Effects of solar wind dynamic pressure on the ionospheric O\(^{+}\) fluence during the 31 August 2005 storm

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[1] The Multifluid–Lyons–Fedder–Mobarry (MFLFM) global simulation model incorporating an ionospheric cusp O\(^{+}\) outflow model based on an empirical relation between downward DC Poynting flux and O\(^{+}\) outflow flux regulated by the precipitating electron number flux \(F_{\text{en}}\) is used to simulate the 31 August 2005 storm. A baseline run incorporating the original solar wind data is contrasted against a case where the solar wind dynamic pressure \(P_{\text{dyn}}\) is artificially adjusted to see what effects this variable has on the O\(^{+}\) fluence generated in the model. Consistent with data, it is found that both the fluence and O\(^{+}\) outflow flux have a positive correlation with the solar wind dynamic pressure. Additionally, changes in \(P_{\text{dyn}}\) affect the downward Poynting flux only marginally and regulates both outflow flux and cusp outflow area via \(F_{\text{en}}\). Increases in \(P_{\text{dyn}}\) lead to increased cusp electron precipitation, which has the physical effect of enhancing the upwellng O\(^{+}\) population available for outflow.


I. Introduction

[2] The ionospheric outflow of O\(^{+}\) is well documented in many observations [e.g., *Yau and Andre*, 1997; *Lennartsson et al.*, 2004] and its importance in altering the characteristics of the magnetosphere is currently the subject of much theoretical study for which global MHD simulations play an important role. *Winglee* [1998] reported the first investigation to consider ionospheric O\(^{+}\) outflow in the context of a multifluid global MHD model. This model has been additionally used and advanced in several subsequent studies [e.g., *Winglee*, 2000; *Winglee et al.*, 2002] and incorporates a population of gravitationally bound oxygen ions close to the model inner boundary that are accelerated outward by either centrifugal or pressure forces. Using a different approach *Gagne* [2005] developed an outflow model based on the empirical Strangeway formula [*Strangeway et al.*, 2005] linking field-aligned DC Poynting flux with O\(^{+}\) outflow flux. Unlike the work of *Winglee et al.* [2002], this model additionally allowed for ionospheric feedback, but was limited by the fact that it was coupled to the single fluid Lyon–Fedder–Mobarry (LFM) global simulation model and so could not consider the outflowing oxygen ions as a separate fluid.


[3] Recent years have seen several observational studies looking at the influence of a wide range of solar wind variables on the ionospheric O\(^{+}\) outflow fluence [see *Cully et al.*, 2003 for a particularly comprehensive study]. Consistent positive correlations have been found in a subset of these variables. Of particular note are the solar wind dynamic pressure [Moore et al., 1999; Elliott et al., 2001; Cully et al., 2003; Lennartsson et al., 2004; Bouhram et al., 2004; Guo et al., 2007], the magnitude of the solar wind electric field \(|E_{\text{rel}}|\) [Lennartsson, 1991; Elliott et al., 2001; Cully et al., 2003], the magnitude of the IMF \(B_{z}\) [Cully et al., 2003] and the sign of the IMF \(B_{z}\) [Lennartsson et al., 2004] wherein the O\(^{+}\) outflow fluence was found to be 2.5–3 times higher for negative \(B_{z}\) than for positive \(B_{z}\).

[4] The significant effects of IMF variations on outflow fluence has been well documented in several theoretical studies. For example, the difference in outflow fluence rates depending on the sign of \(B_{z}\) has been noted in multifluid simulations for both idealized [Winglee, 1998, 2000] and storm time solar wind conditions [e.g., Harnett et al., 2008, Brambles et al., 2010]. *Harnett et al.* [2008] (using the model of Winglee) additionally noted that the strongest outflows during a simulation of the 29 October 2003 Halloween storm occurred for strong southward \(B_{z}\) accompanied by a rapid \(B_{y}\) rotation illustrating the significance that
changes in $B_y$ can have on the magnitude of the outflow. Within the context of storm time simulations, significant solar wind dynamic pressure variations are many times coincident with these IMF perturbations and increased $O^-$ outflows [e.g., Wingale et al., 2002; Brambles et al., 2010]. No attempt however has been made to isolate the effects of solar wind dynamic pressure (independent of IMF changes) on $O^-$ outflow in the context of a global simulation model incorporating ionospheric electron precipitation feedback (particularly with regards to the cusp outflow). In this report we describe results from a study complementing the simulation study of Brambles et al. [2010] who used the MFLFM to simulate the August 31, 2005 storm with and without ionospheric $O^-$ outflow within the context of the model. We consider the same storm interval, but isolate the effects of solar wind dynamic pressure on the total $O^-$ fluence within the storm. The results will be discussed in the context of observations, but will additionally address how variations in solar wind dynamic pressure are driving changes in the outflow $O^-$ flux and fluence. Both this study and Brambles et al. [2010] isolate the effects of cusp-region outflow on the magnetosphere-ionosphere system by constraining the region of outflow while allowing the outflow flux and the area of the cusp outflow to be causally regulated by the system dynamics. A related study by Wiltberger et al. [2010] examines the effects of a fixed cusp outflow on magnetotail dynamics while the study by Garcia et al. [2010] examines the effect of a fixed nightside auroral outflow, both using the MFLFM model for steady, contrived solar wind conditions.

