

Magnetosphere-ionosphere/thermosphere coupling: Self-consistent solutions for a one-dimensional stratified ionosphere in three-fluid theory

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[1] We study the local response of a model ionosphere to a change in the magnetospheric convection, on the basis of a three-fluid (electrons, ions, and neutrals) approach to describing the dynamic processes of solar wind-magnetosphere-ionosphere/ thermosphere coupling. The physical description, including the three-fluid generalized Ohm's law, the plasma momentum equation, and the neutral momentum equation, as well as Maxwell's equations, takes into account electromagnetic coupling among the charged species and collisions among the three species; the geometrical configuration in this initial study, however, is highly simplified and approximates a localized region within the polar cap. We model the driver of the convection by a changing tangential flow of plasma, imposed at the top boundary of the ionosphere, and follow numerically the self-consistent evolution of the entire system, which is assumed to be incompressible. A magnetic field distortion, corresponding to a horizontal (not field-aligned) current, propagates from the magnetosphere to the lower ionosphere, producing at first a strong transient Pedersen current which then decreases to a steady state value. The transient time for the system to settle downscales as the Alfvén-wave travel time between the E layer and the top boundary (verified by redoing the calculations with different heights of the upper boundary). Large perturbations occur during the first 10 Alfvén travel times, and it takes about 20 Alfvén travel times for the system to reach a quasi steady state. After the quasi steady state has been reached, the neutral wind continues to vary slowly (forces due to neutral pressure and effective viscosity have been neglected). When magnetospheric convection is reversed after 1 h, an overshoot of the Pedersen current occurs before the system settles into a new quasi steady state. The electrostatic approximation commonly used in the magnetosphere-ionosphere coupling models remains poor for up to 10 Alfvén travel times (which could translate to more than 15 min in a more realistic geometry); the assumption that the neutrals remain at rest relative to the Earth is poor within the F layer.

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1. Introduction

[2] How to couple the nearly collisionless magnetosphere to the highly collisional ionosphere/thermosphere is one of the most challenging tasks in space physics. Many models have been proposed and investigated over the last decades. Most of

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the models of global nature are based on the classical magnetosphere-ionosphere (M-I) coupling theory [e.g., *Vasyliūnas*, 1970; *Wolf*, 1970] (see reviews by *Cowley* [2000] and *Siscoe* [2001]), in which the ionosphere is treated as a heightintegrated boundary of the magnetosphere, electric fields and currents are linked by a steady state ionospheric Ohm's law (in the neutral-wind frame of reference), and the divergence of horizontal currents in the ionosphere is required to match the Birkeland (magnetic-field-aligned) currents derived from stress balance in the magnetosphere; if the curl of the electric field is assumed negligible, the above relations suffice to calculate the electrostatic potential, from which the flow of plasma both in the ionosphere and the magnetosphere is obtained as the E × B drift.

[3] Within the context of this theory, the ultimate driver of magnetospheric convection is the interaction of the solar

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wind with the magnetosphere and can be specified either as an imposed Birkeland current or as an imposed electric field; correspondingly, models may be classified as either field-aligned current coupling or electric field coupling.

[4] Field-aligned current coupling is widely adopted particularly in connection with global MHD simulation models [e.g., Fedder and Lyon, 1995; Raeder et al., 1995; Tanaka, 1995; Song et al., 1999], where Birkeland currents from the simulation are used to determine the boundary condition on plasma flow at the lower magnetospheric boundary. Electric field coupling, in which the magnetospheric electric field in a specified region, such as at or within the polar cap, is assumed given (e.g., see review by Richmond and Thayer [2000]), allows extended models in which the ionosphere and the neutral wind/thermosphere can be treated as structured layers rather than a single height-integrated layer. Initial investigations on how to self-consistently couple from collisionless to collisional regions in such a system have been made by Song et al. [2001] and by Strangeway and Raeder [2001].

[5] In addition to these global models, there are many local coupling models. Most of these focus on horizontally nonuniform regions, such as auroral zone and field-aligned current regions, and use either a resolved-ionosphere [e.g., *Dreher*, 1997] or a height-integrated-ionosphere approach [e.g., *Lysak and Dum*, 1983] without inclusion of neutral dynamics. *Birk and Otto* [1996] and *Zhu et al.* [2001] have developed a self-consistent magnetosphere-ionosphere/ thermosphere model with applications to 2-D and 3-D situations.

