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THE FLYWHEEL EFFECT: IONOSPHERIC CURRENTS AFTER A GEOMAGNETIC STORM

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Abstract. In the period following a geomagnetic storm the high-latitude, magnetospheric-driven convection pattern is normally weak. However, the neutral circulation, set up by ion-neutral momentum coupling during the main phase of the storm, may continue for several hours after the storm has ended. This persistent neutral circulation has the potential to drive Hall currents for some hours. In this paper we investigate these "flywheel" currents by simulating a storm which occurred on the 23rd of November 1982 using the National Center for Atmospheric Research Thermosphere Ionosphere General Circulation Model (NCAR-TIGCM). The resulting high-latitude, height-integrated Hall currents are dominated by the neutral-wind-driven component for several hours after the end of main phase of the storm. The direction of these currents is reversed from normal. Analysis of the neutral and ion components of this current system indicates that the neutral component may drive as much as 80% of the high-latitude current system immediately after the storm has ended, and may continue to dominate this system for 4 to 5 hours.

Introduction

The electrodynamic effects of thermospheric winds have been studied for many years [e.g., Richmond and Roble, 1987; Forbes and Garrett, 1979]. These studies show that the thermospheric dynamo plays an important role in determining the ionospheric currents at low and middle latitudes. However, the currents at high latitudes are driven primarily by magnetospheric electric fields, which, through collisional processes, also drive the high-latitude, neutral circulation in the upper thermosphere. The magnetospheric convection electric field maps into the high-latitude ionosphere and causes the ions to drift in an **ExB** direction at F-region altitudes, typically resulting in a two-cell ionospheric convection pattern for southward interplanetary magnetic field conditions (IMF B_z southward). These convecting ions impart momentum to the neutral gas through ion-drag forcing, causing the neutral winds to adopt a circulation pattern that is similar to the ion convection pattern.

Killeen and Roble [1984] have studied the momentum forcing terms for the neutral wind in the lower thermosphere. They found that high-latitude E-region neutral winds follow the ion convection pattern as a result of ion-drag forcing, with the peak speed of the neutrals being roughly one-fourth that of the ions during summer. While this pattern represents the normal state of the E-region, high-latitude, neutral circulation, a sudden change in ion convection may result in large transient ion-neutral difference velocities. The relatively long time constant in the E-region for the transfer of momentum from the plasma to the neutral gas implies that the neutral winds that were forced by the ions during the main phase of the geomagnetic storm can persist for a long time after the cessation of magnetospheric-driven forcing, and may drive significant ionospheric and magnetospheric field-aligned currents over the polar cap in a way that is similar to that of the dynamo in low and middle latitudes. Lyons et al. [1985] studied these winds and they showed that, in practice, the neutral circulation in the high-latitude E region can drive a significant Hall current system for up to six hours after the cessation of strong magnetospheric convection - the so-called neutral "flywheel" effect. Some experimental support for this concept exists in the results published by several authors [e.g. Maezawa, 1976; Zanetti, 1984], who showed that ionospheric currents can reverse direction when B_z is northward. In this paper we extend the Lyons et al.[1985] study to investigate the link between the neutral circulation and these reversed currents during the period following a geomagnetic storm.

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Modelling The Storm

Phenomena involving the interaction of the thermosphere and ionosphere are very complicated, especially when they contain feedback processes such as those associated with ionospheric currents. Therefore, we decided to look for a geomagnetic storm where the processes occurring in the post storm period could be simplified in some way. In particular, the ideal storm was one in which the magnetospheric driven electric field terminated abruptly. Such a storm occurred on 23 November 1982. This storm commenced at about 1500 UT when B_z turned southward. High geomagnetic activity continued until 2300 UT when B_z turned northward, and the various indicators of geomagnetic activity available showed that the magnitude of the magnetospheric forcing decreased sharply. B_z then continued to be northward for a long period. The abrupt transition at the end of this storm is ideal for studying the effects of neutral inertia on ionospheric currents. Therefore, we simulated this period by applying magnetospheric inputs specified using algorithms developed by Drs. Reiff and Emery [Reiff and Luhmann, 1986; Emery, private communication] to the NCAR-TIGCM. These magnetospheric inputs are transformed into ion drifts in the NCAR-TIGCM using an ion convection pattern based on the Heelis et al. [1982] model. The inputs for this case are discussed in more detail in Burns et al. [1990], and are not replicated here.

