scale T_i and T_e hot spots, downward ExB drifts, decreased total electron contents, and a lowered ionosphere. Also, there is a significant O^+ → NO conversion, leading to a great increase of NO+ and a lowering of the O^+ peak height. These small-scale electrodynamic and plasma structures are very important for more realistically simulating the ionospheric dynamics during substorms. These results not only help to elucidate the multiscale ionospheric responses to substorms but also provide a theoretical guidance and cautions for the interpretation of various substorm observational data.

1. Introduction

Since the concepts of auroral substorms [Akasofu, 1964] and magnetospheric substorms [Akasofu, 1968] were first proposed, significant progress has been achieved in the study of substorms. It has been realized that a substorm is not a localized auroral phenomenon in the auroral oval regions, but instead is a global transient response of the coupled magnetosphere-ionosphere (M-I) system to the dynamic forcing of the solar wind. It is also known that a substorm involves the interactions between large numbers of plasma processes with various temporal and spatial scales in the vast regions of the magnetosphere and ionosphere [e.g., Lui, 1991]. For the present substorm study it is necessary to put all the important plasma processes into a unified global frame and focus on the cause-effect relationships between these physical processes instead of treating them as isolated elements.

Along the line of such an evolution of our knowledge about substorms, the present observations tend to increasingly use multi-instrument and multisite measurements (ground-based and in situ) to form a coherent global time-varying picture of substorms in order to study the roles played by individual physical processes in the global dynamics of substorms and their interrelationships [e.g., Rostoker, 1991]. In such an observational endeavor, the timing of key physical events with a resolution of the order of minutes in a unified substorm frame has its fundamental importance.

On the other hand, numerical simulations using global physical models have been widely used to explore both the global picture of substorm dynamics and the interconnections among various substorm-related plasma processes. In the magnetosphere this research endeavor has been represented by the development of various global MHD models [LeBoeuf et al., 1978, 1981; Lyon et al., 1981; Ogino, 1986; Watanabe and Sato, 1990; Walker et al., 1993; Raeder, 1994]. These global MHD models have successfully reproduced some of the global-scale substorm features, but presently they are not able to simulate the observed small-scale substorm dynamics features, including sharp convection reversals, channeled precipitation and field-aligned currents, and fine auroral structures, owing to the spatial resolution limits in these models. Furthermore, to fully describe the cause-effect relationship of the global substorm dynamics, the present global MHD models need to incorporate non-MHD effects, mainly the kinetic and particle effects, as well as other MHD effects, such as wave phenomena.

Different from the global MHD models of the magnetosphere, the global physical models of the ionosphere have been developed to such an extent that both the global-scale and small-scale three-dimensional (3-D) dynamical ionospheric features of substorms can be simulated within the model capabilities. However, in order to simulate ionospheric dynamics of substorms, the global ionospheric models need self-consistent, time-varying, global plasma convection and particle precipitation patterns as the model drivers, which can be either observation-based or model-based. Even though the multimeasurements of substorm dynamics in the ionosphere have made significant improvements recently, with much higher spatial resolutions and much better coverages than those in the magnetosphere, an inconsistency between the global convection and particle precipitation patterns derived from the observations still exists.

A way to avoid the inconsistency between the magnetospheric drivers rooted in the observation limits is to use the convection and precipitation outputs at the ionospheric boundary from the magnetospheric MHD models to drive the global ionospheric models. This approach has recently been explored [Sojka et al., 1997], and these studies were quite successful. However, as mentioned above, the present global MHD models are not able to produce small-scale substorm features, and yet these small-scale...
features are crucial to simulate the ionospheric dynamic changes during substorms.

To complement the simulations of ionospheric substorm dynamics driven by a global magnetoospheric MHD model [Sojka et al., 1997], we coupled the Utah State University (USU) Time-Dependent Ionospheric Model (TDIM) to a substorm model that is similar to that proposed by Kan et al. [1988], Zhu and Kan [1990], and Kan and Sun [1996] to study the ionospheric dynamics of substorms. The use of the substorm model to provide the magnetospheric drivers needed by the ionospheric model has several advantages. First, the calculated convection and precipitation patterns not only are time-dependent, global, and self-consistent, but also contain small-scale substorm dynamical features, including sharp convection reversals, channeled precipitation and field-aligned currents, and fine auroral structures. Both the global-scale and small-scale substorm electrodynamic features in the ionosphere calculated by the substorm model are in good agreement with observations. These global patterns with small-scale substorm dynamical features are essential for more realistically simulating the ionospheric dynamics during substorms, and using them as magnetospheric drivers helps to fully utilize the capability of present global ionospheric models. These patterns also have a high spatial resolution (tens of kilometers) and a good temporal resolution (a few seconds), which are well in line with the resolutions of global ionospheric models.

Some preliminary results of this work have been presented in a previous paper [Schunk et al., 1997], where the focus was on the asymptotic features of the ionospheric plasma structures that occur when a "representative" substorm reaches its expansion maximum. In this paper, we present comprehensive modeling results of both the electrodynamic and plasma features of the ionospheric dynamics during a substorm, with the focus on the temporal and 3-D spatial variations.

