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Disturbance in the Daytime Midlatitude Upper *F* Region Associated with a Medium Scale Electrodynamic Vortex Motion of Plasma

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Under the assumption of the presence of a medium-scale **E** × **B** drift vortex of plasma in the daytime midlatitude *F* region, and using a simplified ionospheric model, we demonstrate that the **E** × **B** drift produces noticeable perturbations in the horizontal distribution of the plasma density in the upper *F* region. The pattern of ion density perturbations shows two separate medium scale domains of enhanced and reduced ion density with respect to the background. The **E** × **B** drift does not produce multiple small-scale ion density irregularities through plasma mixing because of the suppression effect of the field-aligned ambipolar plasma diffusion.

Keywords: midlatitude ionosphere, ionospheric perturbations, vortex motion of plasma

1. INTRODUCTION

It is well known that electric fields play an important role in the formation of the main large-scale ionosphere structures, such as the polar tongue of ionization (e.g., Knudsen 1974; Foster 1984), the midlatitude ionization trough (e.g., Knudsen 1974; Spiro et al. 1978), storm-enhanced density (SED) (e.g., Foster 1993; Kelley et al. 2004), and the equatorial ionization anomaly (EIA) (e.g., Hanson & Moffett 1966; Balan & Bailey 1995). Moreover, the electric field is one of the key factors that determine the development of the ionospheric plasma instabilities resulting in the midlatitude and equatorial spread *F* irregularities (e.g., Perkins 1973; Ossakow 1981). Park & Helliwell (1971) showed that a localized rotation of plasma due to **E** × **B** drift can produce field-aligned electron density irregularities in the magnetosphere as a result of plasma mixing. They suggested thundercloud electricity as a possible source of the localized electric field. Dagg (1957) suggested that turbulent neutral wind in the dynamo region could generate localized irregular electric fields. Numerical calculations by Fridman (1990) demonstrated that random electric fields could be responsible for the formation of small-scale irregularities in the midlatitude *F* region. In this paper, we study effects on the daytime midlatitude *F* region ionosphere associated with an assumed medium scale **E** × **B** vortex motion of plasma.

2. FORMULATION OF THE PROBLEM

In the midlatitude *F* region of the ionosphere, the geomagnetic field lines can be considered straight parallel equipotentials. This implies that an electrostatic field is transverse to the geomagnetic field **B** and does not change along the geomagnetic field lines. We introduce a Cartesian coordinate system as illustrated in Fig. 1, with the x axis directed eastward, the y axis poleward, and the z axis vertically upward. The coordinate system origin is located at some geomagnetic field line S_c at every height level. The geomagnetic field vector **B** lies in the yz plane, and is inclined at a dip angle I with respect to the y axis. We assume that the electric field distribution has an axial symmetry

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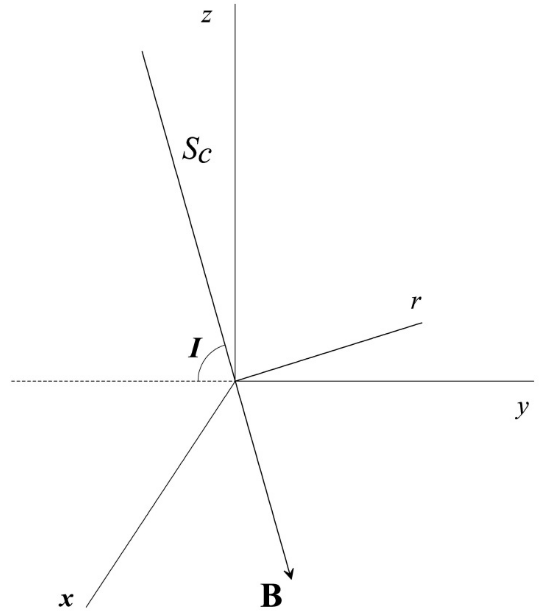

Fig. 1. View of the coordinate system. **B** is the geomagnetic field vector; I is the magnetic dip angle; S_c designates the geomagnetic field line that together with the r axis represents the coordinate system used in deriving (1).

