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Thermospheric Data Assimilation

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14. ABSTRACT
This project demonstrates how the current limit of thermospheric mass density predictability can be extended by systematically integrating observations into a coupled thermosphere-ionosphere first-principles model. An ensemble data assimilation procedure, constructed with the NCAR Data Assimilation Research Testbed (DART) and the NCAR Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIEGCM), can take advantage of the tight coupling between the ionosphere and thermosphere, enabling the inference of thermospheric temperature and compositions from abundant GPS-based ionospheric observations. Observing system simulation experiments suggest that thermospheric states, particularly temperature, can be well inferred by assimilating electron density profiles obtained from the COSMIC/FORMOSAT-3 mission into the TIEGCM. This in turn leads to a significant improvement of the neutral mass density forecasting longer than 3 days. Furthermore, validation of assimilation analyses with independent CHAMP mass density observations confirms that the approach indeed improves the thermospheric mass density specification. Predictability of the ionosphere can also be extended considerably by the approach developed in this project.

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Thermospheric Data Assimilation

Principal Investigator: Dr. Tomoko Matsuo, University of Colorado at Boulder

Program Manager: Dr. Julie J. Moses, AFOSR/RTB1

Abstract

Thermospheric mass density variation is the major source of aerodynamic drag estimation errors at altitudes below about 700 km. This project demonstrates how the current limit of thermospheric mass density predictability can be extended by systematically integrating observations into a coupled thermosphere-ionosphere first-principles model. An ensemble data assimilation procedure, constructed with the NCAR Data Assimilation Research Testbed (DART) and the NCAR Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIEGCM), can take advantage of the tight coupling between the ionosphere and thermosphere, enabling the inference of thermospheric temperature and compositions from abundant GPS-based ionospheric observations. Observing system simulation experiments suggest that thermospheric states, particularly temperature, can be well inferred by assimilating electron density profiles obtained from the COSMIC/FORMOSAT-3 mission into the TIEGCM. This in turn leads to a significant improvement of the neutral mass density forecasting longer than 3 days. Furthermore, validation of assimilation analyses with independent CHAMP mass density observations confirms that the approach indeed improves the thermospheric mass density specification. Predictability of the ionosphere can be extended considerably by estimating neutral compositions from GPS-based ionospheric observations by the coupled thermosphere-ionosphere data assimilation approach developed in this project.

Background

Even though the Earth's upper atmosphere density is tenuous, it is substantial enough to exert significant drag on orbiting spacecraft and debris. Understanding this drag is complicated by the fact that this region is subject to highly variable external drivers from above and below. Also its ionized constituents affect telecommunication and navigation, motivating numerous observational and modeling efforts since the dawn of space exploration. Because of a lack of global observations of thermospheric parameters, our understanding of the density variability rests largely on the averaging of numerous observational samples, limiting our modeling capability to the realm of climatology. To overcome this shortage, the inference of thermospheric parameters from relatively plentiful ionospheric data is aided by exploiting our knowledge of the intimate coupling between the thermosphere and ionosphere using the ensemble Kalman filtering (EnKF) data assimilation system, constructed with the NCAR Data Assimilation Research

Testbed [Anderson et al., 2009] and the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) [Richmond et al., 1992]. The novelty of this approach [Matsuo et al., 2013] allows taking advantage of the expansive increase in recent years of the ability of GPS systems to globally monitor ionospheric parameters. Inferred thermospheric parameters are compared to independent observations obtained from the accelerometer on board the Challenging Minisatellite Payload (CHAMP) [Reigber et al., 2002].

