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Storm time density enhancements in the middle-latitude dayside ionosphere

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[1] Enhancements of the total electron content (TEC) in the middle-latitude dayside ionosphere have often been observed during geomagnetic storms. The enhancements can be as large as a factor of 2 or more, and many sightings of such structures have occurred over the United States. Here we investigate the effectiveness of an expanded convection electric field as a mechanism for producing such ionospheric enhancements. As a test case, we examine the storm period of 5–7 November 2001, for which observations from the DMSP F13 are used to drive the Time Dependent Ionospheric Model (TDIM). Our findings indicate that at favorable universal times, the presence of the expanded electric field is sufficient to create dayside TEC enhancements of a factor of 2 or more. The modeled enhancements consist of locally produced plasma; we do not find it necessary to transport high-density plasma northward from low latitudes.

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1. Introduction

[2] Enhancements of the dayside ionospheric total electron content (TEC) at middle latitudes associated with large geomagnetic storms are now well documented [e.g., *Foster and Rideout*, 2005]. The largest TEC enhancements are seen across the afternoon sector from noon to dusk, and a preponderance of evidence suggests that the American longitude sector may be a favored location for the largest of the observed enhancements. During the evolution of a storm the TEC enhancement appears as a longitudinally confined feature that appears in the early afternoon sector. The poleward edge of the TEC feature appears to migrate poleward and westward toward the cusp where it becomes an enhanced "tongue of ionization" [*Foster et al.*, 2005]. *Foster* [1993] identified such westward moving features as storm enhanced density and subsequently showed that their appearance is consistent with so-called "drainage plumes" observed in UV images of the plasmasphere [*Foster et al.*, 2002]. The storm time density increases may have a significant impact on the propagation of radio signals, and the longitudinal gradients associated with them can be the source of severe radio scintillation.

[3] The mechanisms responsible for these enhancements are still unclear. *Tsurutani et al.* [2004] and *Mannucci et al.* [2005] have shown middle-latitude TEC enhancements to be accompanied by similar enhancements near in the equatorial anomaly and suggest that vertical and horizontal transport from the equator may be responsible. *Heelis and Coley* [2007] have shown that middle-latitude density enhancements in the topside may be unaccompanied by corresponding equatorial density changes and suggest that middle-latitude features may evolve independently of equatorial features. These authors also point out that during large magnetic storms the ionospheric region under the influence of the magnetospheric electric field is significantly expanded. In this paper we investigate the role that an expanded electric field may play in the formation and evolution of the daytime enhancements in TEC at middle latitudes.

2. Expansion of the High-Latitude Convection Pattern

[4] This study is prompted by observations that clearly show the region of the ionosphere under the influence of magnetospheric electric fields expands dramatically to lower latitudes during storm times. Figure 1 (bottom) is derived from the work of *Heelis and Mohapatra* [2009] and shows the zonal ion drift measured from consecutive passes of the DMSP F13 satellite across the northern hemisphere during the storm period of 4–9 November 2001. Figure 1 (top) shows the north-south component of the interplanetary magnetic field (IMF) B_z and the Dst index, allowing the storm onset and development to be recognized. In Figure 1 (bottom) the solid black trace marks the high-latitude convection reversal boundary that broadly separates regions of sunward convection in the auroral zone from antisunward convection in the polar cap. The solid red trace marks the equatorward edge of the auroral electron precipitation region obtained by measurements from DMSP. The solid green trace is a measure of the equatorward extent of the high-latitude auroral flows obtained by noting where the latitude gradient in the zonal

