Driving a physical ionospheric model with a magnetospheric MHD model

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Abstract. This is the first study in which a physical ionospheric model (time-dependent ionospheric model (TDIM)) has been driven through a substorm using self-consistent magnetospheric convection electric field and auroral electron precipitation inputs. Both of these were generated from a simulation of a real substorm event using the MHD model [Fedder et al., 1995b]. Interplanetary magnetic field (IMF) data were available for 1.5 hours until the substorm breakup. Hence the substorm growth and expansion dynamics is captured in a 1.5-hour time period. As a reference against which to compare this TDIM substorm simulation, a typical climatological TDIM simulation was carried out using standard statistical representations of the convection electric field and auroral oval. Note that these statistical representations are driven by the $K_p$ index. This is a 3-hour index, yet the substorm growth and expansion occurs in 1.5 hours. Hence a static convection electric field and auroral oval are used for the TDIM reference simulation. From the comparison of these two simulations, we find, as expected, the $E$ region densities are different. However, these differences lead to factors of 2-4 differences in the integrated Hall and Pedersen conductivities. These conductivities, in turn, are crucial as an ionospheric boundary condition for magnetospheric MHD modeling. The $F$ region spatial and temporal responses are complex and exhibit large differences, from tens of percents to factors of 4 in density and up to $\pm 70$ km in $h_mF_2$. These differences are all larger than typical experimental uncertainties. The dayside and cusp variabilities are very sensitive to the convection pattern and are not well correlated to magnetic indices, such as the 3-hourly $K_p$ index. In the polar cap, the differences in the location of the tongues of ionization and the polar holes readily lead to factors of 2-4 in local density differences. Differences in the locations of “boundaries” in the plasma convection and auroral precipitation lead to large differences in the local $F$ region densities and in the locations of strong density gradients, both of which are relevant to space weather applications.

1. Introduction

It is well known that changes in the solar wind dynamic pressure and the interplanetary magnetic field (IMF) have a dramatic effect on the flow of mass, momentum, and energy in the magnetosphere. It is also well known that the ionosphere is strongly coupled to the magnetosphere via convection electric fields, particle precipitation, and field-aligned currents. These magnetospheric processes act to induce numerous ionospheric effects, including a large-scale horizontal motion at high latitudes, enhanced electron densities, atomic-to-molecular ion composition changes, modifications in $h_mF_2$, elevated electron and ion temperatures, and plasma upwelling events. The changes in the ionosphere then affect the magnetospheric processes through conductivity changes and wind-induced dynamo electric fields. Ultimately, a complete understanding of the dynamics in each region can only be achieved when a model of the coupled magnetosphere-ionosphere system is developed. To date, however, the main focus has been on modeling the two regions separately, with the global magnetosphere typically described by time-dependent magnetohydrodynamic (MHD) models [Fedder et al., 1995a; Walker and Ogino, 1989; Ogino et al., 1986] and the global ionosphere described by time-dependent diffusion formulations [Schunk, 1988; Sojka, 1989; Fuller-Rowell et al., 1988; Roble et al., 1988; Anderson et al., 1996]. Usually, when a given region is simulated, the coupling to the adjacent region is described with the aid of relatively simple parameterizations, empirical inputs, or measurements.

In a first step toward developing a coupled model of the magnetosphere-ionosphere system, the output from an MHD model of the global magnetosphere [Fedder and Lyon, 1987, 1995; Fedder et al., 1995b] was used to drive a global time-dependent ionospheric model (TDIM) [Schunk, 1988; Sojka, 1989]. The emphasis of the study was on both the difficulties
associated with the coupling of the two different models and the improvements achieved as a result of this first step in model coupling. The additional feedback of the ionosphere on the magnetosphere was not considered in this study. Nevertheless, the first step in model coupling is by no means a simple matter of numerical interpolating or smoothing.

