Adv. Space Res. Vol. 8, No. 8, pp. (8)89–(8)92, 1988
Printed in Great Britain.

0273–1177/88 $0.00 + .50

MODELLING OF TIME-DEPENDENT ION OUTFLOWS AT HIGH GEOMAGNETIC LATITUDES

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ABSTRACT

In a recent paper, Gombosi and Killeen (1987) applied a highly parameterized thermospheric Joule heat source as a boundary condition in the time-dependent, ion outflow model of Gombosi et al. (1985) to show that episodic ion outflows at high geomagnetic latitudes could result from low altitude ion frictional heating. To delineate more realistically the time-dependent thermosphere/ionosphere environment, we extend this previous study by using output from the Thermospheric General Circulation Model (TGCM) of the National Center for Atmospheric Research (NCAR) as input to the same hydrodynamic polar wind code for a set of case studies which follow the thermal forcing history of individual, ionospheric, convecting flux tubes. Using derived, time-varying frictional heating rates such as those experienced by these flux tubes, we show that transverse ion heating below 500 km can provide sufficient energy to perturb the velocity distribution of the major ion species. The time-dependent flux tube heating results in localized regions of field-aligned O^+ upflows. These results demonstrate that localized heating, generated from thermosphere/ionosphere interactions, may initiate heavy ion upwellings which, through further energization at higher altitudes, could evolve into the transient ion outflows as seen by the Dynamics Explorer 1 satellite.

1. INTRODUCTION

In addition to confirming the overall correctness of the polar wind theory originally postulated by Axford /1/ and Banks and Holtzer /2/ in 1968, the retarding ion mass spectrometer (RIMS), /3/, onboard the polar orbiting Dynamics Explorer 1 (DE 1) satellite identified large fluxes (10^7 - 10^9 particles cm^{-2} sec^{-1}) of heavy ions moving upward along open geomagnetic field lines /4-6/. This unexpected component of ion outflow consisted primarily of cool (10 eV - 100 eV) O^+ ions, although N^+, N_2^+ and other molecular ions were also detected (Chappell et al /7/; Craven et al. /8/). Convection mapping calculations and observational evidence cited by Waite et al. /5/ and Lockwood et al. /6/ indicated a low altitude dayside cleft or cusp source region for these outflows, while Moore et al. /9/ and Waite et al. /10/ suggested that frictional heating, due to ion-neutral interactions, might provide the source of energy for the observed heavy ion upwellings. Thermospheric measurements by satellite instrumentation have also identified regions of high-latitude frictional heating. Killeen et al. /11/ used simultaneous measurements of ion and neutral velocity vectors, ion densities and temperatures from the DE 2 satellite to show that areas of strong horizontal frictional heating were present at F-region altitudes in both the cusp and auroral regions. These studies suggest that ion frictional heating in localized regions may initiate transient outflows of ionospheric heavy ions.

To examine the transient ionospheric response to variable heating rates experienced by the convecting plasma, Gombosi and Killeen /12/ introduced a highly parametric heat source, normalized to DE 2 observations, into the time-dependent hydrodynamic polar wind model developed by Gombosi et al. /13/. Their simulated horizontal frictional heating episode was based on heating which might be expected at ionospheric altitudes when a flux tube transits the cusp region. Their flux tube was exposed to a gaussian thermal forcing event of 5 minutes duration using a height-dependent frictional heating rate profile normalized to DE 2 observations. The O^+ upwelling they obtained was in agreement with upward directed fluxes observed by the EISCAT radar suggesting that low altitude horizontal frictional heating may trigger upflowing O^+ ions at high geomagnetic latitudes.

In this study, we extend the previous work of Gombosi and Killeen /12/ by using output from the NCAR TGCM to simulate the time and altitude dependent F-region ion frictional heating rate more realistically. Computed as a function of universal time (UT) along the locus of specific flux tubes, these ion heating profiles are used as boundary conditions in the Gombosi polar wind model to simulate the plasma heating history of a flux tube traversing the cusp region. We follow the evolving perturbations within the flux tube to determine if transverse energization, supplied by frictional heating, might lead to O^+ field-aligned upflows.

