Solar and Space Physics (Heliophysics) Decadal Survey

White Paper

Observing Multi-Scale Ionospheric Structures and Modeling I-T Responses

Xian Lu (xianl@clemson.edu), Department of Physics and Astronomy, Clemson University

Yukitoshi Nishimura (toshi16@bu.edu), Department of Electrical and Computer Engineering and Center for Space Physics, Boston University

Wenbin Wang (wbwang@ucar.edu), High Altitude Observatory (HAO), NCAR

Haonan Wu (haonanw@clemson.edu), Physics and Astronomy, Clemson University

Stephen Kaeppler (skaeppl@clemson.edu), Physics and Astronomy, Clemson University

William Bristow (wab5217@psu.edu), Department of Meteorology and Atmospheric Science, Pennsylvania State University

John Meriwether (john.meriwether@clemson.edu), Center for Solar-Terrestrial Research, NJIT

Xueling Shi (xueling7@vt.edu), Center for Space Science and Engineering Research Department of Electrical and Computer Engineering, Virginia Tech & HAO, NCAR

Synopsis

During geomagnetic storms and substorms, a vast amount of magnetospheric energy is deposited into the ionosphere-thermosphere (I-T) system via the convergence of Poynting flux and energetic particle precipitation. This energy deposition leads to significant heating at high latitudes, changes in global circulation, and disturbs neutral and plasma densities. The changes in the I-T system have a significant impact on the near-Earth space environment such as satellite drag, orbiting, and communication. Large-scale storm-time responses have been well studied using I-T models driven by statistical maps of aurora and electric potential, while mesoscale and small-scale processes and cross-scale interaction were much less understood. This is partially attributed to the lack of sufficient multi-scale ionospheric observations that can be used to constrain models. To improve the accuracy of space weather modeling for the I-T system, we need continuous observations of high-latitude forcing (e.g., particle precipitation and electric fields) with sufficient resolution that can separate temporal and spatial structures/variabilities, as well as simultaneous observations of I-T responses such as neutral winds, neutral/plasma temperatures and densities. Such multi-parameter and multi-scale observations will allow one to monitor different scales of forcing and consequences at the same time so as to understand the global, multi-scale dynamics of the I-T system and its responses to external driving conditions, as well as constrain I-T models to improve space weather predictability. This white paper addresses the current challenges for a more realistic space weather simulation and solicits observational and modeling requirements.

I. Current Challenges of Space Weather Observation and Simulation

The Ionosphere-Thermosphere (I-T) system is the ultimate recipient of energy deposition from the solar wind and magnetosphere, and the one that finally connects to the lower atmosphere of Earth. During strong geomagnetic activity, the magnitude of magnetospheric energy deposition is comparable to solar radiation and induces global responses. The perturbations in the I-T system affect radio wave propagation and communication and the current system changes can be mapped down all the way to ground impacting infrastructures. Since the I-T region hosts low-earth-orbit (LEO) satellites and international space stations, the prediction of space weather in this region is critical to evaluate satellite drag and orbiting, reentry of spacecrafts, and the safety of space assets and human beings. **It is therefore important to advance the space weather predictability, which is one of the biggest challenges in the community because observations and modeling have not been seamlessly combined and an accurate prediction of key space weather parameters both globally and locally has not yet been achieved.** In this white paper, we list the challenges from different perspectives followed by the suggestions to tackle them.

Challenge I: Magnetospheric forcing (e.g., Poynting fluxes, aurora and electric fields) and I-T responses (winds, temperatures, and densities) are highly dynamic and structured, but observational coverage and resolution are insufficient to obtain a full picture of multi-scale forcing-response correlations.

