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Modeling of the Coupled Magnetospheric and Neutral Wind Dynamos

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1 INTRODUCTION

1.1 HIGH-LATITUDE ELECTRODYNAMICS

The solar wind interaction with the earth's magnetosphere generates electric fields and currents that flow from the magnetosphere to the ionosphere at high latitudes. Consequently, the neutral atmosphere is subject to the dissipation and conversion of this electrical energy to thermal and mechanical energy through Joule heating and Lorentz forcing. As a result of the mechanical energy stored within the neutral wind (caused in part by Lorentz—and pressure gradient—forces set up by the magnetospheric flux of electrical energy), electric currents and fields can be generated in the ionosphere through the neutral wind dynamo mechanism. At high latitudes this source of electrical energy has been largely ignored in past studies, owing to the assumed dominance of the solar wind/magnetospheric dynamo as an electrical energy source to the ionosphere. However, Thayer and Vickrey (1991) have demonstrated that the available electrical energy provided by the neutral wind is significant at high latitudes, particularly in the midnight sector of the polar cap and in the region of the magnetospheric convection reversal. As a result, the conclusions of a number of broad ranging high-latitude investigations may be modified if the neutral-wind contribution to high-latitude electrodynamics is properly accounted for. These include:

- Studies assessing solar wind-magnetospheric coupling by comparing the cross polar cap potential (as determined by the reversal boundary in the plasma convection) with solar wind parameters
- Research based on the alignment of particle precipitation with convection or field-aligned current boundaries
- Synoptic investigations attributing seasonal variations in the observed electric field and current patterns to external sources.

These research topics have been initiated by satellite and ground-based observations and have been attributed to magnetospheric causes. However, the contribution of the neutral wind to the high-latitude electric field and current systems and their seasonal and local time dependence has yet to be quantitatively evaluated. In this program, we are evaluating the coupled magnetospheric and neutral wind dynamos at high latitudes under various conditions. For example, in addition to examining the impact of seasonal variations, we are investigating the consequences of the separate dynamos having pure current-source or voltage-source behaviors. Indeed, one can imagine the current-voltage characteristics to depend on magnetic topology; our approach is to incorporate such flexibility. In addition, a generalized relationship between conductivity perturbations and magnetospheric electrodynamic structure is addressed. The analysis accounts for gradients in the neutral wind and conductivity and their height dependence, which (depending on magnetospheric boundary conditions) can generate currents or electric fields.

2 PROJECT DESCRIPTION

2.1 SCIENTIFIC APPROACH

In many high-latitude studies of electrodynamics, the ionosphere is treated simply as a resistive load described by the distribution in conductivity. In that instance, the ionosphere acts as a dissipative medium converting electrical energy to thermal energy through Ohmic heating. This approach neglects the reactive nature of the neutral wind, which dynamically influences the electrical properties of the ionosphere-magnetosphere system. Our approach specifically accounts for the inherent energy storage of the neutral wind system. To assess how electrical energy from the neutral wind dynamo is manifested in terms of currents or polarization electric fields requires specific boundary conditions and detailed information on the magnetospheric "load."

If the internal resistance of the magnetospheric generator is small compared to the ionospheric load, the magnetospheric generator will deliver a fixed voltage. In other words, under this assumption, the magnetosphere is considered a pure voltage generator with internal conductivity approaching infinity; the neutral wind dynamo is a pure current generator. Any divergence of perpendicular ionospheric currents is closed through the magnetosphere generator. In the opposite extreme, the magnetosphere can be considered a pure current generator; then its internal conductivity must be zero and the neutral wind dynamo acts as a voltage generator setting up polarization electric fields in the ionosphere. The potential pattern (convection) in the magnetosphere must match what is demanded by the low-altitude dynamo.

The integral nature of the electrical coupling between the ionosphere and magnetosphere precludes the direct separation of the neutral wind and solar wind contributions from observed electric currents and fields. Therefore, to gain some insight into their relative importance, we are performing a series of numerical experiments in which different properties of the two generators are analyzed and their energetics evaluated separately. In our experiments, the generator properties in the magnetosphere dictate the electrical response of the generator in the ionosphere. In these numerical experiments, we investigate the ionospheric current and electric field distribution for a magnetosphere acting as a voltage generator and current generator, respectively, for both a static and dynamic neutral atmosphere. Our initial intent assumes perfect electric field mapping, i.e., equipotential field lines, between the ionosphere and magnetosphere at high latitudes. These experiments are being performed for different local times and seasons to elucidate the generator behavior under different ionospheric conditions. Sensitivity studies evaluating the importance of the conductivity distribution separately from the neutral wind dynamics help to demonstrate how these variations influence the electrodynamics. The thermospheric and ionospheric properties are provided by the Vector Spherical Harmonic (VSH) model, described by Killeen et al. (1987), which provides a spectral representation of numerical simulations performed by the NCAR TIGCM. These experiments evaluate the potential feedback of the neutral wind/ionospheric dynamo on the high-latitude electrodynamics.

