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MODELING OF THE COUPLED MAGNETOSPHERIC AND NEUTRAL WIND DYNAMOS

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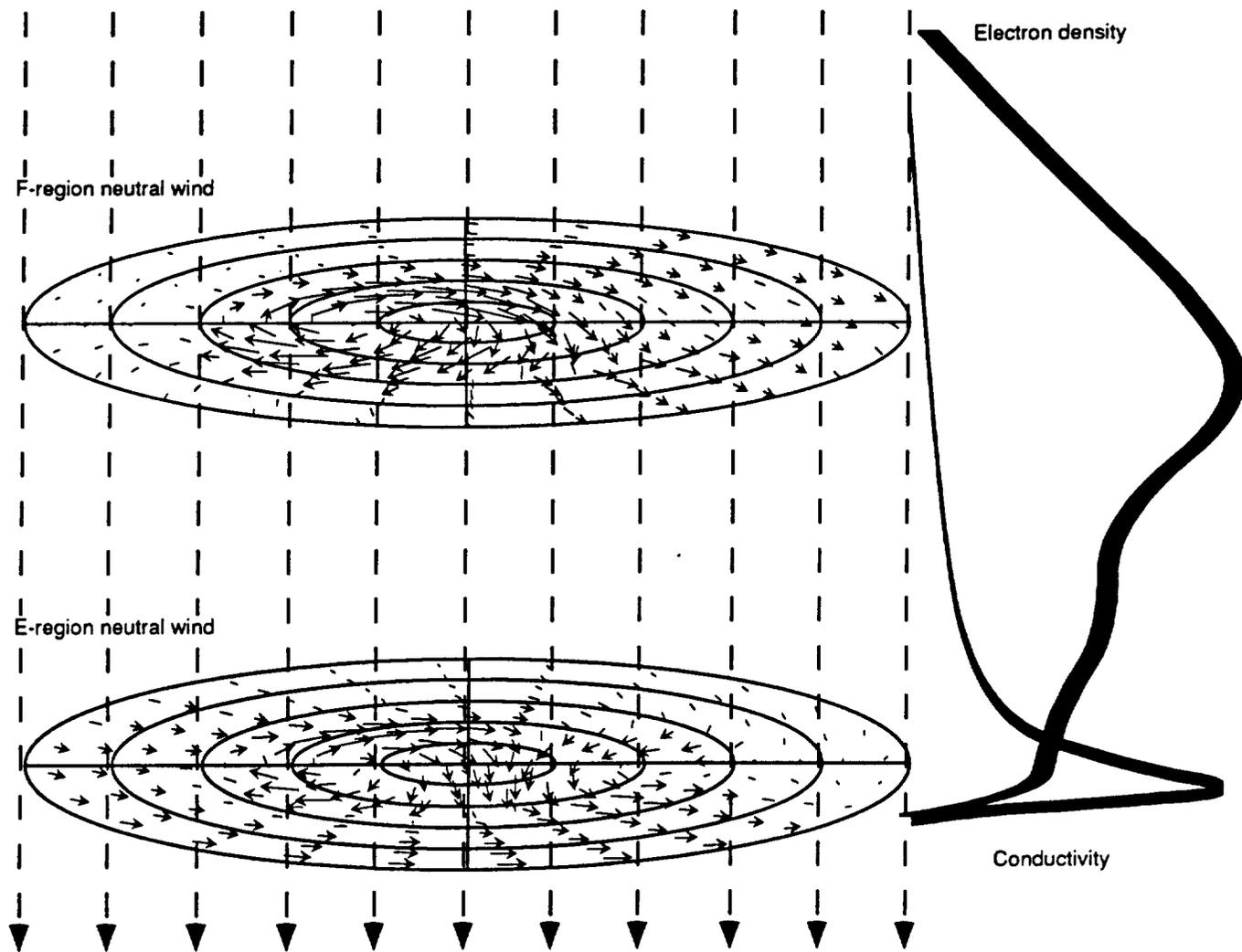
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1 INTRODUCTION