Inherently, this "joint" magnetosphere-ionosphere model is a hybrid of quite different formulations: MHD and transport. As will be discussed, such a hybrid has several inherent limitations. The interface is demonstrated for a specific substorm that had been successfully modeled by the magnetospheric MHD model [Fedder et al., 1995b]. A glimpse of the potential improvement for the ionosphere is obtained by realizing that typical ionosphere-thermosphere models use a 3-hourly $K_p$ index to drive their magnetospheric electric field and auroral precipitation empirical inputs, yet this substorm simulation lasted only 1.5 hours (the entire dynamics is within a single $K_p$ value!). The use of observations that have a higher time resolution as inputs to the ionosphere-thermosphere system are developing, but at this time that approach lacks coupling between the inputs and usually the precipitation is defined by adjusted empirical models.

In the following two sections, the TDIM and MHD models are briefly reviewed. This is followed by a discussion of how the interface is carried out. The results of simulating a substorm with the interfaced MHD/TDIM model are discussed in section 6. This is clearly only a first step, and indeed, the specific substorm is chosen simply because of its "availability." We also preview a subsequent study in which interfaced model results will be compared with observations, with the goal being a validation of the first step in model coupling.

2. Ionospheric Model

The USU (Utah State University) TDIM ionospheric model was initially developed as a midlatitude, multi-ion ($NO^+$, $O_2^+$, $N_2^+$, 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 simplified ion energy equation was also added, which was based on the assumption that local heating and cooling processes dominate (valid below 500 km). Flux tubes of plasma were followed as they moved in response to the convection electric fields. 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 Rea [1980].

The addition of plasma convection and particle precipitation models is described by Sojka et al. [1981a, b]. Schunk and Sojka [1982] extended the ionospheric model to include ion thermal conduction and diffusion thermal heat flow. Also, the electron energy equation was included by Schunk et al. [1986], and consequently, the electron temperature is now rigorously calculated at all altitudes. The theoretical development of the TDIM is described by Schunk [1988], while comparisons with observations are discussed by Sojka [1989].

In addition to the physical processes built into the model, the TDIM requires several inputs. The magnetospheric inputs for the TDIM are the auroral oval and convection electric field. Typically, the auroral electron precipitation has been obtained from the Hardy et al. [1987] model, and the convection has been obtained from the Heppner and Maynard [1987] models. The MSIS-86 model is used to represent the neutral atmosphere [Hedin, 1987], while the neutral wind is represented by the Hedin et al. [1991] HWM 90 model.

In this study, output from the Naval Research Lab (NRL) MHD magnetospheric model is used to drive the TDIM. Hence the question of interface is reduced to matching the magnetospheric convection and precipitation to the TDIM inputs. Of note is that neither of these inputs or outputs are based on regular grids. The TDIM uses a Lagrangian technique, where plasma flux tubes are followed as they move through the neutral gas. Hence the TDIM requires electric field and electron precipitation inputs at arbitrary locations within the high-latitude ionosphere. Normally, the high-latitude ionosphere is defined as magnetic dipole latitudes poleward of 40° (occasionally poleward of 50°). This lower latitude is determined by the requirement that the $F$ region must be corotating at this most equatorward location. Consequently, no boundary condition needs to be developed for $F$ region plasma leaving or entering the model at the equatorward boundary. Typically, this latitude would be several degrees equatorward of the equatorial edge of the diffuse auroral precipitation at midnight, which depends strongly on the level of geomagnetic activity [Gussenhoven et al., 1983]. In addition to the spatial requirements, there are also timing requirements. As will be shown in section 5, this is not a concern for the simple interface scenario considered here. The TDIM solves the continuity, momentum, and energy equations dynamically with variable time steps that are determined by solar and geophysical conditions. During substorm activity, the time step could be as short as 10 s, but more typically it is of the order of tens of seconds, and it increases to minutes at corotating midlatitude locations during quiet geomagnetic conditions. These time steps are longer than those used in an MHD magnetospheric simulation. The details of interfacing the two models are discussed in section 4.

