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THE NEUTRAL WIND "FLYWHEEL" AS A SOURCE OF QUIET-TIME, POLAR-CAP CURRENTS

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Abstract. The neutral wind pattern over the summer polar cap can be driven by plasma convection to resemble the convection pattern. For a north-south component of the interplanetary magnetic field B_z directed southward, the wind speeds in the conducting E-region can become ~ 25% of the electric field drift speeds. If convection ceases, this neutral wind distribution can drive a significant polar cap current system for ~ 6 hours. The currents are reversed from those driven by the electric fields for southward B_z, and the Hall and field-aligned components of the current system resemble those observed during periods of northward B_z. The current magnitudes are similar to those observed during periods of small, northward B_z; however observations indicate that electric fields often contribute to the currents as much as, or more than, the neutral winds.

Introduction

Magnetospheric plasma convection varies with the direction of the north-south component of the interplanetary magnetic field, B_z. Convection is strongest when B_z is southward, in which case convection is anti-sunward over the polar-cap ionosphere and sunward at lower latitudes. Magnetospheric convection is significantly weaker when B_z is northward, and measurements show that currents and electric fields reverse in direction (Maezawa, 1976; Burke et al., 1979; Reiff, 1982). The current and field patterns are generally better defined over the summer polar cap than over the winter polar cap for northward B_z. In this paper, we suggest that a significant portion, though not all, of the current system over the summer polar cap during periods of northward B_z results from the neutral wind distribution set up by ion drag during earlier periods of southward B_z.

Theoretical and observational studies of neutral particle dynamics have shown that electric fields from magnetospheric convection significantly affect the neutral winds via the ion drag force (e.g., Fedder and Banks, 1972; Killeen et al., 1984). Ion drag affects the neutral wind strongly in the F-region, and significant modification of the neutral wind also occurs in the conducting E-region.

Three-dimensional numerical models of the thermosphere (Fuller-Rowell and Rees, 1980; Dickinson et al., 1981) have been used to examine neutral particle dynamics for various geophysical situations (Rees et al., 1983; Roble et al., 1984). Using a potential drop across the polar cap of 60 kV, a modest value for southward B_z, the models show that the F-region neutral wind circulation can be driven to approximate the ion convection pattern, the peak neutral wind speed being about one-half the peak electric field drift ($\underline{E} \times \underline{B}$) speed. These F-region results have been shown to realistically reproduce DE satellite measurements (Roble et al., 1984; Rees et al., 1983; Hays et al., 1984). The models also show that the E-region neutral winds can be driven to approximately follow the ion convection pattern during the summer, though the peak E-region winds are only about one-fourth of the electric field drift speeds. Results for the E-region have not yet been tested, however, due to difficulties in measuring E-region winds.

The E-region winds can drive significant ionospheric and magnetic field-aligned currents over the sunlit polar cap if plasma convection ceases. Such currents should persist over the time it takes ion drag to modify the E-region winds. This time scale is ~ 6 hours, based upon the inverse of the neutral-ion collision frequency.

Here we evaluate the polar cap currents resulting from the neutral winds under the assumption that ion convection ceases. The ionospheric Hall current is proportional to, and in the direction of, $\underline{V}_n - \underline{V}_E$, in the E-region, where $\underline{V}_n$ and $\underline{V}_E$ are the neutral and electric field drift velocities, respectively. Thus the Hall currents can be reduced by approximately 25% by the neutral winds during a period of moderate magnetospheric convection. More interestingly, when $\underline{V}_E$ is reduced to near zero, $\underline{V}_n$ drives a Hall current system in the direction opposite to that driven by magnetospheric convection. Thus the neutral winds should drive a Hall current system of the same pattern as observed for B_z north. Such currents should have a magnitude about one-fourth of those driven by previous convection with $B_z < 0$, and the currents should persist for ~ 6 hours unless interrupted by renewed electric field convection.

The neutral winds should also drive Pedersen currents, and these currents have a non-zero divergence. We assume that the current divergence is continuously balanced by field-aligned currents, so that the divergence does not result in a significant modification of the ionospheric electric field. Under these conditions, the ionospheric electric field remains zero. However, in actuality there may be a tendency for charge to accumulate along field lines containing a divergent ionospheric current.

