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Medium-Range Thermosphere-Ionosphere Storm Forecasts

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Introduction

The development of quantitative models that describe physical processes from the solar corona to the Earth's upper atmosphere creates the possibility of numerical space weather forecasting with a lead time of a few days [*Merkin et al.*, 2007; *Tóth et al.*, 2007]. Developing such a capability for the thermosphere and ionosphere is the objective of an effort described here sponsored by the NASA/National Science Foundation (NSF) Partnership for Collaborative Space Weather Modeling [*Schunk*, 2014]. Despite significant scientific progress in Sun-to-Earth modeling over the last few years, there is currently no system in place that relies on the physics-based model development of the past 10 years, to forecast moderate to intense upper atmosphere storms caused by solar wind disturbances. *Mannucci* [2012] suggests that a physics-based approach to forecasting upper atmospheric space weather has scientific as well as practical benefits.

Despite the initiation of operational approaches to predicting space weather disturbances due to coronal mass ejections (CMEs) [*Tobiska et al.*, 2013], predicting storm intensity with a few days' lead time remains a significant challenge. Predicting the magnitude and orientation of the interplanetary magnetic field component B_z at Earth, which determines storm intensity, is an active research topic [*Zheng et al.*, 2013]. Geospace storms are also caused by high-speed streams (HSSs) in the solar wind, emanating from coronal holes. The arrival of HSSs and their associated corotating interaction regions (CIRs), where the high-speed flow meets the slower ambient flow, can be forecast also with lead times of 2–4 days and possibly longer [*Norquist*, 2013]. For HSSs, there is no clear "eruptive" signature as there is for CMEs [*Tsurutani et al.*, 2006]. However, the persistence of coronal holes and the associated fast wind allows their impact to be predicted with the solar rotation period, which provides a more straightforward predictive capability compared to CMEs. Challenges in forecasting the solar wind speed and the magnitude and orientation of the interplanetary magnetic field remain for HSS, but the heliospheric modeling for HSS is more straightforward than for CMEs [*van der Holst et al.*, 2010].

Space Weather and the Global Thermosphere-Ionosphere Storm

Global thermosphere-ionosphere storms are highly disruptive to numerous technologies, as well as being important subjects of scientific study in their own right [*Mendillo*, 2006]. Storm impacts include increased satellite drag and impairment to communications, navigation, and radar systems due to ionospheric perturbations [*Datta-Barua et al.*, 2014; *Lechtenberg et al.*, 2013; *Tobiska et al.*, 2013]. To illustrate an early effort in this Collaborative Space Weather Modeling Partnership, we focus on ionospheric total electron content (TEC) during HSS-driven storms and differences from the preceding quiet period in response to solar wind driving.

The profound upper atmosphere changes that occur during storms are due to several factors that act simultaneously and affect each other: (1) momentum input from the solar wind creates large-scale changes to high-latitude ionospheric plasma convection, redefining the boundary between quiescent middle latitudes and the strongly convecting higher latitudes; (2) ionospheric electric fields of magnetospheric origin cause global-scale changes to plasma transport processes and plasma structure; (3) frictional heating between convecting ions and neutrals and (4) heating from magnetospheric particle precipitation create large-scale changes to the thermosphere composition, density, and circulation (winds). Ionization from precipitating particles locally affects the high-latitude electron density profile. Thermosphere circulation changes also have electrodynamic impact via the neutral wind dynamo mechanism. These upper atmospheric consequences are represented in first-principles coupled models of the magnetosphere-thermosphere-ionosphere, which is why forecasting these phenomena can be attempted.

