Estimating The Forces That Drive Ionosphere And Thermosphere Variability: Continuous Data And Assimilative Modeling

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THEME: Atmosphere-Ionosphere-Magnetosphere Interactions

EXECUTIVE SUMMARY
Ionosphere-thermosphere science has long been hampered by a lack of measurements of the underlying forces that determine plasma structure. These forces include electric fields, thermospheric composition, winds and solar EUV irradiance. All of these forces are dynamic quantities and of great importance to the underlying science. The rapid proliferation of electron density and total electron content measurements from ground and space-borne GPS receivers and other instruments suggests a great potential in the following indirect approach to estimating these forces: developing a model-based approach to retrieving the forces from the electron density structure and dynamics. The research community has just begun to explore such an approach, which addresses significant science questions previously out of reach. ***We recommend community investment in developing such "inversion" approaches. After further development, the capability should be maintained and implemented systematically on an ongoing basis, providing scientific insight into the causes of ionosphere and thermosphere variability.***

1. Description

Efforts to model daily thermospheric weather and storm-time effects have been hampered by a lack of direct measurements on global scales of neutral composition and density, winds and electric fields. In contrast, ionospheric measurements of electron density and integrated electron content from ground GPS networks, space-based GPS receivers, and space-based UV airglow instruments are a growing source of continuously available global data. The community is poised to develop a data assimilation methodology for estimating thermospheric composition and density, winds, and electric fields from measurements of electron density and total electron content. By combining the strengths of both thermospheric and ionospheric datasets to retrieve thermospheric parameters and their ionospheric effects, one can generate thermospheric characterizations with improved global distribution and temporal resolution. These improved thermospheric datasets will significantly increase scientific understanding of coupled geospace system and benefit the development and validation of coupled, first-principles thermosphere-ionosphere models.

Inversion of thermospheric and electrodynamic drivers from electron density data leverages assimilative modeling approaches developed over the last decade [Pi et al., 2003; Schunk et al., 2004]. The physics-based assimilative modeling approaches start

with a climatological representation of the three-dimensional (3D) electron density distribution based on climatological representations of the underlying driving forces such as neutral composition and density, winds and electric fields. Using the global GPS and other data sets, differences are calculated between the actual electron density and that of the physics-based model. The differences between measured and modeled electron density are the result of differences between the climatological and actual driving forces, assuming that the physics-based models correctly model the relevant physical processes. Thus, the present era characterized by a plethora of electron density measurements presents an opportunity to determine the actual driving forces, by adjusting drivers in the physics-based models so that the adjusted model better fits the data. The research community has experimented with sophisticated mathematical and computational methods to perform the adjustment, yielding the potential to develop an efficient system for estimating the driving forces [Pi et al., 2003; Scherliess et al., 2009; Luan and Solomon, 2008].

We recommend that the community develop a driver estimation capability leveraging progress made in the last few years in modeling and data assimilation. Additional resources include observation system simulations and coupled thermosphere-ionosphere models (e.g. TIMEGCM) in addition to the assimilative model (e.g. GAIM). Coupled models such as TIMEGCM provide a physically self-consistent and plausible representation of the ionosphere-thermosphere state. Model output can be used to test and examine driver estimation algorithms and processes. Once the effectiveness of thermospheric retrievals has been demonstrated using simulations, data assimilation experiments for estimating thermospheric and electrodynamic parameters should be conducted using real measurements from densely-distributed global and regional networks of GPS receivers, spaceborne GPS radio occultation sensors, and ultra-violet airglow emissions from the TIMED GUVI instrument and similar satellite sensors. Validation of the driver retrievals can be conducted with data collected from incoherent scatter radar facilities and satellite measurements of the drivers where they exist (e.g. electric fields from C/NOFS and neutral composition from TIMED).

Our description here is somewhat simplified because model error in the form of "missing physics", which certainly exists particularly over the smaller scales (200 km or less), is a confounding factor. Yet, we expect this will not be a dominant error for studies that focus on larger-scale (1000+ km) driver averages. Also, we assume that the inversion process is run over a sufficiently long period (at least several days) to ensure that initialization error is not a significant factor. As model physics improvements are made through research, so will the inversion approach improve as these model improvements are transferred to the data assimilation capability.

The reason for pursuing this approach is that direct measurements of thermospheric quantities such as composition and winds are far more sparsely distributed than measurements of ionospheric electron density which have improved global distribution and are more widely available. Our goal is to use assimilative modeling to leverage ionospheric data sets and generate thermospheric and electrodynamical data sets with improved global distribution.

After the proposed methodology becomes established, the development and validation of coupled thermosphere-ionosphere first principles models will significantly benefit from large quantities of ionospheric observations, such as those available from the global positioning system satellites, and space-based UV radiance sensors. The development of these sensors is happening far faster than development and deployment of sensors of the underlying thermospheric properties and electric fields. Clearly direct measurement of the drivers is desirable if possible. In addition development of these techniques could fill gaps in missions that may exist.

The research described in this white paper is an excellent opportunity to combine geophysical modeling with advanced mathematical research. Thus, it is well aligned with a recent National Science Foundation research thrust "Collaboration in Mathematical Geosciences (CMG)", whose purpose is to "enable collaborative research at the intersection of mathematical sciences and geosciences, and to encourage cross-disciplinary education." Driver estimation as described here is not unique to the ionospheric realm. The approach fits within the category of the "joint inference problem", where *state* and *parameter* estimation is attempted simultaneously. In this case, *state* refers to the ionospheric electron density, which is well measured. *Parameter* refers to the drivers. As reviewed in Kantas et al., [2009], many approaches to this joint inference problem have been considered, often involving the Ensemble Kalman Filter [Evensen, 2009; Evensen et al., 2007; Evensen, 2007; Chitralekha et al., 2010]. Further study could yield a set of approaches well suited to the application described here that also provide insight into the general mathematical issues applicable to a wide variety of related problems across geophysics and space physics.

2. Conclusions And Recommendations

We have identified a fruitful research direction that combines assimilative modeling techniques with the growing volume of ionospheric and thermospheric data to provide a new modeling capability of great scientific and practical value to the Atmosphere-Ionosphere-Magnetosphere (AIM) community. This capability produces estimates of the underlying physical drivers of ionospheric plasma structure. Incorporating direct measurements of the drivers themselves should be done where possible. This new capability should be developed on an ongoing basis to fill the gap that is likely to exist in measurements of the drivers. On the other hand, measurements of ionospheric structure from GPS and other sources have a long term future of continuous operation. The capability described here will bring benefits to the AIM (AIM=?) community over the long term, deriving maximum scientific information content from the plasma structure measurements.

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4. References

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