A charge accumulation in the ionosphere would reduce the ionospheric currents and the magnitude of their divergence. A charge accumulation only in the ionosphere, and not along the extension of polar cap field lines into the magnetosphere, is unrealistic, since it implies that large (>1 kV)

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TABLE 1. Height Integrated Conductivities

	July 1		August 15		December 1	
	12 LT	24 LT	12 LT	24 LT	12 LT	24 LT
Σ_P	7.1	5.1	5.7	2.9	0.60	0.57
Σ_H	10.4	7.9	8.7	4.5	1.1	0.49

electric potential drops develop along polar cap field lines. Such potential drops would drive field-aligned currents with magnitudes >1 μA/m (Lyons, 1981) which are too large to be balanced by the divergence of the Pedersen currents driven by the neutral winds.

A charge accumulation in the ionosphere should thus be accompanied by a charge accumulation along the magnetospheric extension of polar cap field lines, without the development of large field-aligned potential drops. By developing such a charge distribution, the neutral wind flywheel would maintain the convection pattern that existed throughout the magnetosphere while B_z was southward. Such a charge accumulation probably occurs to some extent, but we do not know whether or not it can be significant.

Analysis

Killeen and Roble (1984) presented neutral wind distributions over the summer polar cap obtained from the NCAR thermospheric general circulation model with a 60 kV potential drop across the polar cap. To estimate the effects of these winds when plasma convection decreases, we assume that E-region winds are first driven to the distribution obtained by Killeen and Roble. This should take ~ 6 hours of relatively persistent convection. We assume that ion convection then ceases entirely, and we evaluate the polar cap Hall current I_H and field-aligned current density $j_\parallel$ driven by the E-region winds existing at the time convection ceased. Field-aligned currents are estimated from the divergence of the height-integrated Pedersen current I_P. Gradients in conductivity and divergence of the neutral winds are ignored, so that the Hall current does not contribute to $j_\parallel$.

A rigorous calculation of the ionospheric Hall and Pedersen currents resulting from the neutral wind would require an integration of $V_n \sigma$ over height, where σ is the ionospheric Pedersen or Hall conductivity. However Killeen and Roble (1984) only presented E-region winds for 120 km, making such an integration impractical at the present time. As an estimate for the height-integrated currents, we assume the winds presented by Killeen and Roble are approximate for the entire conducting E-region, and we calculate representative height-integrated Hall Σ_H and Pedersen Σ_P conductivities using the same ion density model used by Killeen and Roble. Enhanced auroral zone conductivities are not included.

Calculated values for Σ_H and Σ_P for noon and midnight on July 1, August 15, and December 1 at 80°N latitude are shown in Table 1. Based on the July 1 and August 15 values, we have chosen Σ_H = 8 mhos and Σ_P = 5 mhos as typical polar cap values for summer. The winter values are much lower than the summer values and thus allow much lower ionospheric currents.

Figure 1 gives the height-integrated Hall current over the summer polar cap using Killeen and Roble's (1984) values for V_n for 3 UT and Σ_H = 8 mhos. Note the double-vortex current system, which is oppositely directed from the polar cap current system (S_q^P) generally associated with magnetospheric convection. The neutral wind pattern rotates somewhat with UT, since the tilt of the geomagnetic pole brings part of the polar cap into darkness over a range of UT. The maximum displacement in the anti-sunward direction obtained by Killeen and Roble occurs near 15 UT and the Hall current system for 15 UT is shown in Figure 2. Note that Figures 1 and 2 are in geomagnetic coordinates, while Killeen and Roble's original figures are in geographic coordinates.

Maezawa (1976) evaluated the equivalent height-integrated currents over the summer polar cap from ground magnetic field measurements under the assumption the currents were Hall currents. He assumed the current intensities varied linearly with B_z and presented currents per nT of B_z. From Maezawa's Figure 9, the average value of B_z was about 2nT during his observation periods with northward B_z.