This report summarizes the progress made in the first year of NASA Grant No. NAGW-3508 entitled "Modeling of the Coupled Magnetospheric and Neutral Wind Dynamos." Figure 1 is an illustration of the different ionospheric features involved in solving the neutral wind dynamo equations at high latitudes. The approach taken has been to impose magnetospheric boundary conditions with either pure voltage or current characteristics and solve the neutral wind dynamo equation under these conditions. The imposed boundary conditions determine whether the neutral wind dynamo will contribute to the high-latitude current system or the electric potential. The semi-annual technical report, dated December 15, 1993, provides further detail describing the scientific and numerical approach of the project.

The numerical development has progressed and the dynamo solution for the case when the magnetosphere acts as a voltage source has been evaluated completely using spectral techniques. The simulation provides the field-aligned current distribution at high latitudes due to the neutral wind dynamo. A number of geophysical conditions can be simulated to evaluate the importance of the neutral wind dynamo contribution to the field-aligned current system. On average, field-aligned currents generated by the neutral wind dynamo contributed as much as 30% to the large-scale field-aligned current system driven by the magnetosphere.

A term analysis of the high-latitude neutral wind dynamo equation describing the field-aligned current distribution has also been developed to illustrate the important contributing factors involved in the process. Figure 2 summarizes, schematically, the results of the term analysis, showing that the height-integrated neutral wind vorticity weighted by the Pedersen conductivity is the dominant contributor to field-aligned currents generated by the neutral wind dynamo at high latitudes. These results are being compiled and will be the topic of a forthcoming manuscript for submission to a scientific journal. The case describing the neutral dynamo response for a magnetosphere acting as a pure current generator requires the existing spectral code to be extended to a pseudo-spectral method and is currently under development.



$$\int_{z_0}^{z_{top}} \nabla_{\perp} \cdot (\sigma_{\perp}(z) \cdot \nabla \Phi_M) dz - \int_{z_0}^{z_{top}} \nabla_{\perp} \cdot (\sigma_{\perp}(z) \cdot \bar{U}_n(z) \times \bar{B}_0) dz = j_{\parallel}(z)$$