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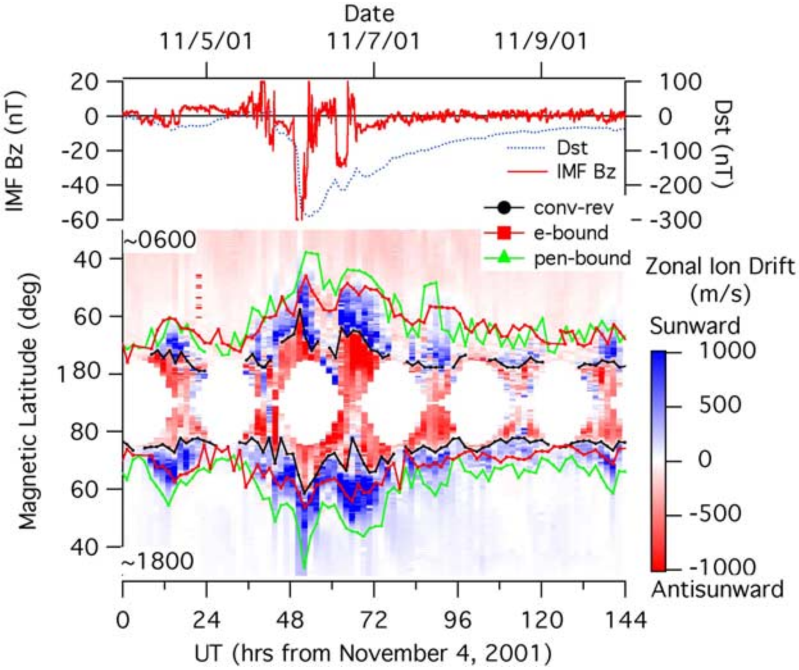

Figure 1. (top) The Dst index and the z component of the IMF during a large storm in the period of 4–9 November 2001. (bottom) The zonal drift observed at each pass of the DMSP F13 satellite across the northern hemisphere during this period. Also shown are the boundaries in the convection pattern and the auroral precipitation defined by the convection reversal boundary (black), the low-latitude limit to the auroral flows (green), and the low-latitude limit to the electron precipitation (red).

flows first exceeds a value of 15 m/s/degree. This line is termed a penetration boundary.

[5] Of particular importance here is to note that the storm time is characterized by the expansion of the convection reversal boundary from nominally 75° magnetic latitude to near 60° magnetic latitude, an expansion of the equatorward edge of the auroral zone from nominally 70° magnetic latitude to 55° magnetic latitude, and an expansion of the lowest-latitude auroral flows from nominally near 60° magnetic latitude to below 40° magnetic latitude. All three of these boundary expansions toward the equator persist for many hours. In fact, zonal flows of magnetospheric origin may extend all the way to the equator for brief periods. Thus these measurements provide a realistic if perhaps conservative specification of the degree to which the region of high-latitude influence expands to middle and low latitudes during a large storm. It is most important to note that sunward zonal flows on the dayside must be accompanied by smaller poleward flows in order to complete a two-cell convection pattern that closes across the polar cap. Such poleward flows are an intrinsic feature of high-latitude electrostatic potential distributions and appear directly in measurements of the convection velocity [e.g., *Heelis*, 1984]. It is the effects of these small poleward and upward drifts in the presence of sunlight [*Tanaka and Hirao*, 1973; *Schunk et al.*, 1975] that we wish to examine as a source for the TEC enhancements described earlier. Specifically, our hypothesis is that the TEC enhancements just equatorward of the auroral zone can be accounted for by the combination of photoionization and upward ion drifts associated with an expanded convection pattern. This means that the density enhancements can be produced while the plasma convects zonally and poleward, and it is not necessary that they be the result of poleward transport from an existing high-density reservoir at more equatorial latitudes.

[6] To test our hypothesis we use the Utah State University Time Dependent Ionosphere Model (TDIM) to simulate the distribution of plasma density along a family of magnetic flux tubes that move through the high- and middle-latitude ionosphere. The TDIM was initially developed as a middle-latitude, multi-ion (NO^+, O_2^+, N_2^+, and O^+) model by *Schunk and Walker* [1973] and subsequently extended to include high-latitude effects associated with convective ion drifts and particle precipitation by *Schunk et al.* [1975, 1976]. Flux tubes of plasma are followed as they move through the polar cap and auroral zones in response to plasma convection and particle precipitation models described by *Sojka et al.* [1981a, 1981b]. A rigorous consideration of the plasma energy balance is included in the calculation of ion and electron temperatures [*Schunk and Sojka*, 1982; *Schunk et al.*, 1976]. The theoretical development of the TDIM is described by *Schunk* [1988], while comparisons with observations are discussed by *Sojka* [1989].

