A Three-Dimensional Time-Dependent Model of the Polar Wind

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A time-dependent global model of the polar wind was used to study transient polar wind perturbations during changing magnetospheric conditions. The model calculates three-dimensional distributions for the NO^+ , O_2^+ , N_2^+ , N^+ and O^+ densities and the ion and electron temperatures from diffusion and heat conduction equations at altitudes between 120 and 800 km. At altitudes above 500 km, the time-dependent nonlinear hydrodynamic equations for O^+ and H^+ are solved self-consistently with the ionospheric equations. The model takes account of supersonic ion outflow, shock formation, and ion energization during a plasma expansion event. During the simulation, the magnetic activity level changed from quiet to active and back to quiet again over a 4.5-hour period. The study indicates the following: (1) Plasma pressure changes due to T_e , T_i or electron density variations produce perturbations in the polar wind. In particular, plasma flux tube motion through the auroral oval and high electric field regions produces transient large-scale ion upflows and downflows. At certain times and in certain regions both inside and outside the auroral oval, H^+ - O^+ counterstreaming can occur, (2) The density structure in the polar wind is considerably more complicated than in the ionosphere because of both horizontal plasma convection and changing vertical propagation speeds due to spatially varying ionospheric temperatures, (3) During increasing magnetic activity, there is an overall increase in T_e , T_i and the electron density in the F-region, but there is a time delay in the buildup of the electron density that is as long as five hours at high altitudes, (4) During increasing magnetic activity, there is an overall increase in the polar wind outflow from the ionosphere, while the reverse is true for declining activity, (5) In certain regions, however, localized ionospheric holes can develop during increasing magnetic activity, and in these regions the polar wind outflow rate is reduced, (6) During changing magnetic activity, the temporal evolution of the ion density morphology at high altitudes can be different from, and even opposite to, that at low altitudes.

1. INTRODUCTION

In the early 1960s, it was recognized that the interaction of the solar wind with the Earth's dipole magnetic field acts to significantly modify the magnetic field configuration in a vast region close to the Earth [Axford and Hines, 1961]. The dynamo action associated with the flow of solar wind plasma across magnetic field lines generates an intense current system, which acts to compress the Earth's magnetic field on the dayside and stretch it into a long comet-like tail on the nightside. The magnetic field lines that form the tail originate in the Earth's polar regions, and since the pressure in the ionosphere is much greater than that in the distant tail, it was suggested that a continual escape of thermal plasma (H^+ and He^+) should occur along these 'open' field lines [Bauer, 1966; Dessler and Michel, 1966].

The early suggestions of light ion outflow were based on a thermal evaporation process. Via thermal evaporation, the light ions would escape the topside ionosphere with velocities close to their thermal velocities and then flow along magnetic field lines to the magnetospheric tail. However, it was subsequently argued that the outflow should be supersonic and it was termed the 'polar wind' in analogy to the solar wind [Axford, 1968]. A simple hydrodynamic description was then used that emphasized the supersonic nature of the flow and the basic polar wind characteristics were elucidated [Banks and Holzer, 1968, 1969; Marubashi, 1970].

The supersonic nature of the polar wind has now been clearly established by both direct and indirect methods [Hoffman and Dodson, 1980; Nagai et al., 1984; Gurgiolo and

Burch, 1985; Persoon et al., 1983]. Also, theoretical modelling has shown that the polar wind is collision-dominated at low altitudes ($\lesssim 2000$ km) and collisionless at high altitudes. The collision-dominated characteristics of the flow have been extensively studied with the aid of hydrodynamic models [Banks and Holzer, 1968, 1969; Marubashi, 1970; Raitt et al., 1975, 1977; Schunk et al., 1978]. When collisions prevail, the temperature (or pressure) distribution is isotropic and the heat flow is proportional to the temperature gradient. In the collisionless regime, on the other hand, the temperature distribution is anisotropic and the mathematical formulation of the polar wind is considerably more complicated. This collisionless regime has been modelled with hydromagnetic [Holzer et al., 1971], kinetic [Lemaire, 1972; Lemaire and Scherer, 1970, 1973], and semi-kinetic [Barakat and Schunk, 1983, 1984] equations. Also, generalized transport equations have been used that include both collision-dominated and collisionless characteristics of the ion outflow, and hence, provide for continuity from the collision-dominated to collisionless regimes [Schunk and Watkins, 1981, 1982; Demars and Schunk, 1986, 1987; Ganguli, 1986; Ganguli and Palmadesso, 1987; Ganguli et al., 1987].

All of the above studies of the 'classical' polar wind were for 'steady state' conditions, with the emphasis on elucidating physical processes. As a result of these studies, significant progress has been made in understanding the basic polar wind characteristics for a wide range of conditions [cf. Schunk, 1986, 1988]. More recently, attention has been focussed on studying the temporal characteristics of the polar wind. However, because of the severe numerical difficulties associated with solving the more complicated sets of transport equations [cf. Schunk, 1977; Demars and Schunk, 1979; Barakat and Schunk, 1982], the initial time-dependent mod-

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els of the classical polar wind were based on a hydrodynamic formulation [Singh and Schunk, 1985; Gombosi et al., 1985, 1986; Gombosi and Schunk, 1988].

Singh and Schunk [1985] studied the temporal evolution of density perturbations in the supersonic collisionless polar wind, including extended density depletions and localized density bumps and holes. For this study, the H^+ continuity and momentum equations were solved without allowance for collisions and assuming constant, isotropic ion and electron temperatures of 3560 K. Also, the effects of localized ion heating on the polar wind were studied by Gombosi et al. [1985, 1986] and by Gombosi and Killeen [1987]. Both high-altitude and low-altitude ion heating events were considered. In these studies, the full hydrodynamic continuity, momentum, and energy equations for H^+ , O^+ , and electrons were solved including collisional conductivities and assuming isotropic, but variable, ion and electron temperatures.

More recently, Gombosi and Schunk [1988] conducted a comparative study of plasma expansion events in the polar wind. The temporal characteristics of the polar wind were studied with both a full set of hydrodynamic equations and a simplified set of collisionless equations that took account of the extremely large ion temperature anisotropies that develop at high altitudes [cf. Holzer et al., 1971; Lemaire and Scherer, 1973]. These temperature anisotropies were shown to be stable with respect to the excitation of electrostatic waves by Barakat and Schunk [1987]. The two different polar wind models were solved with different numerical techniques and the results were compared for a range of idealized expansion scenarios. The models were also used to study the temporal response of the polar wind to varying electron temperature conditions.

All of the time-dependent polar wind studies described above were based on one-dimensional models applied to a single location, with the temporal variations driven by assumed inputs. In this paper, we present a time-dependent, three-dimensional, multi-ion model of the polar wind. The model covers the altitude range of from 120 to 9,000 km and takes account of supersonic ion outflow, shock formation, and ion energization during plasma expansion events. In the first application of the model, we studied the temporal response of the global polar wind to changing magnetospheric conditions, i.e., time-varying convection and precipitation patterns.

2. POLAR WIND MODEL

The three-dimensional time-dependent model of the polar wind consists of a low-altitude ionosphere-atmosphere model and a high-altitude hydrodynamic model. These models are described in the following subsections.