Due to the highly complex, nonlinear, and multi-scale nature (from scales of Earth radii to turbulence) of magnetospheric processes, the responses in the I-T system via magnetosphere-ionosphere-thermosphere coupling follow similar characteristics. For instance, in addition to the large-scale auroral oval, ground-based all-sky imagers depict rich mesoscale structures (10s-100s km) for aurora, while narrow field-of-view imaging reveals small-scale (<10 km) patterns (Nishimura et al., 2021). Electric fields in the polar cap and auroral region also exhibit cross-scale spectra ranging from planetary scales down to a few kilometers (Kozelov and Golovchanskaya, 2006; Golovchanskaya and Kozelov, 2010). As it goes to the inner atmosphere of Earth, another source of the complexity originates from the interplay of neutrals in the thermosphere where density exponentially increases with decreasing altitudes. The large-scale features of the system are relatively well-known, but more and more localized observations have revolutionized our understanding about what fine structures and extreme situations can go during storm times. Here are a few examples that show the localized observations of strong magnetospheric forcing and greatly enhanced I-T responses (not the same time and same event):

1) The Defense Meteorological Satellite Program (DMSP) once observed a local Poynting flux exceeding 170 mW/m^2 during an east-west interplanetary magnetic field (IMF) dominant event (Knipp et al., 2011), which has not been well simulated by models;

2) Satellite observations revealed that localized Earth-directed Poynting fluxes can be several times larger than statistical models (order of 15 mW/m^2) during magnetic storms (Huang and Burke, 2004; Huang et al., 2016).

3) The Fe lidar observation at McMurdo, Antarctica revealed a significant temperature elevation (~500 K) against the quiet-time around 130 km during a Kp=6 storm period, inducing a sharp E-region temperature inversion with peak temperatures of ~1000K (Chu et al., 2011).

4) Neutral winds from three Alaska stations show unusually large vertical winds as a response to the extreme forcing in the 2015 St. Patrick's Day Storm (Kp=8) (Figure 1). More interestingly, the speeds and even direction can be quite different at particular times from these stations, implying a highly inhomogeneous energy input within only a few hundreds of kilometers.

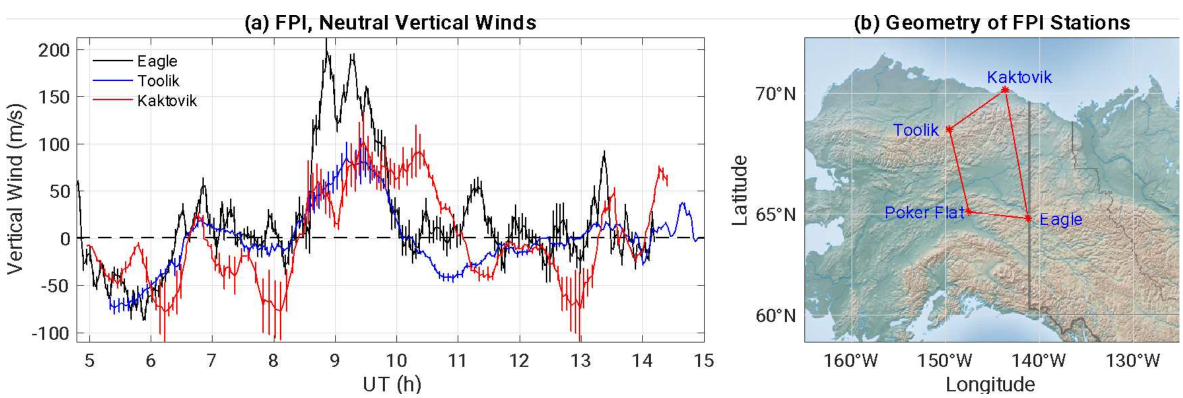

Fig. 1. FPI measurements of neutral vertical winds and the station geometry. Wind speeds and directions can be quite different from the stations that are only a few hundreds of kilometers away.