[5] The paper includes 3 sections. Section 2 describes the multifluid and outflow models while section 3 discusses the simulation results. Section 4 gives our conclusions.

2. Model

[6] The model used is a multifluid extension of the Lyon-Fedder-Mobarry (LFM) global simulation code [Lyon et al., 2004]. It is based on the equations (J. G. Lyon and V. Merkin, Multifluid equations in MHO, manuscript in preparation, 2010)

$$\frac{\partial \rho_{a}}{\partial t} = -\nabla \cdot \rho_{a} \mathbf{u}_{a} \tag{1}$$

$$\frac{\partial \mathbf{p}_{a}}{\partial t} = -\nabla \cdot (\mathbf{p}_{a} \mathbf{u}_{a} + \mathbf{1} \mathbf{P}_{a}) + \mathbf{F}_{a}^{\text{ed}} + n_{o} q_{a} \mathbf{E} \tag{2}$$

$$\frac{\partial n_{a}}{\partial t} = -\nabla \cdot \mathbf{u}_{a} (e_{a} + P_{a}) + \mathbf{u}_{a} \cdot \left( \mathbf{F}_{a}^{\text{ed}} + n_{o} q_{a} \mathbf{E} \right) \tag{3}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times (\mathbf{u} \times \mathbf{B}) \tag{4}$$

where $\rho_{a}$, $\mathbf{p}_{a}$, $\mathbf{u}_{a}$, $P_{a}$ and $e_{a}$ are the species mass density, momentum, velocity, pressure and plasma energy ($e_{a} = \frac{1}{2} \rho_{o} u_{a}^{2} + \frac{P_{a}}{\gamma - 1}$), respectively, and the subscript $a$ (along with $\beta$ in equation (5)) denotes the individual ion species. The magnetic field is denoted by $\mathbf{B}$ while $n_{o}$ and $q_{a}$ are, respectively, the $\alpha$ ion species number density and charge. The ambipolar electric field is $\mathbf{E}_{a} = -\mathbf{\nabla} \cdot \mathbf{P}_{a}/\mathbf{ne}$ where $P_{a}$ is the electron pressure. $\mathbf{F}_{a}^{\text{ed}}$ is the Lorentz force due to the first order (in $1/\Omega_{e} \alpha \tau$) ion drift

$$\mathbf{F}_{a}^{\text{ed}} = \mathbf{b} \times \left[ \mathbf{p}_{a} \nabla \mathbf{u}_{a} + \nabla P_{a} + \frac{\rho_{a} (\mathbf{u}_{a} \mathbf{b} - \mathbf{u}_{a}) \cdot \mathbf{\nabla} \mathbf{B}}{\mathbf{B}} - \frac{\rho_{a}}{\rho} \left( \sum_{\beta} (\nabla \mathbf{u}_{\beta} + \nabla P_{\beta}) + \nabla P_{a} - \mathbf{j} \times \mathbf{B} \right) \right] \times \mathbf{b}, \tag{5}$$

where $\mathbf{b} = \mathbf{B}/\Omega_{a}$, $\Omega_{a}$ is the ion species gyrofrequency, and $\tau$ is the MHD timescale. Within this framework, the ion species $\mathbf{E} \times \mathbf{B}$ drift to zeroth order in $1/\Omega_{a} \tau$ while the flow parallel to $\mathbf{B}$ of the two species is coupled via the parallel electric field.