2.1. Low-Altitude Ionospheric Model

The low-altitude ionospheric model was initially developed as a mid-latitude, multi-ion (NO^+ , O_2^+ , N_2^+ , and O^+) model by Schunk and Walker [1973]. The time-dependent ion continuity and momentum equations were solved as a function of altitude for a corotating plasma flux tube including diurnal variations and all relevant E and F region processes. This model was extended to include high latitude effects due to convection electric fields and particle precipitation by Schunk et al. [1975, 1976]. A simplified ion energy equation was also added, which was based on the as-

sumption that local heating and cooling processes dominate (valid below 500 km). Flux tubes of plasma were followed as they moved in response to convection electric fields. A further extension of the model to include the minor ions N^+ and He^+ , an updated photochemical scheme, and the mass spectrometer/incoherent scatter (MSIS) atmospheric model is described in Schunk and Raitt [1980].

The addition of plasma convection and particle precipitation models is described in Sojka et al. [1981a, b]. More recently, the ionospheric model has been extended by Schunk and Sojka [1982a] to include ion thermal conduction and diffusion-thermal heat flow, so that the ion temperature is now rigorously calculated at all altitudes between 120–800 km. The adopted ion energy equation and conductivities are those given by Conrad and Schunk [1979]. Also, the electron energy equation has been included recently by Schunk et al. [1986], and consequently, the electron temperature is now rigorously calculated at all altitudes. The electron energy equation and the heating and cooling rates were taken from Schunk and Nagy [1978], and the conductivities were taken from Schunk and Walker [1970].

2.2. High-Altitude Hydrodynamic Model

The high-altitude model is based on a numerical solution of the time-dependent coupled continuity and momentum equations for H^+ and O^+ ions. The equations are solved along a diverging 'open' magnetic flux tube with boundary conditions specified at low altitudes and outflow conditions imposed at high altitudes. The specific equations adopted are as follows:

$$\frac{\partial n_i}{\partial t} + \frac{1}{A} \frac{\partial}{\partial r} (A n_i u_i) = P_i - L_i n_i \quad (1)$$

$$\begin{aligned} \rho_i \left[\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial r} \left(\frac{u_i^2}{2} \right) \right] + \frac{\partial}{\partial r} \left(n_i k T_i^{\parallel} \right) - n_i e_i E_{\parallel} \\ + \rho_i \frac{G M_E}{r^2} + n_i k \left(T_i^{\parallel} - T_i^{\perp} \right) \frac{1}{A} \frac{\partial A}{\partial r} \\ = \rho_i \sum_{\alpha} \nu_{i\alpha} (u_{\alpha} - u_i) \Phi_{i\alpha} \end{aligned} \quad (2)$$

where n_i is the density of ion species i (H^+ or O^+), u_i is the field-aligned drift velocity, $T_i^{\parallel}$ is the temperature parallel to the geomagnetic field, $T_i^{\perp}$ is the perpendicular temperature, m_i is the mass, $\rho_i = n_i m_i$, P_i is the production rate, L_i is the loss frequency, $\nu_{i\alpha}$ is the momentum transfer collision frequency for species i and α , $\Phi_{i\alpha}$ is a velocity-dependent correction factor, $E_{\parallel}$ is the polarization electric field, e is the electron charge, k is Boltzmann's constant, G is the gravitational constant, M_E is the Earth's mass, t is time, r is the distance along the magnetic flux tube, and A is the cross-sectional area of a flux tube. At high latitudes $(1/A) \partial A / \partial r \approx 3/r$.

The polarization electric field is obtained from the electron momentum equation

$$E_{\parallel} = - \frac{1}{en_e} \frac{\partial p_e}{\partial r} \quad (3)$$

where subscript e corresponds to electrons, $p_e = n_e k T_e$ and where T_e is assumed to be governed by an equation of state,

$$T_e n_e^{(1-\gamma_e)} = \text{constant} \quad (4)$$

with γ_e the ratio of specific heats. The electron density and drift velocity are obtained by assuming charge neutrality ($n_e = n(\text{H}^+) + n(\text{O}^+)$) and charge conservation ($n(\text{H}^+)u(\text{H}^+) + n(\text{O}^+)u(\text{O}^+) - n_e u_e = J_{\parallel}/e$; $J_{\parallel}$ is the field-aligned current).

At altitudes between 800 and 1300 km, where the plasma is collision-dominated [Raith et al., 1975], an isotropic constant ion temperature is assumed ($T_i^{\parallel} = T_i^{\perp} = \text{constant}$). Above 1300 km, the following ion equations of state are adopted:

$$T_i^{\parallel} n_i^{(1-\gamma_i)} = \text{constant} \quad (5)$$

$$T_i^{\perp}/B = \text{constant} \quad (6)$$

where γ_i is the ratio of specific heats, B is the magnetic field strength, and $T_i = (T_i^{\parallel} + 2T_i^{\perp})/3$.

At high altitudes, the dominant production and loss processes for both H^+ and O^+ stem from the accidentally-resonant charge exchange reaction,

where the forward, k_f , and reverse, k_r , reaction rates are given by [cf. Raith et al., 1975; Barakat et al., 1987]

$$k_f = 2.5 \times 10^{-11} \left[T_n + \frac{T(\text{O}^+)}{16} + 1.2 \times 10^{-8} u^2(\text{O}^+) \right]^{1/2} \quad (8a)$$

$$k_r = 2.2 \times 10^{-11} \left[T(\text{H}^+) + \frac{T_n}{16} + 1.2 \times 10^{-8} u^2(\text{H}^+) \right]^{1/2} \quad (8b)$$

and where T_n is the neutral temperature and the units are $\text{cm}^3 \text{s}^{-1}$.

In the momentum equation (2), H^+ and O^+ were assumed to collide with each other and with neutral atomic oxygen and hydrogen. The appropriate collision frequencies and velocity-dependent correction factors are given by Raith et al. [1975].

The above set of nonlinear, time-dependent partial differential equations are solved with initial conditions and boundary values using the well-known flux-corrected-transport (FCT) technique [Boris and Book, 1976]. The equations are solved along a diverging magnetic flux tube from a lower boundary r_o to a specified upper boundary. At the lower boundary, the ion densities and drift velocities are specified, while at the upper boundary an outflow condition is assumed. Note that when time derivatives are included in the continuity and momentum equations, these equations do not contain a critical (singular) point as do the time-independent hydrodynamic models of the polar wind [Banks and Holzer, 1969].

We did not include He^+ in the high-altitude hydrodynamic model for this study because this would have significantly increased the computing time. However, He^+ will be included in future studies.

2.3. Combined Model

With the combined model, flux tubes of plasma are followed as they convect through a moving neutral atmosphere. With the 'low-altitude' ionospheric model, altitude profiles of the ion and electron temperatures and the NO^+ , O_2^+ , N_2^+ , O^+ and N^+ densities are obtained by solving the appropriate continuity, momentum and energy equations. The equations are solved over the altitude range from 120 to 800 km, with boundary conditions specified at the lower and upper ends. For the densities, chemical equilibrium is assumed at 120 km, and no escape flux is assumed for NO^+ , O_2^+ , N_2^+ and N^+ at 800 km. The O^+ escape flux at 800 km, at a given time step, is obtained from the 'high-altitude' H^+-O^+ model at the previous time step.