[6] The perspective on M-I coupling has been changed fundamentally by three recent developments:

[7] 1. Work by Vasyliūnas [2001] (and earlier in a laboratory context by Buneman [1992]) has shown mathematically that plasma flow can generate the $-V \times B$ electric field, whereas an externally imposed electric field cannot produce the $E \times B$ plasma flow, a notion long familiar within MHD [e.g., Dungey, 1958; Parker, 2007]. The physical reason can be viewed in either of the following ways: (1) When an external electric field is imposed on a plasma, the charge separation at the boundaries creates an electric field that is opposite to the imposed electric field and shields it from penetrating into the plasma. (2) More fundamentally, the electric field exerts no net force on the quasi-neutral plasma and hence cannot set it into motion. As a consequence, the electric field coupling models discussed above reverse the causal relation between the plasma motion and the electric field. (Note that it is easy to prove that the particle $E \times B$ drift in single-particle theory refers to the (self-consistent) internal electric field, not to the externally imposed electric field [e.g., Tu et al., 2008].)

[8] 2. The basic assumptions of M-I coupling theory, determination of current density from stress balance and mapping of electric potential along magnetic field lines, are now recognized as conditions that presuppose stable equilibrium [*Vasyliūnas*, 2005a, 2005b]. The theory thus cannot describe time variations on scales shorter than the Alfvén travel time along a field line, nor propagation effects along a field line, nor situations that are intrinsically unstable (e.g., substorm onset, in many theories).

[9] 3. Although the role of the neutral wind velocity in the ionospheric Ohm's law has always been recognized in

principle, the neutral wind momentum equation that governs it has for the most part not been included in the approach, which therefore is not self-consistent. As a further complication, the neutral wind velocity may in reality be a function of height as well as of time; no formulation with the wind at rest in a single frame of reference is possible.

[10] To describe solar wind-magnetosphere-ionosphere/ thermosphere coupling, Song et al. [2005a, 2005b] developed a self-consistent three-fluid formalism, with electromagnetic coupling and collisions among electrons, ions and neutrals. The three key equations, in addition to Maxwell's equations and continuity equations, are the (three-fluid) generalized Ohm's law and the momentum equations for plasma and neutrals, describing the evolution of three important measurable quantities: electric current, plasma velocity and neutral wind velocity. Vasyliūnas and Song [2005] further derived the energy equations for such a threefluid system, which govern the temperatures or pressures in the fluids, and showed that the electromagnetic energy from the magnetosphere is coupled to the ionosphere primarily through frictional processes (not by Joule heating, in the proper physical sense of the term, contrary to common usage). In principle, the solution of this equation set plus the corresponding continuity equations and Maxwell equations provides a self-consistent description of the coupling from the collisionless solar wind and magnetosphere to the collisional ionosphere and thermosphere, as the collision frequencies vary from zero to finite values. We emphasize the time-dependent self-consistency of the theory in solving for neutral wind, plasma, current, and electric field as functions of height and time. In transient magnetospheric processes (such as those during substorms) plasma motion and electric field and current can vary substantially, and the neutral wind can be accelerated or decelerated at different rates at different heights; when these time and height dependences are included, the description of ionospheric and coupled magnetospheric processes may be substantially different from previous models, and some existing observations may need to be reinterpreted.

[11] To understand the solutions of this equation set, *Song et al.* [2005a] explored first the solutions for simplified onedimensional (1-D) steady states and found that with a selfconsistent neutral wind the ionospheric currents and the plasma velocity are quite different from those with a fixed neutral wind. *Song et al.* [2005b] then examined the wavetype solutions and dispersion relations; they found that the low-frequency perturbations propagate along the magnetic field much more slowly than the Alfvén velocity in the ionosphere, owing to the increasing neutral inertial loading process as collisions become more and more important.

[12] One difficulty in solving the equation set numerically arises from the large range of time scales on which particles respond to changes in the field and collide with particles of other types. At the lower end of the ionosphere, the plasma collision times are in the range of 10^{-6} s whereas they are greater than 10^5 s on the topside of the ionosphere. In the present study we examine the solutions for a one-dimensional system that responds to a change in the magnetospheric driver of the ionosphere/thermosphere system. This gives a simplified description of the local ionospheric responses to an IMF change. Unlike conventional models, the driver in our model is horizontal plasma motion, instead of electric

field or Birkeland current, at the top boundary of the system; as discussed above, in MHD the electric field and current are secondary/derived quantities and should not be used as the drivers [*Vasyliūnas*, 2001, 2005a, 2005b, 2007; *Parker*, 2007].