[7] Within the model, the electron pressure is specified as a fraction of the total ion pressure and partitioned between the ion species based on the relative ion species fractions. In this present study however, we assume that the electrons are a cold neutralizing fluid with zero temperature and pressure which facilitates a complete understanding of the system in this simpler limit, but uncouples the counterstreaming $O^+$ and $H^+$ species in the cusp. If electron pressure effects were included, it is expected that the resulting ambipolar electric field would tend to retard somewhat the velocity of the outflowing $O^-$ plasma. However, the distance in which the two cusp populations counterstream is only an $R_E$ [Brambles et al., 2010] before the $O^+$ stream enters the lobe where the low $H^+$ density implies electron pressure effects would be negligible. Therefore, consideration of a nonzero electron pressure should prove to be a minor correction to the quoted results, but will be addressed in a future study. Further discussion is given in Lyon and Merkin (submitted paper, 2010) and Brambles et al. [2010].

[8] The model equations are solved on a nonuniform grid (which gives higher resolution in the near-Earth and bowshock regions) which stretches from 30 $R_E$ upstream to 300 $R_E$ downstream with cylindrical extent of the simulation domain extending in $\sqrt{y^2 + z^2}$ to a typical radius of $\sim 120 R_E$. The grid has an inner boundary (for the purposes of this simulation) at a geocentric distance of 2 $R_E$. The choice of this radius is partially dictated by computational constraints [e.g., see Wiltberger et al., 2004], but it is also true that the region below this boundary is dominated by collisionless plasma processes that are not well represented by the ideal MHD equations.

[9] The MHD model is coupled to a 2-D height-integrated ionospheric model where the field-aligned currents, the characteristic energy of precipitating electrons and the electron energy flux are mapped to the ionosphere from the inner boundary of the MHD simulation at 2 $R_E$ and are used to modify the conductance via the Robinson et al. [1987] empirical model. The conductance also includes an EUV contribution to the ionization. Given the so-determined ionospheric conductance and field-aligned current, the familiar Poisson equation is solved for the ionospheric potential which is then mapped back up to the MHD inner boundary. The mapped potential is differenced at the inner boundary to obtain $\mathbf{E}$ and $\mathbf{v} = \mathbf{E} \times \mathbf{B}/B^2$ for use as a boundary condition. The details of the ionospheric model are unchanged from the original LFM specification [Fedder...
et al., 1995; Lyon et al., 2004] with the exception that the H+ fluid density has replaced the single-fluid density in calculating the electron characteristic energy and flux, and the potential drop in the gap region between the LFM inner boundary and the ionosphere is now accounted for in mapping the ionospheric potential to the MHD simulation boundary [Gagne, 2005]. The O+ fluid density was neglected in calculating the electron characteristic energy and flux since only precipitating electrons with energies greater than about a keV contribute to the regulation of the outflow (via the ionospheric conductance). Cold electrons upwelling with the O+ ions, if backscattered, do not affect the height integrated conductivity as their energy would primarily be deposited at altitudes where the collision frequency is too low to support perpendicular currents [Robinson et al., 1987].

2.1. Outflow Model

[10] The outflow algorithm in this model is based on that of Gagne [2005] developed for use in the single-fluid LFM and further developed and modified for use in the multifluid LFM by Brambles et al. [2010]. The model uses the empirical Strangeway formula relating the downward field-aligned DC Poynting flux to the O+ outflow flux developed from the analysis of FAST data. The empirical formula is given by

\[
F_{O} = 2.14 \times 10^{7} S_{||}^{2.65},
\]  

(6)

where \(F_{O}\) is the O+ ion outflow flux in units of #/cm²-s and \(S_{||}\) is the field-aligned DC Poynting flux in units of mW/m² given by

\[
S_{||} = \frac{E \times \delta B}{\mu_{o}} \cdot b,
\]  

(7)

where \(b = B/|B|\) and \(\delta B = B - B_{dip}\) (where \(B_{dip}\) is the Earth’s dipole magnetic field). Strangeway additionally developed formulae relating outflow flux to precipitating electron number flux (\(F_{en}\)), electron energy flux (EEF) and ELF (extremely low frequency) wave amplitude. The relationship between Poynting flux and O+ outflow flux was chosen in this study because the correlation coefficient is essentially as high or higher than that of the other empirical relations and because the DC Poynting flux is easily computed from the MHD model electric and magnetic fields.