The high-altitude H^+-O^+ model is solved in parallel with the low-altitude ionospheric model for convecting flux tubes. In this case, the time-dependent nonlinear continuity and momentum equations for H^+ and O^+ are solved to obtain altitude profiles of the densities and drift velocities. These equations are solved over the altitude range from 500 to 9,000 km, which provides for an overlapping region between the low and high altitude models. This overlapping is needed for two reasons. First, the H^+-O^+ model must start at an altitude low enough to obtain reliable H^+ boundary conditions. Also, the low-altitude ionospheric model must go to an altitude high enough to assure an isothermal structure near the upper boundary, as discussed below. With regard to the H^+-O^+ boundary conditions, at the lower boundary (500 km) the densities and drift velocities are specified. The O^+ boundary values at a given time step are obtained from the low-altitude ionospheric model at its last time step. For H^+ , the boundary density at 500 km is obtained assuming chemical equilibrium and using the O^+ , O and H values from the low-altitude model at its last time step. The H^+ drift velocity at 500 km (in the chemical equilibrium region) is assumed to be zero. At the upper boundary (9,000 km), outflow boundary conditions are imposed on both O^+ and H^+ .

Since the low-altitude ionospheric model and the high-altitude H^+-O^+ model are solved with different numerical techniques, different time and space steps are required. The ionospheric model is solved with a 4 km vertical space step, while the H^+-O^+ model is solved with a vertical space step that varies as the flux tube convects (ranging from 10 to 45 km). For the ionospheric model, the time step varies from about 10 to 100 s as the flux tube convects. For the H^+-O^+ model, on the other hand, the time step is much smaller because of the numerical stability criteria associated with the FCT technique [cf. Boris and Book, 1976]. Typically, the time step is only 0.1–0.25 s, and hence, many H^+-O^+ time steps occur between one ionospheric model time step.

The ion and electron temperature profiles are obtained with the low-altitude ionospheric model over the altitude range from 120–800 km. For boundary conditions, local thermal equilibrium is assumed at 120 km, and ion and electron heat fluxes are specified at 800 km. Typically, the ion heat flux is taken to be zero because of the lack of measurements of this parameter. The electron heat flux at 800 km is calculated [cf. Schunk et al., 1986] and it varies with solar zenith angle on the dayside and with the magnitude of the precipitating auroral electron energy flux in the auroral oval. Near 800 km, T_e and T_i are usually constant

with altitude and the constant values are extrapolated to 1300 km. Above 1300 km, the plasma becomes collisionless and the ion temperatures become anisotropic [cf. *Holzer et al.*, 1971; *Lemaire and Scherer*, 1973; *Schunk and Watkins*, 1982]. Therefore, above 1300 km, equations (5) and (6) are used to obtain the anisotropic characteristics of the ion temperature distributions.

The model requires neutral densities over the full range from 120 to 9,000 km. The MSIS atmospheric model of *Hedin et al.* [1977] is used at altitudes between 120 and 1000 km. Above 1000 km, atomic oxygen and hydrogen are assumed to decrease exponentially with altitude at a rate determined by the MSIS neutral scale height at 1000 km.

3. CHANGING MAGNETOSPHERIC CONDITIONS

As noted earlier, all of the time-dependent polar wind studies conducted to date were based on one-dimensional models applied to a single location. In this investigation, we used a time-dependent three-dimensional model of the polar wind to study transient thermal ion outflows during changing magnetospheric conditions. In this first attempt to model the global polar wind, we assumed that the only time-varying magnetospheric inputs were the convection electric field and particle precipitation patterns, with the assumed time-scale for magnetospheric variations on the order of one-half hour. As magnetic activity increases, we simply assumed that the electric field strengths increase, that the auroral oval expands, and that particle precipitation intensifies. This approach to changing magnetospheric conditions is similar to that used in our previous study of *F* region storms [cf. *Sojka and Schunk*, 1983, 1984].

Because of these simplifying assumptions, we did not model the polar wind response to a true magnetic 'storm'. During a storm, the magnetospheric inputs probably change in a more complicated manner than we have assumed. Nevertheless, the basic physics we have included (electric field heating, increased convection speeds, elevated temperatures inside the oval, etc.) is similar. Also, during a storm the neutral wind, composition, and temperature change, and these changes are not included in this study. However, our study was conducted for winter solstice at solar minimum, and in this case the time constant for accelerating the neutral atmosphere in and above the *F* region is of the order of several hours to a day [*Killeen et al.*, 1984]. Since our changing magnetospheric conditions last for only 4.5 hours, our neglect of the atmospheric response should not appreciably affect our results.

Figure 1 shows the variation of *Kp* as a function of time for changing magnetic conditions. Prior to changing magnetic conditions, the *Kp* index was set at 1.5. Then, at 3.5 hours UT, the *Kp* index increased linearly to a value of 8 over a one-half hour period. This value was maintained for one hour, and then *Kp* decreased linearly back to 1.5 over a 3-hour period. After this time, *Kp* was kept fixed at 1.5. Changing magnetic conditions occurred for only 4.5 hours, from 3.5 to 8 hours UT. The model study was continued beyond 8 UT in order to allow the ionosphere sufficient time to relax back to a quiet time situation. The arrows at the top of Figure 1 show the times at which results are displayed in subsequent figures.

The dependence of the convection pattern on *Kp* is not well-known at the present time, and in our study *Kp* was

Fig. 1. Variation of *Kp* with time for changing magnetic conditions. The activity increase is over a 1/2 hour period, the enhanced activity lasts for 1 hour, and the decay is over a 3-hour period. The selected times t_1 – t_7 correspond to the times ionospheric parameters will be shown in subsequent figures; these times are 3.6, 3.9, 4.25, 4.75, 6, 7 and 9.5 hours UT, respectively.

only used as a rough guide in selecting convection patterns [cf. *Reiff et al.*, 1981]. We adopted two convection patterns, one for *Kp* = 1.5 (quiet time) and one for *Kp* = 8 (active time). Both convection patterns were symmetric two-cell patterns of the *Heelis et al.* [1982] type. For *Kp* = 1.5, the potential drop across the polar cap was 40 kV, while for *Kp* = 8 it was 125 kV. (Only the cross polar cap potential Φ was relevant to our study. The index *Kp* was merely used to track the temporal morphology of our magnetic storm. To relate *Kp* and Φ we used the simple linear relation, $\Phi = 20 + 13Kp$ (keV), proposed by *Heppner* [1973]). At latitudes equatorward of the polar cap boundary, the electrostatic potential was assumed to decrease as the inverse of the fourth power of sine colatitude. When the corotational potential is added to the adopted quiet-time and active magnetospheric potential patterns, the resulting potential patterns take the form shown in Figure 2. Note that the quiet-time (*Kp* = 1.5) and active (*Kp* = 8) convection patterns were imposed on the ionosphere only at the appropriate level of *Kp*. For changing *Kp*, the convection pattern varied systematically between the two patterns. That is, during increasing and declining activity the 'actual' convection pattern evolves from the quiet-time to the active pattern or vice versa.