3. Testing the Principles

[7] When dayside middle-latitude plasma convects poleward, an upward ion drift is induced by the inclination of the magnetic field. This vertical drift component becomes smaller at higher latitudes, as the magnetic field becomes nearly vertical. To demonstrate the effectiveness of this upward motion in the presence of sunlight in producing enhancements of TEC, we use the TDIM model in a simplified study, presented in Figure 2. Three cases, A, B, and C, each follow the history of one plasma flux tube for a period of 2 h. The

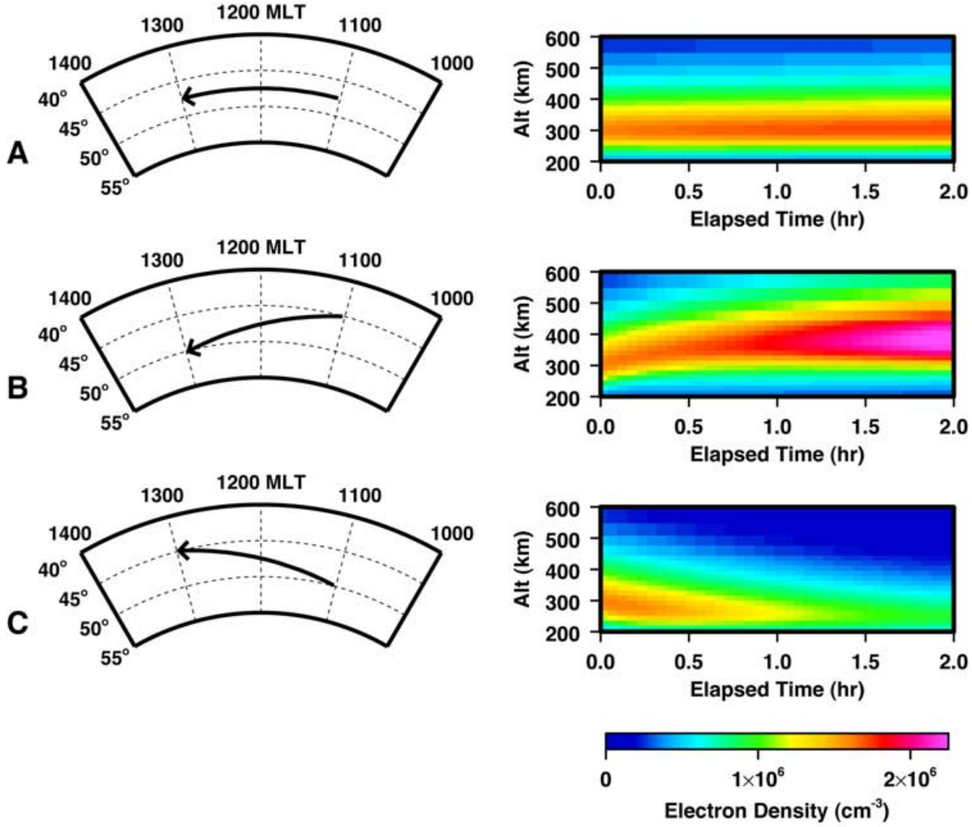

Figure 2. TDIM model simulations showing the effect of poleward or equatorward convective flow. Each case follows the history of one dayside plasma flux tube for 2 h. Case A: purely zonal motion of the flux tube, i.e., corotation only. Case B: the same zonal motion as case A, but additionally there is a northward (poleward) component. Case C: The flux tube trajectory path has an antipoleward component. The color plots show altitude profiles of electron density.

flux tube trajectory paths are plotted in latitude and local time on the left. In case A, no added electric field is present, and the flux tube travels zonally under the influence of corotation. The altitude distribution of electron density N_e, to the right, shows a slight increase in density during the 2-h period, owing to the continuing exposure to ionizing solar EUV radiation. TEC increases from 40 to 43 units in 2 h. This is the ‘‘normal’’ case, for quiet conditions with no influence from an expanded high-latitude electric field.