Finding 1

"Assimilation of COSMIC/FORMOSAT-3 electron density data into a coupled thermosphere-ionosphere general circulation model can extend the predictability of thermospheric mass density more than 3 days"

The observing system simulation experiments (OSSEs) are conducted for a geomagnetically quiet 12-hour period from 0000 UT through 1200 UT of March 20, 2009, with a one-hour assimilation window and 90 ensemble members. Note that 90-member ensemble simulations are not centered at the truth from which synthetic observations for OSSEs are sampled, so the model ensemble is not entirely free of model biases. This 12-hour data assimilation period is followed by the 72-hour ensemble forecast period. Ensemble forecast simulations are initialized by the assimilation analyses obtained by the OSSEs. To examine the impact of data assimilation, additional ensemble simulations are run without data assimilation and referred to as the control. The experiment setup is described in detail in Hsu et al. [2016]. Figure 1 compares the neutral mass density errors from three 90-member ensemble forecast experiments, which are initialized with results from different OSSEs, to the control case. These OSSEs are executed with different filters constructed with different sets of the TIEGCM state variables being included in the ensemble Kalman filtering state vector. Suppose $\mathbf{f}$ represents a vector of a given TIEGCM model state variable defined on the model grid. The EnKF state vector for each filter is composed of (a) the electron density $\mathbf{f}_{e^-}$, the atomic oxygen ion $\mathbf{f}_{O^+}$, and the temperature $\mathbf{f}_T$; (b) $\mathbf{f}_{e^-}$, $\mathbf{f}_{O^+}$, $\mathbf{f}_T$, the atomic oxygen mixing ratio $\mathbf{f}_O$, and the molecular oxygen mixing ratio $\mathbf{f}_{O2}$; and (c) $\mathbf{f}_{e^-}$, $\mathbf{f}_{O^+}$, $\mathbf{f}_T$, $\mathbf{f}_O$, $\mathbf{f}_{O2}$, as well as the horizontal neutral winds $\mathbf{f}_u, \mathbf{f}_v$. Note that the sum of the mixing ratios of atomic oxygen, molecular oxygen, and molecular nitrogen is set to 1 in the TIEGCM, so the molecular nitrogen mixing ratio is adjusted according to the changes in the atomic oxygen mixing ratio $\mathbf{f}_O$ and the molecular oxygen mixing ratio $\mathbf{f}_{O2}$, even thought it is not included in the state vector.

The comparison suggests that thermospheric states, particularly temperature, can be well inferred by assimilating COSMIC/FORMOSAT-3 data into the TIEGCM, which leads to an improvement of the neutral mass density forecast by more than 3 days. Effects of the neutral composition initialization, though smaller than the impact of neutral temperature initialization, are long-lasting when combined with the neutral wind initialization.