10.1002/2014SW001125

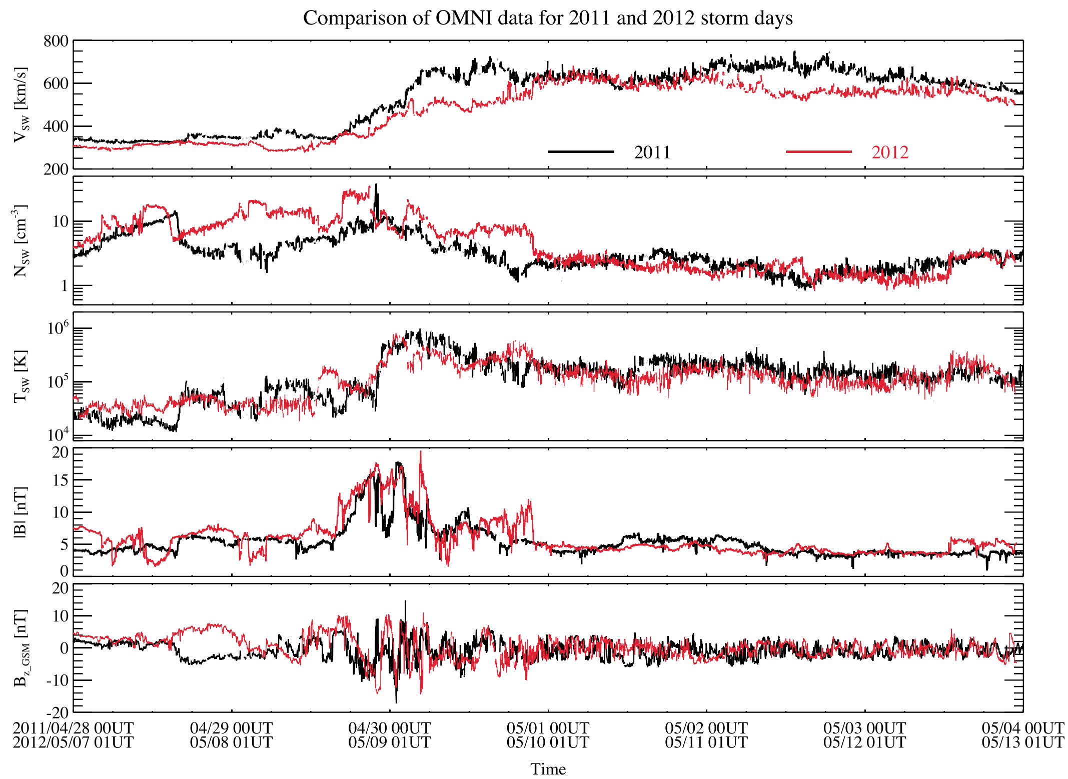

Figure 1. Two high-speed streams in the solar wind occurring during the ascending phase of solar cycle 24.

Examples of the steps required for an upper atmosphere forecast can be found in *Merkin et al.* [2007] and *Tóth et al.* [2007]. Such forecasts begin with solar observations that provide information on the solar origin of the resulting storm, for example, the detection of a coronal mass ejection that hurls hot magnetized plasma earthward, for eventual interaction with Earth's magnetosphere if the CME path intersects Earth.

Such data are useful to specify the CME's speed and direction of propagation within a model of the Sun's corona [e.g., *Manchester et al.,* 2014], which then provides inputs to a model that calculates resulting changes to the magnetized plasma in the heliosphere. Propagation time of the disturbance through the heliosphere from Sun to Earth typically lasts 1–4 days for CMEs.

Solar wind conditions at Earth, as predicted by the heliospheric model, are used to drive physics-based models of near-Earth space, consisting of a global magnetosphere model and models of solar wind-magnetosphere-ionosphere interaction. This provides drivers for models of the upper atmosphere, such as the global ionosphere thermosphere model (GITM) [*Ridley et al.,* 2006], which are then used to estimate upper atmospheric conditions. Storm impacts are calculated from the model output, such as increased satellite drag and impairments to communications, navigation, and radar systems, due to ionospheric perturbations.

Similar considerations apply for storms caused by high-speed streams in the solar wind. However, forecasting the onset times of upper atmospheric disturbances due to high-speed streams could reach higher levels of accuracy sooner than for CMEs. Physics-based heliospheric modeling shows promise for reproducing the impacts of coronal holes where HSSs originate [*van der Holst et al.,* 2010]. Predictable empirical relationships between heliospheric and upper atmosphere conditions for HSS are being realized in recent research [*McGranaghan et al.,* 2014; *Sojka et al.,* 2014].