3. Magnetospheric Model

The NRL MHD model of the magnetosphere has been described in detail by Fedder and Lyon [1995] and Fedder et al. [1995a]. This model solves the ideal MHD equations for the solar wind and the outer magnetosphere (beyond 3.5 $R_E$). A nonorthogonal adapted mesh is used, which maximizes the spatial resolution at the low magnetopause, in the ionosphere, and in the geomagnetic tail. By using a time step of about 1 s, the model is able to describe, unambiguously, the propagation of fast waves on the mesh. Fedder and Lyon [1987] have shown that the model simulates the important process of magnetic merging in such a way that the reconnection rate is determined by the physical boundary conditions, namely, the solar wind and the conducting ionosphere.

Of specific relevance to this study is the question of how the MHD model's inner boundary at 3.5 $R_E$ is determined. Fedder et al. [1995a] and prior researchers matched the inner boundary to a line-tying ionosphere, in the sense of Coroniti and Kennel [1973] and used a uniform conductance of 5 mhos. A more realistic inner boundary condition was developed by Fedder et al. [1995b], in which the ionospheric conductance is a parameterized empirical model of both the solar EUV and auroral precipitation ionization sources. The procedure
involves using parameters in the innermost MHD mesh points to compute the field-aligned electric potential energy and the field-aligned currents. The major improvement resulting from these parameters is that a dynamic auroral conductance is obtained. The basic difficulties of self-consistently matching an ionosphere to the inner boundary of an ideal MHD model is extensively discussed by Goodman [1995], who also sets up the detailed mapping transformations. Fedder et al. [1995b] demonstrate that in order to obtain the auroral dynamics observed by the Viking satellite and the ionospheric currents inferred from the auroral A indices, the parameter selection for these ionospheric-MHD inner boundary empirical algorithms is of key importance. The resulting electric field and auroral electron precipitation from Fedder et al. [1995b] is used as the ionospheric driver for the simulations presented in section 6.

4. Interfacing the MHD Magnetosphere and TDIM Models

The MHD magnetosphere model has been used to simulate a substorm whose expansion onset occurred at 1132 UT on October 19, 1986 [Fedder et al., 1995b]. During the period 1010-1200 UT, IMF data were available from IMP 8, and these data were used to drive the MHD model. Hence, at each time step (~1 s) the MHD model calculates the electric potential distribution on the inner boundary at 3.5 RE, as well as the auroral electron energy flux and average energy. These distributions are available as data fields mapped down to the ionosphere. Figure 1 shows, geometrically: the scale sizes of the MHD model, its inner boundary, and the mapping region from the inner boundary to the ionosphere, which in turn is simulated by the TDIM.

To interface the output fields from the MHD model to the TDIM, an interpolation routine is used. This routine is a bicubic spline interpolation based upon the MHD ionospheric mesh. Figure 2 (right half of the polar dial plot) shows the MHD ionospheric mesh points. At the pole these mesh cells are approximately 300 km × 300 km in the ionosphere, whereas at lower latitudes the resolution improves to almost 100 km × 100 km. In contrast, the left side of Figure 2 shows two regular TDIM grids in the polar projection. The coarser of these two is an output grid suitable for TDIM climatology simulations, while the higher-resolution one is used for TDIM weather simulations. These two grids have approximately 250 km × 250 km and 80 km × 80 km resolutions, respectively. As noted earlier, the TDIM uses a Lagrangian scheme; that is, individual plasma flux tubes are followed in the magnetic latitude-MLT frame. Therefore, at arbitrary positions the magnetospheric electric potential, precipitating electron energy flux, and precipitating electron average energy are needed; this is achieved using the bicubic spline interpolation.