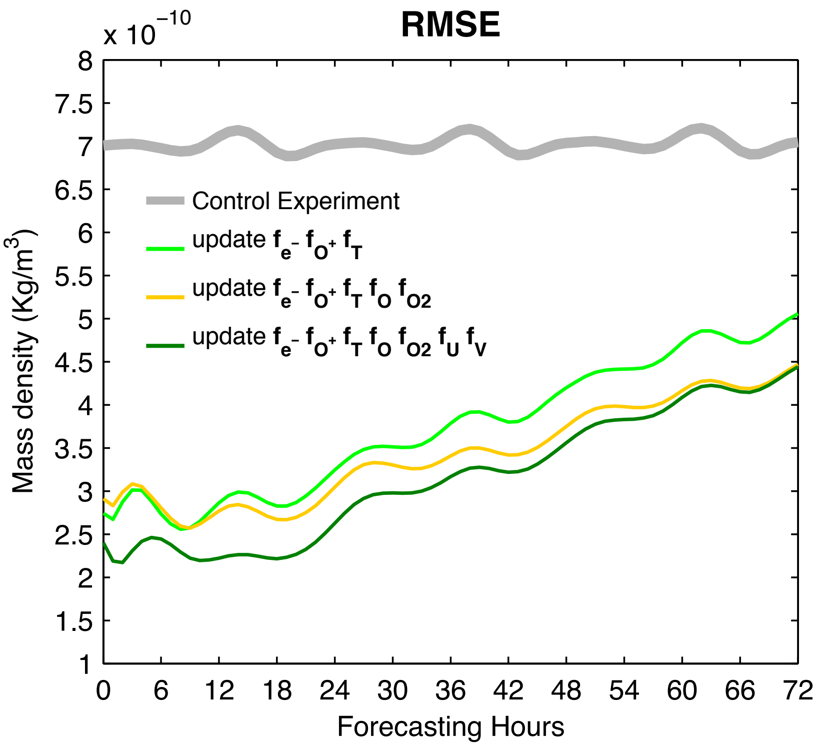

Figure 1. The root-mean-squared error (RMSE) of the neutral mass density over the course of the 72-hour ensemble forecast period. RMSE of the control experiment, in which no data is assimilated during the preceding 12-hour assimilation, is shown in gray. RMSE of the 90-member ensemble forecast experiment is shown in light green, yellow, and dark green, respectively, for model initialization with the three different filters described in the main text.

Finding 2

"Thermospheric mass density can be estimated from COSMIC/FORMOSAT-3 electron density data"

Actual COSMIC/FORMOSAT-3 electron density profile data are assimilated into the TIEGCM for a geomagnetically quiet period of 23-25 June, 2008 using the ensemble data assimilation experiment setup described in Lee et al. [2012]. In this experiment, the EnKF state vector is composed of $\mathbf{f}_{e^-}, \mathbf{f}_T, \mathbf{f}_U, \mathbf{f}_V, \mathbf{f}_O, \mathbf{f}_{O_2}$. A one-hour assimilation window and 90 ensemble members are used. To validate the neutral mass density analysis resulting from this assimilation experiment, the result is compared to independent CHAMP in-situ mass density observations. During this period, the CHAMP satellite orbits at 330-360 km along the noon-midnight local time plane 30 times.

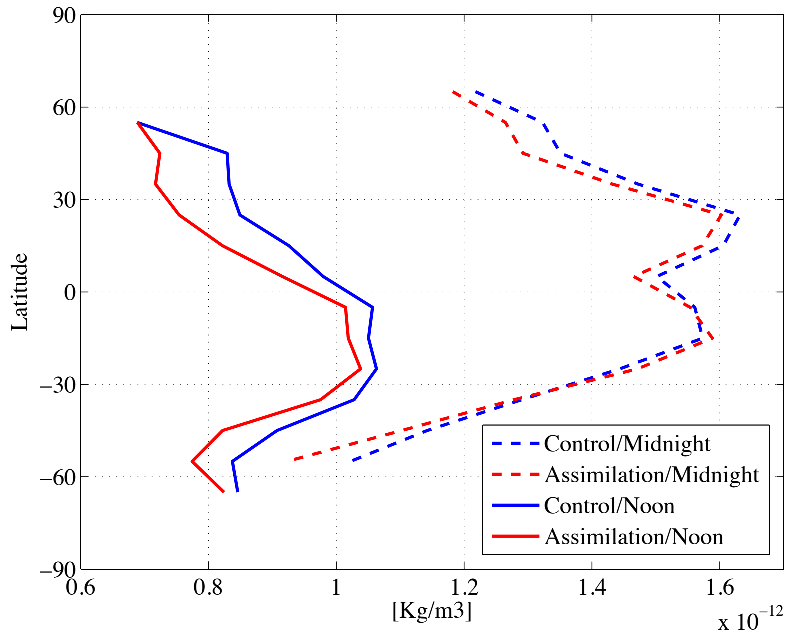

Figure 2. The root-mean-squared difference (RMSD) of CHAMP observations with the neutral mass density analyses and the control simulation is shown in red and blue, respectively, with the noon and midnight orbit displayed by solid and dashed line.

The squared difference between the CHAMP neutral mass density and the density analysis evaluated at the CHAMP location is computed and sorted for the noon and midnight orbits with respect to 10^o latitude bins, and summarized as the RMSD as shown in Figure 3. For the noon orbit, the neutral mass density inferred from the assimilation of COSMIC/FORMOSAT-3 electron density observation agrees better with the CHAMP observations than the ensemble control simulations. For the midnight orbit, the neutral mass density specification is not improved by data assimilation over the control simulation.