To describe the variation of the auroral electron energy flux during changing magnetic activity, we adopted the empirical model developed by *Spiro et al.* [1982]. The energy flux displays a systematic variation with the auroral index *AE*, which was varied from a value of 65 for quiet times to a value of 600 for active times. The quiet-time and active precipitation patterns are shown in Figure 3, where contours of the auroral electron energy flux are displayed in an MLT-magnetic latitude reference frame. For the quiet-time pattern, the electron energy flux reaches its highest value of $3 \text{ ergs cm}^{-2} \text{ s}^{-1}$ in the midnight-dawn sector. For the active pattern, the auroral oval is expanded, the precipitation is considerably more intense, and the maximum electron energy flux occurs in the dusk-midnight sector where it reaches

Fig. 2. Plasma drift trajectories for magnetically quiet and active conditions. Both patterns are for symmetric two-cell convection with corotation included. For the quiet pattern the total cross-tail potential is 40 kV, while for the active pattern it is 125 kV. The contour separation is 10 kV.

a value of $15 \text{ erg cm}^{-2} \text{ s}^{-1}$. During changing magnetic activity, when Kp and AE changed, we varied the energy flux by interpolating smoothly between the average fluxes for the AE ranges given by *Spiro et al.* [1982].

As noted above, the atmospheric response to changing magnetospheric conditions was not modelled self-consistently with the ionospheric response in this first global polar wind study. For the atmospheric densities, we adopted the MSIS empirical model [*Hedin et al.*, 1977] with $A_p = 10$, day 350 for winter conditions, and $F_{10.7} = 70 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$ for solar minimum. For the neutral wind pattern, we adopted the model discussed by *Sojka et al.* [1981a]. In this model, the wind blows from 1300 LT over the pole to 0100 LT. The wind speed at F region heights is 55 m/s on the dayside and 250 m/s on the nightside. Near the terminator, the wind varies smoothly from the dayside to the nightside value. Note that the nightside value is consistent with the 'average' meridional wind measured in the dark polar cap by *Meriwether et al.* [1988].

4. POLAR WIND RESPONSE TO CHANGING MAGNETIC ACTIVITY

The low-altitude ionospheric model was first run with the quiet-time auroral precipitation and convection patterns for 36 hours in order to obtain diurnally varying ionospheric densities and temperatures. The high-altitude $\text{H}^+ - \text{O}^+$ model was run in parallel with the ionospheric model so that self-consistent polar wind profiles could be obtained. Then, starting at 2.5 hours UT, the magnetospheric inputs were varied according to the 'storm' profile shown in Figure 1 and the resulting response of the ionosphere and polar wind was calculated. Since the polar wind fluctuations are driven by variations in the F region densities and temperatures, it is convenient to present the F region response first.

4.1. Global F Region

Plate 1 shows 'snapshots' of $n(\text{O}^+)$, T_e , and T_i at 300 km above the polar region for times corresponding to increas-

Fig. 3. Contours of the auroral electron energy flux ($\text{erg cm}^{-2} \text{ s}^{-1}$) for quiet ($AE = 65$) and active ($AE = 600$) conditions in a magnetic latitude-MLT reference frame. The contour separation is $2 \text{ erg cm}^{-2} \text{ s}^{-1}$.

Plate 1. Contours of $\log_{10} n(O^+)$, T_e and T_i at 300 km for times corresponding to increasing (t_1), high (t_4), and declining (t_6) magnetic activity. A magnetic latitude-MLT reference frame is used.

ing activity (t_1), high activity (t_4), and declining activity (t_6). The variations of the different ionospheric parameters are color coded and displayed in an MLT-magnetic latitude reference frame. Red corresponds to high densities and temperatures, while blue corresponds to low densities and temperatures. Before the storm, the O^+ density exhibits a dayside trough at this UT, but it is enhanced in the auroral oval due to production via precipitating electrons. As magnetic activity increases, the auroral oval expands, the intensity of electron precipitation increases, and the plasma convection speeds increase. The enhancement in auroral precipitation leads to higher O^+ densities in the auroral F region, and these enhanced densities are then transported into the polar cap on the dayside and to lower latitudes on the nightside due to plasma convection. Note that the most extensive region of enhanced O^+ densities occurs at time t_6 , which is near the end of the magnetic storm (see Figure 1). As noted in a previous study, the F region density changes exhibit a significant time delay with respect to changing magnetospheric inputs [Sojka and Schunk, 1983]. This time delay increases with altitude, and since the source of H^+ in the polar wind is the $O^+ + H \rightleftharpoons H^+ + O$ reaction, the polar wind response to changing magnetic activity should also exhibit a time delay.

The electron temperature variation during changing magnetic activity is shown in the middle row of Plate 1. In contrast to the O^+ density variation, the T_e variation tends to follow the storm profile shown in Figure 1 because the time constant for T_e changes is of the order of a few seconds. However, residual storm effects can still occur because the electron-ion thermal coupling is determined by the O^+ density, which exhibits time delays. During increasing magnetic activity (t_1), elevated electron temperatures appear on the dayside and in the auroral oval, particularly on the nightside. At this time, T_e over the polar region varies from 900 to 2500 K, with T_e in the sunlit region being greater than that in the auroral oval. However, during high magnetic activity (t_4), T_e is increased in the auroral oval via energy transfer from precipitating electrons, and T_e in the nocturnal oval reaches 3000 K at 300 km (purple shows the region where $T_e \geq 2400$ K). When the magnetic activity decreases (t_6), there is a corresponding decrease in the region of high auroral electron temperatures.

The ion temperature variation during changing magnetic activity is shown in the bottom row of Plate 1. Before the storm, T_i is elevated slightly on the dayside and in the auroral oval owing to thermal coupling to the hot electrons. However, the ion thermal balance is mainly controlled by frictional interactions with the neutral atmosphere [cf. Schunk and Sojka, 1982a]. Therefore, at high magnetic activity (t_4), the increased plasma convection speeds lead to enhanced ion temperatures. For the adopted symmetric two-cell convection pattern, the largest electric fields occur on the dayside where the plasma turns to enter the polar cap. Consequently, two ion temperature 'hot spots' are collocated with these large electric field regions [cf. Schunk and Sojka, 1982b]. During declining activity (t_6), when convection subsides, the ion temperature decreases.

Changes in the ionospheric plasma pressure, due to T_e , T_i or O^+ density changes, will produce polar wind changes because the underlying ionosphere feeds the polar wind. Therefore, as magnetic activity, and hence, T_e , T_i and $n(O^+)$ increase, there should be an overall increase in the global H^+

escape rate, while for declining activity the reverse should be true. However, as we will show below, superimposed on this general trend is a complicated polar wind structure because of ionospheric time delays, horizontal plasma convection, and varying vertical propagation times.