In comparing the MHD mesh and TDIM grids in Figure 2, concern may arise at the lowest latitudes where no MHD mesh points exist. From Figure 1, these locations correspond to the innermost closed, and presumably dipolar, field lines. In this region the assumption is made that the plasma is corotating and that no auroral precipitation is present. This then raises the question of how the auroral precipitation is generated by...
the MHD code. Fedder et al. [1995b] discuss this extensively and show how they convert the MHD field-aligned currents into auroral conductances, electron energy flux, and average energy. These conversions rely heavily on empirical relationships between the parameters, and the relationships adopted are primarily from the work of Robinson et al. [1987]. In addition, the conversion scheme leaves at least two adjustable parameters. Hence this MHD representation of auroral precipitation is at an early stage and is in fact an area in which coupled magnetospheric-ionospheric studies will provide validation for the scheme. Other independent empirical data do establish where the equatorward edge of the diffuse electron precipitation lies as a function of local time and geomagnetic activity [Gussenhoven et al., 1983]. For the period of interest the $K_p$ was 4, which implies that the midnight equatorward boundary should lie at 60ø with a standard deviation of about ±2ø; see Figure 4a of Gussenhoven et al. [1983]. From Figure 2, it can be seen that at midnight the 60ø ±2ø region is almost reached by the MHD mesh. At all other local times, the mesh will encompass the equatorward edge, since the "oval" equatorward edge is at higher latitudes.

The question of how well the electric potential is handled at the equatorward boundary is more complex. Magnetospheric electric fields can penetrate to lower latitudes, but usually a ring current shielding is assumed to be operating to ensure that corotation dominates at middle and low latitudes. For a substorm simulation, however, this may not be valid, since the ring current shielding has a time constant similar to the substorm expansion phase (30 min). Hence the lower boundary (ring current) will be dynamically adjusting to the changing magnetospheric electric field. For this first study, the details of this ring current shielding issue are beyond the capability of either model and are deferred to future studies. The assumption is made that the lowest latitudes of the magnetospheric mesh are equipotential, and hence corotation is dominant in the ionosphere at this boundary.

5. The Ionospheric Substorm

This TDIM substorm simulation is the first of its kind in that the auroral and electric field dynamics are synchronized in a physical self-consistent manner via the MHD simulation. In all prior ionospheric studies, this self-consistency was not achieved. Sojka and Schunk [1983] simulated storms by varying a $K_p$ index that controlled empirical models of the electric fields and precipitation. Sojka et al. [1989, 1992] used DE 1 auroral images to specify the auroral dynamics but had to resort to an empirical electric field. The present-day use of high-time-resolution assimilated mapping of ionospheric electrodynamics (AMIE) convection maps [Knipp et al., 1993] lack an equivalent evolution for the auroral precipitation. In such studies it was generally accepted that the lack of synchronization of electric field and precipitation can lead to potentially large differences between the real and modeled ionosphere. Sojka et al. [1992] demonstrated and discussed this issue at length.

Figure 3 shows the cross-tail polar cap potential difference between the maximum and minimum potential value in the high-latitude pattern according to the MHD simulation (solid curve) during the period of study, October 19, 1986. The dashed line represents the cross-tail potential associated with a Heppner and Maynard [1987] DE pattern for a $K_p = 4$, the appropriate value for this substorm interval. Prior to the beginning of the substorm expansion phase at 1125 UT, the two potentials are comparable in magnitude. However, as will be shown, this does not mean that the convection patterns are similar. During the main phase of the substorm, the polar cap potential increases from 60 to 185 kV. The substorm simulation ends at 1200 UT, but this is only because the IMP 8 data do not extend beyond this time.

Figure 4 shows a series of MHD convection patterns and the time-averaged Heppner-Maynard DE pattern that applied to the entire period. Before 1125 UT, the MHD electric field pattern
Figure 3. Time evolution of the cross-tail potential difference $\Phi$ according to the MHD simulation. For comparison the dotted line shows the value of $\Phi$ appropriate for $K_p = 4$.

is a very asymmetric two-cell pattern, unlike the conventional well-defined two-cell pattern of the Heppner-Maynard empirical model. This MHD convection is consistent with the IMP 8 IMF data at that time. After 1125 UT, the substorm MHD electric field pattern becomes a strong two-cell pattern, which is again consistent with the southward IMF observed by IMP 8. Fedder et al. [1995b] show the IMP 8 data and discuss the evolution of the auroral oval in detail; hence it is not repeated here.