Figure 1 NEUTRAL WIND DYNAMO MECHANISM AT HIGH LATITUDES

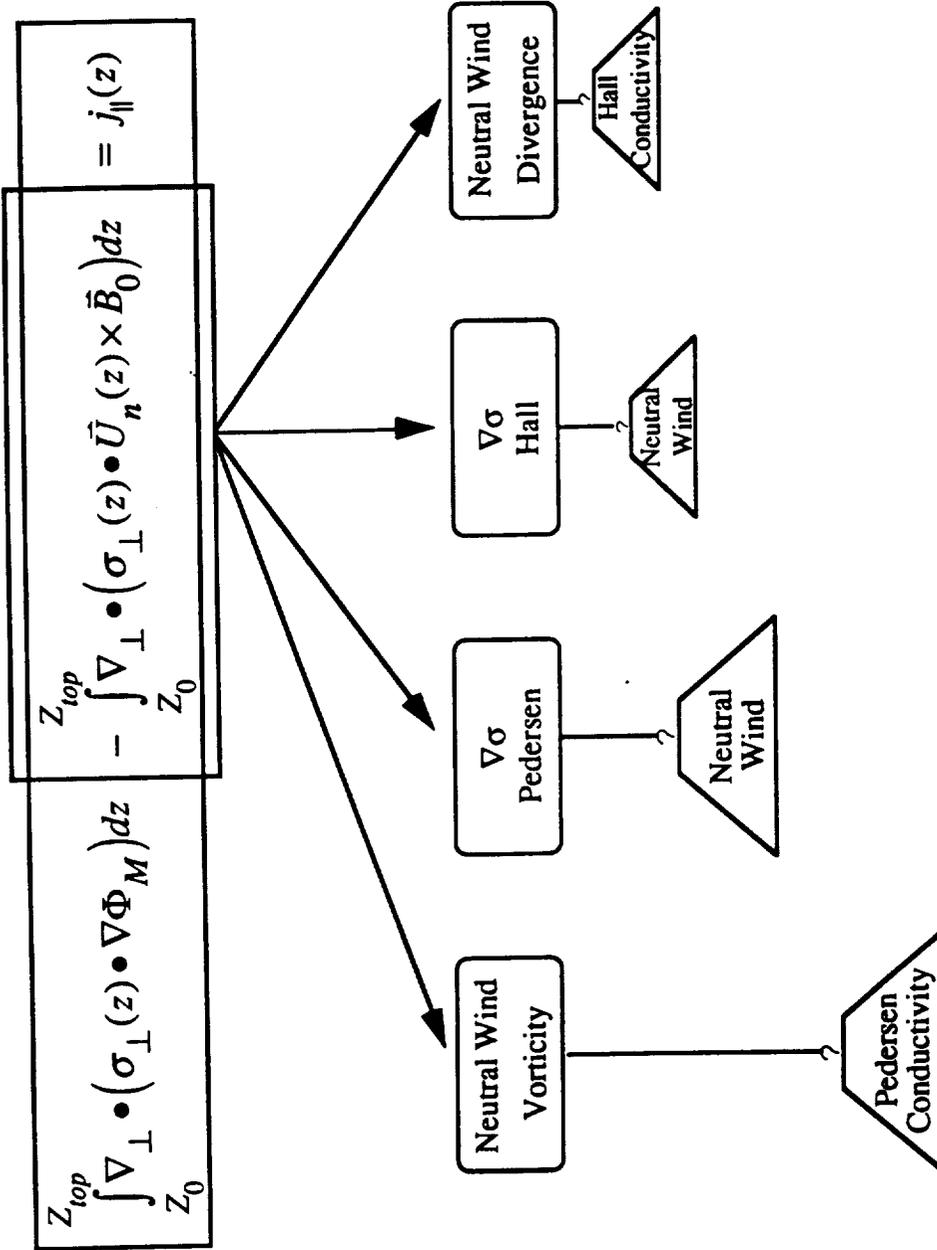


Figure 2 NEUTRAL WIND CONTRIBUTION TO FIELD-ALIGNED CURRENT

Since submitting the semi-annual report, we have begun to investigate how calculations of the energy flux at high latitudes might help in evaluating the importance of the high-latitude neutral wind dynamo. The calculation of the divergence in the magnetospheric DC Poynting flux describes the electrical energy transfer between the ionosphere and magnetosphere, irrespective of whether the magnetosphere acts as a current or voltage generator or some hybrid of the two. Therefore, the impact of the neutral wind dynamo can be quantitatively assessed by evaluating the conversion of mechanical energy to electrical energy. The energy flux determined will be the same whether the neutral wind dynamo contributes to the currents or the electric potential of the system. The imposed assumptions of the modeling study are similar to those imposed for the dynamo equations, i.e., steady state conditions, highly conductive magnetic field lines, and a large-scale magnetospheric source driving the high latitude ionosphere/thermosphere system. This effort is summarized in the following section of this report.