2. Substorm and Ionospheric Models

The substorm model that we used to produce time-dependent convection and precipitation patterns in the ionosphere was based on a substorm model described by Zhu and Kan [1990], with the physical scenario closely following that proposed by Kan et al. [1988] and Kan and Sun [1996]. In this substorm model the growth phase is initiated by an enhanced global magnetoospheric convection that is driven by enhanced reconnection at the dayside magnetopause due to a southward turning of the interplanetary magnetic field. Alfvén waves are launched in association with the enhanced magnetoospheric convection. When the Alfvén waves arrive in the ionosphere, they can be partially reflected, and the features of the reflected waves depend on the conductivity in the ionosphere. At the same time, the precipitation associated with the Alfvén waves enhances the ionospheric conductivity, and the temporal change of the ionospheric conductivity launches secondary Alfvén waves toward the magnetosphere. These Alfvén waves provide the coupling between the ionosphere and magnetosphere during the substorm. The enhanced global magnetoospheric convection associated with a southward turning of the IMF not only drives the growth phase of the substorm, which is mainly a directly driven process, but also causes the thinning of the plasma sheet [Kan and Sun, 1996]. The plasma sheet thinning eventually leads to reconnection and dipolarization on the closed field lines of the plasma sheet, which is mainly an unloading process, and the observed localized enhanced convection and wedge-like field-aligned currents are produced from the reconnection. These localized convection and field-aligned currents are again carried by Alfvén waves, and the time when they arrive in the ionosphere represents the beginning of the expansion phase of the substorm. The substorm development in the ionosphere during the expansion phase is controlled by the M-I coupling processes, with the Alfvén waves associated with these localized convection and field-aligned currents as driving forces. In the above physical scenario, which is adopted in our model, the ionosphere plays an active role in the substorm development, and this is most apparent when the secondary Alfvén waves are launched from the ionosphere.

The basic mathematical formulation of the substorm model has been described by Zhu and Kan [1990]. Several improvements of the present substorm model over the previous M-I coupling models of substorms [Kan et al., 1988; Zhu and Kan, 1990; Kan and Sun, 1996] need to be listed here. In the previous models a constant ratio of Hall and Pedersen conductances was assumed. In reality, the hardness of the substorm auroral precipitation is highly variable in both space and time. The variation of precipitation hardness can lead to an enhanced ionospheric conductivity with different characteristics (Hall conductivity versus Pedersen conductivity), thereby leading to a different closure of the magnetoospheric currents in the ionosphere. Hence the assumption of a constant conductivity ratio was removed in the present substorm model and an energy-dependent ionization treatment for substorm auroral precipitation was included, in which the conductivity ratio is allowed to vary both spatially and temporally according to the hardness of the substorm auroral precipitation. Also, in the previous models the self-consistency between the quiet-time (presubstorm) ionospheric background convection and precipitation patterns was overlooked. In the present model, self-consistent background convection and precipitation patterns were obtained from an asymptotic solution of a time-dependent simulation. The self-consistent, quiet-time, background convection and precipitation patterns help to improve the self-consistency of the entire substorm simulation and prevent unrealistic sharp gradients during the substorm growth and expansion phases in the simulation.

One important strength of the present model and its base version [Zhu and Kan, 1990] over the other M-I coupling models [Kan et al., 1998; Kan and Sun, 1996] is the use of a fully time-dependent electron continuity equation for calculating the ionization caused by substorm auroral precipitation, instead of an algebraic relation for the field-aligned current intensity and Hall conductance that is not differentiable [Kan and Sun, 1996]. The significance of using such a time-dependent equation in the M-I coupling model of substorms is twofold. First, it substantially increases the temporal resolution of the model (from a few minutes to a few seconds). Second, it includes a new characteristic timescale in the substorm simulation, which is the recombination timescale of the ionospheric ionization process. This not only allows the interaction between two physical processes with different characteristic timescales in the model, one being the Alfvén wave propagation between the magnetosphere and ionosphere (timescale of a few minutes) and the other being the ionization process caused by precipitation (timescale of tens of seconds), but also allows the ionosphere to launch secondary Alfvén waves toward the magnetosphere. Such secondary Alfvén waves propagating from the ionosphere to the magnetosphere are generated by the temporally changing ionospheric conductivity, and these waves can be very strong at
the expansion onset since the precipitation is highly variable at that time. The ionosphere-generated secondary Alfvén waves are very important in the M-I coupling processes of substorms and represent the active role of the ionosphere in substorm dynamics.

The USU Time-Dependent Ionospheric Model (TDIM) is a multispecies (NO^+, O^+, N_2^+, O^-, N^-, He^+) model that is based on a numerical solution of the coupled continuity, momentum, and energy equations [Schunk, 1988; Sojka, 1989]. The TDIM is a Lagrange-Euler hybrid model in that the equations are solved as a function of altitude for horizontally convecting plasma flux tubes. The three-dimensional natures of the model are obtained by following numerous flux tubes in a given simulation. However, the TDIM requires several global inputs, with the primary ones being the atmospheric parameters and the magnetospheric convection and precipitation patterns. The global inputs adopted in this study are discussed in section 3.