2. MODEL FORMULATION

The time-dependent hydromagnetic polar wind model used for this study was developed by Gombosi et al. /13/ and represents the first model capable of describing time-dependent ion outflows. The model simultaneously solves the coupled continuity, momentum and energy equations for a two ion (H^+ and O^+), quasi-neutral plasma along vertically diverging field lines between 200 and 8000 km, taking into account the effects of ionization, charge exchange, recombination, collisions, heat conduction and external heat sources. The ion and electron gases are treated as perfect fluids with internal degrees of freedom and no net field-aligned electric currents are permitted. An MSIS 86-derived neutral atmosphere consisting of N_2, O_2, O and H is used with photoionization and charge exchange representing source terms for O^+ and H^+ respectively. O^+ is chemically removed by reactions with molecular nitrogen or O_2, while H^+ is lost through charge exchange with O^+. Momentum and energy transfer terms describing ion-ion, ion-neutral and ion-electron collisions, as well as heat conduction, were taken from Raitt et al. /14/. Throughout the model calculations, ionization rates were turned on and off to maintain consistency with convection across the solar terminator. The model flux tube connected two infinite external reservoirs, with ions in the lower reservoir at 200 km initially in photochemical and thermal equilibrium. The upper reservoir at 8000 km was assumed to be a stationary low pressure medium and a downward directed electron heat flux of 5×10^{-3} ergs cm^{-2} sec^{-1} was adopted to simulate energy deposition from the magnetosphere. We assumed no ion heat flow at the upper boundary of our model but adopted time-varying ion frictional heating rates between 220 km and 500 km to simulate convection through regions of localized frictional (Joule) heating. The full set of seven time-dependent partial differential equations, described by Gombosi and Killeen /12/, are repeatedly solved after each heating update using a combined Godunov scheme/Crank-Nicholson method with time splitting which is capable of solving systems of parabolic partial differential equations with propagating shocks and other discontinuities.

The National Center Atmospheric Research (NCAR) TGCM provides a useful means of specifying the dynamic variability between the thermosphere and ionosphere. The model provides self-consistent solutions to the fully coupled hydrodynamic, continuity and energy equations for the neutral thermosphere using an effective 5 degree horizontal grid spacing and 25 constant-pressure surfaces between approximately 97 and 500 km. Since the modelled solutions reflect ion as well as neutral dynamics and composition, all parameters needed to compute frictional heating (proportional to the product of the square of the ion-neutral velocity difference and the ion density) are available in the history output fields and can be calculated self-consistently along the modelled trajectory of a convecting flux tube.

To calculate ion frictional heating rates, we apply a post processor package to the TGCM output fields (Killeen et al. /15/). This diagnostic program allows us to track an individual flux tube in both space and time as it moves through the TGCM output fields for selected universal times (UTs). Using a simple weighted interpolation scheme to step forward in UT, we extract neutral and ion wind vectors and ion densities at selected altitudes for points along the flux tube trajectory. The ion heating rate is calculated from these parameters and then applied as a boundary condition to the polar wind model to simulate temporal variations in ion frictional heating as seen in the rest frame of a convecting flux tube. Since TGCM output fields are global in coverage, we examine the effects of localized frictional heating by selecting trajectories which traverse suspected source regions for upwelling ions, i.e., the dayside cusp and cleft.

3. RESULTS AND DISCUSSION

We selected a steady state, diurnally-reproducible TGCM run based on geophysical conditions corresponding to 16 Jan 1982 (Kp = 1, F10.7 = 140, By = +3.3 nT) for trajectory and heating rate calculations. To examine the relationship between cusp heating and O^+ upwellings, we chose a flux tube trajectory which passed through known regions of elevated frictional heating near the dayside cusp and used the derived heating rates along the path in the polar wind model. The time history of ion frictional heating and flux tube convection trajectory for our case study is summarized in Figure 1, as are various parameters used to compute heating rates