[8] In case B, the flux tube undergoes the same zonal movement as before but additionally moves poleward at a speed of about 75 m/sec associated with an eastward electric field of 4 mV/m. This causes the plasma to drift northward by 5 degrees of latitude in 2 h. This northward movement induces an upward ion drift of approximately 40 m/sec. In the electron density plot to the right, it is seen that the F layer peak is being continually lifted, with the density increasing during the 2-h period. The increase occurs because the lifting of the plasma has moved it to altitudes of reduced recombination, while photoionization continues to produce new plasma as before. TEC is increased from 40 to 70 units during the 2-h period.

[9] In case C, the flux tube moves equatorward, away from the pole and there is a downward induced ion drift of about 30 m/sec. This causes the F layer to be lowered into an altitude range dominated by recombination, with the result that TEC is reduced from 40 to 18 units during the 2-h period.

4. Specification of the Expanded Convection Pattern

[10] In order to model an expanded convection pattern we have incorporated information about the spatial extent and magnitude of the ionospheric convection seen in Figure 1 into a model of the magnetospheric electric potential. This temporally evolving driver is then used as input to the TDIM to determine its effects on the ionospheric density.

[11] To accomplish this in a simple way we use a description of the two-cell high-latitude convection pattern provided by *Volland* [1978]. This model is characterized by three parameters: the potential drop across the polar cap, the radius of the polar cap, and the rate of falloff of the electric potential with latitude below the convection reversal boundary. The DMSP observations in Figure 1 independently verify that the expansion of the polar cap boundary is approximately the same across the dawn and dusk sides for the storm period in question. Thus, these three parameters can be specified to represent the data shown in Figure 1, thereby providing a first-order ‘‘data-driven’’ time-varying model of the convection pattern. We emphasize that it is not our intent to model