[13] Given that the magnetosphere-ionosphere coupling has been a subject of debate for decades, we will focus on some fundamental and immediate consequences from the formalism, merely checking that the results are not in conflict with established general observations; direct comparisons with specific observations are to be made after the theory has been developed to a relatively more realistic level. Since this work represents a first attempt to understand the M-I coupling in a self-consistent way, we will start with the simplest one-dimensional situation, leaving the more interesting cases of two and three dimensions for later investigations. In section 2, we present the fundamental equations and outline the physical problems we are targeting and our simplifications. In section 3, we show the selfconsistent solutions for a one-dimensional system which may be taken as representing the local ionosphere near the pole; we describe the ionospheric plasma motion, the formation and evolution of the current, the acceleration of the neutral wind, and the response of the system both in time and in height to a magnetospheric convection reversal (which can result from an IMF reversal). In section 4 we discuss the physical insights from the calculation and the differences from conventional models.

2. Basic Equations and Numerical Setup

[14] The three-fluid theory treats three species, that is, electrons, ions, and neutrals [e.g., *Gombosi*, 1994; *Schunk and Nagy*, 2000]. The momentum equations for the three species can be combined and rewritten [*Song et al.*, 2005b] as the generalized Ohm's law, the plasma momentum equation, and the neutral momentum equation:

$$-\frac{m_e}{e}\frac{\partial \mathbf{j}}{\partial t} = \mathbf{j} \times \mathbf{B} - N_e e(\mathbf{E} + \mathbf{V} \times \mathbf{B}) - N_e m_e(\nu_{en} - \nu_{in})(\mathbf{V} - \mathbf{U}) + \frac{m_e}{e} \left(\frac{m_e}{m_i}\nu_{in} + \nu_{en} + \nu_{ei}\right) \mathbf{j}, \tag{1}$$

$$m_i N_e \frac{\partial \mathbf{V}}{\partial t} = \mathbf{j} \times \mathbf{B} - N_e (m_i \nu_{in} + m_e \nu_{en}) (\mathbf{V} - \mathbf{U}) + \frac{m_e}{e} (\nu_{en} - \nu_{in}) \mathbf{j}, \qquad (2)$$

$$m_n N_n \frac{\partial \mathbf{U}}{\partial t} = N_e (m_i \nu_{in} + m_e \nu_{en}) (\mathbf{V} - \mathbf{U}) - \frac{m_e}{e} (\nu_{en} - \nu_{in}) \mathbf{j}, \quad (3)$$

where e, $N_{\eta \tau}$ **j**, **V**, **E**, **U**, **B**, $m_{\eta \tau}$, and $\nu_{\eta \xi}$ are the elementary electric charge, the number density of species η , the electric current, the plasma bulk velocity, the electric field, the bulk velocity of neutrals, the magnetic field, the mean mass of particles of species η , and the collision frequency between particles of species η and ξ , respectively. Subscripts *i*, *e*, and *n* denote ions, electrons, and neutrals, respectively. Note that all the different ions have been lumped together into one ion species, and likewise all the different neutrals into one neutral species; composition is taken into account only in determining the mean mass $m\eta$. We have assumed that $m_i\nu_{in} \gg m_e\nu_{en}$, that the ions are singly charged, and that charge quasi-neutrality holds in the plasma, or $N_e = N_i$. For simplicity, we have neglected all other forces, in particular all the kinetic-tensor terms (flow and pressure gradients). Invoking conservation of momentum in collisions, we have written the plasma-neutral collisions terms that constitute the right-hand side of equation (3) as minus the plasmaneutral collision terms of equation (2).

[15] Equations (1)-(3) describe the behavior of the current, plasma motion, and neutral wind, as well as their corresponding species: electrons, ions, and neutrals, respectively. An interesting feature of equations (1)-(3) is that they contain no spatial derivatives and thus cannot, by themselves, communicate temporal variations between different locations in space, that is, describe propagation effects; for that, one must invoke the electromagnetic field through Maxwell's equations:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},\tag{4}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j},\tag{5}$$

where μ_0 is the permeability in vacuum. In the following calculations, we neglect the time derivative of the current in equation (1), an approximation valid when dealing with phenomena on space and time scales large in comparison to those of electron plasma oscillations, as discussed in detail by *Vasyliūnas* [2005a, 2005b]; under the same conditions, plasma quasi-neutrality holds, and equation (5) has no displacement-current term.