4.2. Global Polar Wind

Plate 2 shows snapshots of the O^+ density at 500 km (bottom row), 2500 km (middle row) and 9000 km (top row) above the polar region for times corresponding to increasing activity (t_1), high activity (t_4), and declining activity (t_6). As with Plate 1, the O^+ densities are displayed in an MLT-magnetic latitude coordinate system and color coded. As before, red corresponds to high densities and blue to low densities, but note that the different altitudes have different color scales that are kept fixed throughout the storm. At the start of increasing magnetic activity (t_1), the O^+ density features at 500, 2500, and 9000 km are similar to those in the F region (300 km), with relatively high densities in the auroral oval, moderate densities in the polar cap, and low densities in the dayside trough region. However, note that the O^+ density features get distorted with increasing altitude because the O^+ scale height depends on both T_e and T_i , which vary over the polar region. Also, horizontal plasma convection, coupled with spatially varying vertical propagation speeds, acts to distort the O^+ features as altitude increases, but this effect is small at the beginning of the storm.

As the storm intensifies, the increases in T_e , T_i and the O^+ density in the F region (Plate 1) act to induce a large-scale O^+ upwelling, which leads to a general increase in the O^+ density at all altitudes (compare times t_4 and t_1 in Plate 2). As before, the large-scale O^+ features seen in the F region are also seen at higher altitudes, but because of the greater horizontal convection speeds during high magnetic activity the O^+ features are distorted. The situation is further complicated when there are high O^+ density and high temperature regions close to one another in the F region, as is the case at t_4 between about 0400 MLT and 1600 MLT in the auroral oval (see Plate 1). In the F region, the high O^+ density region between 0400 MLT and 1000 MLT is contiguous with the regions of high T_e and T_i that extend from about 0900 MLT to 1600 MLT. Since enhancements in $n(O^+)$, T_e and T_i lead to O^+ upwellings, the O^+ density at high altitudes (2500 and 9000 km) tends to be elevated over this entire local time sector (Plate 2). However, there is one region at high latitudes where the O^+ density is lower during the storm than before the storm. This region is located between about 70–90° magnetic latitude on the nightside of the polar cap (compare t_1 and t_4 results in Plate 2). Note that the biteout in O^+ density extends throughout the F region and topside ionosphere (Plates 1 and 2). This localized polar hole is a result of plasma convection. As the plasma convects away from the magnetic pole on the nightside, there is a downward 'vertical' $\mathbf{E} \times \mathbf{B}$ drift component that is strong during high activity, which drives the F layer down and reduces the O^+ density. This occurs because although the $\mathbf{E} \times \mathbf{B}$ drift velocity is perpendicular to $\mathbf{B}$, the magnetic field is inclined to the vertical.

During the declining phase of the storm (t_6), the O^+ density enhancement at 300 km is greater than that during the high activity period (t_4). As noted earlier, this time delay in the buildup of the F region density is associated with the

Plate 2. O^+ density contours at 500 km (bottom row), 2500 km (middle row) and 9000 km (top row) for times corresponding to increasing (t_1), high (t_4), and declining (t_6) magnetic activity. A magnetic latitude-MLT reference frame is used. Note that different color scales are associated with the different altitudes.

Plate 3. H^+ density contours at 500 km (bottom row), 2500 km (middle row) and 9000 km (top row) for times corresponding to increasing (t_1), high (t_4), and declining (t_6) magnetic activity. A magnetic latitude-MLT reference frame is used. Note that different color scales are associated with the different altitudes.

diffusion time required to transport plasma from the precipitation source at low altitudes to the F region. However, at higher altitudes (500, 2500 and 9000 km), the O^+ density variation over the polar region tends to be more uniform than during the high activity (t_4) or increasing activity (t_1) phases of the storm. Also, at high altitudes, the O^+ densities are generally lower in and near the oval at time t_6 than during high magnetic activity (t_4) despite the fact that the O^+ densities in the underlying F region are higher. The basically lower, more uniform O^+ densities at high altitudes result from the opposing effects of an F region density buildup and decreasing electron and ion temperatures. In some areas the O^+ flow is upward, while in other areas it is downward. This complicated behavior will be discussed in more detail in the next subsection where the dynamics associated with individual convecting flux tubes will be presented.

The H^+ densities that correspond to the O^+ densities in Plate 2 are shown in Plate 3, where contours of $\log_{10} n(H^+)$ are displayed at 500 km (bottom row), 2500 km (middle row) and 9000 km (top row) for times corresponding to increasing activity (t_1), high activity (t_4) and declining activity (t_6). The H^+ densities are color coded, with red corresponding to high densities and blue to low densities. The different altitudes have separate color scales that are fixed throughout the storm. At the start of increasing magnetic activity (t_1), the H^+ density morphology is similar to the O^+ morphology, with relatively high densities in the oval in the midnight-dawn-noon sector, moderate densities in the central polar cap, and low densities in the dayside trough region. This result is not surprising, since at low altitudes O^+ is the source of H^+ via the $O^+ + H \rightleftharpoons H^+ + O$ reaction.

As the storm intensifies, there is a large-scale H^+ upwelling that occurs in association with the O^+ upwelling, and during high activity (t_4) the two ions again display similar morphological features. In particular, note that the polar hole in the O^+ density is reflected in the H^+ density as well. However, at high altitudes, the dynamic range of the H^+ density variation is much smaller than that of O^+ . For example, at 9000 km, the O^+ density varies from 10^{-1} to 10^3 cm^{-3} over the polar region, while the H^+ density variation is from 10 to 10^3 cm^{-3} . This smaller dynamic range for H^+ is related to the polar wind outflow characteristics [Banks and Holzer, 1969; Raitt et al., 1975]. Specifically, the H^+ density scale height is generally much greater than the O^+ scale height at high altitudes, and since H^+ is usually in an outflow situation, temperature changes do not dramatically affect the H^+ scale height. Changes in the much smaller O^+ scale height, on the other hand, can produce large O^+ density variations at high altitudes.

During declining magnetic activity (t_6), the H^+ density at 500 km is generally higher than what it was at any time during the storm. This time delay in the H^+ density buildup at low altitudes is simply a consequence of the time delay in the O^+ density buildup, which was discussed above (see Plates 1 and 2). However, at 2500 km, there are some polar regions where the H^+ density is lower than at the storm's main phase (t_4) and other polar regions where it is higher. Furthermore, at high altitudes (9000 km), there is an overall reduction in the H^+ density at t_6 relative to the storm's main phase (t_4) even though there is an overall H^+ density increase at low altitudes (500 km). This indicates that at times the temporal evolution of the H^+ density morphology at high altitudes can be opposite to that at low

altitudes during changing magnetospheric conditions. At other times, the H^+ density morphology at high and low altitudes can be different, but not opposite. Only for sustained magnetospheric conditions are the high and low altitude morphologies similar. The reason for the difference in the H^+ density morphologies at high and low altitudes during changing magnetospheric conditions is that there is a finite propagation time for low-altitude perturbations to reach high altitudes and vice versa. The situation is further complicated by horizontal plasma convection, changing vertical propagation speeds with changing plasma temperatures, and localized regions where H^+ downflows can occur. These additional complications are more evident when individual convecting flux tubes are followed.

4.3. Polar Wind Dynamics and Structure

The contour plots shown in the previous subsection were useful for studying the global polar wind during changing magnetic activity. However, in certain places and at specific times, the polar wind can be highly dynamic and exhibit a considerable amount of structure. This can best be shown by following individual convecting flux tubes of plasma as they move across the polar region.