Using Data-Driven Models to Improve Forecasts Where Needed

Models that span distances from Sun to Earth (~1.5×10^8 km) do not have the spatial resolution to resolve structures in the solar wind causing hourly variability at Earth. Fluctuations in the solar wind on subhourly time scales are relevant for the response of the thermosphere and ionosphere [*Solomon et al.,* 2012]. We are investigating the use of data-driven models based on *dynamical systems theory*, for which forecasts are

10.1002/2014SW001125

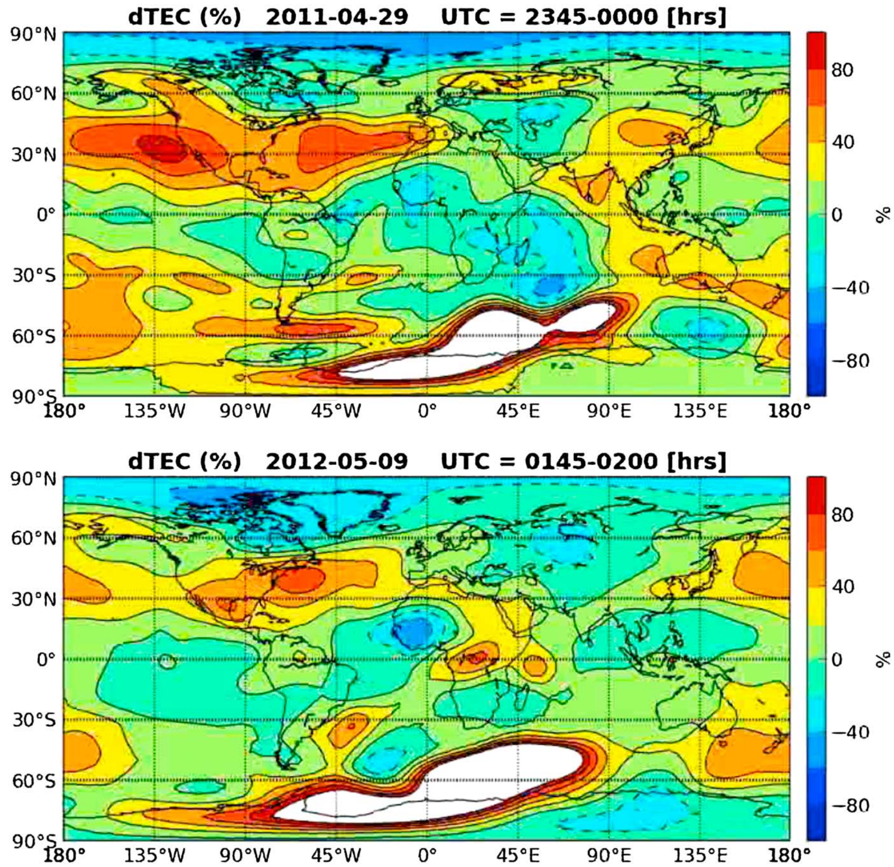

Figure 2. Percent differences in global TEC estimates at comparable phases of the two storms (2011 and 2012). White areas indicate percentage differences above 100%.

generated based on time series of heliophysical variables such as solar wind parameters or geomagnetic indices that correlate with driving the upper atmosphere. These time series capture subhourly variability that is under resolved in the large-scale heliosphere and magnetosphere physics-based models. We are investigating techniques that reconstruct the dynamical behavior of the system from time series data alone, independent of modeling assumptions, yielding predictions. State space reconstruction techniques [*Sharma*, 1995] yield multidimensional data from a single time series. An integrative approach that uses these techniques with the physics-based modeling will be adapted for the thermosphere-ionosphere system. Using dynamical systems theory in upper atmosphere forecasts is a new approach that is distinct from approaches based on empirical models [e.g., *Tobiska et al.*, 2013] or downscaling using additive noise [*Owens et al.,* 2014].