Past magnetospheric investigations have applied both of these generator conditions to describe some of the physical processes of high-latitude electrodynamics. Observational evidence for both types of generators has also been presented (i.e., Fujii et al., 1981; Robinson, 1984; Vickrey et al., 1986). However, Lysak (1985) points out that neither of these cases is completely realistic and that an intermediate generator condition must be found. A variable conductivity related to the Alfvén speed can be used to provide a range between the current and voltage generator extremes. The temporal development of currents and/or electric fields is modulated by Alfvén waves traveling between the ionosphere and magnetosphere. The reflection of Alfvén waves is determined by the ratio of the ionospheric height-integrated conductivity to an effective Alfvén conductivity. Lysak (1990, 1991) considers Alfvén wave reflection with different types of generator conditions and different feedback processes. Our initial approach is to fix the magnetospheric generator condition; this implicitly neglects Alfvén wave reflection from both the magnetosphere and ionosphere. Subsequently, we will adopt an Alfvén wave reflection model for the ionosphere that is similar to that discussed by Knudsen et al. (1991).

2.2 NUMERICAL APPROACH

We use the NCAR-TIGCM, described by Roble et al. (1988) and references therein, to simulate the neutral dynamics, composition, and charged species distribution at high latitudes. Each NCAR-TIGCM simulation is uniquely determined by the input parameterizations to the model (i.e., EUV and UV fluxes, auroral particle precipitation, high-latitude ionospheric convection, and lower thermospheric tides). The model is run until the output reaches a diurnally reproducible state, providing output at 24 different pressure levels ranging in altitude from 97 km to 500 km on a 5° geographic grid. The Heelis convection model (Heelis et al., 1982) has been incorporated into the model formulation to account for the neutral momentum and energy created by the ion convection in terms of ion drag and Joule heating. High-latitude particle precipitation in the auroral oval, cusp, and polar cap has been parameterized within the NCAR-TIGCM by Roble and Ridley (1987) to account for this additional energy source of energy and ionization. Through various combinations of the input parameters, the NCAR-TIGCM can simulate the neutral winds in three dimensions so that local time, season, and geomagnetic storm effects can be studied. The extension of the model to include a self-consistent aeronomic scheme of the thermosphere and ionosphere allows the global distribution of ion and electron densities to be calculated within the model. The NCAR-TIGCM model does not currently include electrodynamic feedback on the imposed high-latitude convection resulting from the generated neutral wind motion in the model. Thus, the potential electrical energy generated in the thermosphere is contained within the mechanical energy of the neutral gas and the distribution in conductivity.

The Vector Spherical Harmonic (VSH) model has been developed (as discussed by Killeen et al., 1987) to make the NCAR-TIGCM output more manageable for applications of thermosphere/ionosphere studies. This spectral model uses scalar and vector spherical harmonics as the basis functions to represent scalar and vector output fields from the NCAR-TIGCM on the sphere. The model performs a spectral fit to the output fields from a specific NCAR-TIGCM run, providing a library of spectral coefficients that are used to recover desired fields from a particular run. Recently, the VSH model has been extended to allow specific geophysical conditions to be studied by interpolating between NCAR-TIGCM runs that are nearest these conditions. The VSH model also provides the framework for the development of a semi-empirical thermospheric model. This latter application has now become possible because of the existence of a large empirical database of thermosphere/ionosphere observations.

Given the tractable nature of spherical harmonics for problems on a sphere, the spectral model can also be used to solve differential equations on the sphere. Because spherical harmonics are the natural basis functions for problems on the sphere, difficulties occurring near the pole by other spectral functions or numerical techniques are eliminated. The output from the NCAR-TIGCM contains the thermospheric and ionospheric quantities needed to solve the neutral wind dynamo equations. The spectral representation of these variables by the VSH model allows for these equations to be solved spectrally. Any scalar field defined on the surface of a sphere can be expanded in terms of scalar spherical harmonics. The vector basis set generated from a vector field defined on the surface of a sphere are the vector spherical harmonics whose components are linear combinations of scalar harmonics. The vector basis set constitutes an orthogonal and complete system with the horizontal vector components representing the nondivergent and irrotational components of the horizontal vector field. The approach of this research is to use these attributes of vector and scalar spherical harmonics, as well as their derivative properties, to simplify the dynamo equations into a set of algebraic equations. This technique facilitates a term analysis of each equation and determines the importance of the neutral wind dynamo mechanism to high-latitude electrodynamics.

