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The Upper Atmosphere: Problems in Developing Realistic Models

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The atmosphere above 100 km is less than one-millionth as dense as at ground level, but it has important influences on satellite trajectories and on ionospheric electron densities, which in turn affect satellite radio communications and measurement applications like GPS. The upper atmosphere is strongly affected by variable ultraviolet and X-ray radiation from the Sun, as well as by bombardment from energetic auroral electrons and by electric current flowing from the magnetosphere above. It is also influenced by atmospheric waves that propagate up from lower levels. Unlike the lower atmosphere, the upper atmosphere is heterogeneous, with diatomic nitrogen and oxygen giving way to monatomic oxygen at the higher levels. Also unlike the lower atmosphere, the dynamics is strongly influenced by molecular viscosity, heat conduction, and diffusion, as well as by the force exerted by the electric current flowing through the Earth's magnetic field. Strong external forcing and relatively rapid dissipative processes mean that the model cannot run freely for long simulated times without updates to the inputs, unlike lower-atmospheric weather and climate models.

Our group has developed a simulation model of the upper atmosphere, the NCAR Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM; Dickinson et al., 1984; Roble et al., 1988; Richmond et al., 1992; Roble and Ridley, 1994), which includes the primary physical and chemical processes that determine its structure and dynamics. Simulation results depend on the model inputs and boundary conditions, including solar radiation, magnetospheric currents, auroral particle fluxes, and global-scale atmospheric waves from below, but there are large uncertainties in what these highly variable inputs should be at any given time. Observations are relatively sparse, and extrapolation of the observations in space in time to get complete specification of the boundary conditions is uncertain, although techniques like the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure (Richmond and Kamide, 1988) have been developed for this purpose. There are also uncertainties in some of the model parameters and parameterizations. For example, turbulent (eddy) diffusion has a big influence, but its magnitude and variability are poorly known. The rates of some chemical reactions and molecular collision processes are also uncertain, and there are large uncertainties in how to parameterize sub-grid-scale processes like atmospheric gravity waves. These uncertainties create difficulties for trying to simulate realistic upper-atmospheric behavior, both for average conditions and for events like magnetic-storm disturbances.

The TIME-GCM is being coupled with a magnetospheric model to improve the understanding of how the upper atmosphere is affected by the magnetosphere and vice versa (Wang et al., 2004; Wiltberger et al., 2004). The magnetospheric model solves the equations of magnetohydrodynamics (MHD), and its dynamics is driven by the variable solar wind. The solar wind is a supersonic plasma that carries with it the magnetic field of the Sun. If the field direction in the solar wind is opposite to that of the Earth's dipole magnetic field then subsequent interactions allow for significant amounts of mass, momentum and energy to be transferred into the magnetosphere. These conditions usually result in magnetic storms that produce strong auroral particle bombardment and strong electric currents which close in the ionosphere and drive rapid upper-atmospheric motions.

Some research problems where advanced statistical approaches might be able to help improve the models are the following:

1. How can uncertain model parameters be optimized to provide the best agreement, on the average, with observations?

2. How can model variability about the average, including information about scale sizes of this variability, best be compared with variability in observations to determine agreement or disagreement?

3. How can we improve the extrapolation of observations of model input parameters in space in time to get complete specification of the boundary conditions?

4. In developing parameterizations of sub-grid phenomena, such as the transport of momentum and the creation of turbulence by breaking gravity waves, what is a good measure of intermittency, and how can its effects be parameterized?

5. How can relatively rare and sparse observations of extreme events like large magnetic storms be used to characterize upper-atmospheric behavior and test simulations for such events?

6. What can statistical comparisons tell us about underlying biases in our models?

7. What are the best measures to monitor model improvement over time?

References

Dickinson, R.E., E.C. Ridley, and R.G. Roble, Thermospheric general circulation with coupled dynamics and composition, J. Atmos. Sci., 41, 205-219, 1984.

Richmond, A.D., and Y. Kamide, Mapping electrodynamic features of the high-latitude ionosphere from localized observations: Technique, J. Geophys. Res., 93, 5741-5759, 1988.

Richmond, A.D., E.C. Ridley, and R.G. Roble, A thermosphere/ionosphere general circulation model with coupled electrodynamics, Geophys. Res. Lett., 19, 601-604, 1992.

Roble, R.G., and E.C. Ridley, A thermosphere-ionosphere-mesosphere-electrodynamics general circulation model (time-GCM): equinox solar cycle minimum simulations (30-500 km), Geophys. Res. Lett., 21, 417-420, 1994.

Roble, R.G., E.C. Ridley, A.D. Richmond, and R.E. Dickinson, A coupled thermosphere/ionosphere general circulation model, Geophys. Res. Lett., 15, 1325-1328, 1988.

Wang, W., M. Wiltberger, A.G. Burns, S.C. Solomon, T.L. Killeen, N. Maruyama, and J.G. Lyon, Initial results from the coupled magnetosphere-ionosphere-thermosphere model: thermosphere-ionosphere responses, J. Atmos. Solar-Terr. Phys., 66, 1425, doi:10.1016/j.jastp.2004.04.008, 2004.

Wiltberger, M., W. Wang, A.G. Burns, S.C. Solomon, J.G. Lyon, and C.C. Goodrich, Initial results from the coupled magnetosphere-ionosphere-thermosphere model: magnetospheric and ionospheric responses, J. Atmos. Solar-Terr. Phys., 66, 1411, doi:10.1016/j.jastp.2004.04.026, 2004.