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SELF-CONSISTENT LARGE-SCALE MAGNETOSPHERE-IONOSPHERE
COUPLING: COMPUTATIONAL ASPECTS AND EXPERIMENTS

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Introduction

Both external and internal phenomena impact the terrestrial magnetosphere. For example, solar wind and particle precipitation effect the distribution of hot plasma in the magnetosphere. Numerous models exist to describe different aspects of magnetosphere characteristics. For example, Tsyganenko has developed a series of models (e.g., [TSYG89]) that describe the magnetic field, and Stern [STER75] and Volland [VOLL73] have developed an analytical model that describes the convection electric field. Over the past several years, NASA colleague Khazanov, working with Fok and others, has developed a large-scale coupled model that tracks particle flow to determine hot ion and electron phase space densities in the magnetosphere. This model utilizes external data such as solar wind densities and velocities and geomagnetic indices (e.g., Kp) to drive computational processes that evaluate magnetic, electric field, and plasma sheet models at any time point. These models are coupled such that energetic ion and electron fluxes are produced, with those fluxes capable of interacting with the electric field model. A diagrammatic representation of the coupled model is shown in Figure 1.
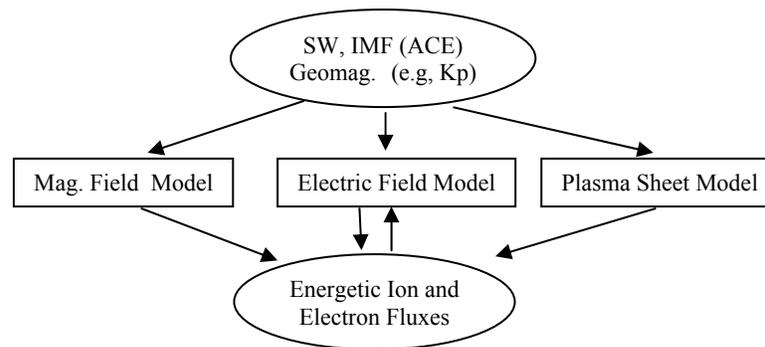

Figure 1: Coupled Model

In this coupled model, the two magnetic field models that have been used to date are the dipole and the Tsyganenko (1996) magnetic field models. The electric field models that have been used to date are the Volland-Stern convection, Weimer, Rice Convection Model (RCM), and AMIE models.

In this report, some of the experiments we have performed (during the NASA Fellowship program) using this model are described. The experiments that were performed involved extending the model and building variations on the model. We have also considered computational aspects of the model, and some of our work in this area is also described.

Contributions

The new model combinations that have been utilized in our work include incorporation (into the coupled model) of time-dependent cross-tail potential within the Volland-Stern convection model, addition of a heavy proton (oxygen) in the Rice Convection Model, and incorporation of the AMIE potential model.

The Coupled Model

The coupled model solves for the hot plasma kinetic energy using a bounce-averaging approach that incorporates effects such as diffusion and charge exchange (decay). Equation 1 expresses the model's kinetic energy solution for each particle species:

$$\frac{\partial Q}{\partial t} + \frac{1}{R_o^2}\frac{\partial}{\partial R_o}\left(R_o^2\left\langle\frac{dR_o}{dt}\right\rangle Q\right) + \frac{\partial}{\partial \varphi}\left(\left\langle\frac{d\varphi}{dt}\right\rangle Q\right) + \frac{1}{\sqrt{E}}\frac{\partial}{\partial E}\left(\sqrt{E}\left\langle\frac{dE}{dt}\right\rangle Q\right) + \frac{1}{f(\mu_o)\mu_o}\frac{\partial}{\partial \mu_o}\left(f(\mu_o)\mu_o\left\langle\frac{d\mu_o}{dt}\right\rangle Q\right) = \left\langle\frac{\delta Q}{\delta t}\right\rangle_{collis} \quad \text{(Eqn. 1)}$$

The coupled model solves for potential using the specified electric field model. In the case of the Rice Convection Model, NASA colleague Khazanov has suggested an extension that allows the cross-field potential to be determined in a self-consistent way through solution of the Poisson's Equation (Eqn. 2):

$$\nabla \cdot \left(-\overleftrightarrow{\Sigma} \cdot \nabla \Phi\right) = \sum_{\alpha} J_{\|\alpha} \sin I \qquad \text{(Eqn. 2)}$$

The coupled, self-consistent RCM-based model involves solution, at each time step, of the Equations 1 and 2. Details of the computational flow of the coupled RCM-based model are omitted from this report. However, we have developed a coarse-grained parallel method to solve Equation 1 and 2 for the coupled RCM-based model. Our solution dedicates one CPU to solution of Equation 1 for each particle species. One CPU is also dedicated to solve the Equation 2. At a high level, the parallel method can be said to operate as follows:

For each time T_i:
        For each CPU C_a:
                Solve Eqn. 1 for species a
                Assemble right-hand side (RHS) of Eqn. 2
        Master CPU:
                Solve Eqn. 2
                Communicate Result

Some Experiments

Next, some of the experiments that have been performed are described. Most of the experiments have been performed on the May 2, 1986 storm, which is particularly interesting because it has a long main phase. A comparison of the potentials computed by the model near the start, middle, and end of this storm are shown in Figure 1. The figure compares the potentials that were computed from the use of a dipole magnetic field model and three potential models. In the top of the figure, the coupled, self-consistent Rice Convection Model's output is shown. This model calculates an electric field that is more compressed, reflecting a higher potential drop over a smaller region. (In addition, our studies indicate that the coupled, self-consistent RCM enables penetration of plasma sheet particles to low L-shells. Those results are omitted here due to space constraints.) The middle portion of the figure shows the limited self-consistent model (i.e., RCM

without the joint potential solution; RCM based on only the hydrogen species). The bottom portion of the figure uses the Volland-Stern electric field model.