2.3 PROGRESS DURING THE REPORTING PERIOD

The governing equations describing dynamo action, derived from Ohm's law and the steady-state form of Faraday's and Ampere's law in a reference frame rotating with the earth, can be written as

$$\nabla_{\perp} \bullet (\sigma_{\perp} \bullet \nabla\Phi) = \nabla_{\perp} \bullet \left(\sigma_{\perp} \bullet \vec{U}_n \times \vec{B}_0\right) + \frac{\partial j_{\parallel}}{\partial z} \quad ,$$

$$\nabla \times \left(\overline{\sigma}^{-1} \bullet \vec{j}\right) = \nabla \times \left(\vec{U}_n \times \vec{B}_0\right) \quad ,$$

$$\nabla \bullet \left(\overline{\sigma}^{-1} \bullet \vec{j}\right) = -\nabla^2\Phi + \nabla \bullet \left(\vec{U}_n \times \vec{B}_0\right) \quad ,$$

where $\nabla\Phi$ is the polarization electric field, $\vec{B}_0$ is the background geomagnetic field, $\vec{j}$ is the current density, $\sigma_{\perp}$ is the perpendicular to $\vec{B}_0$ anisotropic conductivity tensor, $\overline{\sigma}$ is the three-dimensional conductivity tensor, $\vec{U}_n$ is the neutral wind vector, and $\perp$ refers to perpendicular to the geomagnetic field.

As discussed above, the different boundary conditions imposed on the magnetosphere yield different solutions to the dynamo equations. Currently, the condition that the magnetosphere acts as a voltage generator has been addressed and the necessary software development has been carried out. The large-scale electric field, described by the Heelis convection pattern, maps directly into the high-latitude ionosphere along highly conductive magnetic field lines. The subsequent current system remains variable and dependent on the dynamics of the load and the neutral motion in the ionosphere. In this case, the neutral wind dynamo must act as a current generator in which any divergence in the perpendicular current is balanced by field-aligned currents closed through the zero-impedance magnetospheric "load." Under these boundary conditions, no polarization electric field is established by dynamo action in the ionosphere, thus the resulting dynamo equation to be solved is

$$\int_{Z_0}^{Z_{top}} \nabla_{\perp} \bullet (\sigma_{\perp} \bullet \nabla\Phi_M) dz = \int_{Z_0}^{Z_{top}} \nabla_{\perp} \bullet \left(\sigma_{\perp} \bullet \vec{U}_n \times \vec{B}_0\right) dz + j_{\parallel}(z) \quad ,$$

where $\nabla\Phi_M$ is the fixed magnetospheric electric field mapped into the ionosphere, Z_{top} is 400 km, and Z_0 is 110 km.

In this case, the magnetospheric electric field and neutral wind contribute independently to the total electrodynamics. The above equation can therefore be separated into parts to interpret the individual contributions of the magnetospheric electric field and neutral wind dynamo to the field-aligned current. The equation accounting only for the magnetospheric electric field contribution, assuming the neutral atmosphere is static, can be written as

$$\Sigma_p \nabla_\perp \bullet \nabla_\perp \Phi_M + \nabla_\perp \Phi_M \bullet \int_{Z_0}^{Z_{top}} \nabla_\perp \sigma_p dz + \hat{b} \times \nabla \Phi_M \int_{Z_0}^{Z_{top}} \nabla_\perp \sigma_h dz = j_{\parallel}(Z_{top}) \quad .$$

Thus, only height-integrated gradients in Hall and Pedersen conductivities and the magnetospheric electric field contribute to the field-aligned current for a static atmosphere. The magnetospheric electric field and the conductivities from the TIGCM simulation have been expanded in scalar and vector spherical harmonics. Once expanded, each term in the expression can be evaluated using the derivative properties of spherical harmonics and can be integrated over the altitude range of the ionosphere (110 to 400 km). The derivative properties have been described by Swartztrauber (1981, 1984) and applied in the VSH code by Thayer (1990), and Thayer and Killeen (1992). The conductivity is dependent on the neutral composition and electron density profile, both of which are solved for in the NCAR-TIGCM formulation. We have performed a term analysis for the above equation and are developing the necessary graphical displays to interpret the results. This effort will be completed by the end of the next reporting period.