The flux tube trajectory (Figure 1d), plotted as a function of magnetic local time and latitude, was calculated within the TGCM using the Heelis (1982) convection pattern with time steps of one hour UT. To select a trajectory which passes through the cusp, we compute and plot cusp heating (parametrically modelled as a soft particle precipitation heat source) to the neutral thermosphere as a function of UT (see Figure 1e). This diagnostic feature permits us to identify the UT periods corresponding to cusp transit. The time series on the left of Figure 1 show derived ion and neutral temperatures (Figure 1a), frictional heating rates (Figure 1b), ion densities and the square of the difference between ion and neutral winds at approximately 200 km (Figure 1c). The latter two quantities are used to compute the volumetric ion frictional heating as described by Killeen et al. /11/. For our case study, we examined the interval between 11 and 13 UT when the flux tube experienced an order of magnitude increase in frictional heating during cusp region transit. This time interval corresponds to convection from a region where the ion and neutral winds were closely coupled into a region of much greater wind shear. For a steady state convection case such as this, we expect little in the way of strong wind shears since steady momentum transfer from the ions to the neutral species will keep such shears from developing. As a result, this study period represents very quiet conditions with exceptionally low frictional heating rates. Nevertheless, we use these values to establish confidence in our modelling approach.

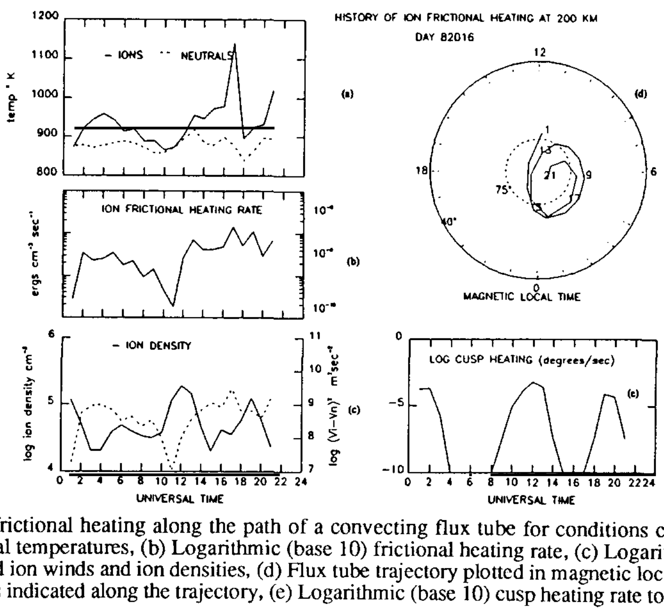

Fig. 1. History of ion frictional heating along the path of a convecting flux tube for conditions corresponding to January 16, 1982. (a) Ion and neutral temperatures, (b) Logarithmic (base 10) frictional heating rate, (c) Logarithmic (base 10) square of the difference in neutral and ion winds and ion densities, (d) Flux tube trajectory plotted in magnetic local time and magnetic latitude with corresponding UTs indicated along the trajectory, (e) Logarithmic (base 10) cusp heating rate to the neutrals.

In adapting our derived ion frictional heating rates to the polar wind code, we compute heating rates for the 220 to 500 km interval as a function of UT. These profiles are reduced to a set of coefficients which are used in the polar wind code to reproduce the ion heating rate at any intermediate level or universal time. In this study, heating rates are applied as boundary conditions for each 20 km interval up to 500 km and are updated every 600 seconds between 11 and 13 UT. Our study consisted of two model runs. In the first case, we adopted the relatively low heating rates described above and found that no perturbations occurred in the flux tube plasma, indicating that our model coupling was stable and showing that very low frictional heating rates do not noticeably affect the diffusive equilibrium profile for O^+. For our second case, we simulated moderate levels of frictional heating rates by increasing the strength by a factor of 100, consistent with heating rates obtained from DE 2 measurements for a more geomagnetically active period when varying electric fields produce much greater ion-neutral velocity differences /11/. The profile shape and temporal variations specified by the TGCM, however, were not altered. With these moderate ion heating rates, significant plasma disturbances occurred.