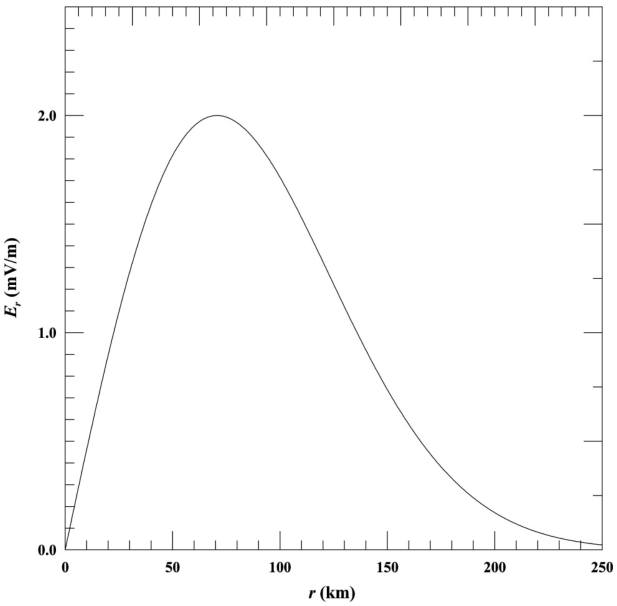

Fig. 2. Assumed electric field strength plotted as a function of distance r from the geomagnetic field line S_c.

such that the electric equipotentials are concentric circles around some geomagnetic field line S_c, and the electric field vector is directed radially from this line. The field magnitude is expressed by

$$E_r = A\, r \exp(-r/b)^2 \tag{1}$$

where $A = 4.7 \times 10^{-2}$ mV/m^2, r is the distance from line S_c, and $b = 100$ km (see Fig. 2). Thus, the maximal magnitude of E_r is 2 mV/m at $r_{max} \sim 70$ km. This electric field drives (through the **E** × **B** drift) charged particles to have circular trajectories around the geomagnetic line S_c in the plane perpendicular to **B** with an angular velocity $\omega \sim \exp(-r/b)^2$ in the clockwise direction if viewed from above. It is suggested that the source of the electric field is the dynamo action of a proper neutral wind eddy that can presumably appear in the E region of the ionosphere.

In order to evaluate effects of the electric field on the F region of the ionosphere, we use the continuity equation for the O^+ ions which are dominant in the F region, i.e., $N(O^+) \sim N_e$. This equation can be written as

$$\partial N(O^+)/\partial t + \mathrm{div}\{N(O^+)\,[\mathbf{V}_d+\mathbf{W}+\mathbf{U}]\} = q - \beta\, N(O^+) \tag{2}$$

where $\mathbf{V}_d$ is the velocity of O^+ ion diffusion along the geomagnetic field, $\mathbf{W} = (\mathbf{E} \times \mathbf{B})/B^2$ is the electrodynamic drift velocity, **U** is the ion drift velocity along the geomagnetic field due to the neutral wind, and q and β are the O^+ production and loss frequency rates, respectively. The expression for $\mathbf{V}_d$ follows that of Schunk (1988). The O^+ ions are mainly lost because of charge exchange with N_2 and O_2 molecules in the reactions

$$O^+ + N_2 \rightarrow NO^+ + N \tag{3}$$

$$O^+ + O_2 \rightarrow O_2^+ + O \tag{4}$$

with their respective rate constants k_1 and k_2 given by St.-Maurice & Torr (1978). Thus, the O_+ loss frequency is given by

$$\beta = k_1\, N(N_2) + k_2\, N(O_2) \tag{5}$$

The production rate for the O^+ ions is taken from Banks & Kockarts (1973). We assume that the initial distribution of $N(O^+)$ is horizontally homogeneous and determined by the equation

$$\mathrm{div}\{N(O^+)\,[\mathbf{V}_d + \mathbf{U}]\} = q - \beta\, N(O^+) \tag{6}$$