Even though the above observations suggest that the I-T system can behave much more dynamically than being appreciated, the puzzles of how large strong responses expand, how energy is being transferred from ions to neutrals and at what scales, and what are the impacts on other important parameters were not totally clear due to the lack of multi-parameter and simultaneous neutral and ion observations to trace down the correlation and causality, and/or the lack of regional observations that can unambiguously resolve spatial structure, which if we have, would assist in the scale analysis naturally. The global and altitude-resolved observations of neutral wind, temperature, and density in the critical region of 100-400 km are generally sparse and not well coordinated with ion/electron observations. Therefore, the common-volume observations of neutrals, ions, and particle precipitation cannot be easily identified to study storm activities with various levels. Up to now, the ground-based instruments such as SuperDARN coherent scatter radars, ISRs, and THEMIS/ASIs have provided ionosphere observations and auroral particle precipitation on a more regular basis. But the distributions are still insufficient in the Southern Hemisphere such as Antarctica, which makes it difficult to study space weather as a magnetically coupled and a global system, as well as to understand interhemispheric connection and asymmetry.

Challenge II: Current observations are still not able to provide global, realistic and multi-scale magnetospheric forcing that can be incorporated into I-T models which leads to significantly large uncertainty in the simulated I-T responses to storms, especially locally. The first principles modeling of I-T space weather, including dynamic range, variability, and nonlinear feedback and interaction needs a major advance.

Recently emerging modeling work has revealed that in order to reproduce local observations such as the lidar and FPI observations listed as 3) and 4) in Challenge I, and GNSS TEC observations of TIDs, magnetospheric forcing in I-T models needs to be better constrained by the information from observations. Empirical model drivers which only provide large-scale auroral morphology (e.g., Hardy et al., 1985; Roble and Ridley, 1987; Newell et al., 2009) and electric fields (e.g., Heelis et al., 1982; Weimer, 2005) do not satisfy the simulation of local features. For instance, Wu et al. (2020) found that an implementation of electric fields varying on short temporal scales and auroras observed by DMSP/SSUSI into the TIEGCM is essential to reproduce the Thermospheric Temperature Enhancement and Inversion Layer (TTEIL) observed by the Fe-Boltzmann lidar at McMurdo, Antarctica. Sheng et al. (2020) found that the Global Ionosphere Thermosphere Model (GITM) driven by the THEMIS/ASI auroral observations better resolves the magnitude of TIDs (doubled) than that by empirical auroral inputs. Figure 2 shows a recent effort of comparing the TIEGCM runs with and without assimilated magnetospheric drivers (aurora and electric fields) during the 2015 St Patrick's Day storm (Lu et al., 2022). Data assimilation uses SuperDARN and PFISR ion drifts for electric fields (Wu and Lu, 2022), and SSUSI and THEMIS/ASIs data for aurora (Wu et al., 2022). Compared with local PFISR observations, the default run driven by empirical aurora and electric fields misses strong storm-time I-T responses including large electron density from 100-200 km, significantly elevated electron and ion temperatures, and large neutral vertical winds as observed by the FPIs (Fig. 1), which are all improved in the TIEGCM run driven by assimilated aurora and electric fields. The short-term (tens of min to hours) I-T variability which is important for the prediction of irregularity and scintillation is also only captured as the data assimilation of drivers is involved. **This study strongly suggests that observations need to provide more realistic drivers to I-T models in order to accurately simulate the localized storm-time change of the space environment.**