[16] For illustration purposes, we discuss the local ionosphere near the north pole, far from regions of significant Birkeland currents. This region can be simplified as onedimensional, all quantities varying spatially only with height. We define coordinates as x direction antisunward, y direction toward dawn, and z direction upward. For the ionosphere/thermosphere region we are interested in, from 80 km to 1000 km, Figure 1 shows the height-dependent gyrofrequencies, collision frequencies, plasma density, and Alfvén velocity, at the north magnetic pole during the winter solstice. They are calculated from formulas by Kelley [1989], Richmond [1995], and Schunk and Nagy [2000], with the use of values from the MSIS model [Hedin, 1987, 1988] and the International Reference Ionosphere (IRI) model [*Bilitza*, 2001]; the magnetic field of strength $B_0 =$ -50,000 nT is taken as constant with height and directed downward. The main cause for the changes in the ion gyrofrequency is the mean ion mass; at 1000 km height, the ion mass is about 2.8 atomic mass units, and the plasma number density is about 45,000 cm⁻³. Our fluid treatment is valid below the ion gyrofrequency, which is less than 273 s^{-1} . The ionosphere can be described as consisting of an F layer centered around 300 km and an E layer near 100 km; the collision effects become dominant below 200 km where the collision frequencies become larger than the ion gyrofrequency. The Alfvén speed is about 3000 km s^{-1} at the top, decreases in the F layer, and increases rapidly below the *E* layer where the plasma density drops sharply.



Figure 1. Ionospheric parameters used in the calculation. (left) The collision frequencies and gyrofrequency $f_i = eB/2\pi m_i$ as functions of altitude are calculated from formulas given by *Kelley* [1989]. (right) The electron density and the mean ion mass, which affects the Alfvén speed and the ion gyrofrequency, are derived from the International Reference Ionosphere model. The magnetic field is assumed constant with height.

[17] For simplicity we assume no flow or current along the magnetic field, that is, a horizontally stratified geometry. Vectors such as **j**, **E**, **V**, and **U** as well as the variation of the magnetic field then have only two components, in the horizontal plane. All the divergences are zero and the continuity equations are not needed. (These geometrical simplifications are assumed to hold within the region under study, up to the upper boundary at 1000 km; they need not apply much higher up, within the magnetosphere proper.) Since the perturbed magnetic field is much smaller than the background field, **B** is taken as **B**₀ in all the equations except equations (4) and (5). Combining equations (1)–(5), dropping smaller collision terms, and assuming the densities constant in time, we have as the equations to be solved

$$\frac{\partial \mathbf{V}}{\partial t} = -\frac{B_0}{m_i N_e \mu_0} \frac{\partial \mathbf{B}}{\partial z} - \nu_{in} (\mathbf{V} - \mathbf{U}) - \frac{m_e}{e m_i N_e \mu_0} (\nu_{en} - \nu_{in}) \frac{\partial \mathbf{B}}{\partial z} \times \hat{z},$$
(6)

$$\frac{\partial \mathbf{B}}{\partial t} = -B_0 \frac{\partial \mathbf{V}}{\partial z} - \frac{B_0}{eN_e \mu_0} \left[\frac{\partial^2 \mathbf{B}}{\partial z^2} - \frac{\partial N_e}{N_e \partial z} \frac{\partial \mathbf{B}}{\partial z} \right] \times \hat{z} \\
+ \frac{m_e}{e^2 \mu_0} \left[\frac{\nu_{en}}{N_e} \frac{\partial^2 \mathbf{B}}{\partial z^2} + \frac{\partial}{\partial z} \left(\frac{\nu_{en}}{N_e} \right) \frac{\partial \mathbf{B}}{\partial z} \right],$$
(7)

$$\frac{\partial \mathbf{U}}{\partial t} = \alpha \nu_{in} (\mathbf{V} - \mathbf{U}) + \frac{m_e}{m_n N_n e \mu_0} (\nu_{en} - \nu_{in}) \frac{\partial \mathbf{B}}{\partial z} \times \hat{z}, \qquad (8)$$

where $\alpha = m_i N_e / m_n N_n$.