[11] In the context of the model, the outflow flux is multiplied by three regulating functions such that

\[
F_{O}' = 2.14 \times 10^{7} S_{||}^{2.65} M_{e} M_{v} F_{en},
\]  

(8)

where \(F_{O}'\) is the modified O+ outflow flux and \(M_{e}\) and \(M_{v}\) are spatial and velocity regulating functions, respectively, that restrict the outflow to the region of the cusp. The cusp is the source of most intense outflow flux as was reported by Lennartsson et al. [2004] and Bouhram et al. [2004] and where the Strangeway formula is valid. \(M_{F_{en}}\), a source region regulating function based on the precipitating electron number flux (\(F_{en}\)) derived from the MFLFM precipitation model. Soft electron precipitation in the cusp causes the ionosphere to upwell there [Nilsson et al., 1994; Prölss, 2006] which enhances the ion source population for cusp outflows [Liu et al., 1995; Seo et al., 1997]. In order to isolate the cusp, the spatial regulating function \(M_{e}\) is 0 for \(x < 0\) and 1 for \(x > 0\) which restricts outflow to the dayside hemisphere; and the velocity regulating function \(M_{v}\) is 0 for \(v_{v} > 0\) and 1 for \(v_{v} < 0\) which further restricts the outflow to the antisunward convection region around the cusp.

[12] Although, in principle, the empirical formula from Strangeway et al. [2005] utilizing \(F_{en}\) could have been used in determining \(F_{O}\), the choice of the \(S_{||}\) empirical formula allows the \(F_{en}\) to be used to define a regulating function that conveys information about the state of the upwelling ion population. The logic being that an increase in the number of precipitating electrons increases the ionospheric electron scale height which causes an increase in the number of upwelling ions via the ambipolar parallel electric field generated to maintain quasi neutrality. The functional dependence of the \(F_{en}\) regulating function takes the form [Gagne, 2005]

\[
M_{F_{en}}(\Lambda, \phi) = \min \left( \frac{F_{en}(\Lambda, \phi)}{F_{en}(\text{baseline})}, 1 \right),
\]  

(9)

where \(\Lambda\) is invariant latitude and \(\phi\) is the magnetic local time. If the \(F_{en}\) exceeds the baseline (\(F_{en}(\text{baseline}) = 1.25 \times 10^{8} \#/cm²\)) then \(M_{F_{en}}\) is set to 1. The baseline was tuned so that an MFLFM simulation with quiet steady southward solar wind conditions (\(n_{en} = 5/cc\), \(B_{z} = -5\) nT, \(v_{v} = -400\) km/s) yielded total O+ outflow fluxes on the order of \(1 - 2 \times 10^{24}\) ions/s which is the same order of magnitude but generally less than the perigee observations for \(B_{z} < 0\) evident in Figure 2 of Lennartsson et al. [2004]. As we are restricting this study only to the consideration of cusp outflow, it is reasonable that the calculated fluence rates are below observed averages.

[13] As mentioned in the previous section, the MHD model has an inner boundary at a geocentric distance of 2 R_E, while the FAST altitude relevant for the Strangeway observations is at 4000 km above the surface of the Earth. Therefore, the DC Poynting flux is computed close to the inner boundary of the MHD model and then dipole mapped to the FAST altitude where equation (5) is used to calculate the O+ outflow flux and the \(M_{F_{en}}\) regulating function is also applied. For the determination of the Poynting flux, a geocentric distance of 2.9 R_E was chosen. This choice is a compromise between maximizing Poynting flux to drive outflow (numerical considerations lead to a drop in \(S_{||}/B_{dip}\) with reduction in altitude close to the inner boundary) and the practical consideration of allowing Poynting flux to be mapped to as low a latitude as possible. Once the product of \(F_{O}\) (from equation 6) and \(M_{F_{en}}\) has been determined, it is then dipole mapped back to the inner boundary of the MHD model where the spatial and velocity regulating functions are applied. For the present study, to be approximately consistent with the observed statistical results of Bouhram et al. [2004], a constant outflow velocity of \(v_{v} = 50\) km/s and a constant temperature for the outflowing population of 100 eV are assumed. See also Brambles et al. [2010]. The ratio of the
calculated $F_O$ for a given cell and the assigned value of $v_{||}$ define the number density of O$^+$, and thus the mass, that is added to the cell at each time step.