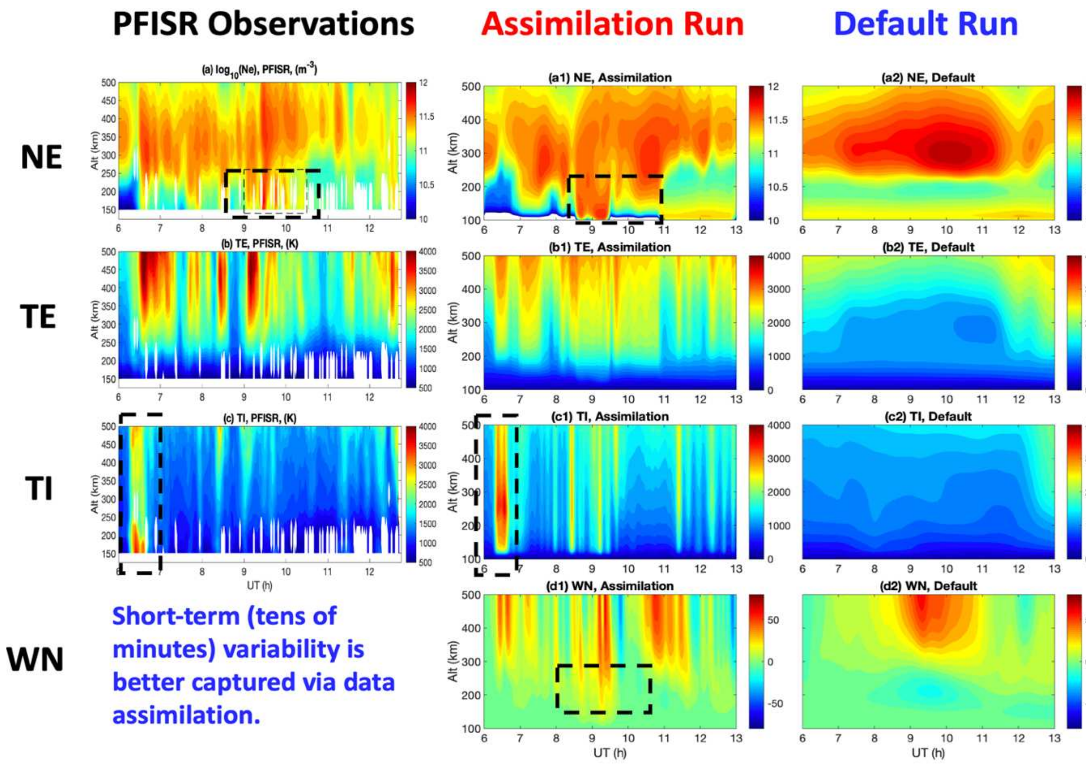

Fig. 2. 1st column: PFISR observations of electron density, electron temperature, ion temperature. 2nd and 3rd columns are the same except for the TIEGCM runs with and without model driver assimilation, respectively. 4th row is the simulations of neutral vertical winds from the two runs.

The traditional statistical approach and assimilation method using global spherical harmonics fitting tend to be limited at large-scale features, while the medium to small scales which are important to dictate localized responses are not well represented. Some high-resolution assimilation methodologies are recently being proposed as in Bristow et al. (2016), Wu and Lu (2022), and Wu et al. (2022). A thorough comparison of the different assimilation methods including their own strengths and limitations need to be further investigated in order to potentially deliver an optimal approach for the community to use. As for data assimilation, observations are still the key in order to approach the reality, which recalls Challenge I about the requirement of more simultaneous and common-volume observations of both ions and neutrals.

For this study, even though the simulation at Poker Flat has been significantly improved, the remaining challenges include: 1) aurora observations after combining THEMIS/ASIs and SSUSI cannot provide continuous global maps especially for the day-time sector; 2) only relying on SuperDARN measurements whose data amounts vary for different events cannot fully resolve small-scale electric fields for all high-latitude region. For locations that do not have the support from ISRs, simulations can still have significant uncertainty, even if it is much improved against the default run; 3) last but not the least, observations of neutrals were still sparse to resolvescales and structure of thermospheric responses, which also jeopardizes the modeling globally.

Due to the inertial and diffusive nature of the neutral atmosphere, neutrals do not necessarily respond in a one-to-one correspondence manner in terms of scales. The generation of waves such as traveling atmospheric disturbances (TADs) that represents for a self-adjustment of neutral atmosphere to a heating source makes the whole picture more complex. How different scales of magnetospheric forcing transfer to those of neutrals, what are the wave spectra generated by different scales of aurora and Joule heating, won't be clear until data and models can cover the majority of the scales of the spectra. Auroral observations can have very high spatial resolution. What resolution do models need to go in order to simulate the resultant I-T responses as observed? And any new physics needs to be considered as models push to higher resolution? All these answers need the development of high-resolution models or nested-grid models and model results need to be systematically evaluated against observations.