[18] The system starts with $\mathbf{V} = \mathbf{U} = 0$ and $\mathbf{B} = \mathbf{B}_0$. At t = 0, the *x* component of the plasma velocity at the top boundary increases to $V_0 = 0.001 V_{A0}$ in 1 s, where V_{A0} is the Alfvén speed at 1000 km (top boundary). This may correspond to the time scale of a reconnection onset, the ion gyro period at the subsolar magnetopause. At the top boundary, the spatial derivative of the (perturbation) mag-

netic field is assumed to be zero. At the bottom boundary we assume that the spatial derivative of the plasma velocity is zero. For the magnetic field at the bottom boundary, we tested two different boundary conditions: either the current or the transverse magnetic field set to zero. Both boundary conditions give similar overall results but the former is less stable numerically and requires numerical dissipation to be explicitly introduced. The similarity between the two results is due to the fact that the plasma barely moves near the lower boundary because of the heavy neutral collisions. In this paper, the results from the latter boundary condition are presented. (Note that there is still some uncertainty concerning boundary conditions. One complicating factor is matching to the solution in the nonconducting atmosphere below the ionosphere, which cannot be described in the 1-D approximation.)

[19] Equations (6)–(8) are solved numerically with the use of a forward time centered space (FTCS) method [*Morton and Mayers*, 2005]. The spatial resolution of the calculation is 4 km and the time step is 10^{-7} s, smaller than any of the characteristic time scales in the equation set. Note that the extremely short collision periods at the bottom of the ionosphere are what dictate the time step of the whole calculation.

3. Self-Consistent Solution of the Dynamically Coupled System

3.1. Plasma Motion

[20] Figure 2 shows the plasma velocity, in V_{A0} , as a function of time and height. The initial motion at the top of the ionosphere propagates downward along the field through Alfvénic perturbations, while collisions reduce the amplitudes of the perturbations and the neutral inertia loading reduces the propagation speed for lower frequency perturbations [Song et al., 2005b]. The typical Alfvén speed in the system is 800 km s⁻¹. The Alfvén travel time is about 1 s. The perturbations are partially reflected owing to the density gradient, and these upward waves are reflected



Figure 2. (a, b) The horizontal plasma velocity, normalized to V_{A0} with V_x antisunward and V_y dawnward, as a function of height, for the first 30 s after the top boundary starts moving.

again at the top boundary where the driver is imposed. Figure 3 gives a close look at this initial transition. The topside velocity transition occurs in 1 s as assumed. The initial perturbation reaches the bottom of the system in about 1 s. The full strength of the driver is felt at the bottom in 2 s. Large velocity fluctuations occur in the first 10 s; see Figure 2b. The antisunward velocity profile reaches an overall quasi-steady shape for plasma in about 20 s, or about 20 Alfvén travel times although, as shown later, the neutrals continue to accelerate afterward. We also made calculations with the upper boundary at 500 km and at 2000 km (not shown) and found that the times to reach steady state are 12 s and 39 s, respectively, confirming that it takes about 20 Alfvén travel times for the system to reach quasi steady state.

[21] The dawn-dusk component of the velocity, V_y , is a fraction of the antisunward velocity. To understand the dawn-dusk flow, let us first take a look at equation (6). The first term on the right of equation (6) is the magnetic tension force which can be considered as Alfvénic, the second term the plasma-neutral collisional frictional force, and the third the effect of the difference between the electron and the ion collisions with neutrals. The last effect is less important in the *F* layer, and the first effect is less important in the *E* layer.

[22] At the beginning of the transient process, when t is less than 10 s, a dawnward flow in the topside F layer is produced by the secondary effect associated with the sunward bending of the field shown in the last term of equation (6), where we describe bending in a perspective from a higher altitude. The dawnward bending of the field line associated with this flow produces an additional antisunward flow perturbation, which results in a higher antisunward flow velocity than the driver velocity for a short period of time.

[23] In the E layer, while the collisions reduce the flow speed, the bending of the field affects the flow tangentially, the last term on the right of equation (6), instead of the first. In this case, the sunward bending of the field line produces a strong duskward flow in the E layer. The velocity profile continues evolving slowly in quasi steady state as the neutral wind velocity changes.