### 3. Simulations

[14] Figure 1 summarizes the solar wind conditions for the August 31, 2005 storm obtained using the OMNI one minute averaged multispacecraft interplanetary parameters (IP) data from the NASA Coordinated Data Analysis Web site. Dotted lines in Figures 1a and 1c, respectively, indicate the density profile used in case B and corresponding profile of solar wind dynamic pressure ($P_{dyn} = 1/2 m_H n_{sw} v_{sw}^2$). The time frame from 0800 to 2000 UT is the period of primary interest for this study.

Dotted lines in Figures 1a and 1c, respectively, indicate the density profile used in case B and corresponding profile of solar wind dynamic pressure ($P_{dyn} = 1/2 m_H n_{sw} v_{sw}^2$). The time frame from 0800 to 2000 UT is the period of primary interest for this study.

[15] For case B, the solar wind density was set to a constant value of 7.8/cc from 08:00 UT. This time precedes the commencement of the large density perturbation in the unmodified solar wind profile as well as any significant outflow activity which commences after the solar wind $B_z$ goes southward at about 09:30 UT. The value $n_{sw} = 7.8/cc$ was chosen as this was the magnitude in the original solar wind data at 08:00 UT.

[16] As discussed in the previous section, the outflow is being driven by the field-aligned DC Poynting flux via the Strangeway empirical relation. Figure 2a illustrates the northern hemisphere integrated ionospheric Joule dissipation, which is essentially equivalent to the integrated Poynting flux, for both cases and a strong agreement is evident between the two for the length of the run. The magnitude of $P_J$ begins to increase dramatically with the turning of the IMF $B_z$ southward at 09:30 UT. An hour long interval of predominantly northward IMF $B_z$ at about 10:45 UT results in a drop in $P_J$ followed by an increase when the IMF turns southward again at about 12:00 UT. The relatively constant IMF conditions between about 13:00 UT and 17:00 UT lead to a relatively constant integrated Joule dissipation as well followed by a drop when the magnitude of $B_z$ is reduced after 18:00 UT. Although not shown, the profiles of integrated cross polar cap potential and integrated field-aligned current are similarly consistent between the two cases illustrating that for the conditions of this storm, solar wind density does not greatly effect the magnetospheric activation.

[17] In Figure 2b, the O$^+$ fluences in both cases are plotted and they are order of magnitude consistent with the statistically averaged O$^+$ cleft observations given in Table 1 of Yau and Andre [1997] for a consistent range of $K_P$. Even though this is a moderate storm, the resulting fluence still has a significant impact on the magnetosphere-ionosphere system as summarized in the study by Brambles et al. [2010]. The resulting trends of fluence as a function of time in both cases is consistent with the trends for $P_J$ in Figure 2a with the exception that the magnitude of the fluence is significantly reduced for case B relative to case A. There is additionally a large spike in fluence that occurs at about 10:42 UT in case A that does not occur in case B.

**Figure 1.** Solar wind parameters for the 31 August 2005 storm obtained using the OMNI one minute averaged multispacecraft interplanetary parameter data (NASA Coordinated Data Analysis Web site). Dotted lines in Figures 1a and 1c, respectively, indicate the density profile used in case B and corresponding profile of solar wind dynamic pressure ($P_{dyn} = 1/2 m_H n_{sw} v_{sw}^2$). The time frame from 0800 to 2000 UT is the period of primary interest for this study.

**Figure 2.** (a) Time series of Northern Hemisphere integrated Joule dissipation ($P_J$) for both simulation cases. (b) Time series of Northern Hemisphere fluence.
The significance of this in case A is generally upwelling which increases the ion outflow flux, the ions/m

The reason for the differences between the fluences in the two cases becomes apparent when we examine the time series of average $F_{en}$ displayed in Figure 5e where the precipitating $F_{en}$ profile is consistently larger for case A (consistent with increased solar wind density). The dashed line in the plot defines the $F_{en(baseline)}$ function used in equation (9). Above this line, increases in $F_{en}$ can only lead to increases in outflow area, while below this line, these increases can be manifested by both increases in outflow flux and area. For the earlier part of the simulation (before 12:00 UT), $F_{en}$ in both cases is generally below this threshold and it appears that the relative increase between outflow flux and area between the cases is fairly consistent. After about 12:00 UT, the average $F_{en}$ in case A is generally above the threshold value and the result is that a majority of the increase in fluence is caused by an increase in outflow area. It is also clear that the relatively constant profiles evident in Figures 5a–5c between about 12:30 and 17:00 UT (indicated by vertical solid lines) in case A are a direct result of the form of the imposed $M_{F_{en}}$ regulating function. The average $F_{en}$ profile for case A exhibits relatively more variation over the same interval.