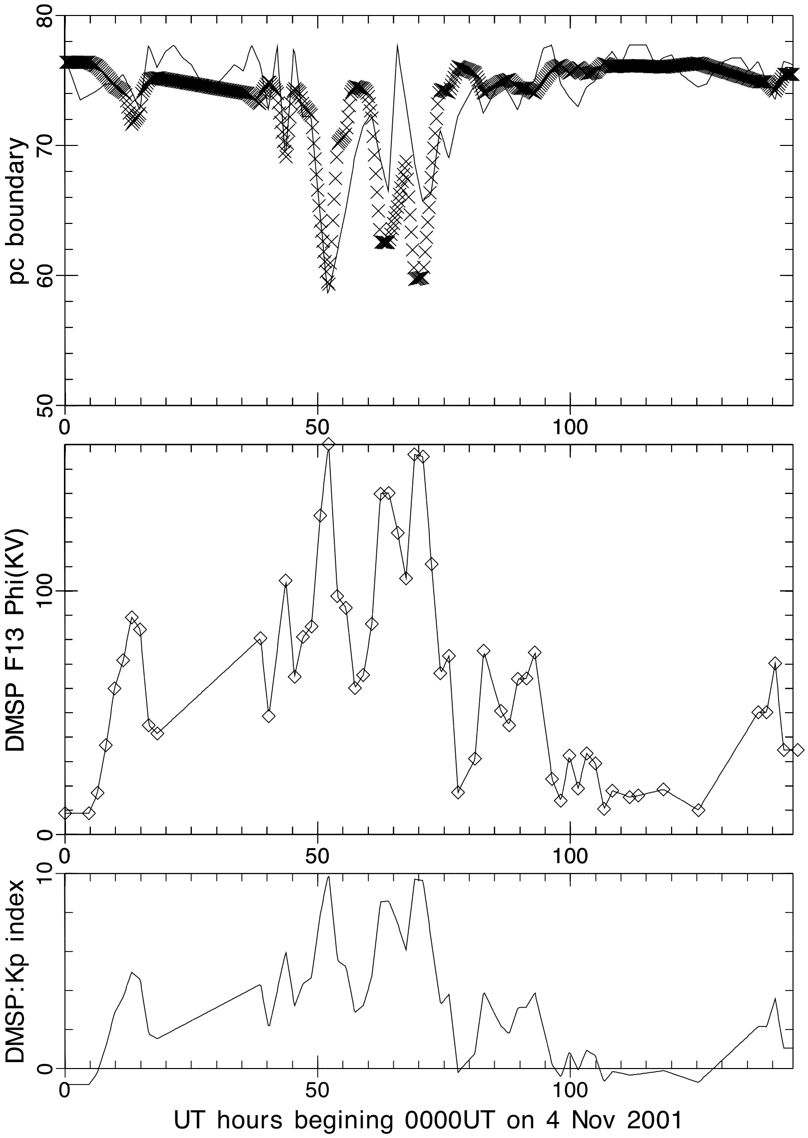

Figure 3. The solid line in the top plot shows the location of the polar cap (convection reversal) boundary determined from the data in Figure 1. The middle plot shows the corresponding cross polar cap potential derived from the same data. A special-Kp index shown in the bottom plot is used to drive a modified Volland convection pattern that locates the polar cap boundary as shown by the crosses in the top plot.

the observations for this storm period, but to investigate the role of poleward directed flows in the postnoon sector at middle latitudes produced by an expanded convection pattern. Thus we use the observations only to provide realistic estimates for the size and rate of expansion of the convection pattern.

[12] The convection pattern is driven by Kp, therefore out first requirement is to derive a higher-resolution version of the Kp index, specific to the storm event being studied. We will call this the "special-Kp," and it is computed by applying the formula: PHI = 14 * Kp + 20 (kV) from *Volland* [1978] to the DMSP observed values of the polar cap potential (PHI) drop. Figure 3 (middle) shows the DMSP cross polar cap potential, and the derived special-Kp index is shown in Figure 3 (bottom). The time resolution of the new index is about twice that of the Kp index. When this special-Kp, or even the regular Kp, is then used to drive the standard Volland two-cell model, it is found that the polar cap radius and falloff do not yet agree with the DMSP measurements of these boundaries. The Volland model is based on "average" conditions and should not be expected to simulate events during a powerful geomagnetic storm.

[13] Therefore, we obtain values for the polar cap radius and falloff by inspection of the DMSP data, and these new specifications of the radius and falloff are used in the modified Volland model. *Heelis and Mohapatra* [2009] discusses two boundaries specified by the magnitude of the zonal ion flow and by the latitudinal gradient in the zonal ion drift. Flows that extend beyond the boundary specified by the latitude gradient can be due to electric fields of magnetospheric origin or due to wind dynamo fields that are modified by magnetospheric energy inputs. Here we consider the boundary determined by the latitude gradient as the most conservative representation of the extent of the auroral

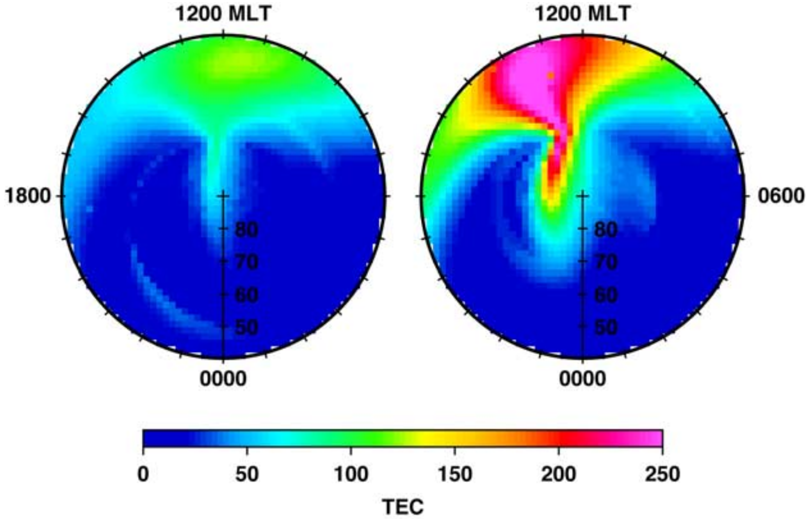

Figure 4. Total electron content (TEC) as simulated by the TDIM model, at 1900 UT. To the left is the case for the standard Volland convection; at right the simulation is driven by the expanded convection model.

convection electric field. We used the observed boundaries (Figure 1) to create modifications in the Volland two-cell algorithm to reproduce the observed expansion of the convection pattern as a function of the special-Kp index. Figure 3 (top) shows the comparison between the observed polar cap radius, solid line, and the new expanded Volland convection polar cap radius. The expansion of the Volland convection into middle latitudes is represented by a smooth function, an inverse sine to the power of the falloff factor. The DMSP observed expansion is quite structured. However, with a suitable dependence of the falloff factor on the special-Kp the Volland formulation extends the convection to the lower middle latitudes where it is observed by DMSP. This model formulation is necessary because out interest in this study is the effect of an electric field on the dayside at midlatitudes, where as our only direct information about the electric field is across the dusk-dawn path of the DMSP satellite. Despite the obvious limitations to this approach it allows us to apply some observational reality to a simple TDIM simulation.