2 PROGRESS DURING THE REPORTING PERIOD

The magnetosphere–ionosphere (M–I) system at high latitudes can exhibit a diverse character in the distribution of currents and electric fields and in the population and energy of plasma particles. These features help to define the various regions of the M–I system and are coupled through the exchange of energy between the electromagnetic field and the plasma. The basic equation describing this process is Poynting’s theorem,

$$\iiint_V \frac{\partial}{\partial t} \left(\frac{B^2}{2\mu_0} + \frac{\epsilon_0}{2} E^2 \right) dV + \iiint_V \frac{\nabla \circ (\vec{E} \times \vec{B})}{\mu_0} dV + \iiint_V \vec{j} \circ \vec{E} dV = 0 , \quad (1)$$

where the first term is the electromagnetic energy density within the volume, the second term is the divergence of the electromagnetic (Poynting) energy flux within the volume, and the third term is the volume energy transfer rate. The derivation of Poynting’s theorem comes directly from Maxwell’s equations using the identity $\nabla \circ (\vec{E} \times \vec{B}) \equiv \vec{B} \circ (\nabla \times \vec{E}) - \vec{E} \circ (\nabla \times \vec{B})$.

Poynting’s theorem has been used to provide a general description of the energy exchange between the solar wind and magnetosphere (e.g., Hill, 1983; Cowley, 1991) for the interpretation of time-varying electromagnetic fields (e.g., Fraser, 1985) and for the evaluation and interpretation of large-scale energy transfer in the ionosphere (e.g., Cowley, 1991; Kelley *et al.*, 1991; Thayer and Vickrey, 1992; Gary *et al.*, 1994). It is this latter usage of Poynting’s theorem that will be used in our modeling study.

For magnetospheric–ionospheric applications, the magnetic field energy density, to a very good approximation, greatly exceeds the electric field energy density. Eq. 1 now becomes

$$\iiint_V \frac{\partial}{\partial t} \left(\frac{B^2}{2\mu_0} \right) dV + \iiint_V \frac{\nabla \circ (\vec{E} \times \delta\vec{B})}{\mu_0} dV + \iiint_V \vec{j} \circ \vec{E} dV = 0 , \quad (2)$$

with $\delta\vec{B}$ representing the perturbation magnetic field due to the large-scale ionospheric current system (see Kelley *et al.*, 1991). Assuming steady state conditions, the divergence of the Poynting flux must be equal to the energy transfer rate within the volume, which leads to the expression

$$-\iiint_V \frac{\nabla \circ (\vec{E} \times \vec{B})}{\mu_0} dV = \iiint_V \{ \vec{j} \circ \vec{E}' + \vec{u}_n \circ (\vec{j} \times \vec{B}_0) \} dV \quad (3)$$

described by Thayer and Vickrey (1992). This formalism has important implications on studies of ionospheric energetics that can be best understood by deriving it from basic principles using the MHD energy and momentum equations.

The ionospheric energy equation describing the total energy of the gas using the MHD or single fluid approximation can be expressed as

$$\rho \frac{D}{Dt} (u) + \rho \frac{D}{Dt} \left(\frac{V^2}{2} \right) + \nabla \circ (\vec{P} \circ \vec{V}) + \nabla \circ \vec{q} = \rho \vec{V} \circ \vec{g} + \rho Q + \vec{j} \circ \vec{E} , \quad (4)$$

where the terms on the LHS are the time rate of change of the internal energy of the gas, the time rate of change of the kinetic energy of the gas, the divergence of the momentum flux vector, and the divergence of the heat flux vector. The terms on the RHS are the kinetic energy of the gas caused by gravity, the internal energy of the gas caused by chemical and radiative processes, and the electromagnetic energy transfer rate describing the rate of electrical energy conversion, dissipation, or generation within the gas. This equation describes the kinetic and internal energies of the gas, however, it is useful to have a separate equation to describe each of these forms of energy. The kinetic energy equation, derived by taking the inner product of the velocity with the MHD momentum equation, is expressed as

$$\rho \frac{D}{Dt} \left(\frac{V^2}{2} \right) + \vec{V} \circ (\nabla \circ \vec{P}) = \rho \vec{V} \circ \vec{g} + \vec{V} \circ (\vec{j} \times \vec{B}) , \quad (5)$$

where the first term is the time rate of change of kinetic energy of the gas while the other terms represent the work done by mechanical and electrical forces on the gas. To describe only the internal energy of the gas, the kinetic energy equation can be subtracted from the total energy equation resulting in the expression,

$$\vec{j} \circ \vec{E} - \vec{V} \circ (\vec{j} \times \vec{B}) = \vec{j} \circ \vec{E}' = \rho \frac{D}{Dt}(u) + \nabla \circ \bar{q} - \rho Q + \bar{P} : \nabla \vec{V} . \quad (6)$$