Figure 3 shows the currents obtained by Maezawa for a northward B_z of 2nT. Note that the figure covers only 15° in latitude, while Figures 1 and 2 cover 30°. Maezawa's observations were from the northern polar cap, while Killeen and Roble's (1984) calculations were for the southern polar cap. We therefore have redrawn Maezawa's figure to agree with the local time convention of Figures 1 and 2. Figures 1 and 3 show quite similar currents, both in magnitude and in the overall pattern. A noticeable difference is that the center of the vortices is ~ 3000 km apart in Figure 1, but only ~ 2000 km apart in Figure 3. The current pattern for 15 UT in Figure 2 is rotated with respect to the observations. How-

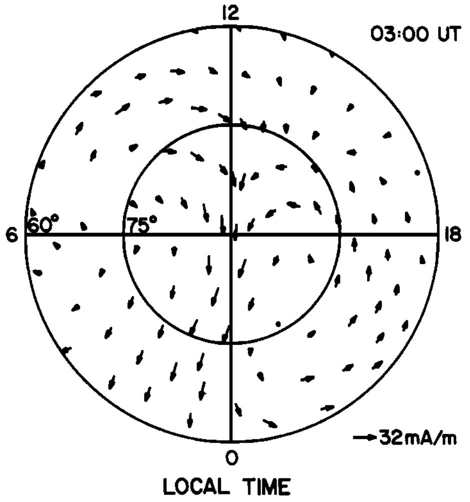

Fig. 1. Height-integrated Hall current over the summer polar cap obtained from Killeen and Roble's (1984) model values for V_n for 3 UT and Σ_H = 8 mhos. Geomagnetic coordinates are used.

ever, the analysis of the observational data did not allow for possible UT variations.

Solely on the basis of the comparison with Maezawa's results, it appears that the neutral wind flywheel can account for the entire polar cap current system for $B_z > 0$. However, other observations indicate that the neutral winds only drive a portion of the currents. Burke et al. (1979) presented polar cap measurements showing that electric fields drive sunward convection near the center of the polar cap for $B_z > 0$, and such electric fields will contribute to the current system for $B_z > 0$. In addition, Iijima et al. (1984) have observed stable currents for large B_z (> 5 nT). These currents are nearly an order of magnitude greater than those in Figures 1-3, and they have been observed to persist for up to 10 hours.

The neutral winds over the polar cap give a large-scale distribution of field-aligned currents as well as ionospheric currents. Assuming a spatially uniform, vertical geomagnetic field, we have:

$$j_\| = -\underline{\nabla} \cdot \underline{I}_P = \frac{\Sigma_P}{\Sigma_H} \underline{\nabla} \times \underline{I}_H ,$$

where $j_\|$ is positive in the upwards direction. Thus the dawn vortex in the Hall current over the polar cap is associated with upward field-aligned currents, while the dusk vortex is associated with downward currents.

Figure 1 can be used to estimate the magnitude of the field-aligned currents driven by the neutral winds. The peak magnitude of I_H in Figure 1 is about 40 mA/m. For $\Sigma_P = 5$ mhos and $\Sigma_H = 8$ mhos, we obtain a peak Pedersen current of about 25 mA/m. The current reverses direction over a distance of approximately 3000 km, so that the mean value of $j_\|$ is approximately:

$$|j_\|| \approx \frac{50 \times 10^{-3}\ \text{A/m}}{30 \times 10^{5}\ \text{m}} \approx 2 \times 10^{-8}\ \text{A/m}^2 .$$

Such a value for $j_\|$ is about two orders of magnitude below the values typically associated with the auroral zone. However such currents should be measurable, particularly since the currents extend throughout the summer polar cap as illustrated in Figure 4. Figure 4 shows visual estimates of regions where $\underline{\nabla} \times \underline{I}_H$ in Figure 1 is significant, so that $j_\|$ is of the order of 10^{-8} A/m^2. A large-scale region of upward current is expected on the dawn side, and a large-scale region of downward current is expected on the dusk side. Such a large-scale, field-aligned current distribution has been observed by Iijima et al. (1984) for $B_z > 5$ nT; however their reported current densities are more than an order of magnitude greater than those expected from the neutral winds.