Figure 5 shows the integrated auroral electron energy flux according to the MHD electron precipitation patterns at each time step during the study period (solid curve). The dashed line is the integrated energy flux from the Hardy et al. [1987] statistical precipitation model for $K_p = 4$. As with the cross-tail potential, the static quantity (the $K_p = 4$ empirical model value) is slightly higher prior to the substorm, but once the substorm begins at 1125 UT, the MHD model's integrated energy flux increases rapidly and exceeds the static value by more than a factor of 2.

The distributions of auroral electron precipitation are also different. Figure 6 shows the Hardy et al. [1987] $K_p = 4$ energy flux (left panel) in the same polar MLT-magnetic latitude format as used in Figure 4. Three snapshots of the MHD electron precipitation are also shown in the right column of Figure 6, and they correspond to the three convection patterns in Figure 4. Although Figure 5 indicates that the integrated energy flux obtained by the time-evolving MHD and static Hardy et al. models are comparable in magnitude, the distribution of the energy flux is quite different, as seen by comparing the left and top right panels of Figure 6. The MHD distribution is more diffuse and, in fact, more uniform in local time. It shows significant precipitation in the early afternoon that is lacking in the statistical distribution. This enhanced precipitation did correspond to a region of significant light emission in the Viking satellite images used in the Fedder et al. [1995b] substorm study. The maximum local energy flux in both the statistical case and the MHD model during the substorm reaches 4 ergs cm$^{-2}$ s$^{-1}$.

The remaining problem for a TDIM substorm simulation is that of obtaining a reasonable initial condition for the ionosphere. Typically, the TDIM requires 2-6 hours of aeronomy time in order to become independent of initial conditions. In this case, no MHD data are available prior to 1030 UT. Therefore we had no choice but to use empirical drivers to establish the prestorm ionosphere. While this does allow us to gauge the magnitude of the impact of the MHD drivers, it also means that we cannot expect to compare results with actual observations.

6. Comparison of Substorm and Statistical TDIM Simulations

TDIM simulations were carried out for the two sets of drivers described in the previous section. One simulation is driven by MHD-generated convection electric field and electron precipitation flux and represents the first simulation of the ionospheric response to self-consistent time-varying convection and precipitation inputs determined in relation to the solar wind input; this will be referred to as the "substorm simulation." The second case, the "statistical simulation," was driven by the Hardy et al. [1987] auroral model and the Heppner-Maynard "DE" convection model, with geomagnetic activity held to a constant level ($K_p = 4$). For this latter simulation, any differences between the starting ionosphere (1030 UT) and the ending ionosphere (1200 UT) will be entirely due to the UT effect associated with the motion of the solar terminator in the magnetic frame. This effect is quiet small over a 1.5 hour period, which allows us to use this simulation as a baseline for comparing the impact of the time-varying MHD inputs.

The $E$ and $F$ regions respond differently to the dynamics of the substorm and will be discussed separately. The differing responses are due to the time constants in the two regions. It is very fast in the $E$ region, allowing almost instantaneous reflection of the substorm drivers, but it is considerably slower in the $F$ region, which integrates up substorm changes.

Figure 7 shows key $F$ region parameters for both simulations at 1200 UT, the end of the substorm period. The left and middle columns show snapshots from the substorm and statistical simulations, while the right-hand column, with its own gray scale key, shows either the ratio or difference between the two TDIM simulations. These ratio or difference plots show the magnitude of the $F$ region integration of the substorm dynamics between 1125 and 1200 UT. Each dial plot uses the same polar coordinate system as in other figures in this paper (most MLT labels have been omitted to save space).