[14] The TDIM additionally requires input for the solar EUV conditions, neutral atmosphere, neutral wind and auroral precipitation. The MSIS-86 model [*Hedin*, 1987] is used for the neutral atmosphere, and the horizontal wind model [*Hedin et al.*, 1991] is used for the neutral wind. In the present study, for solar conditions we use an extreme solar maximum value of $F_{10.7} = 230$, as determined by the actual conditions for 5 November 2001. The atmosphere and ionosphere are more responsive to long-term (80-day) solar flux inputs and thus the background ion concentrations presented here may be larger than observed. The *Hardy et al.* [1985] model is used to specify the auroral precipitation, and the location of its equatorward boundary was found to agree well with that observed by the DMSP F13 during the storm. *Heelis and Mohapatra* [2009] notes that for this 2001 storm the region of electron precipitation observed in the dusk sector becomes smaller in latitude extent even as the region moves equatorward. However, this behavior was not seen in the November storm of 2003. Thus, it may be fortuitous that the model for the equatorward boundary of the electron precipitation matches the observations. Here we examine the effects of expanded convection velocities equatorward of this boundary and thus the major features of our results are unaffected by the precise location of the electron precipitation boundary. It is important to note that we have constructed a realistic description of an expanded convection pattern to examine its contribution to enhanced TEC in the afternoon sector. We have not tried to model an event. Equatorward neutral winds will also produce an uplift of the ionosphere that, if present, is not reproduced by the wind model. Similarly, storm responses in the neutral atmosphere are not included in our model. All these features will likely change the details in a given observation but will not remove the fundamental response that we describe.

5. Storm Evolution of the High-Latitude Ionosphere

[15] To study the storm time evolution of the ionosphere that results from drivers described in section 4, we have performed two simulations with the TDIM in the high and middle latitudes. The first represents the usual, weakly expanded, way of modeling the storm time ionosphere, that is, with the standard Volland two-cell convection pattern (Figure 4, left). Our second simulation (Figure 4, right) incorporates the modified, expanded, Volland convection. Both are driven by the special-Kp index. Within this latter simulation both the polar cap radius and equatorward falloff are significantly changed.

[16] The storm modeled here has three periods during which the cross polar cap potential becomes very large and the polar cap boundary expands to magnetic latitudes near or below 65°. The first of these expansions occurs near 0400 UT on 6 November and at that time the northern magnetic pole is displaced toward midnight. The expansion of the convection pattern results in the penetration boundary that does not extend beyond the terminator in the dayside winter hemisphere. No significant enhancements in TEC are therefore expected or were found in the simulation. For the expansion

that occurs near 1800 UT on 6 November, the magnetic axis is tilted toward the dayside and the expansion of the convection pattern places the penetration boundary on the dayside of the terminator in the northern hemisphere. In this case the small poleward and upward flows associated with the dayside convective flows occur in sunlight and should produce significant enhancements in TEC.

[17] Figure 4 shows the distribution of vertical TEC at 1900 UT from the two simulations for this time period. The latitude scale extends to 40° in each plot. Figure 4 (left) shows the usually modeled situation for which the cross polar cap potential is increased but the storm expansion of the convection pattern is not realistically modeled. We note that a weak tongue of ionization (TOI) is formed owing to the projection of the convection pattern into the dayside where the plasma moves poleward. Previous modeling of the TOI [*Sojka et al.*, 1993] has shown the universal time dependence of this feature in the northern hemisphere associated with the location of the magnetic pole with respect to the terminator. On the night side of the terminator the effects of precipitation and plasma transport produce small features in TEC that are scarcely visible in Figure 4. We note however that across the afternoon sector between 1200 and 1800 local time the local time gradient in TEC near 40° magnetic latitude is about 12 TEC units per hour. This contrasts sharply with that seen in Figure 4 (right). In this case the model is driven by a convection pattern that is expanded in accordance with observations. Between 1400 and 1600 local time the TEC changes by 100 TEC units. Such dramatic increase in TEC over such relatively small local time extents are typical of the storm time perturbations reported by *Foster and Rideout* [2005]. As the dense dayside plasma convects poleward a very enhanced TOI is found, extending deep into the dark polar cap. We emphasize that the TEC enhancements are produced by the plasma uplift in the presence of sunlight associated with poleward motions on the dayside and are thus produced most effectively when the solar zenith angle is small.