3. Simulation of Ionospheric Dynamics during a Substorm

3.1. Specifications and Inputs

3.1.1. Specifications and inputs for the substorm model.

The ionospheric domain of the substorm model covers the magnetic latitudes >50° in the Northern Hemisphere. Initially, the quiet-time (presubstorm) ionospheric background conditions for the model were calculated by running the substorm model for a sufficiently long time to reach the asymptotic state. The ionospheric conductance, convection, and precipitation patterns that were obtained in this way are physically self-consistent and are shown in Figures 1a, 1b, and 1c, respectively. In the simulation the quiet-time (presubstorm) period is the period earlier than 1200 UT.

The substorm growth phase started at t=0 min (1200 UT), which is when the Alfvén waves associated with the enhanced magnetospheric convection was initiated at the dayside magnetopause reached the ionosphere. A two-cell convection pattern with a polar cap potential drop of -73 kV (shown in Figure 1d) was adopted for such an enhanced convection carried by the Alfvén waves. These global-scale Alfvén waves were the driving forces for the phase dynamic characteristics in the plasma sheet, which lasted -24 min. Note that since the ionospheric conductivity is finite and anisotropic, such an ionospheric-originated enhanced convection cannot be fully loaded on the ionosphere and can also be distorted. The enhanced convection actually loaded on the ionosphere at t=0 min (1200 UT), which is different from the convection pattern shown in Figure 1d, is self-consistently determined in the simulation by calculating the reflected Alfvén waves at the ionosphere. Since the energy source of the global-scale Alfvén waves is from the solar wind, the physical process during this period is mainly a directly driven process. At the end of the growth phase, the wedge-like field-aligned currents and localized enhanced convection were produced from the reconnection in the plasma sheet, and they were again carried by earthward propagating Alfvén waves. When these waves arrived in the ionosphere, the expansion phase started. Since the energy source for the waves carrying the wedge-like field-aligned currents and localized enhanced convection was from the plasma sheet, the physical process during the expansion phase in this simulation is mainly an unloading process. The simulation continued until t=35 min (1235 UT), which is when the substorm reached the expansion maximum. It should be noted that even though the driving forces for both the growth and expansion phases in this simulation were from the magnetosphere, the substorm features generated in the ionosphere were determined by the M-I coupling with Alfvén wave propagation, and the ionosphere plays an active role via both the reflected Alfvén waves and the ionosphere-generated secondary Alfvén waves.

In the simulation, various electrodynamical parameters were calculated from the substorm model, including convection, precipitation (energy flux and characteristic energy), field-aligned and horizontal currents, Hall and Pedersen conductances, and Joule heating rates. All these physical parameters are time-varying, with a resolution of 5 s, and are physically self-consistent.

3.1.2. Specifications and inputs for the ionospheric model.

To study the temporal and 3-D spatial features of plasma structures in the ionosphere during the substorm, we used the TDIM. To run the TDIM, both the neutral atmosphere and the magnetospheric convection and precipitation patterns are needed. In this simulation the MSIS atmospheric model was adopted, and the conditions chosen were near winter solstice (day 330) and low solar activity (F10.7 = 100). The thermospheric wind was obtained from the Hedin et al. [1991] empirical model.

Before the substorm simulation started, the TDIM was run for 24 hours using the quiet-time convection and precipitation patterns shown in Figure 1 as magnetospheric drivers. This procedure ensured that all quiet-time physical quantities in the TDIM are self-consistent and diurnally reproducible. Then, at t=0 min (1200 UT), the substorm model started to feed the TDIM time-varying substorm convection and precipitation (energy flux and characteristic energy) patterns every 30 s, which were used as the magnetospheric drivers for the ionospheric model during the substorm. These patterns were self-consistent, and more important, they contained the small-scale electrodynamical features that are in good agreement with observations and which the global MHD models are unable to produce. Figure 2 shows snapshots of two of the magnetospheric drivers for the TDIM: the energy flux of precipitating electrons and the magnitude of the convection electric field. In addition, Figure 2 shows snapshots of the time-varying Hall conductance pattern calculated by the substorm model. The growth phase of the substorm started at t=0 min (1200 UT), and the expansion phase started at around t=24 min (1224 UT). The expansion maximum was achieved at around t=35 min (1235 UT).

It can be seen from Figure 2 that at the end of the growth phase (1224 UT), the auroral oval has already undergone a significant poleward expansion in the evening-midnight sector (from 2000 to 2400 magnetic local time (MLT)). Then, during the expansion phase, the auroral oval breaks up, and structured precipitation and aurora quickly develop in this region. At the same time, the precipitation associated with the substorm aurora dramatically enhances the conductivity in the auroral breakup regions and the Hall conductance increases by a factor of 15, reaching 25 mho. The results show that before the substorm (1200 UT), the maximum value for the energy flux in the substorm aurora breakup region (75° latitude, 2100 MLT) is 0.3 erg cm^{-2} s^{-1}, while at the expansion maximum the value approaches 7 erg cm^{-2} s^{-1}. The patterns of the precipitation's characteristic energy (not shown) are qualitatively similar to the energy flux patterns, and the maximum characteristic energies in the aurora breakup region are 0.5 keV (presubstorm) and 7 keV (expansion maximum).