Although the $F_{en}$ regulator is heuristic, it does represent the physical effect of soft electron precipitation in enhancing ionospheric O+ upwelling which increases the ion source population available to the outflow. An increase in solar wind density feeds an increase in the solar wind

**Figure 3.** Northern Hemisphere O+ outflow flux at 1550 UT for the original solar wind data (case A) and for constant solar wind density (case B).

**Figure 4.** Outflow fluence as a function of time over the entire Northern Hemisphere and when restricted to include only O+ fluxes greater than $2 \times 10^{13} / m^2 \cdot s$. 

[18] Figure 3 plots the hemispheric distributions of O+ outflow flux for both cases at 15:50 UT. This time is within the period of relatively constant IMF conditions in which the individual fluences are at a maximum. Consistent with the drop in fluence between these two cases evident in Figure 2b, there is a drop in magnitude of the outflow flux. However, along with this drop in flux magnitude, there is also a drop in the cusp area from which the outflow is emerging. Also evident in Figure 3, in addition to the cusp outflow, is a small flux patch due to region 1 currents that sometimes escape the effect of the $M_{F_{en}}$ regulating function. The significance of this patch outflow, relative to the cusp, is however small.

[19] The drop in both fluence and flux in case B relative to case A at first appears surprising given that the main driver of the outflow is the DC Poynting flux. However, it is important to remember that the outflow is also regulated by the precipitating electron number flux ($F_{en}$) which conveys information about the state of the upwelling ion population. In order to achieve a more complete understanding then, it is beneficial to examine the effects of the individual variables within the outflow model to see how they are effecting the characteristics of the outflow in the two individual cases. In order to do this, we define a reference area in which to conduct the analysis. For this analysis, we have chosen a minimum value of $0.2 \times 10^{13} \text{ions/m}^2 \cdot \text{s}$ to define a masking function that is valued 0 below this threshold and valued 1 above it. A spatial mask that eliminates the affect of the noncusp outflow patch noted in Figure 3 is also applied.

[20] Figure 4 displays the total outflow fluence across the entire northern hemisphere (solid line) for case A contrasted with the total fluence achieved by only integrating the O+ outflow flux with the region defined by the mask. The choice of the $0.2 \times 10^{13} \text{ions/m}^2 \cdot \text{s}$ cutoff baseline captures the majority of the outflow. The fluence within this defined region is plotted for both simulation cases in Figure 5a and the same general characteristics as noted in Figure 2b are still evident. Figures 5b and 5c plot the outflow area (as defined by the mask) and the average O+ outflow flux within that region, respectively. The increase in both outflow area and flux in case A relative to case B evident in Figure 3 are also apparent here.

[21] In order to elucidate the reason for this behavior, Figures 5d and 5e plot the times series of the average Joule dissipation (Poynting flux) and average precipitating electron number flux, respectively, accessing the outflow region in the two cases. As with the average O+ outflow flux, the average $F_{en}$ and average Joule dissipation values are achieved by integrating the individual quantities over the outflow area and then dividing this by the relevant outflow area as displayed in Figure 5b. If the outflow area is zero, then the average quantity is defined as zero as well.

[22] The results for the average Poynting flux displayed in Figure 5d are consistent with what would be expected given Figure 2a in that there is little difference in the average Poynting flux between the cases. This consistency between Figures 5d and 2a illustrates that the hemispheric characteristics with regard to integrated Poynting flux evident in Figure 2 are consistent with those in the cusp region alone. Therefore, changes in solar wind dynamic pressure (as defined by changes in solar wind density) affect the downward field aligned Poynting flux marginally within this storm interval.