This equation accounts for only the internal energy of the gas, with the new term $\vec{j} \circ \vec{E}'$ representing the Joule heating rate of the gas. The last term of Eq. 6 accounts for the internal energy of the gas caused by expansion or contraction of the gas and viscous heating. To a good approximation in the ionosphere, the center of mass velocity, \vec{V} , can be replaced by the neutral wind, \vec{u}_n , because the mass density of the neutrals is much greater than that of the ions. The Joule heating rate is then expressed in the more familiar form $\vec{j} \circ \vec{E}' = \vec{j} \circ (\vec{E} + \vec{u}_n \times \vec{B})$. Rearranging Eq. 6, the energy transfer rate can be written as $\vec{j} \circ \vec{E} = \vec{j} \circ \vec{E}' + \vec{u}_n \circ (\vec{j} \times \vec{B})$ and substituted into Eq. 2 to obtain the relationship given in Eq. 3 among the divergence in the Poynting flux, the Joule heating rate, and the mechanical energy conversion rate.

The expression $\vec{j} \circ \vec{E} = \vec{j} \circ \vec{E}' + \vec{u}_n \circ (\vec{j} \times \vec{B})$ could have also been derived by a straight forward transformation of $\vec{j} \circ \vec{E}$ into the non-accelerating reference frame of the neutral wind, \vec{u}_n , however, the full derivation provides more physical insight. For instance, given a better understanding for the quantities $\vec{j} \circ \vec{E}$ and $\vec{j} \circ \vec{E}'$, it is worth reviewing the approaches taken by many investigators in evaluating, empirically, the Joule heating rate in the high-latitude ionosphere. These investigations are mainly to quantify the height-integrated Joule heating rate to describe the internal energy of the gas caused by the dissipation of electrical energy in the ionosphere. The height-integrated Joule heating rate can be obtained without approximation given a measure of the height distribution of the neutral wind, electric field, and either the conductivity or the current density. Because of the difficulty in determining the neutral wind with height, approximations to the neutral wind are typically made when calculating the Joule heating rate from measurements. However, the manner in which the approximation to the neutral wind is treated can result in different interpretations for the evaluated Joule heating rate.

For the case when the height distribution of the conductivity and electric field (assumed independent of height) are known and the neutral wind is assumed to be zero, the form of the height-integrated Joule heating rate is $\vec{J} \circ \vec{E} = \sum_p \vec{E}^2$. This form of the equation means that the kinetic energy of the gas is zero and that the electromagnetic energy from the magnetosphere described by the divergence in the Poynting flux is dissipated entirely into the ionosphere (acting as a resistive load described by the height-integrated Pedersen conductivity) as thermal energy .

A different interpretation results for this case if the height distribution of the current density is known instead of the conductivity. For instance, if the current distribution is determined by solving the expression $\vec{j} = en_e(\vec{V}_i - \vec{V}_e)$ from measurements at different altitudes and the neutral wind is said to be zero, then the height-integrated Joule heating rate

is not that at all but actually the total electromagnetic energy flux converted, dissipated, or generated in the ionosphere; that is, the quantity being determined is $\vec{j} \circ \vec{E}$ which is equal to $\vec{j} \circ \vec{E}' + \vec{u}_n \circ (\vec{j} \times \vec{B})$. This can be seen more clearly if you express the current density in the form of $\vec{j} = \sigma \circ (\vec{E} + \vec{U}_n \times \vec{B})$. This shows that height distribution of the neutral wind is implicit within the measurement of \vec{j} . Also, the Joule heating rate is a positive definite quantity but the determination of $\vec{j} \circ \vec{E}$ could be of either sign, as discussed by Thayer and Vickrey (1992). Therefore, for this case, the statement that the neutral wind is assumed zero is false and it is the total energy flux being calculated. The same result occurs if the height-integrated current density is determined from a satellite measurement using the expression