6. Discussion

[18] In further discussing TEC enhancements produced by the expanded high-latitude convection pattern it is important to distinguish between enhancements created at middle latitudes and those associated with the expansion of the equatorial anomaly. While both these features are a common occurrence in many storms, here we have only examined the change in TEC that results from a high-latitude convection pattern that is expanded to middle latitudes; the TDIM simulations do not include transport from the equatorial anomaly region. Our convection pattern also does not include localized changes in the ion drifts required to ensure current continuity across the terminator.

[19] The expanded convection pattern results in small poleward and upward flows in the dayside. In the afternoon sector the westward auroral flows are in opposition to the corotation flows leading to a local time sector over which the zonal flows are quite small and hence the zonal plasma flow approaches a stagnation state. When this stagnation occurs in the presence of small poleward and upward flows in a region of sunlight the TEC is dramatically increased. We find that these optimal conditions exist during storm expansions that occur when the magnetic pole is tilted toward the dayside. Under such conditions the small zonal flows increase the residence time in sunlight and poleward drifts that lift the F layer reduce the chemical recombination rate. These features combine to produce large enhancements in TEC.

[20] TEC enhancements will be conjugate features, but the magnitude of the enhancements will not. Enhancements should be largest when the longitude region incorporating the magnetic pole is tilted toward the dayside. Thus the most effective universal times for TEC enhancements should occur in the northern hemisphere near 1900 UT and in the southern hemisphere near 0700 UT. Opportunities to examine conjugate effects in the passage of large TEC enhancements in the northern and southern hemisphere are very sparse. In addition the universal time evolution of the convection and precipitation patterns can be quite different for different storms. However, the measurements shown by *Foster and Rideout* [2007] are in general agreement with these expectations. In particular the storm of 16 July 2000 occurring near 0000 UT shows quite modest enhancements projecting toward the pole in the northern hemisphere while the storm of November 2003 occurring near 1900 UT shows more dramatic features.

7. Conclusions

[21] Recent observations have shown that the region influenced by electromagnetic energy inputs expands to low and middle latitudes during large magnetic storms. We have investigated the effects of such an expansion using quantitative estimates for the size of the high-latitude convection measured during the storm of 6 November 2001. In the sunlit local time region between noon and dusk the auroral flows have a westward component that opposes the corotation flow to the east. Thus, reduced zonal flows exist in a zone near the equatorward edge of the convection pattern where these flow components are in opposition. At this location the primary plasma transport is toward the pole and if the convection pattern is expanded to lower latitudes, where the magnetic field has a significant inclination, then the poleward flows have a vertical component. In the presence of sunlight small vertical drifts result in a significant decrease in the chemical losses and dramatic increases in TEC. We find that this mechanism by itself is capable of producing regions of enhanced TEC that project from middle to high latitudes in the early afternoon, as is frequently observed during large magnetic storms. This mechanism is a simple consequence of the expansion of the high-latitude magnetospheric driver to lower latitudes. Preferred longitudes and seasons at which the enhancements will be most dramatic are dependent on the solar zenith angle in the region of poleward flows. While a more detailed analysis is required to elucidate these properties they appear generally consistent with data published to date.

[22] Finally we emphasize that this simple picture could be expanded to include modification of the ion drift by field-aligned currents and ionospheric conductivity. However, such modifications are not required to produce the phenomenon. Indeed in this modeling study no plasma transport occurs between the northern equatorial anomaly and the midlatitude region. Hence, there is not a requirement that plasma is first enhanced in the equatorial anomalies.

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