Figure 4a shows a typical convection trajectory in the dawn sector. At the start of the storm profile shown in Figure 1, the flux tube is located at 65° magnetic latitude and 0430 MLT. Subsequently, the plasma flux tube moves sunward, enters the dayside auroral oval, passes through the convection throat, moves antisunward across the polar cap, enters the evening auroral oval, and then convects sunward again. The variations of T_e , T_i and T_n along the convection trajectory at an altitude of 500 km are shown in Figure 4b, while the corresponding O^+ , O and H density variations are shown in Figure 4c. An altitude of 500 km was selected for presentation of atmospheric and ionospheric parameters because the H^+ outflow typically begins above this altitude [Banks and Holzer, 1969; Raitt et al., 1975]. The associated H^+ and O^+ density variations along this trajectory are shown in Figures 4d and 4e, respectively, as a function of altitude, latitude, and time along the trajectory. Finally, H^+ and O^+ drift velocity profiles are shown at selected times in Figure 4f.

Fig. 4a. Convection trajectory of a selected flux tube of plasma during changing magnetic activity. At the start of the storm profile shown in Figure 1, the flux tube is located at 65° magnetic latitude and 0430 MLT.

Fig. 4b. Variation of T_e , T_i and T_n at 500 km versus time along the dawn convection trajectory. The peaks in T_e correspond to flux tube movement through the auroral oval.

In tracing the flux tube history, it starts convecting at $t = 2.5$ hrs UT during quiet geomagnetic activity. One hour later ($t = 3.5$ hrs UT), the storm commences, the auroral oval begins to expand, precipitation intensifies, and the convection speed increases. The flux tube enters an expanded dayside oval at $t = 3.7$ hrs UT (65° latitude, 0650 MLT) and then convects into the dayside high electric field region. The first broad T_e peak shown in Figure 4b corresponds to movement through the dayside storm auroral oval, while the T_i peak primarily results from ion-neutral frictional heating in the region of large electric fields. The sharp increase in both T_e and T_i between about 3.7 to 4.1 hrs UT results in a large-scale upwelling of both H^+ and O^+ , as seen by the increase in the H^+ and O^+ densities at high altitudes (Figures 4d and 4e) and by the enhanced upward flow velocities (Figure 4f, $t = 3.9$ hrs UT). The ion upwelling is also fed by a gradually increasing O^+ density in the underlying ionosphere during this time period (Figure 4c).

The maximum T_e and T_i are encountered at about $t = 4.1$ hrs UT (70° latitude, 1008 MLT) which corresponds to a time of high geomagnetic activity. Subsequently, the flux tube convects out of both the large electric field region and the region of intense precipitation. The resulting decreases in both T_e and T_i trigger H^+ and O^+ downflows that commence at $t = 4.25$ hrs UT when the flux tube is still in the auroral oval (oval exit is at 4.4 hrs UT) and continue until 4.9 hrs UT (see Figure 4f, $t = 4.55$ hrs UT). The O^+ response to the sharp decrease in T_e and T_i is dramatic in that the entire topside quickly collapses (Figure 4e). For H^+ , the density at high altitudes collapses due to a downflow in a manner similar to O^+ , but at low altitudes the H^+ density continues to increase. This buildup at low altitudes is partly due to the downflow from above and partly due to an H^+ upflow from the underlying ionosphere. Note that the increase in the O^+ density that occurs at low altitudes when the flux tube of plasma is in the dayside oval decays much more slowly after exiting the oval than T_e and T_i (Figures 4b and 4c). The H^+ density near 500 km builds up in response to this elevated O^+ density, but there is a time delay in the buildup of the upward H^+ flux in the low-altitude diffusion regime (500–800 km). Consequently, although the enhanced O^+ density at 500 km decays slowly, the upward H^+ flux continues to increase in response to the elevated low-altitude O^+ density, and eventually an upward H^+ flow and density increase are established at all altitudes, from $t = 4.9$ to 5.5 hrs UT (Figure 4d). This upward H^+ flow then induces an upward

O^+ flow and density increase at high altitudes, again from $t = 4.9$ to 5.5 hrs UT (Figure 4e). At this time, both O^+ and H^+ in the polar wind have adjusted to the elevated O^+ density in the underlying ionosphere, and after $t = 5.5$ hrs the subsequent decrease in both ion densities at all altitudes basically follows the decay of the underlying O^+ density as the plasma flux tube convects across the dark polar cap.

Geomagnetic activity begins to decrease when the plasma flux tube is still in the polar cap ($t = 5$ hrs UT), and is at the halfway point in its decay when the convecting plasma flux tube enters the nocturnal auroral oval at $t = 6.4$ hrs UT (72° latitude, 0130 MLT). In Figure 4b, the second region of elevated T_e corresponds to flux tube movement through the nocturnal auroral oval. The ion temperature is also elevated in the nocturnal oval, but because the convection electric field is weak in this region, it is not as large as that found in the dayside 'hot spot'. The O^+ density at low altitudes (500 km and below) is also increased in transit through the nocturnal oval because of O^+ production from precipitating electrons. As was found on the dayside, the sharp increase in T_e and T_i leads to transient H^+ and O^+ upflows, and the subsequent decrease in the temperatures leads to ion downflows that start at $t = 7.1$ hrs. As before, O^+ responds more dramatically to temperature changes than does H^+ , and at $t = 7.4$ hrs the collapse of the high-altitude O^+ density due to the sharp decrease in T_e is sufficiently rapid to trigger a downward propagating O^+ shock (Figure 4e). The O^+ shock weakens as it propagates and eventually dissipates near 850 km due to an enhanced collision frequency (at $t = 7.7$ hrs). Note, however, that the O^+ shock induces a downward propagating H^+ response that is superimposed on a larger-scale H^+ upflow/downflow auroral response.

The last T_e increase that is shown in Figure 4b begins at $t = 8.5$ hrs (69° latitude, 0912 MLT). The T_e increase is due to plasma flux tube convection into sunlight in a region equatorward of the quiet auroral oval. However, at this time the H^+ and O^+ densities along the flux tube are still adjusting to the auroral disturbance, and this gradually increasing T_e and associated H^+ upflow do not control the density structure.

Other convecting plasma flux tubes are not subjected to large disturbances, and hence, their temporal history is not as complicated as that discussed above for the dawn convection trajectory. Figures 5a–5f show a series of plots that describe the history of a 'trough' convection trajectory. At the start of the storm profile shown in Figure 1, the plasma

Fig. 4c. Variation of the O^+ , O and H densities ($\log_{10}$) at 500 km versus time along the dawn convection trajectory.