During the substorm the intensity of the convection electric field in the ionosphere also increases significantly owing to both
the enhanced global-scale convection that is initiated by the enhanced reconnection at the dayside magnetopause and the localized enhanced convection caused by the reconnection in the plasma sheet. The maximum values of the electric field in the substorm onset region are 5 mV m\(^{-1}\) (presubstorm) and 50 mV m\(^{-1}\) (expansion maximum). Correspondingly, the polar cap potential drop increases from 18 kV (presubstorm) to ~100 kV (expansion maximum). An important feature shown in Figure 2 is that during the substorm the regions where the precipitation and electric field maximize are not colocated. This feature leads to the spatially separated electron and ion hot spots during the substorm, which will be discussed in the following sections.

The outputs of the TDIM ionospheric model during the substorm were the electron and ion (NO\(^+\), O\(_2^+\), N\(_2^+\), O\(^+\), N\(^+\), He\(^+\)) densities and temperatures (\(T_e, T_{\parallel}, T_{\perp}\)) over the altitude range from 90 to 800 km and for all latitudes > 50° magnetic. Also, the model calculated the \(h_mF_2, n_mF_2\), total electron content, and drift velocities.

**3.2. Temporal Features of the Ionospheric Dynamics During a Substorm**

With the global pictures of the substorm shown in Figure 2 in mind, we now discuss the simulation results with the focus on the temporal features of the ionospheric dynamics in the substorm onset region.

Figure 3 shows snapshots of the temporal variations of the energy flux and the magnitude of the electric field in the substorm onset region (1800-0200 MLT, 55°-85° magnetic latitude). The snapshots start at 1200 UT (the beginning of the growth phase) and end at 1235 UT (the expansion maximum) with a 5 min interval. Before the substorm starts, there is a well-defined precipitation band stretching in the east-west direction with the center at ~67°. This quiet-time precipitation is the diffuse aurora precipitation and corresponds to the quiet-time auroral oval. When the substorm starts, the auroral oval gradually expands poleward during the growth phase. After the
substorm onset (around 1224 UT), structured precipitation quickly develops in the localized region around 75° and 2100 MLT, where the substorm aurora breaks up and the bulge-like aurora forms. The developed substorm aurora is highly structured, which corresponds to the channeled precipitation. In the aurora breakup region the energy flux increases from the quiet-time level of $\approx 0.3$ erg cm$^{-2}$ s$^{-1}$ to $\approx 1$ erg cm$^{-2}$ s$^{-1}$ at the end of the growth phase, then quickly reaches 7 erg cm$^{-2}$ s$^{-1}$ at the expansion maximum. Correspondingly, the maximum values of the characteristic energy in this region changes from 0.5 keV (1200 UT) to 1.8 keV (1224 UT) and then to 7 keV (1235 UT).

The strong precipitation mainly consists of energetic downward precipitating electrons, which are the carriers of the upward field-aligned currents. The model also calculated the time-varying field-aligned current distributions (not shown), and the patterns are qualitatively similar to those of the energy flux. Before the substorm the field-aligned current in the region where the substorm aurora will subsequently break up is mainly
Figure 3. Snapshots of the temporal variations of the energy flux and the magnitude of electric field in the substorm onset region.

Associated with the diffuse auroral precipitation, and its maximum value is only $\sim 0.1 \mu A \, m^{-2}$. Around the substorm onset it increases to $0.4 \mu A \, m^{-2}$ and then quickly reaches $2 \mu A \, m^{-2}$ at the expansion maximum. Associated with the channeled precipitation are the multiple upward-downward field-aligned current pairs. It is important to note that the scale size of these upward-downward current pairs or the channeled precipitation is $\leq 100 \text{ km}$, and such a characteristic spatial scale is not intrinsically contained in the magnetospheric drivers for the substorm model. We believe that it is the M-I coupling process, via the propagating Alfvén waves, that leads to the development of such small-scale structures. In the M-I coupling process the ionosphere plays an active role with the launching of secondary Alfvén waves, through which the characteristic temporal and spatial scales of the ionospheric condition are brought into the M-I coupling process.

The electric field patterns shown in Figure 3 indicate that during the substorm, there is a very sharp spatial gradient of electric field along the auroral oval, which changes from 5 to $50 \text{ mV m}^{-1}$ in a distance of only 1000 km. The regions where the
electric field and precipitation maximize are not colocated, but several regions where the electric fields minimize are well colocated with the strong precipitation regions (68°–77°, 2000–2200 MLT). This is because the strong substorm auroral precipitation greatly enhances the conductivity, which, in turn, reduces the electric field in these regions.