At present, there is no consensus on the most appropriate ion convection pattern for B_z northward. Certainly the convection pattern is more complex for this state than for B_z southward, and, thus, there is no suitable parameterization for magnetospheric convection at this time. Therefore, we have modeled the period after the storm by assuming that geomagnetic activity is very low when Bz is northward (~ 10 kV). This assumption is more reasonable than it might at first seem as the ion drifts that occur during Bz northward conditions are very weak and little particle precipitation occurs at this time. In general, Burns et al. [1990] showed that the NCAR-TIGCM was able to simulate neutral composition during the 5 day period up to and including November 24, 1982, giving us some confidence that our simulation of inertial effects will at least approximate what is happening in the real thermosphere.

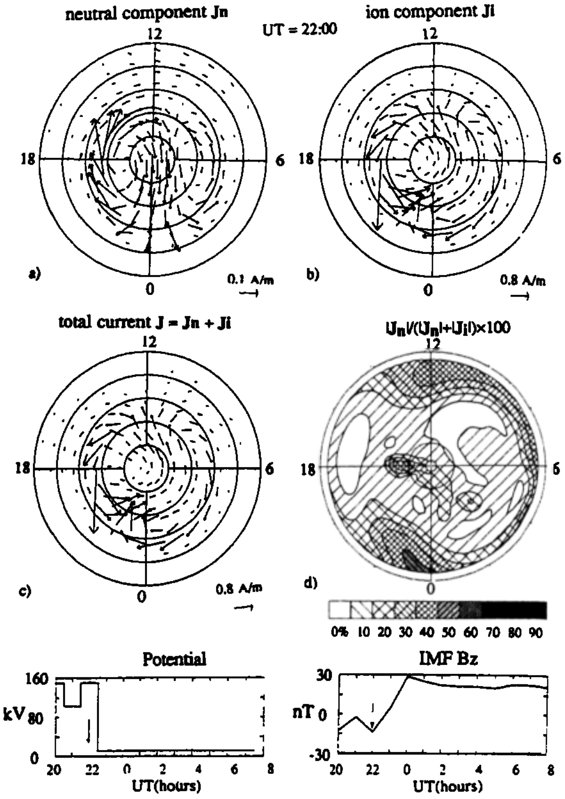

Fig. 1 Calculated height integrated Hall currents in the southern hemisphere for (a) the neutral component, (b) the ion component and (c) the total current. The contribution of the neutral component to the total current, calculated using $|J_n|/(|J_n|+|J_i|)\times100$, is given as a percentage in (d). These values are plotted in the geomagnetic coordinates from 40°S to the geomagnetic pole at 2200 UT.The simulated cross cap potential for the 23rd and 24th of November 1982 are given in (e), while the measured values of Bz for the same period are given in (f). In (e) and (f) the time corresponding to the calculation of the Hall currents is indicated by the arrow.

Killeen and Roble [1984] developed a diagnostic package for the NCAR-TIGCM which treated the output from the model in much the same way as data is treated. That is, the model output can be analyzed further to understand the physical processes that cause changes in the model. Lyons et al. [1985] used this processor to study ionospheric currents in a qualitative fashion. We have refined this previous work here to include calculations of the height-integrated Hall and Pedersen conductivities and thus more accurate Hall and Pedersen currents. These improvements, and the introduction of an ionosphere that responds to changes in the neutral thermosphere in the NCAR-TIGCM, enable us to investigate ionospheric currents with confidence that these currents represent well those that occur in the thermosphere.