Fig. 4d. Contours of the H^+ density ($\log_{10}$) along the dawn convection trajectory. The contours are plotted versus altitude, magnetic latitude, and time along the trajectory.

flux tube is located on the midnight magnetic meridian at about 60° latitude (Figure 5a), which is in the main trough just equatorward of the quiet auroral oval. Subsequently, the plasma drifts toward dawn and catches the edge of the oval just before the onset of magnetic activity (at $t = 3.45$ hrs; 60° latitude and 0100 MLT). In the oval, T_e increases from about 750 K to 1800 K due to heating from precipitating electrons, with the peak T_e occurring at $t = 3.9$ hrs (60°

latitude, 0130 MLT). In the oval, T_i is only slightly elevated due to the weak electric fields in this region (Figure 5b), and near the edge of the oval, ion production only has a small effect on the O^+ density. Note that at 500 km the O^+ density is about 10^4 cm^{-3} throughout the night and only starts to increase after the plasma convects into sunlight (Figure 5c).

In the auroral oval, the increase in T_e with time acts to

Fig. 4e. Contours of the O^+ density ($\log_{10}$) along the dawn convection trajectory. The contours are plotted versus altitude, magnetic latitude, and time along the trajectory.

Fig. 4f. H^+ (dashed) and O^+ (solid) drift velocity profiles at selected times along the dawn convection trajectory. The times and locations are $t = 3.9$ hr (67° latitude, 0820 MLT) and $t = 4.55$ hr (78° latitude, 0940 MLT).

induce a transient O^+ upflow and to enhance the already existing H^+ upward flow. Associated with the increased upward ion velocities are enhancements in the high-altitude O^+ and H^+ densities (Figures 5d and 5e). After $t = 3.9$ hours, T_e begins to decrease as the plasma starts to convect out of the nocturnal oval. This decreasing T_e induces a transient O^+ downflow and a corresponding decrease in the O^+ density at high altitudes. For H^+ , however, the decrease in T_e with time is too slow to induce a downflow, although the magnitude of the upward flow from the ionosphere is significantly reduced, and hence, the high-altitude H^+ density also decreases. This H^+ - O^+ counterstreaming, which occurs over a significant altitude range (Figure 5f), persists from $t = 3.9$ to 5.7 hrs UT, at which time the plasma flux tube is located at 60° latitude and 0650 MLT.

The polar wind variation along a typical dusk convection trajectory is shown in Figures 6a-6e. At 3 hrs UT, the plasma is located at 65° and 1930 MLT, which is a region of very low convection speeds. Between 3 and 3.5 UT, the plasma slowly drifts toward a region of increasing, but weak, precipitation in the quiet auroral oval, which accounts for the increasing T_e during this time period (Figure 6b).

Fig. 5a. Convection trajectory of a trough flux tube of plasma during changing magnetic activity. At the start of the storm profile shown in Figure 1, the flux tube is located at 60° magnetic latitude and midnight MLT.

Fig. 5b. Variation of T_e , T_i and T_n at 500 km versus time along the trough convection trajectory. The peak in T_e corresponds to flux tube movement through the edge of the nocturnal auroral oval.

Between 3.5 and 3.9 hrs UT, the precipitation increases owing to the increase in magnetic activity (Figure 1), which accounts for the further increase in T_e . However, the convection electric field remains small in this region during this time period. At $t = 3.9$ hours, the electric field strength increases and the plasma flux tube reverses direction and convects toward the dayside, with the plasma first moving into a region of lower precipitation (decreasing T_e) and then into a dayside region of higher storm precipitation (increasing T_e) that is also on the edge of the enhanced storm electric field region. The plasma reaches this region just before $t = 5$ hrs UT (Figure 6b). At $t = 5$ hrs (71° latitude, 1430 MLT), the plasma flux tube convects antisunward across the polar cap as magnetic activity declines, but enters the nocturnal oval before quiet conditions return (at about $t = 6.6$ hours; 71.5° latitude and 2110 MLT). This accounts for the sharp increase in T_e at this time (Figure 6b).

Note that although T_e and T_i exhibit a considerable amount of structure at 500 km, the O^+ density at this altitude displays a much smaller variation owing to time delays associated with the longer diffusion time constant (Figure 6c). Also, as noted earlier, the changing thermal structure affects the high-altitude H^+ and O^+ densities more than the low-altitude densities (Figures 5d and 5e), and the disturbances are displaced horizontally due to plasma convection. However, for H^+ , the magnitude of a temperature-induced disturbance depends on the magnitude of the H^+ outflow velocity.

Fig. 5c. Variation of the O^+ , O and H densities ($\log_{10}$) at 500 km versus time along the trough convection trajectory.

Fig. 5d. Contours of the H^+ density ($\log_{10}$) along the trough convection trajectory. The contours are plotted versus altitude, magnetic latitude, and time along the trajectory.

5. SUMMARY AND DISCUSSION

We developed a time-dependent, three-dimensional, multi-ion model of the global polar wind. The model covers the altitude range from 120 to 9,000 km and takes account of supersonic ion outflow, shock formation, and ion energization during plasma expansion events. At low altitudes (120–800 km), three-dimensional distributions for the NO^+ , O_2^+ , N_2^+ , N^+ and O^+ densities and the ion and electron temperatures are obtained from a numerical solution of the appropriate continuity, momentum and energy equations. At

high altitudes (500–9000 km), the time-dependent, nonlinear, hydrodynamic equations for O^+ and H^+ are solved self-consistently with the ionospheric equations taking into account collisions, charge exchange chemical reactions, flux tube divergence, and ion temperature anisotropies.

In this first application of the model, we studied the temporal response of the global polar wind to changing magnetospheric conditions. During the simulation, the magnetic activity level changed from quiet to active and then back to quiet again over a 4.5-hour period. When the activity

Fig. 5e. Contours of the O^+ density ($\log_{10}$) along the trough convection trajectory. The contours are plotted versus altitude, magnetic latitude, and time along the trajectory. The dotted contours correspond to negative log values, i.e., very low O^+ densities.

Fig. 5f. H^+ (dashed) and O^+ (solid) drift velocity profiles at a time along the trough convection trajectory when H^+ and O^+ counterstream. The time and location are $t = 5.2$ hrs UT and (57.5° latitude, 0535 MLT).

level increased, the auroral oval expanded, particle precipitation became more intense, and the convection electric field strengths increased. The reverse occurred during declining magnetic activity. The simulation was conducted for winter solstice and solar minimum conditions in the northern polar region.

From our study we found the following:

1. Plasma pressure perturbations in the ionosphere due to variations in T_e , T_i or electron density are reflected in the polar wind, but the perturbations may or may not steepen into shocks depending on the strength of the perturbations.
2. Flux tube motion through the auroral oval and high electric field regions produces transient large-scale ion upflows and downflows. The O^+ and H^+ flows may or may not be in phase. Typically, when T_e and/or T_i increase (convection into oval), the O^+ flow is upward and when they decrease (convection out of oval) it is downward. The

Fig. 6b. Variation of T_e , T_i and T_n at 500 km versus time along the dusk convection trajectory.

strength of the upward H^+ flow is generally increased when T_e and/or T_i increase, but when the temperatures decrease it can remain upward at a reduced strength and this leads to an H^+ - O^+ counterstreaming situation. Alternatively, if the temperature decrease is rapid (upon convection out of the oval), a 'transient' H^+ downflow can be triggered at intermediate altitudes even though the H^+ flow is still upward from the ionosphere and upward at high altitudes (9,000 km).