Figure 4 shows snapshots of the temporal variations of the Joule heating rate and Hall conductance. In the substorm aurora breakup region the maximum value of Joule heating rate increases from the quiet-time level of <0.2 erg cm\(^{-2}\) s\(^{-1}\) to ~4 erg cm\(^{-2}\) s\(^{-1}\) at the end of the growth phase and then increases to 11 erg cm\(^{-2}\) s\(^{-1}\) at the expansion maximum. It can be seen that when the substorm fully develops, the distributions of the Joule heating rate are highly structured. Comparing Figures 3 and 4, it is apparent that the structure in the Joule heating rate is not similar to that of either the precipitation or the electric field, and the regions where the three parameters maximize are not spatially colocated with each other. This can be explained by the fact that the Joule heating rate has a dependence on both the conductivity and electric field, while the precipitation and electric field are not.
connected to only one of these two physical quantities. In contrast, the structure in the Hall conductance shown in Figure 4 is quantitatively similar to that seen in the precipitation pattern. This is because the hardness of the substorm auroral precipitation is in the several keV range and such precipitation most effectively enhances the Hall conductance, leading to the similarity between the structures of these two physical quantities. In the substorm aurora breakup region, the maximum value of the Hall conductance increases from the quiet-time level of 1 mho to 9 mho at the end of the growth phase and then increases to 25 mho at the expansion maximum.

As mentioned in the preceding sections, the improved substorm model removed the assumption of a constant ratio between the Hall and Pedersen conductances and allowed them to change independently with the precipitation. Our simulation results show that during the substorm, the enhancement of the Pedersen conductance in the substorm onset region is far less significant than that of the Hall conductance. The maximum value of the Pedersen conductance in this region increases from the background level of 1 mho to 6.9 mho at the expansion maximum, which is a much smaller percentage change (a factor of 7) compared to that of the Hall conductance (a factor of 15). Also, the enhanced Pedersen conductance in the substorm onset region is relatively uniform and much less structured than the Hall conductance. The different features of the enhanced Pedersen and Hall conductances are apparently determined by the hardness of the structured substorm auroral precipitation, which is in the several keV range.

The relatively uniform enhanced Pedersen conductance in the substorm aurora breakup region means that the highly structured magnetospheric field-aligned currents in this region cannot be closed by the Pedersen currents in the ionosphere. Our simulation results indicate that the small-scale structured field-aligned currents in the aurora breakup region are mainly closed by the Hall currents. The structure in the Hall conductance is very similar to that associated with the small-scale field-aligned currents. This current closure feature in the aurora breakup region is different from that in the large-scale field-aligned current regions, where the field-aligned currents are mainly closed by the ionospheric Pedersen currents.

Complementing the simulation results of the ionospheric electrodynamics from the M-I substorm model, the USU Time-Dependent Ionospheric Model (TDIM) was used to calculate the substorm variations of a number of plasma parameters, including the electron and ion densities, temperatures ($T_e$, $T_i$, $T_{iL}$), $h_mF_2$, and $n_mF_2$, drift velocities, and total electron content (TEC), over the altitude range from 90 to 800 km and for all latitudes $>50^\circ$ magnetic. Again, we will focus on the temporal features of the ionospheric plasma structures in the substorm onset region when we present the simulation results from the TDIM in this section.

Figure 5 shows the temporal variations of electron temperature $T_e$ at an altitude of 600 km. During the growth phase the electron temperature of the plasma in the regions poleward of the quiet-time auroral oval is gradually elevated from $<1000$ K to $2000$ K, with a relatively uniform distribution. During the expansion phase, temperature structures quickly develop, and a small-scale $T_e$ "hot spot," with a temperature of up to 6000 K, appears in the region where the substorm aurora breaks up (75° and 2100 MLT). This large $T_e$ increase is caused by the auroral precipitation that is associated with the strong upward field-aligned currents in the region.

The substorm not only significantly elevates the electron temperature in the substorm onset region but also greatly increases the ion temperature. The peak ion heating occurs near 200 km and is caused by the ion-neutral frictional interactions
During the substorm, the plasma (or electron) density distribution in the ionosphere also changes significantly. Figure 7 shows the temporal variations of $N_e$ at 160 and 800 km altitudes. The increases of $N_e$ in the $E$ region (160 km) follow the patterns of the precipitation (Figure 3), but in an extended region near midnight, the $N_e$ at 800 km actually decreases when the substorm develops. The simulation results show that in this region, there exists a large-scale downward $E\times B$ drift. It is this downward drift that causes the lowering of the ionosphere and leads to the decrease of $N_e$ at altitudes higher than 300 km, which is opposite to the situation in the $E$ region where $N_e$ increases owing to hard auroral precipitation.

The lowering of the ionosphere caused by the downward $E\times B$ drift also affects other ionospheric parameters. Figure 8 shows snapshots of the temporal variations of $h_mF_2$ and TEC. The results indicate that $h_mF_2$ in the substorm onset region decreases from 280 km (presubstorm) to 220 km (expansion maximum). In addition, the TEC also decreases in an extended region, except the region where the substorm aurora breaks up, as shown in Figure 8b. The decrease of the TEC during the substorm is again due to the lowering of the ionosphere and the consequent increased recombination.