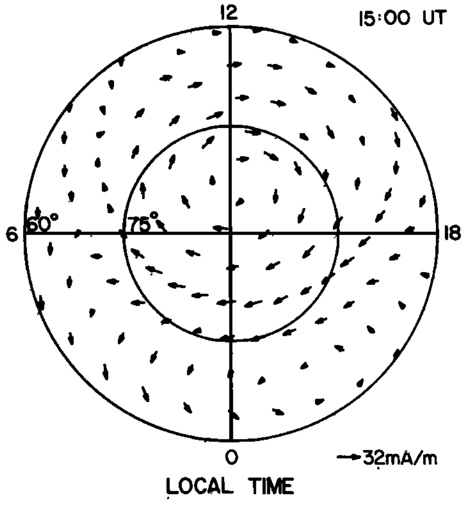

Fig. 2. Same as Figure 1, except for 1500 UT.

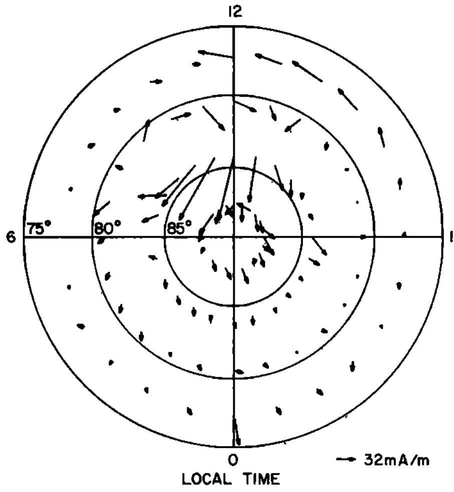

Fig. 3. Height-integrated currents obtained by Maezawa (1976) over the summer polar cap from ground magnetic field measurements under the assumption the currents were Hall currents. The current values are for a B_z of 2 nT.

Conclusions

Our results suggest that neutral winds can contribute significantly to ionospheric and field-aligned currents in sunlit polar regions. Here we have specifically considered the effects of neutral winds modified by magnetospheric convection over the summer polar cap. For southward B_z, the neutral wind pattern is driven to resemble the plasma convection pattern, though the wind speeds in the conducting E-region are about 25% of the plasma convection speeds. If convection ceases, this neutral wind distribution can drive a significant polar cap current system for ~ 6 hours. The current directions are reversed from those driven by the electric fields for southward B_z, and the Hall and field-aligned components of the current system resemble those observed during periods of northward B_z.

The magnitude of the Hall currents driven by the neutral winds are comparable to those reported by Maezawa (1976) for northward B_z values below a few nT. This indicates that the neutral wind flywheel can at times account for a significant portion of the polar cap currents for northward B_z. However, electric field measurements and current measurements for $B_z > 5$ nT show that electric fields often contribute as much or more to the currents as do the neutral winds.

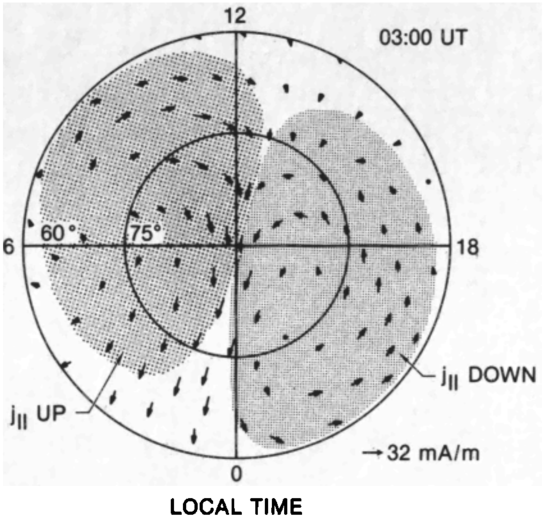

Fig. 4. Same as Figure 1, except visual estimates of regions where $j_\parallel$ is significant are shaded.

The neutral winds drive currents resembling those observed for northward B_z only during the ~ 6 hours it takes the winds to relax to their velocities with no previous magnetospheric convection. It should be noted that the winds without convection can also drive ionospheric and field-aligned currents, and we are currently investigating such current generation. Future work will also consider more realistic conductivity profiles including the effect of enhanced precipitation in the auroral zone.

Our analysis neglects any charge accumulation along polar cap field lines that might arise from the divergence of ionospheric Pedersen currents driven by the neutral winds. However, the question of whether such charge accumulation can develop significant magnetospheric electric fields presents an interesting problem for future study.

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