3. The density structure in the polar wind can be considerably more complicated than in the ionosphere because of both horizontal plasma convection and changing vertical propagation speeds due to spatially varying ionospheric temperatures.

4. During the storm, there is an overall increase in T_e , T_i , and the O^+ density in the F region. The maximum electron and ion temperatures occur during the storm's main phase, when the auroral precipitation and convection speeds are the strongest. However, there is a time delay in the buildup of the O^+ density, with the peak densities occurring near the end of the storm.

5. During increasing magnetic activity, there is an overall increase in the polar wind outflow rate from the ionosphere, while for declining magnetic activity the reverse is true. However, superimposed on this general trend is a complicated polar wind structure because of ionospheric time delays, horizontal plasma convection, and temporally varying vertical propagation speeds.

6. Even though the general trend is for an increased outflow rate from the ionosphere during the storm, an ionospheric hole develops in the polar cap and in this region there is a decreased polar wind outflow rate during the storm.

Fig. 6a. Convection trajectory of a dusk flux tube of plasma during changing magnetic activity. At 3 hours UT, the flux tube is located at 65° magnetic latitude and 1930 MLT.

Fig. 6c. Variation of the O^+ , O and H densities ($\log_{10}$) at 500 km versus time along the dusk convection trajectory.

Fig. 6d. Contours of the H^+ density ($\log_{10}$) along the dusk convection trajectory. The contours are plotted versus altitude, magnetic latitude, and time along the trajectory.

7. During changing magnetospheric conditions, the temporal evolution of the ion density morphology at high altitudes (~ 9000 km) can be different from, and even opposite to, that at low altitudes (~ 500 km). For example, at times during declining magnetic activity, there is an overall reduction in both the H^+ and O^+ densities at high altitudes (9000 km) relative to those during the storm's main phase, while

at low altitudes (F region) there is an overall increase in the ion densities (the ionospheric time delay effect).

It should be noted that the 'storm' scenario we adopted is one of an infinite number of possible cases. The adoption of different convection and precipitation patterns and a different temporal variation for the storm profile will lead to different quantitative and, in some cases, qualitative re-

Fig. 6e. Contours of the O^+ density ($\log_{10}$) along the dusk convection trajectory. The contours are plotted versus altitude, magnetic latitude, and time along the trajectory.

sults. Also, the selection of different seasonal and solar cycle conditions can lead to different results. Nevertheless, the parameters we selected are 'reasonable' and, therefore, the general features we obtained for changing magnetospheric conditions should be indicative of the behavior of the global polar wind.

It should also be noted that our global polar wind model should not be regarded as a final accurate model, but rather as a first attempt in the development of a time-dependent global model of the polar wind. In the future, it would be useful to couple our global polar wind model to a thermospheric circulation model so that the atmospheric changes that occur during magnetic storms can be included in a self-consistent manner. The atmospheric changes are expected to be important for solar maximum and summer conditions as well as for magnetic storms that persist for a much longer time than the 4.5-hour storm considered in this study. However, an ionosphere-thermosphere coupling study of this nature would require an excessive amount of computing resources if we were to maintain the same spatial and temporal resolution used in this study. Also, in the future, it would be useful to include the effects of wave-particle interactions on auroral field lines. The initial attempts to include these effects in a fluid model via an anomalous resistivity process look very encouraging [Palmadesso *et al.*, 1988; Ganguli and Palmadesso, 1988]. If the resistivity model can be simplified so that it can be included in a global-scale model, it would be an important step forward in modelling the global polar wind.

Wave-particle interactions may also play a role in non-auroral regions. Our model predicts that at certain times and in certain regions both inside and outside of the auroral oval an H^+O^+ counterstreaming situation can occur. Recently, several ion-ion streaming instability papers have been published that are relevant to the question of polar wind stability [Bergmann, 1984; Bergmann and Lotko, 1986; Gary and Omid, 1987; Bergmann *et al.*, 1988; Dusenbery *et al.*, 1988; Barakat and Schunk, 1989]. Although the bulk of this work deals with the electrostatic stability of 'energetic' ion beam-plasma configurations, the studies indicate that it is likely some of our H^+O^+ counterstreaming situations are unstable, depending on the densities, temperatures and relative flow velocities.

Although some of the H^+O^+ counterstreaming situations we predict may be unstable, it is not clear what effect the instabilities will have on the flow. The precise effect will depend both on the characteristics of the unstable wave mode and on the wave amplitudes in the nonlinear saturated state. If the waves propagate at an angle to the geomagnetic field, they may simply propagate away and not appreciably affect the flow. Also, the instability may lead to elevated ion temperatures, which can act to stabilize the plasma if acoustic-like waves are dominant. Hence, in the marginally stable state, the H^+O^+ counterstreaming may continue, but with a reduced relative velocity and an elevated ion temperature. In this regard, it should be noted that ion counterstreaming has been observed at high latitudes on closed geomagnetic field lines [Sojka *et al.*, 1983]. In addition, highly non-Maxwellian ion beams, conics and toroidal distributions are observed in association with cusp ion outflows [cf. Lockwood, 1986; Chappell, 1988, and references therein]. Despite the fact that these ion distributions are unstable in the 'linear' approximation, they are observed, which indicates that the

excited waves are not strong enough to destroy the highly non-Maxwellian ion distributions.

Finally, we note that Persoon *et al.* [1983] presented measurements of the local electron density at high altitudes in the northern 'polar cap' region. The electron densities were determined from the upper cutoff of whistler mode radiation at the electron plasma frequency using the plasma wave instrument on the Dynamics Explorer 1 spacecraft. The data were obtained during a 'solar maximum' period that included both equinox and winter conditions (September, 1981 to February, 1982). Nearly one hundred 2-hour spectrograms taken in the polar cap were analyzed to obtain the electron densities. The data covered the altitude range from 6378 to 23,343 km (2–4.66 R_E). The electron densities, which were plotted in one figure as a function of radial distance, displayed a fairly wide scatter at a given distance. The scatter was anticipated because the electron density exhibited a large variation both on individual orbits as well as from orbit to orbit. No doubt, the variation is related to the fact that densities from different latitudes, local times, and magnetic activity levels were used in the data base.

In the altitude range relevant to our study (6378–9000 km), the measured electron densities varied from about $10\text{--}90\text{ cm}^{-3}$ (The scatter was much greater at higher altitudes where there were more data). In our simulation, the calculated electron density at 9000 km varied both spatially and temporally in the polar cap (Plates 2 and 3, top row). At time t_1 (increasing activity), n_e in the polar cap varies from about $160\text{--}190\text{ cm}^{-3}$; at t_4 (high activity) n_e varies from about $65\text{--}190\text{ cm}^{-3}$; and at t_6 (declining activity) n_e varies from about $30\text{--}190\text{ cm}^{-3}$. These values are in general agreement with the electron densities measured by Persoon *et al.* [1983], but it might be argued that our upper limit is a little high. However, the Persoon *et al.* measurements pertain to solar maximum conditions, while our simulation was for solar minimum. At solar minimum, the H^+ densities (and limiting escape fluxes) are typically greater than at solar maximum [cf. Barakat *et al.*, 1987]. Therefore, the slightly higher electron densities we calculated are consistent with the solar cycle trend.

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