Our simulation also shows that during the substorm there are substantial composition changes. The most significant composition change is the change of $O^+ \rightarrow NO^+$. In a large region near midnight, the NO$^+$ density increases significantly during the substorm. The increased NO$^+$ comes from the composition change of $O^+ \rightarrow NO^+$. The $O^+ \rightarrow NO^+$ conversion is caused by the elevated $T_i$ owing to the energy dependence of the $O^+ + N_2 \rightarrow NO^+ + N$ reaction rate [Schunk et al., 1975] and the lowering of the ionosphere.

### 3.3. Altitude Features of the Ionospheric Dynamics During a Substorm

In this section we present and discuss the altitude features of the plasma structures during the substorm. Specifically, we show altitude profiles of the various plasma parameters in three regions with unique characteristics, which are the regions with the strongest upward field-aligned current ($T_i$ hot spot), the strongest...
Figure 7. Snapshots of the temporal variations of the electron densities at the altitudes of 160 and 800 km.
Figure 8. Snapshots of the temporal variations of $h_mF_2$ and the total electron content (TEC).
downward field-aligned current, and the strongest electric field ($T_e$ hot spot).

### 3.3.1. Strong upward current region (75°, 2100 MLT).

This is the region where the substorm aurora breaks up. At the substorm expansion maximum the intensity of the upward field-aligned current in this region reaches 2 $\mu$A m$^{-2}$. Correspondingly, there is a very strong precipitation with a characteristic energy of 7 keV and an energy flux of 7 erg cm$^{-2}$ s$^{-1}$.

Figure 9 shows altitude profiles of $T_i$, $T_e$, NO$^+$, O$^+$, and $N_e$ at 75° and 2100 MLT for presubstorm (1200 UT, curve a) and expansion maximum (1235 UT, curve b), respectively. In this region the electron temperature increases significantly, with a larger increase at the higher altitudes. Such a significant increase of $T_e$ is obviously caused by hard electron precipitation in the region. $T_i$ also has a noticeable increase in the region, and the change is nearly uniform at all altitudes. Since the electric field in this region is relatively weak, owing to the existence of a high conductance, the increase of $T_i$ is mainly caused by the coupling of $T_i$ and $T_e$ through collisions between the ions and scattering electrons, which are initially produced by the auroral precipitation.

In section 3.2 we showed that there is a lowering of the ionosphere in the substorm onset region, which is caused by downward ExB drifts. The lowering of the ionosphere can be clearly seen in the altitude profiles of $N_e$, where the F region peak of $N_e$ almost disappears during the substorm. In contrast, the E region peak $N_e$ increases significantly, which is mainly due to the hard auroral precipitation in the region. In addition, the elevated $T_i$ and the downward ExB drifts in the region cause the O$^+$ $\rightarrow$ NO$^+$ conversion, which in turn leads to a lowering of the O$^+$ peak height, as shown in Figure 9.

### 3.3.2. Strong downward current region (72°, 2100 MLT).

The results shown in Figure 2 indicate that the substorm aurora and auroral precipitation are highly structured. The structured aurora corresponds to the structured field-aligned currents or the upward-downward current pairs, and the structured electric fields. These small-scale substorm electrodynamic features are very important for the development of the ionospheric plasma structures and for more realistically simulating the ionospheric response to substorms. To quantitatively explore the effects of these small-scale electrodynamic features on the plasma structures, we examined the altitude profiles of plasma parameters in a region with a strong "upward" current (72°, 2100 MLT) and compared these to the plasma features in the substorm aurora breakup region (strong "upward" current) shown in Figure 9. The intensity of the downward current in the region is $\sim$1 $\mu$A m$^{-2}$ at the time when the substorm reaches the expansion maximum and the main carriers of the current are upward moving thermal electrons.

Figure 10 shows the altitude profiles of $T_i$, $T_e$, NO$^+$, O$^+$, and $N_e$ in the downward current region. It can be seen that the changes of these plasma parameters in this region due to the substorm are very small compared to those in the substorm aurora breakup region, which is only 300 km away. The ability to resolve these small-scale channeled plasma structures with sharp horizontal gradients during the substorm is made possible by the unique capabilities of the substorm model and the TDIM used in this modeling study. These small-scale plasma structures are important to the study of the substorm dynamics in the ionosphere. The reason for these sharp small-scale plasma structures being sustained during the substorm is not only the developed channeled electrodynamic structures but also because the convection is not efficient in smoothing the plasma structures since the electric field is basically perpendicular to the channeled structures. These small-scale electrodynamic and plasma structures during substorms resulting from the simulation may provide useful information as well as cautions for the interpretation of various observational data.

### 3.3.3. Strong electric field region (73°, 2300 MLT).

In this region the electric field gets as high as 50 mV m$^{-1}$ at the substorm expansion maximum. As discussed in section 3.2, the strong electric field in this region increases the ion-neutral frictional interactions and leads to an ion hot spot.