For a nonstatic neutral atmosphere, the neutral wind contribution to the field-aligned current can be expressed as

$$\int_{Z_0}^{Z_{top}} \left\{ \sigma_p \nabla_\perp \bullet \left(\bar{U}_n \times \bar{B}_0\right) + \left(\bar{U}_n \times \bar{B}_0\right) \bullet \nabla_\perp \sigma_p + \sigma_h \nabla_\perp \bullet \hat{b} \times \left(\bar{U}_n \times \bar{B}_0\right) + \hat{b} \times \left(\bar{U}_n \times \bar{B}_0\right) \bullet \nabla \sigma_h \right\} dz = -j_{\parallel}(Z_{top}) \ .$$

Again, the neutral wind and conductivities from the TIGCM simulation have been expressed in terms of scalar and vector spherical harmonics and a preliminary evaluation of each term from the above equation has been performed. Once adequate display software has been developed, the interpretation of the results will be facilitated.

2.3.1 Travel

There was no travel during this reporting period.

2.3.2 Subcontract

A subcontract to the University of Texas at Dallas (UTD) has been established and is under the direction of Professor Rod Heelis. During the reporting period, UTD has continued an examination of the DC Poynting vector as an indicator of electromagnetic energy transport through the high latitude ionosphere. A major effort devoted to ensuring reliable baselines for the measurement of electric and magnetic fields from the Dynamics Explorer-2 (DE-2) satellite is now complete. When combined with appropriate data quality flags and determination of adequate vehicle attitude knowledge, a reliable determination of the field-aligned component of the Poynting vector from any pass of the DE-2 spacecraft across the high latitude region can be obtained. Examination of the data reveals that the Poynting flux is generally directed downward under all conditions, with large changes in spatial distribution and magnitude dependent on the z-component of the IMF. Other significant differences appear to be dependent on season, wherein a low ionospheric conductivity in the polar cap, associated with the winter hemisphere, gives rise to a preferential distribution of the Poynting flux in the auroral zones. Regions of upward Poynting flux are sporadically located over small spatial scales, suggesting that a direct signature of a large scale flywheel effect from the underlying neutral atmosphere is difficult to obtain. However, regions of upward Poynting flux can occur near small scale reversals or gradients in the ionospheric electric field associated with auroral arcs. The configuration of the electric field and neutral winds in such cases is yet to be determined. A statistical study of the spatial distribution of the Poynting flux for different magnetic and interplanetary conditions is nearing completion, while a thorough description of the process by which the Poynting vector can be determined is in press.

2.3.3 Scientific Reports

A scientific report describing the dynamo solutions at high latitudes is in preparation. A paper by the UTD group describing the technique and giving examples of Poynting flux measurements from DE-2, entitled "Field-Aligned Poynting Flux Observations in the High-Latitude Ionosphere," by J.B. Gary, R.A. Heelis, W.B. Hanson, and J.A. Slavin, is in press in the *Journal of Geophysical Research*. SRI personnel were closely involved in their analysis and interpretation which led to this paper and which contributed to the early development of Poynting flux measurements from DE-2.

2.4 PLANS FOR THE COMING PERIOD

We have begun preliminary evaluation of the case in which the magnetosphere acts as a voltage generator and the ionospheric dynamo acts as a current generator. A complete term analysis and graphical display development is forthcoming. The conductivity distribution is an important parameter, playing a role in the generation of field-aligned currents in both a static and dynamic neutral atmosphere. However, for the dynamic atmosphere situation the height-integrated contribution is weighted by the neutral wind. We plan to evaluate the seasonal variations in the field-aligned currents associated with the seasonal variations in the conductivity and neutral wind.

The case in which the magnetosphere acts as a current generator and the ionospheric dynamo acts as a voltage generator will be the next development of the spherical harmonic code. This numerical development will be more complex than out previous model (Thayer and Vickrey, 1991) and will require further evaluation.

Aspects of the numerical modeling will be compared with observed electrodynamic features from the DE-2 spacecraft in coordination with the UTD team. There is a close relationship between the Poynting flux measurements made by DE-2 and the neutral wind dynamo processes, as discussed by Thayer and Vickrey (1991) and Gary et al. (1994, in press). We will be pursuing this line of study to help elucidate the electrodynamic processes involved in contributing to the observed Poynting flux measurements.

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