3.2. Evolution of Magnetic Field and Currents

[24] Figures 3b and 3c show the x component of the magnetic field, in units of B_0 , and the y component of the current, derived from equation (5) (in units of eV_0N_{e0} , where $N_{e0} = 45,000 \text{ cm}^{-3}$ is the plasma number density at 1000 km) during the first 2 s, respectively. At this dynamic stage, the kinks in the magnetic field line, which correspond to (horizontal) electric currents, propagate



Figure 3. (a) The *x* component of the plasma velocity normalized to V_{A0} , (b) the *x* component of the magnetic field normalized to B_0 , and (c) the *y* component of the current normalized to $eN_{e0}V_0$, for the first 2 s.



Figure 4. (a, b) The horizontal components of the magnetic field, normalized to B_0 , as functions of height, for the first 30 s.

down from the top ionosphere. In other words, the Pedersen current in the dynamics stage does not need to be formed by connecting downward and upward field-aligned currents; it simply propagates down horizontally from the magnetosphere. The F layer current is particularly strong during the first second.

[25] Figures 4 and 5 show the two horizontal components of the magnetic field and of the current, respectively, during the first 30 s. In about 20 s, the ionosphere reaches a quasi steady state. Above the F layer, the plasma moves with the same speed as at the top boundary. If the field line is visualized as moving with the plasma, in a quasi steady state it cannot be continuously bent when the topside continues to move while the bottomside stays still, hence slippages occur in between. Above the E layer, the slippages are proportional to the vertical shear of the horizontal velocity, as shown in Figure 2. The slippage is also associated with a change in the current (although the density and collision frequency profiles play a role in it as well), as can be easily understood by taking spatial derivatives of equation (2) in the steady state.

[26] In a quasi steady state, the Pedersen current is proportional to $m_i N_e \nu_{in}$. In the *F* layer, a peak in the Pedersen current is produced by the density profile. In the

lower portion of the ionosphere, the rapid increase in the collision frequency in the upper part of the *E* layer and the rapid decrease in the density at the bottom of the *E* layer combine to produce a peak in the Pedersen current. In the *F* layer, although the Pedersen current is weaker than in the *E* layer, it occupies a thicker layer and contributes significantly to the height-integrated Pedersen effect. The Pedersen current reaches its peak value more quickly than the Hall current and starts decreasing. There is an antisunward Hall current in the *F* layer around $t = 2 \sim 3$ s, correlated with the dawnward plasma flow.

3.3. Neutral Wind Acceleration

[27] The neutrals are accelerated by the collisions with ions, the main part of the first term on the right of equation (3), and by electrons, the main part of the last term of equation (3). Figure 6 shows the neutral wind velocities for 30 s and for 1 h. The neutral wind acceleration is, not surprisingly, mainly in the antisunward direction because it is driven by the plasma flow through collisions. The fastest acceleration occurs near 350 km in the *F* layer where the effective neutral-ion collision frequency ν_{ni} , defined from momentum conservation by $m_i N_e \nu_{in} = m_n N_n \nu_{ni}$, is maximum. At this height the collision time, equivalent to the



Figure 5. (a, b) The horizontal components of the current, normalized to $eN_{e0}V_0$, as functions of height, for the first 30 s.



Figure 6. The horizontal neutral wind velocity components, normalized to V_{A0} , as functions of height, for (a, b) the first 30 s and (c, d) 1 h.

acceleration time, is about 2 h in our case. This is the time scale for the neutrals to catch up with the ions and (ultimately) reduce the current to zero. In 1 h, the neutrals are accelerated to a half of the driving plasma speed. It is important to point out that while there is little acceleration in the E layer, the neutrals at the top boundary pick up some plasma speed over time.

[28] In the dawn-dusk direction, the neutral velocity is much smaller. It is, however, interesting that the neutrals in the E layer and F layer move initially in the opposite directions and later all duskward. In general, the effective neutral-ion collision frequency, ν_{ni} , is much larger in the F layer than that in the E layer, and hence the F layer neutrals respond to the plasma motion more quickly. The small initial dawnward motion in the F layer is caused by the dawnward plasma motion, as discussed above. At later times, the plasma in the F layer maintains a small duskward flow, so weak that it cannot be seen in Figure 2. Since the neutral velocity is in general much smaller in the dawn-dusk direction, the duskward F layer neutral wind can be seen in Figure 6d, noting that at the end of 1 h, the neutral wind speed has reached about 50% of the plasma speed in the F layer. The E layer neutral wind is accelerated by the large E layer plasma flow over a longer time scale because of the smaller effective neutral-ion collision frequency there.

[29] All the statements about longtime acceleration of the neutrals must be qualified, however, by the remark that all dynamical effects of the neutrals alone (not related directly to the plasma) have been neglected in our models so far (with the exception of the steady state calculation of *Song et al.* [2005a]).