Figure 11 shows the altitude profiles of $T_i$, $T_e$, NO$^+$, O$^+$, and $N_e$ for the presubstorm and substorm maximum in this specific region. Comparing the altitude profile of $T_i$ in this strong electric field region near midnight to that in the substorm aurora breakup region shown in Figure 9, it can be seen that the features of the two are quite different. The increase of $T_i$ in the aurora breakup region is nearly uniform at all altitudes, while the increase of $T_i$ shown in Figure 11 has a maximum in the E region. The different features of the $T_i$ altitude profiles are due to the different ion heating mechanisms in these two regions. In the strong electric field region, $T_i$ is increased by the enhanced ion-neutral frictional interaction associated with the strong electric field, and such an interaction is strongest in the E region where the neutral density is high. In the substorm aurora breakup region the auroral precipitation elevates $T_e$, and $T_i$ is increased by the collisions between ions and scattering electrons, which leads to a uniform increase of $T_i$ at all altitudes.

These physical explanations are further supported by the simulation results of the altitude profiles of $T_i$ shown in Figure 11. Even though $T_i$ is significantly enhanced in the region, the $T_e$ distribution at the substorm expansion maximum is almost the same as the presubstorm $T_e$ distribution. This is because strong precipitation does not occur in this region, and it leads to the lack of a large number of scattering electrons. The lack of scattering electrons reduces the heat exchange between ions and electrons and leaves $T_e$ almost unchanged even though $T_i$ is higher than $T_e$ in the E region.

Comparing the altitudes profiles of plasma parameters shown in Figures 9 and 11, it can be seen that the features of the lowerings of the ionosphere and the O$^+$ peak height, as well as the O$^+$ $\rightarrow$ NO$^+$ conversion, occur in both regions. However, in the aurora breakup region the NO$^+$ density is noticeably higher than that in the $T_i$ hot spot. Also, the O$^+$ and $N_e$ at higher altitudes increase during the substorm instead of decreasing as in the $T_i$ hot spot. Such a difference of the plasma altitude distributions is obviously due to the existence of strong precipitation in the aurora breakup region, which enhances the ionization process in the ionosphere.

### 4. Discussion

The ionospheric evolution during the substorm that is shown in Figures 2-8 represents dynamics and structuring caused by the M-I coupling processes in the model. Although both the growth and expansion phases were initiated in the magnetosphere, the enhanced convection in both cases was still structureless and global. Hence none of the detailed structures shown in these figures corresponds to a structure in the initial drivers or imposed energy terms. As an example, the electron temperature hot spot region, which also corresponds to the enhanced auroral precipitation, Hall conductance, and electron density at 160 km, is self-consistently generated in the simulation. This region has a
The question of how important this structure is can be tested, because the time-evolving Joule heating patterns generated by the coupled M-I and TDIM models can be fed into the thermosphere, thermosphere-ionosphere coupled model.

The purpose of this study is not to model a specific substorm; instead, we tried to theoretically study the ionospheric electrodynamics and plasma dynamics of a representative substorm. More specifically, we tried to study the small-scale electrodynamical and plasma structures of substorms in a self-consistent fashion, which was made possible by combining the strengths of two developed models. Such a theoretical model study, which focuses on small-scale substorm ionospheric features while keeping the self-consistency of global-scale electrodynamical patterns, can complement the global-scale MHD substorm simulations [e.g., Sojka et al., 1997] in which the small-scale substorm dynamics cannot be simulated.

It should also be noted that this work is not intended to model all the typical features of a substorm, and, actually, to date, no single substorm model can fulfill such a task [Hones, 1979; McPherron, 1970; Rostoker and Eastman, 1987; Kan et al., 1988; Zhu and Kan, 1990; Lui, 1979; Goertz and Smith, 1989; Roux, 1985; Lyons, 1995]. It has been pointed out by both Lui [1991] and Rostoker [1996] that while each substorm model is justifiable on the basis of certain features of substorm activity, it
is very possible that the ultimate substorm model will contain features of most, if not all, of those models. For the M-I coupling substorm model used in this study, a major weakness is the lack of enhanced westward electrojet in the morning sector during the growth phase of substorm. A more sophisticated treatment of the ionization processes associated with precipitating ions and thermal electrons is needed in the regions to further improve the M-I coupling substorm model. Nevertheless, the present model [Zhu and Kan, 1990; this paper] successfully reproduces a number of important features of substorm activity, including substorm current wedge in the premidnight regions, poleward and westward expansion of substorm aurora, substantially enhanced eastward and westward electrojets in the evening-premidnight sector, typical convection distortion near Harang discontinuity, and various small-scale electrodynamic features.

A number of modeled small-scale dynamic features of substorms, which is the focus of this paper, are qualitatively consistent with the observed features of substorms. For example, a dislocation of strong localized electric field and electron precipitation and the small-scale structured precipitation and field-aligned currents in the aurora onset region were observed by Freja satellite [Marklund et al., 1998]. A significant increase of the Hall and Pedersen conductance ratio in the aurora breakup region was found by the high time resolution measurements of EISCAT [Lester et al., 1996]. Detailed one-to-one qualitative and quantitative comparisons between the modeled small-scale substorm dynamic features and the observed ones and model study of specific substorm events will be very useful for validating the models and constraining the model inputs and will certainly be the future tasks for our study of small-scale substorm dynamics, but they are beyond the scope of this paper.