Analysis of the Hall Current System

The relative importance of neutral winds in driving ionospheric currents can be assessed by looking at the neutral and ion contributions to the Hall current system separately. Figure 1 shows these components of the calculated height-integrated Hall current system just before the end of the storm, at 2200 UT. The "neutral" Hall current component, shown in Figure 1a, has approximately the same characteristic pattern as the neutral winds themselves at 120 km, except in the auroral region where the corresponding magnitudes of the currents are larger, a result of enhanced auroral conductivities. Since the Hall conductivities maximize in the lower thermosphere, the neutral component of the height-integrated Hall current is dominated by lower thermospheric winds, and is not influenced strongly by the conditions in the upper thermosphere. However, the "ion" component of the Hall current (Figure 1b) is similar to the magnetospheric convection pattern, except that the ion motion is in the opposite direction to the current. Other minor changes from the ion convection pattern do occur because height-integrated conductivities are smaller over the polar cap than they are in the auroral oval, and thus currents are relatively weaker over the polar cap than they are in the oval. The combination of the ion and neutral components results in a Hall current system that is dominated by the ion component during the main phase of the geomagnetic storm, as is shown in Figure 1c. The magnitudes of these primarily ion-driven Hall currents are reduced somewhat by the neutral component. Figure 1d illustrates the percentage change in the total Hall current system when neutral winds are included in the calculation. It may be seen that the contribution of the neutral component to the total Hall current is relatively small - about 10-20% through most of the polar cap.

At about 2300 UT, Bz turns northwards and the our parameterized cross-cap potential drops from about 150 kV to 10 kV. As a result of this potential drop, the maximum magnitude of the ion drifts is reduced from about 1500 m/s to about 150 m/s, which, in turn, leads to a significant reduction in the ion component of the Hall current system. However, the self-consistently-calculated neutral winds in the lower thermosphere do not change so rapidly, because of the large inertia of the neutral gas. These neutral winds can drive a significant part of the Hall current system after ion forcing is diminished at the end of the substorm, and the neutral component of the Hall current becomes larger than the ion component at this time - the "flywheel" effect. The neutral component of the Hall current, which is more important than the ion component at 2300 UT, is directed in the opposite direction to the magnetospheric-convection-driven polar-cap current system that dominates during southward B_Z conditions. These neutral currents also have double-vortex forms, but the current now flows in an antisunward direction over the polar cap and in a sunward direction at lower latitudes. Figure 2 shows the neutral component, the ion component and the total Hall current at 2300 UT, during the recovery phase of the storm. The same format is used as for the preceding figure. It is immediately apparent that the modelled total Hall current system (Figure 2c) is dominated by the neutral component (Figure 2a). Figure 2d shows the contribution of the neutral component to the total current. At this time the neutral component can account for up to 90% of

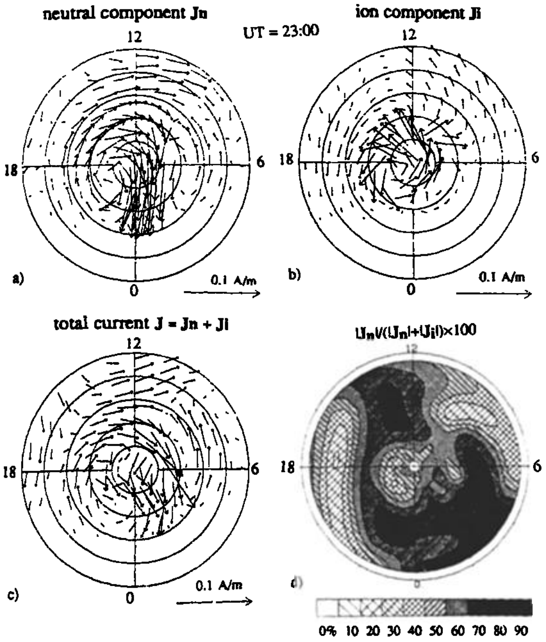

Fig. 2 The same as Figure 2 a) - d) except at 2300 UT.