As the boundary conditions to solve (2) and (6), we assume that at the upper boundary $z = 800$ km the upward O^+ flux of 1.5×10^8 cm^{-2}s^{-1} is specified, whereas at the lower boundary $z = 180$ km the O^+ density is determined from the condition of photo-chemical equilibrium, i.e., $N(O^+) = q/\beta$ for $t = 0$. For the calculations, the electric field is assumed to be turned on at time $t = 0$, and the neutral wind is neglected (**U** = 0). The NRLMSISE-00 neutral atmosphere model is used to provide the required neutral densities and temperatures (http://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php). The case of midday conditions for Equinox near the solar maximum is considered. We assume that the ion and electron temperatures are equal to the temperature of neutral particles, $T_n = T_i = T_e$. The dip angle I is set to be 60°.

3. RESULTS AND DISCUSSION

Fig. 3 represents the calculated initial vertical profile of the O^+ density. Figs. 4–5 show the calculated contours of the O^+ density normalized to its initial value in the coordinates (x, y) at the horizontal planes z = 300 and 500 km for t = 60 min. Note that the coordinate origin (x = 0, y = 0) is coincident with the intersection point of the geomagnetic line S_c and the plane, so that the coordinates' origin at the z = 500 km plane is displaced equatorward by a distance of ~115.5 km relative to the coordinate origin at the z = 300 km plane. As is seen from Figs. 4–5, the horizontal ion density distribution just above the F peak (at z = 300 km) shows small perturbations under the influence of the electric field, whereas in the upper F region (at z = 500 km), the ion density perturbations are much more pronounced. The perturbation pattern at z = 500 km consists of domains of positive and negative disturbances of the O^+ density with dimensions of about 100 km. The foci of the negative and positive perturbations are at a distance of ~90 km southwest and northeast of the coordinate origin, respectively. In the focus of positive disturbance, the ion density exceeds its undisturbed value by more than 40 %, and in the negative focus, $N(O^+)$ decreases by more than 30 %. The difference between values of the ion density in the foci reaches a factor of 2. In the case of the reverse direction of the electric field, the horizontal ion density distributions at t = 60 min are the

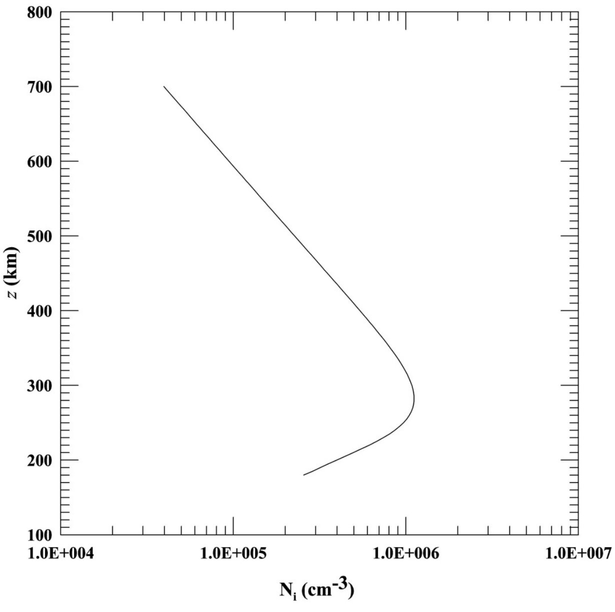

Fig. 3. Calculated altitude profile of the O^+ ion density at t = 0.