The $F$ region layer height, $h_F = F_2$ (bottom row), is raised in some locations and lowered in others, by as much as 75 km compared with the baseline statistical simulation (bottom middle panel). These changes are associated with the enhanced electric fields (see Figure 6) and occur in the noon sector cusp and polar cap, where the layer is lifted, and in the night sector auroral oval, where it is lowered. However, there is one region at midnight between 60° and 66° magnetic latitude in which the
Figure 4. Electric field convection patterns (with corotation added) for the Heppner-Maynard "DE" model (left panel) and three distinct times from the MHD simulation (right column). Each pattern is shown as a set of equipotential contours at 7-kV intervals in polar magnetic latitude/MLT coordinates.

The maximum $F$ layer density represented by $N_mF_2$ shows differences that range from tens of percent up to a factor of 3 (Figure 7, middle row). These differences are mainly in the auroral nightside and in the night sector polar cap. The polar cap $N_mF_2$ difference is over a factor of 3 and represents the mismatch in the locations of the polar hole between the two simulations. The high-density region of the polar cap is associated with a tongue of ionization found in the noon-cusp region that extends into the afternoon sector of the polar cap. In this region the density differences are also nonnegligible, with the substorm simulation values increased by 20-80% over the baseline values. The two tongues of ionization are morphologically very similar, which indicates that the Heppner-Maynard DE convection pattern was indeed a reasonable choice from the various statistical patterns that are available.

At 800 km, the electron density differences are larger than at the $F$ layer peak. This is shown in the top row of Figure 7. This is attributed to at least two features that are different in the two simulation inputs. First, as already described, in some regions, $h_mF_2$ is higher in the substorm simulation. In such regions, given the same $N_mF_2$ and scale height, one would expect $N_e$ at 800 km to be larger. However, in the night sector auroral oval, the substorm simulation has a higher electron density but lower $h_mF_2$. In this region this mechanism works against the simulation results; the topside scale height must be increased to give a larger density ratio at 800 km over that at the $F$ peak. This is a result of the larger electric fields in the substorm simulation has a higher $F$ layer; this difference is due to the fact that the substorm convection is almost purely eastward, while the statistical pattern still has a strong equatorward component. Hence the statistical convection pattern actually lowers the layer, making the substorm simulation $F$ layer appear to have been raised, whereas in actuality it has not been raised. This is one example of how mismatched inputs to the ionosphere will lead to misinterpretation. Equatorward of 55° magnetic latitude the difference in $hmF_2$, as well as in the other parameters, is zero because the MHD simulation does not provide convection or precipitation at these lower latitudes.
Figure 5. Time evolution of the integrated auroral energy flux in the northern hemisphere according to the MHD simulation. For comparison, the dotted line shows the corresponding value derived from the Hardy et al. [1987] auroral model for $K_p = 4$.

Substorm model, which lead to enhanced ion temperatures. Also, there is an increased downward electron heat flux at the upper boundary in regions of strong auroral precipitation, which leads to enhanced electron temperatures. Both effects act to increase the topside scale height. The regions of maximum $N_e$ ratios are mainly associated with regions of lower electron density and strong density gradients, reflecting mismatches in midlatitude troughs and polar holes. However, the highest density regions, the cusp and dayside polar cap associated with the tongue of ionization (top right and middle panels of Figure 7), show significantly different densities. In fact, these differences are 60-130% (a factor of 2), which although large are not as large as the extreme factor of 4 shown in the grey scale for the ratio plot. At noon to 1400 MLT, just equatorward of the cusp, there is a very large ratio of up to 4. This is associated with the difference in convection patterns (Figure 4) and how they channel high-density solar-illuminated plasma to the cusp.

Overall, the F region shows changes in electron density ranging from tens of percent to factors of 2-4 in response to this substorm. These changes are all much larger than instrument uncertainty and the modeling uncertainty goals for

Figure 6. Auroral energy flux patterns for the Hardy oval (left panel) and three distinct times from the MHD simulation (right column). The layout and polar coordinates are the same as in Figure 4.
Figure 8 shows the $E$ region integrated Hall (top row) and Pedersen (middle row) conductivities along with the $N_e$ at 160 km (bottom row). These snapshots are also at 1200 UT and use the same format as Figure 7. As stated earlier, the $E$ region time constant is short, and the parameters in Figure 8 reflect the immediate differences in the drivers. In the $E$ region, the driver is primarily the auroral electron precipitation; hence, in Figure 6 the differences in the Hardy oval (left panel) and the MHD oval (bottom right) are the major causes of the differences found in Figure 8.