the total current in the pre-midnight sector between 40° - 70°S geomagnetic latitudes. At latitudes higher than 70°S, the neutral contribution is somewhat less, due to the relatively strong ion component of the Hall current, an indication that the ion convection pattern is still important at these latitudes in our simulation. Antisunward Hall currents have been observed during northward B_Z conditions by many authors [e.g. Maezawa, 1976; Zanetti et al.,1984]. Normally, the currents that occur in these conditions have been associated with sunward magnetospheric convection flow. Our calculations, which do not include this sunward ion convective flow, indicate quantitatively that neutral flywheel effects also make a significant contribution to these currents.

Figure 3 shows the variation of the average contributions of the neutral component with time for all latitudes above 60°S. These contributions decrease from a value of over 65% at 2300 UT to just over 50% some 4 or 5 hours later. The low cross-cap potential used in this simulation insures that the neutral contribution to the Hall current remains high after this time. These averages indicate that the neutral component dominates the Hall current system for about 4 to 5 hours after Bz turns northward. However, the calculations discussed above were made using a model in which ion motion was not influenced directly by the neutral winds. We intend to re-evaluate the importance of the neutral contribution at a later date using a fully coupled electrodynamic model.

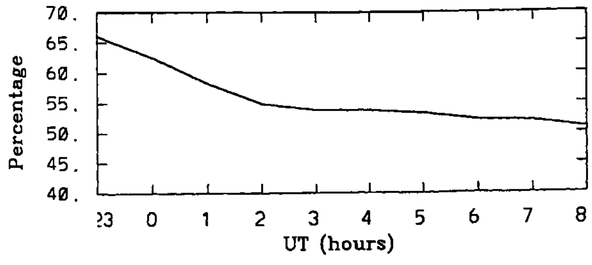

Fig. 3 The average of contribution of neutral component to the total current at latitudes above 60°S.

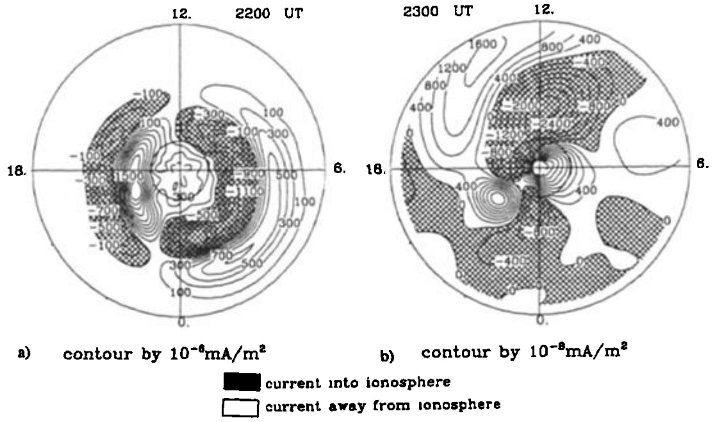

Fig. 4 Calculated field-aligned current density over the southern hemisphere using geomagnetic coordinates from 40°S to the geomagnetic pole (a) at 2200 UT and (b) 2300 UT.