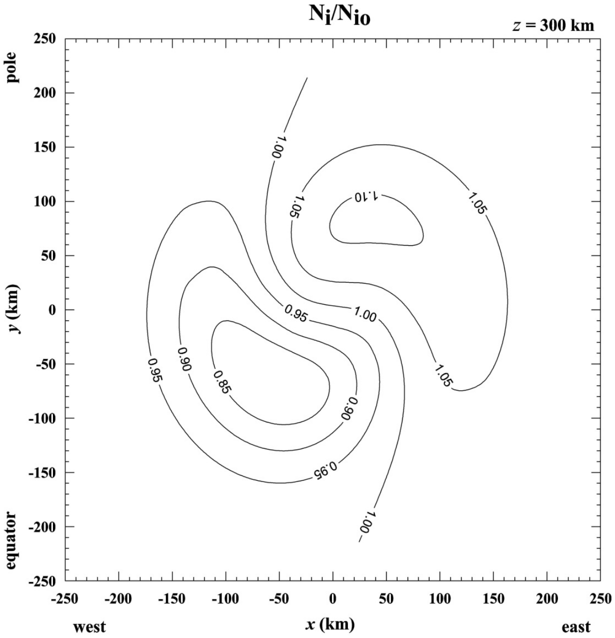

Fig. 4. Calculated contours of the O^+ ion density normalized to its initial value at the horizontal plane z = 300 km for t = 60 min. The coordinate system (x, y) is centered at the point where the geomagnetic field line S_c intersects the plane. The x and y – axes are eastward and poleward, respectively.

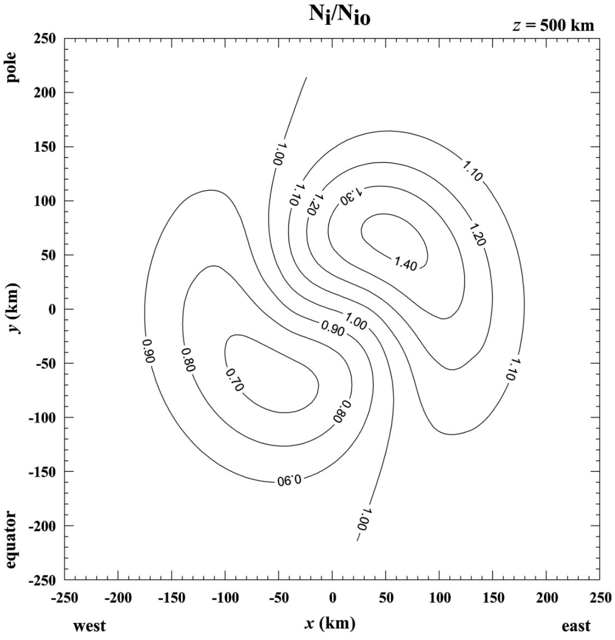

Fig. 5. Same as Fig. 4, but at z = 500 km.

mirror images of the patterns presented in Figs. 4-5.

It is suggested that the electric field is generated through the dynamo action of a medium-scale neutral wind eddy that, as we hypothesize, can appear in the *E* region because of, for example, the breakup of a strong neutral wind burst stipulated by high-intensity auroral activity. The **E** × **B** drift related to this electric field produces plasma rotation with an angular velocity similar to that of neutral gas rotation in the dynamo region. Park & Helliwell (1971) suggested that a localized electrodynamic rotation of magnetospheric plasma could be caused by tropospheric electric fields.

We see that the medium-scale plasma vortex is not accompanied by the formation of multiple small-scale irregularities in the midlatitude *F* region, as is the case near the equatorial plane in the magnetosphere according to Park & Helliwell (1971). This can be explained by the fact that the field-aligned ambipolar plasma diffusion plays a very important role in the plasma density distribution in the *F* region and suppresses the effects of plasma interchange by **E** × **B** mixing on the horizontal plasma density distribution. In our case, the positive and negative variations in the ion density horizontal distribution are caused by upward and downward **E** × **B** drift components, respectively.

4. CONCLUSION

The results of this study indicate that, if the presence of medium-scale **E** × **B** vortex motion of plasma in the daytime midlatitude *F* region is assumed, the lateral distribution of plasma density in the upper *F* region is noticeably perturbed under the influence of the **E** × **B** drift. The pattern of ion density perturbations has a dipolar structure that consists of two separate domains of enhanced and reduced ion density compared to the background. Plasma mixing by the **E** × **B** drift does not result in the formation of multiple small-scale ion density irregularities due to the suppression effect of the field-aligned ambipolar plasma diffusion.

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