Initial conditions for our second model run using the enhanced ion frictional rates are shown in Figure 2 for 11 UT. At this time, no external heating had been applied, so the plasma was in photochemical and thermal equilibrium. The minor ion, H^+, undergoes steady outflow along open field lines (Figure 2a) due to the pressure differential applied at the upper and lower boundary of the model (Figure 2e). This field-aligned flow attains supersonic velocity and a constant flux profile near 3000 km (Figure 2b). The major ion, O^+, is gravitationally bound and limited to very low diffusive velocities parallel to the field lines (Figure 2a). Both upward and downward fluxes are present at F-region altitudes (Figure 2b) due to diffusion away from the source region. At 11:10 UT we begin applying ion frictional heating to the lowest 300 km interval of the flux tube. Heating rates are updated to be consistent with the new trajectory location and model calculations continue through 13 UT, when the flux tube moves out of the cusp and across the polar cap.

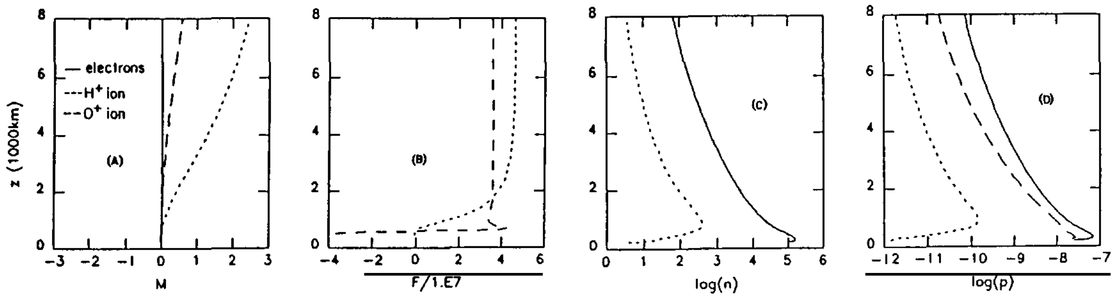

Fig 2. Profiles of (a) Mach numbers, (b) particle fluxes, (c) number density, and (d) pressure before application of time-varying frictional heating. At this point, the plasma is in photochemical and thermal equilibrium. Electron profiles are shown as solid lines, H^+ as short dashes and O^+ as long dashes

Figure 3 is a series of altitude profiles for various UTs showing the temporal evolution to the oxygen ion flux profile as a result of frictional heating. Minutes after the modified heating rates were applied, a perturbation in the O^+ field-aligned velocity and number density appeared just above the heated region. This feature developed from a readjustment in the major ion scale height due to (perpendicular) heating. Perturbations to the O^+ flux profile were apparent after 20 minutes (11:20 UT) with the flux perturbation moving vertically upward from the region of frictional heating. After 30 minutes, our modified ion heating rates have increased by one order of magnitude and the O^+ plasma disturbance (Figure 3a) has reached maximum strength, clearly exceeding the upward flux of lighter H^+ ions near 2000 km. Throughout the heating interval, H^+ exhibits virtually no change from the (preheating) dynamic equilibrium state since minor ion species receive little in the way of perpendicular heating. After 60 minutes (Figure 3c), the O^+ flux disturbance has reached the upper boundary of the model as a new plasma equilibrium develops. We calculate the propagation velocity of this upwelling disturbance at approximately 1.3 km/s which is equal to the local O^+ acoustic velocity.