3.4. IMF Reversal

[30] After 1 h of elapse physical time in the model, we reverse the direction of the plasma flow at the top boundary to investigate the possible ionospheric consequences due to a reversal of the IMF, from southward to northward. Figure 7 shows the results of the first 30 s after the reversal.

[31] With some oscillations, the plasma flow quickly reverses to sunward. The dawn-dusk plasma flow swings back and forth a few times in the F layer but reverses relatively quickly in the E layer. The magnetic field, on the other hand, is settled down more quickly in the dawn-dusk direction but fluctuates more in the x direction.

[32] The most prominent response to the IMF reversal is the dawn-dusk (Pedersen) current. There is an overshoot in the current by a factor of 3 in the *E* layer and over 50% in the *F* layer. The Hall current also overshoots by about 50%. The response in the neutrals is negligible during the first few minutes after the reversal.

4. Discussion

4.1. M-I Coupling Mechanism

[33] In our model, the change of magnetospheric convection is imposed as a flow at the top of the ionosphere, and the downward propagation of the change is explicitly described. Conventional M-I coupling models postulate a



Figure 7. (a, b) The horizontal plasma velocity normalized to V_{A0} , (c, d) the horizontal components of the magnetic field normalized to B_0 , (e, f) horizontal components of the current normalized to $eN_{e0}V_0$, and (g, h) horizontal components of the neutral wind velocity normalized to V_{A0} , as functions of height, for 30 s after the flow reversal, which occurs 1 h after the start of the calculation at the magnetospheric boundary.



Figure 8. The *y* component of the electric field, normalized to B_0V_0 , as a function of height, for (a) the first 20 s after the top boundary starts moving and (b) 20 s after the flow reversal at the magnetospheric boundary, which occurs 1 h after the start of the calculation.

change, either of electric field or of Birkeland current, along the entire height range, in effect occurring instantaneously. The imposition of the electric field can be viewed, of course, as completely equivalent to the imposition of an equivalent plasma flow (in accordance with the discussion in the introduction). No instantaneous change at all heights with the same value, however, can be considered physical, and describing propagation explicitly is an essential part of any self-consistent model.

[34] In our model, the ionosphere is driven by the (horizontal) plasma flow in the magnetosphere and locally via the magnetic tension force; no explicit reference to a field-aligned current is required. Field-aligned currents are only an end effect, at places where the flow or plasma is not uniform. The Pedersen current therefore is not produced by linking upward and downward Birkeland currents but propagates down directly from the magnetosphere as kinks on the field lines, kinks that later dissolve to become field line slippages. It is therefore not surprising that the currents are stronger at the beginning of the transition. A quasi steady state is reached when the tension force is balanced by the neutral collision force. (A detailed description of current formation in these terms is given by Vasyliūnas [2005b].) In a steady state, owing to the slippage along a field line associated with the Pedersen current, plasma on the segment of the field line below the current moves more slowly than plasma above it. This slippage allows the plasma at the bottom of the ionosphere to remain attached to the neutral atmosphere while plasma on the topside segment moves with the magnetospheric convection. In contrast to the conventional field-aligned current coupling, the coupling in our model takes place over the entire polar cap, not just in the narrow regions where the field-aligned currents are strong.

[35] In the current stage of development of our model, we have not included the energy equations and hence cannot follow the energy flow paths and transformations in detail. Energy is supplied at or above the top boundary, by whatever process produces and maintains the assumed increase of the plasma bulk flow, and is carried downward as electromagnetic energy by the Poynting vector (the simplified model geometry precludes a downward transport of mechanical energy). This accounts directly for the energy in magnetic field perturbations, via $\mathbf{E} \bullet \mathbf{J}$ for the kinetic energy of plasma bulk flow, and further via collisions for the kinetic energy of neutral bulk flow. The additional dissipation and frictional heating of both plasma and neutrals can be calculated only with the use of the energy equations, described by *Vasyliūnas and Song* [2005]. Note that all these processes can take place without the presence of local field-aligned currents.

4.2. Dynamical Coupling Processes

[36] When the magnetospheric convection changes, the field lines will be distorted and the additional tension force will accelerate the local plasma at each altitude until a new quasi steady state is reached. In the quasi steady state, the neutrals continue to be accelerated by the plasma through collisions, over much longer time scales.