[23] The reason for the differences between the fluences in the two cases becomes apparent when we examine the time series of average $F_{en}$ plotted in Figure 5e where the precipitating $F_{en}$ profile is consistently larger for case A (consistent with increased solar wind density). The dashed line in the plot defines the $F_{en(baseline)}$ function used in equation (9). Above this line, increases in $F_{en}$ can only lead to increases in outflow area, while below this line, these increases can be manifested by both increases in outflow flux and area. For the earlier part of the simulation (before 12:00 UT), $F_{en}$ in both cases is generally below this threshold and it appears that the relative increase between outflow flux and area between the cases is fairly consistent. After about 12:00 UT, the average $F_{en}$ in case A is generally above the threshold value and the result is that a majority of the increase in fluence is caused by an increase in outflow area. It is also clear that the relatively constant profiles evident in Figures 5a–5c between about 12:30 and 17:00 UT (indicated by vertical solid lines) in case A are a direct result of the form of the imposed $M_{F_{en}}$ regulating function. The average $F_{en}$ profile for case A exhibits relatively more variation over the same interval.
electron number flux that precipitates in the cusp. The resulting increased source population increases both outflow flux and cusp outflow area. This positive correlation between both flux and fluence and solar wind density (dynamic pressure) is consistent with several observational studies. For example, Cully et al. [2003], using ion outflow data from the Akebono satellite (combined with solar wind data from Wind and IMP-8 satellites), noted a positive correlation between O$^+$ outflow fluence and both solar wind density and solar wind dynamic pressure while Elliott et al. [2001] recorded a positive correlation between O$^+$ outflow flux and solar wind dynamic pressure (with outflow data from the Polar satellite). More specific to the cusp region alone, both Guo et al. [2007] and Kistler et al. [2010], using Cluster data, observed larger O$^+$ outflows with increased solar wind dynamic pressure. The increase in outflow area is supported by observational results from Newell et al. [2006] which revealed a direct correlation between solar wind dynamic pressure and cusp width.

[25] As a final point, we return to consideration of the large spike in fluence for case A in Figures 2b, 4, and 5a at 10:42 UT that is not apparent for case B. Given the otherwise largely consistent trends as a function of time between the two cases, this at first appears peculiar. However, closer examination reveals that rather than being a factor of the IMF (which is consistent in both cases), this spike in fluence is associated with the second (and larger) of the two relatively sharp density perturbations that occur in case A starting just after 10:00 UT (Figure 1a). This was confirmed by removing these two peaks in the case A density profile so that there was only a smooth monotonic increase in density over the interval and re-doing the simulation (not shown). The large spike in fluence evident in the original case A was then found to be greatly reduced. Likewise, the assumption of a constant density in case B negates the appearance of this spike in this latter case as well. Consistent with the discussed trends apparent between the cases in Figures 2a and 2b the spike in $P_J$ that occurs at the same time (Figure 2a), was found not to be significantly effected by this density smoothing.

4. Conclusions

[26] In this paper we have studied the effect of solar wind dynamic pressure on the total outflow fluence evident in the Multifluid-Lyon-Fedder-Mobarry global simulation model coupled to the Gagne O$^+$ outflow model. This outflow model is based on the Strangeway et al. [2005] empirical...
formula relating the field aligned DC Poynting flux to the ionosphere O⁺ outflow flux multiplied by a regulating function ($F_{en}$) based on the $F_{en}$. This function represents the state of the upwelling O⁺ population since increased $F_{en}$ serves to cause an upwelling of ionospheric oxygen. Spatial and velocity regulating functions are also applied that restrict the outflow to the region of the cusp for which the Strangeway formula is valid.

[27] In the simulations, it was found that artificially reducing the solar wind dynamic pressure (by reducing the solar wind density) does not greatly affect the DC Poynting flux flowing into the high-latitude region, but affects the outflow via the $F_{en}$ regulating function by reducing the $F_{en}$ and consequently reducing both the O⁺ outflow flux and cusp outflow area. This connection with $F_{en}$ makes physical sense since the reduction of the precipitating electron number flux reduces the electron scale height which would result in the upwelling of fewer oxygen ions. The positive correlation between the O⁺ fluence and dynamic pressure is also noted in several observational studies. However, the difficulty in finding intervals in data that effectively isolate individual solar wind variables, combined with the coupling between possible causes of outflow makes it difficult to elucidate the physical reason behind this correlation with data analysis alone. Therefore, controlled numerical experiments are a necessity in providing progress in understanding and the simulation results presented here offer an initial interpretation of how the coupling between solar wind dynamic pressure and fluence might work in nature.

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