Challenge III: Cross-disciplinary collaboration is necessary for cross-validation of different datasets, data assimilation and combining with models, and model-data validation. Large team work with targeted objectives are desirable.

Ground-based measurements have decent temporal resolution and networking provides regional information, but they can be weather sensitive and some of them are limited to night-time only. Meanwhile, it takes hours for a single sun-synchronous satellite to resample the same region thus the along-track observations are a mixture of temporal and spatial variabilities. During strong geomagnetic activity periods, magnetospheric forcing changes rapidly both day and night while it is still difficult to monitor that continuously and globally. The idea of combining different data sources is appealing especially for data assimilation purposes. Then the cross-validation of various ground-based and space-borne data sets including uncertainty estimation, which involves different types of expertise for different techniques, becomes important. To reproduce electron density and

TEC comparable to the PFISR and GNSS/TEC observations for the 2015 St. Patrick's Day storm event, we have to decrease the observed aurora energy flux to half for data assimilation, and then use it to drive TIEGCM. Such an accommodation raises questions about what uncertainty sources from both modeling and observational sides are causing this, and what might be the gaps in our physical understanding, what are the scenarios for other activity levels and different cases. Since such an effort ultimately improves space weather prediction, it is highly desirable and needs to involve a cross-disciplinary collaboration among technique, data analysis, and modeling regimes.

2. Requirements

2.1 Observation Requirements

1. Common-volume, simultaneous, and multi-parameter observations of both ions/electrons and neutrals that facilitate the examination of correspondence.

2. Observations that allow for scale analyses in both temporal and spatial domains and can be used to identify most important contributors and to study cross-scale interactions.

The Geospace Dynamics Constellation (GDC) mission proposed by the Decadal Survey for Solar and Space Physics (2013-2022) was designed as a constellation of identical satellites in low Earth orbit providing simultaneous, global observations of the Atmosphere-Ionosphere-Magnetosphere (AIM) system over roughly the range of local times over which magnetospheric drivers (and thus AIM responses) are organized. **Therefore, the GDC mission would provide a tremendous thrust to the system science of space weather and must be carried out without reducing the mission scope.**

2.2. Modeling Requirements

1. Global observations of both the plasma and neutrals with sufficient temporal and spatial resolution to quantify the energy and momentum inputs from the magnetosphere during storms, as well as forcing due to lower atmospheric waves.
2. I-T models that can incorporate realistic magnetospheric forcing and self-consistently reproduce realistic responses of neutrals and ions.
3. Sophisticated high-resolution and multi-scale data assimilation technique that combines different datasets and reproduces the global maps of model drivers with important scales included.
4. High-resolution I-T models that can resolve different scales of magnetospheric forcing and simulates realistic neutral responses.

References

Bristow, W. A., D. L. Hampton, and A. Otto (2016), High-spatial-resolution velocity measurements derived using Local Divergence-Free Fitting of SuperDARN observations, Journal of Geophysical Research: Space Physics, 121, 1349-1361, doi:10.1002/2015JA021862

Chu, X., Yu, Z., Gardner, C. S., Chen, C., & Fong, W. (2011). Lidar observations of neutral Fe layers and fast gravity waves in the thermosphere (110–155 km) at McMurdo (77.8°S, 166.7°E), Antarctica, Geophysical Research Letters, 38, L23807. https://doi.org/10.1029/2011GL050016

Golovchanskaya, I. V., and Kozelov, B. V. (2010), On the origin of electric turbulence in the polar cap ionosphere, Journal of Geophysical Research: Space Physics, 115(A9), A09321, doi:10.1029/2009JA014632