$$\vec{j} = \frac{\nabla \times (\delta \vec{B})}{\mu_0} .$$

Another situation is one in which the neutral wind is accounted for but assumed height-independent. In this case, with the height distribution of the conductivity and electric field (assumed independent of height) known, the Joule heating rate can be written, $\vec{j} \circ \vec{E}' = \Sigma_p \vec{E}'^2$. The only time this approach can be correct is if the assumed neutral wind is equal to the effective neutral wind expressed as:

$$\vec{U}_{eff} = \frac{\int_z \sigma_{\perp} \circ (\vec{u}_n \times \vec{B}) dz}{\Sigma_p} = \frac{\int_z \sigma_p (\vec{u}_n \times \vec{B}) + \sigma_h |\vec{B}| \vec{u}_n dz}{\Sigma_p} . \quad (7)$$

Expressed in this manner, the height-integrated current density in the direction of \vec{E}' would be written as $\vec{J} = \Sigma_p \vec{E} + \Sigma_p \vec{U}_{eff}$ and $\vec{E}' = \vec{E} + \vec{U}_{eff}$. It is interesting to note that from independent measurements of \vec{J} , \vec{E} , and Σ_p , the effective neutral wind could be determined. Evaluated this way, \vec{U}_{eff} would represent the neutral wind contribution to only the observed current density. The neutral wind contribution to any polarization electric fields would be contained within the measure of E but not accounted for in the determination of \vec{U}_{eff} . From a modeling viewpoint, it can be assumed that no polarization electric fields are set up and that neutral wind contributes entirely to the current density allowing the electrical energy generated by the neutral wind dynamo to be evaluated for the coupled system.

Thayer and Vickrey (1992) studied the relationship given in Eq. 3 assuming two uncoupled systems made up of a magnetospheric circuit and an ionospheric circuit. They then quantified the electrical energy contained in each system, separately, to demonstrate the importance of the neutral wind dynamo as a source of electrical energy at high latitudes. Here, we will pursue a modeling effort to treat the coupled aspects of the M-I system by evaluating Eq. 3 in detail and investigating some of the issues raised in the discussion given above. The modeling effort will

require some assumed boundary conditions on the magnetosphere but these assumptions will not impact the goal to determine how much electrical energy the neutral wind dynamo can contribute in a coupled system.

2.1 TRAVEL

There was no travel during this reporting period.

2.2 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 satellite measurements 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 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. A second paper describing the statistical study of the spatial distribution of the Poynting flux from DE-2 observations is in preparation entitled "Distribution of Field-Aligned Poynting Flux Determined from DE 2 Observations," by J.B. Gary, R. A. Heelis, and J. P. Thayer.

3 PLANS FOR THE COMING PERIOD

A number of aspects of this research will be addressed in the coming period. The neutral wind dynamo analysis will continue with further development in modeling the currents and/or electric fields under different geophysical conditions and for different seasons. A term analysis will also be carried out to describe the importance of each term in the dynamo equation under these different geophysical conditions. Further development of the spectral code is required to accommodate the latest version of the NCAR-TIEGCM. New model runs from the NCAR-TIEGCM will be anticipated, which will provide better tidal parameterization within the model and include a better electrodynamic simulation.

The modeling of the electrical energy flux between the ionosphere and magnetosphere will be pursued further providing a new view and new insights into describing the role of the neutral wind dynamo in terms of its electrical energetics. This modeling effort will benefit from the dynamo calculations and address similar issues.

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 (1992) and Gary *et al.* (1994). 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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