$N_e$ at 160 km shows marked differences, by as much as a factor of 5. These are due to the highly expanded MHD oval as well as the stronger noon sector precipitation. Also, the statistical oval lies at a higher latitude; that is, during this dynamic phase of the substorm the $K_p = 4$ statistical oval is not appropriate. This mismatch will also be present in the integrated Hall and Pedersen conductivities (upper two rows in Figure 8). In the auroral regions, the integrated Hall conductivities exceed the corresponding Pedersen conductivities, which is consistent with expectations for auroral electron precipitation of characteristic energies ranging from 1 to 10 KeV. The Hall conductivity differences are large, ranging from -10 to +10 mhos. This is of the order of tens of percents to factors of more than 2. In the postnoon oval, the substorm simulation Hall conductivity exceeds the statistical baseline by more than a difference of 10, but in the prenoon oval the reverse is true. Hence, in both cases the mismatch between the auroral ovals is the source of the differences. It should be pointed out that this ionospheric difference is crucial to magnetospheric MHD model simulations, where the ionosphere is represented by a statistical oval versus those in which a more "self-consistent" $E$ region is included, i.e., like in this study.

Unfortunately, Figures 7 and 8 do not show the temporal response of the ionosphere to the substorm. In the $E$ region, the time response is close to instantaneous so that the auroral
Figure 8. A comparison of Hall conductivity (top row), Pedersen conductivity (middle row), and $N_e$ at 160 km (bottom row) from the statistical input and MHD input. This figure uses the same layout, geometry, and grey scaling as in Figure 7.

precipitation time history indicated in Figures 5 and 6 represents accurately the expected $E$ region response. A similar simplification does not hold for the $F$ region, in which $E \times B/B^2$ transport dominates and longer time constants exist. Figure 9 shows the $F$ region time evolution at five specific locations fixed in the magnetic frame by showing how $N_mF_2$ varies for the two simulations. The top two panels are for two locations just equatorward of the cusp region, from which high-density sunlit plasma is convected into the cusp and then into the polar cap to form the tongue of ionization. The two locations respond entirely differently to the substorm. In the uppermost panel, the presubstorm effects reduce the density of the MHD-driven simulation after the first 15 min. In contrast, at the second location, the MHD-driven simulation increases the density, with a maximum $N_mF_2$ increase of 70% occurring at 1110 UT and a minimum increase of 15% occurring as the substorm develops at 1135 UT. These variations are complex, do not follow the substorm time history, show $F$ region positive and negative storm effects, and, in general, are a manifestation of space weather.

Somewhat in contrast to what occurs equatorward of the cusp is the polar hole region, which as a large morphological phenomenon shows the same substorm evolution in both simulations. Figure 7 highlighted the difference in the polar holes for the two simulations at 1200 UT. Figure 9 (middle panel) shows this region's time evolution. For most of the simulation, up to 1135 UT, the two polar holes are equivalent. However, as the substorm convection electric field intensifies and the $F$ region responds, the polar hole location moves. This shifting of the polar hole leads to factors of 2-4 difference in the $N_mF_2$.