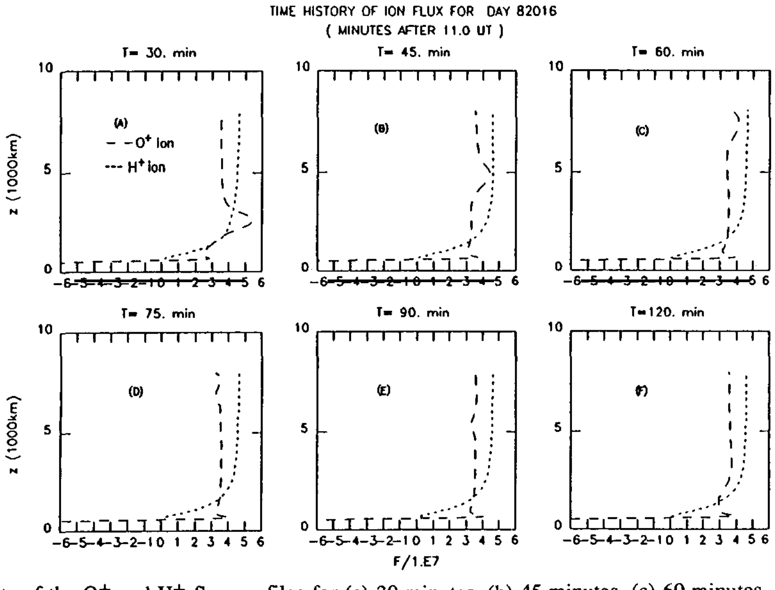

Fig 3. Snapshots of the O^+ and H^+ flux profiles for (a) 30 minutes, (b) 45 minutes, (c) 60 minutes, (d) 75 minutes, (e) 90 minutes and (f) 120 minutes following application of UT-dependent frictional heating rates.

The lower series of flux profiles correspond to the 12 UT to 13 UT interval when our modified heating rates increased only slightly (about $3x10^{-7}$ ergs cm^{-3} sec^{-1} over the one hour interval). During this period, a small downward-moving disturbance in the flux profile of the major ion is apparent as a new thermal equilibrium develops in the absence of rapidly varying frictional heating rates.

In comparing the two time intervals with the respective heating rates described above, the major ion species respond in two different ways to reach a new equilibrium after heating. When frictional heating rates are high, but steady (e.g. 12-13 UT), the major ion population can attain equilibrium through collisional heat exchange with the more numerous neutrals and therefore, are less likely to exhibit bulk upwelling. Conversely, rapid order-of-magnitude increases in ion frictional heating rates (e.g. 11-12 UT) cannot be rapidly compensated for by heat exchange so a readjustment in plasma scale height occurs, resulting in a bulk motion upwards by the O^+ population. This characteristic response suggests that strong spatial gradients in frictional heating rates might be more effective in inducing O^+ upwelling transients than regions where higher, but less confined frictional heating occurs.

4. SUMMARY

Realistic, time-varying frictional heating profiles were computed using a TGCM-derived thermosphere/ionosphere environment to evaluate the role of short-duration frictional heating in generating transient heavy ion outflows in the polar F region. These derived ion heating rates were used as variable boundary conditions to simulate the plasma heating history of a flux tube convecting through the cusp region. For the baseline case with very low frictional heating rates ($< 10^{-9}$ ergs cm^{-2} sec^{-1} near 200 km), insufficient energy was available to overcome the O^+ gravitational barrier and no noticeable changes from diffusive equilibrium occurred. At higher levels of ion heating ($\sim 10^{-9}$ ergs cm^{-2} sec^{-1} near 200 km) a bulk upward motion of O^+ ions developed. We conclude that :

(1) Transient perturbations in O^+ fluxes may develop from transverse energization associated with ion frictional heating. This heating forces rapid adjustment to the plasma scale height resulting in bulk, field-aligned motion upwards.

(2) For the two cases examined in this study, O^+ upwellings are most pronounced where frictional heating rates rates have the strongest horizontal (temporal in the rest frame of the convecting flux tube) gradients suggesting that, in some cases, sharp variations to heating rates may be more important than relative heating strength in generating O^+ ion upwellings.

In follow-on studies, we plan to test this last point in greater detail by examining strong wind shear patterns (and the related frictional heating variability) due to storm time forcing. Using TGCM - derived frictional heating rates for geomagnetically disturbed periods, we hope to refine further and to quantify the relationship between the intensity of ion frictional heating and the magnitude of fluxes associated with heavy ion upwellings.

ACKNOWLEDGEMENTS

We wish to thank Drs. J. H. Waite and B. A. Emery for helpful suggestions and assistance in using the TGCM, respectively. The work presented in this paper was supported by NASA Grants NAG5-472 and National Science Foundation Grant ATM-850873 (T.I.G.) and NASA Grant NAG5-465 and National Science Foundation Grant ATM-86100085 (T.L.K.). The majority of this study was carried out using the computing facilities of the National Center for Atmospheric Research which is sponsored by the National Science Foundation.

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