Finding 3

"Thermospheric composition can be estimated from GPS-based electron density data"

Predictability of the ionosphere can be extended considerably by estimating neutral compositions from GPS-based ionospheric observations by the coupled thermosphere-ionosphere data assimilation approach developed in this project. The fact that the ionospheric forecast is aided by the inference of thermospheric compositions is confirmed within the context of OSSEs for the COSMIC I mission [Hsu et al., 2014; 2016] and for the COSMIC II mission [Lee et al., 2013]. Furthermore, Chartier et al. [2016] and Chen et al. [2016] adopted the approach to assimilation of actual ground-based TEC data during storm periods, and showed that the approach indeed extended the ionospheric forecast capability of a coupled thermosphere-ionosphere general circulation model. Though these are indirect evidences, thermospheric compositions can be estimated from both space-based and ground-based GPS observations to the extent that results in a considerable improvement of the ionospheric forecast by up to 24 hours.

Peer-review Publications Supported by This AFOSR Award (8)

Matsuo, T., I. T. Lee, and J. L. Anderson (2013), Thermospheric mass density specification using an ensemble Kalman filter, *J. Geophys. Res. Space Physics*, 118, 1339–1350, doi:10.1002/jgra.50162.

Matsuo, T. (2013), Upper atmosphere data assimilation with an ensemble Kalman filter, *AGU Monograph on modeling the Ionosphere-Thermosphere system* edited by J. D. Huba et al., ISBN: 978-0-87590-491-7.

Lee, I. T., H. F. Tsai, J. Y. Liu, C. H. Lin, **T. Matsuo**, and L. C. Chang (2013), Modeling impact of FORMOSAT-7/COSMIC-2 mission on ionospheric space weather monitoring, *J. Geophys. Res. Space Physics*, 118,6518–6523, doi:10.1002/jgra.50538.

Hsu, C.-T., **T. Matsuo**, W. Wang, and J.-Y. Liu (2014), Effects of inferring unobserved thermospheric and ionospheric state variables by using an Ensemble Kalman Filter on global ionospheric specification and forecasting, *J. Geophys. Res. Space Physics*, 119, 9256–9267, doi:10.1002/2014JA020390.

Chartier, A. T., **T. Matsuo**, J. L. Anderson, N. Collins, T. J. Hoar, G. Lu, C. N. Mitchell, A. J. Coster, L. J. Paxton, and G. S. Bust (2016), Ionospheric data assimilation and forecasting during storms, J. Geophys. Res. Space Physics, 121, 764–778, doi:10.1002/2014JA020799.

Chen, C. H., W. H. Chen, C. H. Lin, I. T. Lee, **T. Matsuo,** J. T. Lin, J. Y. Liu, and C. T. Hsu (2016), Ionospheric data assimilation with TIE-GCM and GPS-TEC during geomagnetic storm conditions, *J. Geophys. Res. Space Physics*, under review.

Matsuo, T., and C.-T. Hsu (2016), Ensemble data assimilation for thermospheric mass density specification and forecasting, *Progress in Earth and Planetary Science*, under review.

Hsu, C.-T., **T. Matsuo**, W. Wang, and J.-Y. Liu (2016), Seasonal and Solar activity dependence of a coupled thermosphere-ionosphere ensemble data assimilation system for ionospheric forecasting: FORMOSAT-3/COSMIC observing system simulation experiments, *Space Weather*, under review

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Anderson, J. L., T. Hoar, K. Raeder, H. Liu, N. Collins, R. Torn, and A. F. Arellano 397 (2009), The Data Assimilation Research Testbed: A community data assimilation 398 facility, *Bull. Am. Meteorol. Soc.*, 90, 1283–1296, 399 doi:10.1175/2009BAMS2618.1.

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Matsuo, T., and E. A. Araujo-Pradere (2011), Role of Thermosphere-Ionosphere Coupling in a Global Ionospheric Specification, *Radio Science*, 46, RS0D23, doi:10.1029/2010RS004576.

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Richmond, A. D., E. C. Ridley, and R. G. Roble (1992), A thermosphere/ionosphere general circulation model with coupled electrodynamics, *Geophys. Res. Lett.*, 19, 457 601-604.

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Julie J Moses

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Abstract

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