Hardy, D. A., Gussenhoven, M. S., and Holeman, E. (1985), A statistical model of auroral electron precipitation, Journal of Geophysical Research: Space Physics, 90(A5), 4229-4248, doi:10.1029/JA090iA05p04229

Heelis, R. A., Lowell, J. K., and Spiro, R. W. (1982), A model of the high-latitude ionospheric convection pattern, Journal of Geophysical Research: Space Physics, 87(A8), 6339, doi:10.1029/JA087iA08p06339

Huang, C. Y., and Burke, W. J. (2004), Transient sheets of field-aligned current observed by DMSP during the main phase of a magnetic superstorm, Journal of Geophysical Research: Space Physics, 109(A6), A06303, doi:10.1029/2003JA010067

Huang, Y., Wu, Q., Huang, C. Y., and Su, Y.-J. (2016), Thermosphere variation at different altitudes over the northern polar cap during magnetic storms. Journal of Atmospheric and Solar-Terrestrial Physics, 146, 140-148, doi:10.1016/j.jastp.2016.06.003

Kozelov, B. V., and Golovchanskaya, I. V. (2006), Scaling of electric field fluctuations associated with the aurora during northward IMF, Geophysical Research Letters, 33(20), L20109, doi:10.1029/2006GL027798

Lu, X., Wu, H., Kaeppler, S., Meriwether, J., Nishimura, Y., Wang, W., Li, J., Shi X. (2022), Understanding Strong Neutral Vertical Winds and Ionospheric Responses to the 2015 St. Patrick's Day Storm Using TIEGCM Driven by Data-Assimilated Aurora and Electric Fields, Journal of Geophysical Research: Space Physics, about to submit.

Newell, P. T., Sotirelis, T., and Wing, S. (2009), Diffuse, monoenergetic, and broadband aurora: The global precipitation budget, Journal of Geophysical Research: Space Physics, 114(A9), A09207, doi:10.1029/2009JA014326

Nishimura, Y., Deng, Y., Lyons, L. R., McGranaghan, R. M., and Zettergren, M. D. (2021), Multiscale Dynamics in the High-Latitude Ionosphere, doi:10.1002/9781119815617.ch3

Roble, R. G., and Ridley, E. C. (1987), An auroral model for the NCAR thermospheric general circulation model (TGCM), Annales Geophysicae Series A-upper Atmosphere and Space Sciences, 5(6), http://n2t.net/ark:/85065/d70v8ckz

Sheng, C., Deng, Y., Zhang, S.-R., Nishimura, Y., and Lyons, L. R. (2020), Relative contributions of ion convection and particle precipitation to exciting large-scale traveling atmospheric and ionospheric disturbances, Journal of Geophysical Research: Space Physics, 125(2), e2019JA027342, doi:10.1029/2019JA027342

Weimer, D. R. (2005), Improved ionospheric electrodynamic models and application to calculating Joule heating rates, Journal of Geophysical Research: Space Physics, 110(A05), 0148-0227, doi:10.1029/2004JA010884

Wu, H., and Lu, X. (2022), Data assimilation of high-latitude electric fields: Extension of a multi-resolution Gaussian process model (Lattice Kriging) to vector fields, Space Weather, 20, e2021SW002880, doi:10.1029/2021SW002880

Wu, H., Lu, X., Lu, G., Chu, X., Wang, W., Yu, Z., et al. (2020), Importance of regional-scale auroral precipitation and electrical field variability to the storm-time thermospheric temperature enhancement and inversion layer (TTEIL) in the Antarctic E region, Journal of Geophysical Research: Space Physics, 125, e2020JA028224, doi:10.1029/2020JA028224

Wu, H., Tan, X., Zhang, Q., Huang, W., Lu, X., Nishimura, Y., and Zhang, Y. (2022), Multi-Resolution Data Assimilation for Auroral Energy Flux and Mean Energy Using DMSP SSUSI, THEMIS ASI, and an Empirical Model. Space Weather, 20, e2022SW003146, doi:10.1029/2022SW003146