[37] In our model, we do not assume that the horizontal electric field is constant along the magnetic field, and no potential mapping is invoked. The electric field as a function of height can be self-consistently derived from equation (1) and is shown in Figure 8, normalized to V_0B_0 , for 20 Alfvén travel times. The variations in the electric field can be over 50% during the transition time. After the quasi steady state has been reached, the electric field is constant, and the potential mapping becomes a useful method to simplify calculations. We should mention that the time scale for establishing potential mapping is longer than 10 Alfvén travel times (not light travel times!).

[38] The key relationship used in conventional M-I coupling theories is the ionospheric Ohm's law in the neutral frame of reference. It can be derived from the steady state versions of equations (1) and (2) by eliminating V [see, e.g., *Song et al.*, 2001; *Vasyliūnas and Song*, 2005] to obtain

$$\mathbf{j} = \stackrel{\leftrightarrow}{\sigma} \bullet (\mathbf{E} + \mathbf{U} \times \mathbf{B}) = \stackrel{\leftrightarrow}{\sigma} \bullet \mathbf{E}',\tag{9}$$

where $\vec{\sigma}$ is the conductivity tensor. Note that this derivation assumes a quasi steady state both in the magnetic field and in the plasma motion. As we have shown above, this assumption is not valid within 20 Alfvén travel times and is very poor in 10 Alfvén travel times.



Figure 9. The y component of the electric field in the neutral wind frame of reference, normalized to B_0V_0 , as a function of height, for 1 h after the start of the calculation.

[39] If the source of the perturbations is 15 R_E above the polar ionosphere, the Alfvén travel time is about 1.5 min, corresponding to at least a 15-min transition time. The strong enhancement, during the first 10 Alfvén travel times after the reversal of magnetospheric convection in our calculation, of the dawn-dusk current by a factor of 3 (see Figure 5b) imply an enhancement of the Pedersen current, an effect that may possibly be related to preconditioning of the magnetosphere for substorms. Furthermore, the sign of the current can change during the transient process, giving oscillations in the current. This is an interesting aspect of the model, in view of the ubiquitous occurrence of observed oscillatory magnetic field perturbations.

4.3. Neutral Wind Effect in M-I Coupling

[40] In many conventional models, in particular the global MHD models, the neutral atmosphere is assumed to be at rest in the frame of reference of the Earth: $\mathbf{U} = \mathbf{0}$ in equation (9). Figure 9 shows the error from this approximation, which can become as large as 50% in the F layer in 1 h and increases with time as the neutrals are accelerated up to the plasma flow speed. The error in the electric field remains negligibly small in the sunward direction in all heights, within a few hours. Since the error is largest in the F layer, additional care is needed when interpreting observations or assimilating measurements from different heights to models.

5. Conclusions

[41] To study the magnetosphere-ionosphere coupling, we have applied a three-fluid formalism to a geometrically highly simplified local patch of the ionosphere, which may nevertheless describe the essence of the situation well within the polar caps. In this stratified 1-D ionosphere/ thermosphere with vertical magnetic field without vertical flow, the system is driven by a (locally uniform) horizontal magnetospheric flow at the top boundary, the effect of which is propagated downward by the magnetic tension force. The horizontal electric field varies both in time and in height, instead of being simply mapped down. The horizontal currents propagating down from the magnetosphere

are associated directly with the kinks on the magnetic field lines, in contrast to the notion that horizontal currents result from Birkeland (magnetic field-aligned) currents; the latter are here just an end effect of the horizontal currents. Furthermore, the neutral wind velocity also varies in time and height, in contradiction to the single time-independent frame of reference of the neutral wind widely assumed in magnetosphere-ionosphere coupling models.

[42] Time-dependent solutions are derived selfconsistently for this 1-D model. The system responds to the magnetospheric driver very quickly, on a time scale of the Alfvén travel time. However, large perturbations persist for about 10 Alfvén travel times, and the system takes about 20 Alfvén travel times to reach a quasi steady state, a dynamic process substantially longer than what has been assumed in many global models. During the transition period, flows and Pedersen currents are enhanced over their eventual quasi steady state values, and velocity reversals with height may also occur, both in plasma and in neutral wind. The horizontal electric field typically overshoots by about 50% before settling to its quasi steady state value. The acceleration of the neutral wind is fastest in the F layer, where in the absence of purely neutral stresses plasma and neutral flows can become equal in a few hours.

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