5. Summary

A comprehensive theoretical model study of ionospheric dynamics during a substorm has been conducted in which both the substorm electrodynamical and plasma structure features in the ionosphere were studied. The substorm study was accomplished by using two developed global models. One is an improved substorm model based on the work of Zhu and Kan [1990], and the other is the USU Time-Dependent Ionospheric Model (TDIM) [Schunk, 1988; Sojka, 1989]. The substorm electrodynamical parameters calculated by the substorm model not only are time-dependent, global, and self-consistent but also contain small-scale substorm dynamical features, including channeled precipitation, field-aligned current pairs, and fine auroral structures. With the self-consistent global convection and precipitation patterns containing the small-scale substorm
dynamical features as drivers, the TDIM was used to simulate the substorm plasma dynamics, with the focus on the effects of the small-scale substorm electrodynamics on the ionosphere and the development of small-scale substorm plasma structures. These small-scale electrodynamical and plasma structures are very important for more realistically studying the ionospheric dynamics during substorms. The present simulation work uniquely complements the previous global modeling studies of substorm ionospheric plasma structures using the observation-based or global magnetospheric MHD model-based drivers, in which either the adopted magnetospheric drivers were not self-consistent or the spatial resolution was too low to produce small-scale substorm features.

The major results from this simulation study of the substorm ionospheric dynamics are summarized as follows:

1. Small-scale structured aurora and precipitation, as well as channeled field-aligned currents, develop in the substorm aurora breakup region during the expansion phase. For the substorm simulated in this study, which is driven by an enhanced global-scale two-cell convection with a polar cap potential drop of ~73 kV, the maximum values for the energy flux, characteristic energy, and upward field-aligned currents in the aurora breakup region are around 7 erg cm$^{-2}$, 7 keV, and 2 µA m$^{-2}$, respectively.

2. The scale size of the channeled precipitation or the upward-downward current pairs is <100 km, and such a characteristic spatial scale is not intrinsically contained in the magnetospheric drivers of the substorm model. It is the M-I coupling process via the propagating Alfven waves, in which the temporal and spatial scales of the ionospheric conditions are added in, that leads to the development of such small-scale structures.

3. Owing to the hard precipitation, the Hall conductance in the substorm aurora breakup region increases by a factor of 15 for the simulated substorm, reaching 25 mho at the expansion maximum, and it is highly structured. In contrast, the Pedersen conductance increases only by a factor of 7, reaching 6.9 mho in the same region, and it is relatively uniform. The different features of the enhanced Hall and Pedersen conductances indicate that the magnetospheric field-aligned currents in the aurora breakup region are mainly closed by the Hall currents, which is different from that in the large-scale field-aligned current regions where the field-aligned currents are mainly closed by the Pedersen currents.

4. The regions with the strong precipitation and electric field are spatially separated by a distance of about 1000 km. Between the two regions, there exists a region with strong Joule heating. The structure of the small-scale regions where the electric fields

Figure 11. Altitude profiles of the ion and electron temperatures and the NO$^+$, O$^+$, and electron densities in the region with strong electric fields (73°, 2300 MLT) for (a) the presubstorm (1200 UT) and (b) the substorm expansion maximum (1235 UT).
minimize is very similar to the precipitation structure.

5. Corresponding to the regions with the strong precipitation and electric fields, there are a $T_i$ hot spot (in the aurora breakup region) and a $T_e$ hot spot (near the midnight), where $T_e$ (600 km) increases to 6000 K and $T_i$ (200 km) increases to 2000 K, respectively.

6. There is a second $T_i$ hot spot, and it is located in the aurora breakup region. The altitude variation of the $T_i$ increase in the aurora breakup region is almost uniform, while that in the region of strong electric fields near midnight has a peak increase in the $E$ region. The heating for the former is caused by the collisions between ions and the scattering electrons produced by the hard auroral precipitation, and the heating mechanism for the latter is the enhanced ion-neutral frictional interaction associated with strong electric fields.

7. During the substorm, there is a significant lowering of the ionosphere in the large substorm onset region owning to the enhanced ion-neutral frictional interaction associated with auroral precipitation, and the heating mechanism for the latter is of strong electric fields near midnight has a peak increase in the $E$ region.

8. As a consequence of both the lowering of the ionosphere and the ionization associated with substorm auroral precipitation, in the substorm onset region the substorm changes of $N_e$ at altitudes lower than 300 km and at altitudes higher than 300 km show opposite temporal variations. The former increases while the latter decreases. This opposite variation of $N_e$ during the substorm does not hold in the aurora breakup region, where the ionization associated with auroral precipitation surpasses the effect of the lowering of the ionosphere.

9. The most significant composition change in the substorm onset region is the change of $O^+ \rightarrow NO^+$. The $O^+ \rightarrow NO^+$ conversion is caused by the elevated $T_i$ and the lowering of the ionosphere, which lead to a significant NO$^+$ increase in the region. Correspondingly, there is a significant lowering of the O$^+$ peak height.

These small-scale electrodynamic and plasma structures in the ionosphere during substorms have significant theoretical and observational importance. They can not only help to understand the multiscale ionospheric responses to substorms and the active roles played by the ionosphere but also provide testable theoretical substorm predictions as well as cautions for the interpretation of various substorm observational data.

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