Analysis of the Field-Aligned Current

The field-aligned currents, $J_{\parallel}$, are calculated using divergences calculated from the VSH algorithm discussed by Killeen et al. [1987, 1991]. Our modeled values for the southern hemispheric field-aligned currents are given in Figure 4a for 2200 UT, the middle of the substorm. This figure reproduces the well-known, two-region field aligned current pattern [e.g., Iijima and Potemra, 1978]. Region 1 currents are found at higher latitudes and are directed down into the ionosphere in the morning sector between 65°S and 75°S, while they are directed upwards from the ionosphere in the evening sector above 70°S. The Region 2 currents occur at lower latitudes and flow in the opposite direction to the Region 1 currents. These Region 2 currents are found in the morning sector between 55°S and 65°S and in evening sector between 60°S and 70°S. Maximum Region 1 current densities of about 1.7 $\mu A/m^2$ occur at 1900 UT in the evening sector and 0200 UT in the morning sector. At these times the magnitude of the Region 1 current is about a factor of 3 greater than that of the corresponding Region 2 current. Our calculations of the field-aligned currents produce a pattern that is very similar to the Iijima and Potemra [1978] results, and our maximum amplitudes are of the same order of magnitude. This similarity gives us confidence that we can investigate the physical processes responsible for the changes of field-aligned currents using the NCAR-TIGCM and the VSH model algorithm with certain reservations. A major source of uncertainty in our calculations of the field-aligned currents involves the grid resolution of the NCAR-TIGCM (5° in latitude and longitude). This relatively coarse resolution spreads the field-aligned currents out over a latitude range that is a factor of 2 wider than the observed range, which is about 5 degrees. Also, the magnitude of our calculated currents will be decreased as a result of this smearing.

The structure of these field-aligned currents at 2300 UT, one hour after the end of the substorm, is shown in Figure 4b. Because of the low value of the cross-cap potential assumed at this time (10 kV), this figure shows a field-aligned current system that is driven primarily by the neutral winds. The current here has changed considerably from the normal two region current pattern. Two large-scale regions of downward current are seen around geomagnetic noon at about 70°S, and around geomagnetic midnight at 75°S. There are two large-scale regions of upward current, one in the evening sector with a peak at 75°S, and one in the morning sector with a peak near the geomagnetic pole. The maximum densities of these neutral-wind-driven, field-aligned currents are about 0.04 $\mu A/m^2$ for both the upward and the downward currents. Such large-scale, field-aligned current distributions have been observed in the dayside by Iijima et al. [1984] for $B_Z>5$ nT. However, their reported current densities are an order of magnitude greater than ours. Zanetti et al. [1984] have used the same observational data as Iijima et al. [1984] to determine the morphology of the Hall current in the polar cap, and they confirmed the presence of an antisunward flowing Hall current for northward IMF, which is consistent with our predictions of the behavior of the Hall current, made in the previous section. Therefore, there is a discrepancy between the Iijima et al. [1984] results and our calculations of the magnitude of the "neutral"-driven field-aligned current system during storm-time recovery, but some general agreement as to the morphology of the current system. Part of this discrepancy may be due to the smearing effect mentioned in the previous paragraph. Another cause for our discrepancy may involve our not modeling the magnetospheric convection pattern for B_z northward conditions. A further source of uncertainty in our work on field-aligned currents involves our assumption that the field-aligned currents are determined solely by the divergence of the Pedersen currents (R. Heelis, private communication). By doing this we treat the magnetosphere as a perfect conductor, whereas in reality some polarization electric fields will probably develop.

Summary

We have extended the Lyons et al. [1985] study to conduct an investigation into neutral flywheel effects using an NCAR-TIGCM simulation of a geomagnetic storm that occurred on 23 November 1982. We confirmed their results that neutral winds contribute significantly to the ionospheric Hall currents and field-aligned currents during the periods of northward B_z conditions. Our principal new results are the following:

1) Neutral-wind-driven Hall currents can contribute as much as 80% of the polar Hall current system during the storm-time recovery and these transient effects may last several hours.
2) The morphology of the calculated field-aligned currents during southward B_z conditions is in general agreement with observations, but smearing effects occur due to the limited (5°x5°) spatial resolution of the model.
3) Magnitudes of these calculated field-aligned currents appear to be too small to explain the observed currents without invoking other mechanisms when B_z is northward

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