May 2, 1986 Magnetic Storm
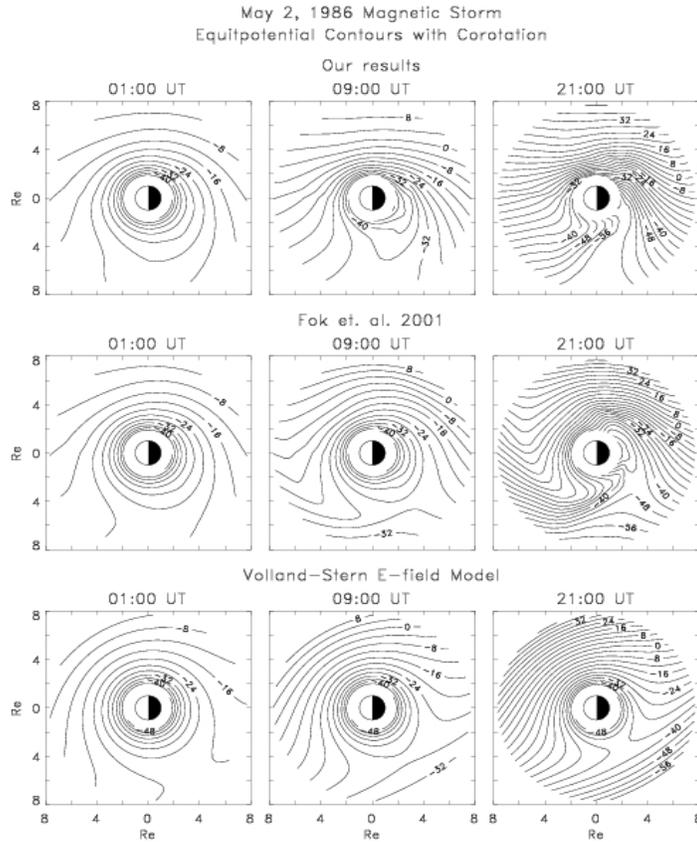**Equipotential Contours with Corotation**

Our results

Figure 1. Experimental Results, May 2, 1986 Storm

We have also explored the impact of incorporating a heavy ion species into the coupled, self-consistent RCM model. Our experiments indicate that the impact of adding a heavy ion species is not significant.

Another experiment that was performed explored the impact of incorporating time-dependent cross-tail potential drops (i.e., substorms), such as those suggested by Chen et al. [CHEN93], into the Volland-Stern model. A series of experiments were conducted using Chen et al.'s model substorm, shown in Figure 2. Chen's sub-storm has 9 "spikes" over a 3 hour period.
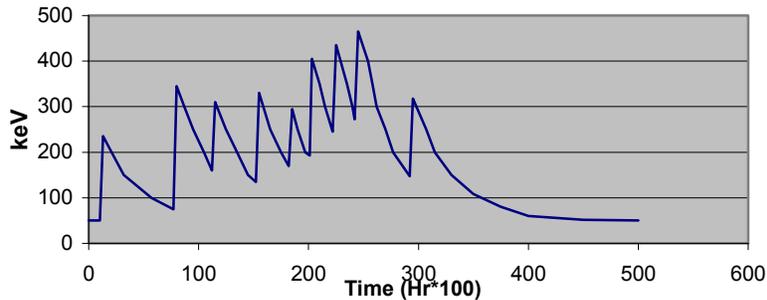

Figure 2. Chen et al. [CHEN93] Model Sub-storm

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Computational Considerations

A number of computational improvements have been explored for the large scale model. In the fellowship effort, focus has been on coarse-grained parallel processing of the model. To achieve this parallelism, we have made use of the popular, portable Message-Passing Interface (MPI) on SGI Origin and Linux cluster computers. MPI allows tasks operating on networked CPUs to communicate data and to synchronize operation. The two most basic constructs in the MPI are a synchronized send and synchronized receive operation. Our approach to parallelizing non-self-consistent runs of the model (e.g., using the Weimer or Volland-Stern electric field models) is to simultaneously spawn separate species-specific executables on each CPU in the parallel environment. (Each executable applies the large-scale model to a single particle species.) This very brute-force approach achieves approximately 95% efficiency for a 168 hour simulation run on the May 1-7, 1998 storm. (The large scale model can be computed, with 15 second time steps, in approximately 86 hours on a cluster of two Pentium III/1000 MHz CPUs. Therefore, as long as the time steps are at least 10 seconds, the model can be executed in faster than real-time.) For the coupled, self-consistent version of the RCM, the approach is slightly different; as mentioned above, at each time step, the executables must communicate the RHS of Equation 2 to the Master CPU. This communication takes place using MPI's synchronized send/receive operations. The Master CPU also uses MPI's synchronized send/receive operations to communicate the solved LHS potentials back to the species-specific executables. The large scale model, when used with the coupled, self-consistent version of the RCM, can be computed in approximately the same time as the brute-force parallelization of the non self-consistent runs (e.g., about 72.5 hours to complete a 168 hour simulation with 15 second time steps).

Conclusion

We have demonstrated that self-consistent incorporation of electrons in a hot plasma phase space density solver can allow more sophisticated modeling of magnetosphere-ionosphere coupling. In addition, we have demonstrated that coarse-grained parallel approaches to model computation can allow efficient, real-time calculation of the model.

References

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