The two lower panels of Figure 9 show the premidnight trough/oval region, where a trough forms due both to the lack of precipitation and to a balancing of convection and corotational electric fields which produces an $F$ region plasma stagnation in darkness. However, the exact location and depth of the trough, especially its poleward edge, are critically dependent upon the equatorward edge of the auroral precipitation. The 59°, 2248 MLT location is such that the auroral precipitation levels are very small up until almost the
end of the simulation. In this case, both models would imply the location is in the trough. This can also be inferred from Figure 7, the $N_mF_2$ and $N_e$ at 800 km 1200 UT snapshots. In Figure 9 (bottom panel), this is not the case for the substorm simulation even though the latitude is slightly more equatorward. In this case, the region has continuous electron precipitation and represents the poleward wall of the trough. This particular region is especially important for space weather applications, since density gradients are a source of plasma instabilities that lead to irregularities. Furthermore, these strong $F$ region inhomogeneities play havoc on over-the-horizon radar propagation paths. However, a note of caution concerning the substorm simulation is worth restating. The equatorward limit of the NRL-MHD simulation and its inner boundary conditions lie on an L shell that falls within the trough region. Hence further validation work is needed to verify the electric field and auroral precipitation near this boundary.

7. Conclusion

This is the first study in which a physical ionospheric model has been driven through a substorm using self-consistent magnetospheric convection electric field and auroral electron precipitation inputs. Both of these were generated from a simulation of a real substorm event using the NRL MHD model [Fedder et al., 1995b]. As a reference against which to compare this TDIM substorm simulation, a typical climatological TDIM simulation was carried out using standard statistical representations of the convection electric field and auroral oval. From the comparison of the two ionospheric simulations, the following conclusions can be drawn:

1. As expected, the $E$ region densities are different, in line with the differences in the auroral precipitation patterns. However, these differences lead to factors of 2-4 differences in the integrated Hall and Pedersen conductivities, and these, in turn, are crucial as an ionospheric boundary condition for magnetospheric MHD simulations.

2. The $F$ region spatial and temporal responses are complex and exhibit large differences, from tens of percents to factors of 4 in density and up to 70 km in $h_mF_2$. These differences are all larger than typical experimental uncertainties.

3. The dayside and cusp variabilities are very sensitive to the convection pattern and are not well correlated to magnetic indices, such as the 3-hourly $K_p$.

4. In the polar cap, the differences in the locations of the tongues of ionization and the polar holes readily lead to factors of 2-4 in local density differences.

5. The differences in the locations of "boundaries" in the plasma convection and auroral precipitation lead to large differences in the local $F$ region densities and in the locations of strong density gradients, both of which are relevant to space weather applications.

Evaluating the ionospheric feedback to the magnetosphere is beyond this interfaced scenario; however, a self-consistency

Figure 9. Time evolution of $N_mF_2$ at five polar cap locations. In each panel the solid curve represents the result of the TDIM-MHD substorm simulation and the dashed line shows the result of the TDIM simulation based on statistical input models.
check on the conductivity can be done. The magnetospheric model uses a simple time-evolving conductivity as its ionospheric boundary condition. This time evolution, as well as the specific values of the Hall and Pedersen conductances, are obtained independently from the TDIM outputs. Hence, in follow-on studies, emphasis will be placed on these parameters. The active role for the ionosphere as a source of Alfvén waves for the MHD magnetosphere is beyond the current modeling capabilities. In a fully coupled model, this would be a new aspect to be investigated.

This pilot study has highlighted and demonstrated the scale and magnitude of the ionosphere's sensitivity to space weather, without necessarily validating the superiority of the MHD simulation outputs as ionospheric inputs. The speculation is that this should be the case, since the electric field and precipitation are now physically coupled rather than statistically related. In this study, the simulation spanned a period of only 2 hours (less than one 3-hourly $K_p$ period), which unfortunately is too short a time period to argue that the $F$ region densities are independent of the initial conditions. Hence it is not particularly fruitful to compare these simulation results with ionospheric measurements. However, this task of comparing a MHD-driven ionosphere with ionospheric density observations has already begun, and initial results were presented at the 1996 annual meeting of the American Geophysical Union held in San Francisco [Bowline et al., 1996; Sojka et al., 1996]. In this follow-on work, a 24-hour-duration simulation was carried out, and ionospheric observations from a DMSP satellite were obtained. This much longer simulation period will ensure that the initial ionosphere will not influence the major part of the study period and hence will provide a reliable model database that can be compared with the observations.

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