Two High-Speed Stream Storms: Similarities and Differences

The initial focus of the project is forecasting thermosphere-ionosphere disturbances due to solar wind high-speed streams (HSSs) and associated corotating interaction regions (CIRs) [*Verkhoglyadova et al.,* 2013]. HSS is a persistent global-scale feature of the quiet Sun that emanates continuously from coronal holes. These fast wind patterns can be predicted with a variety of techniques that rely upon synoptic magnetograms to model the global structure of the coronal magnetic field [*van der Holst et al.,* 2010]. Models of the evolving heliospheric structure predict the periodic impact of HSSs at Earth (modulated by solar rotation), which permits a predictive capability with a lead time of a few days. Due to the persistence of coronal holes, which can last for weeks, lead times for HSSs can be longer than for CMEs.

Nature has provided two useful events occurring in 2011 and 2012 that highlight the upper atmosphere forecasting challenge. Solar wind parameters for these two events, both occurring in the April–May season, are shown in Figure 1 derived from the ACE or WIND spacecraft and time shifted to account for travel time to Earth's magnetopause (data available at http://cdaweb.gsfc.nasa.gov). The solar wind time history of these two interactions is largely similar, at least as recorded at the spacecraft. The 2012 period is associated with more solar active regions, a more highly distorted heliospheric current sheet, and somewhat higher solar flux than 2011 ($F_{10.7}$ of 130 versus 111 for 2012 and 2011, respectively).

The following question is relevant to forecasting space weather in the ionosphere-thermosphere system: is the response of the upper atmosphere similar, given that these storms occurred at similar times of year and at similar (though not identical) phases of the solar cycle? We address this question using ground-based TEC data from the GPS global network [*Mannucci et al.,* 1998]. These data are combined into global ionospheric maps (GIMs), which are space and time interpolations of the ground-based TEC data. Using GIM, in Figure 2 we plot global TEC fractional differences between the HSS period and an average of five quiet days preceding each event. The fractional TEC difference at each location is the TEC difference between storm time and quiet time, divided by the corresponding quiet time TEC. These difference maps are meant to approximate the global ionospheric response to the evolving geomagnetic storm. A snapshot of fractional TEC differences at similar storm phases is shown in Figure 2. At the latitudes north of 30°S, similarities are found: in both storms, fractional TEC increases are observed in broad midlatitude bands (orange to red). The largest increases occur in the North American sector. It is also clear that the fractional response in 2011 is larger, particularly over North America. The southern high-latitude increase is quite significant and largely similar between the two events. We note that the fractional difference method can cause an apparent extreme amplification of differences in regions where the background values are low during quiet times (e.g., the white regions in the Southern Hemisphere in Figure 2).

Global coupled models, such as the global ionosphere thermosphere model (GITM) [*Ridley et al.,* 2006], available at http://csem.engin.umich.edu/tools/swmf, and the thermosphere ionosphere electrodynamics general circulation model, available at http://www.hao.ucar.edu [*Roble et al.*, 1988; *Richmond et al.*, 1992], are being run for these periods to assess how they capture these ionospheric "weather patterns," driven primarily by the solar wind parameters shown in Figure 2. The models will also be run using solar wind forecasts to assess how solar wind forecast errors affect the thermosphere-ionosphere response. Subgrid-scale fluctuations will be added to drivers of the response based on the dynamical systems theory approach we are developing.

Conclusions

Building on nearly two decades of focused space weather research, the scientific community is on the threshold of a new era in space weather forecasting, and scientific understanding of the connected Sun-Earth system, enabled in part by the development of physics-based modeling capabilities that span the solar corona to the Earth's upper atmosphere (thermosphere and ionosphere). Combining comprehensive observations and global models, a system to forecast thermosphere and ionosphere space weather is being developed under the NASA/NSF Partnership for Collaborative Space Weather Modeling [*Schunk*, 2014]. The focus of this project is on ionospheric total electron content during storms and differences from the preceding quiet period in response to solar wind driving. This requires detailed understanding of the physical processes that cause changes in the thermosphere and ionosphere and how these processes are represented in global models.

Achieving forecast lead times of a few days will require accurate solar wind forecasts. This appears to be tractable for high-speed streams and the corotating interaction regions that accompany them, using synoptic maps of the coronal magnetic fields as input to magnetohydrodynamic models of the solar wind. Upper atmosphere research shows that solar wind variability that is subgrid scale with respect to heliospheric models can have significant impacts. Therefore, a portion of this modeling project is devoted to dynamical systems theory as a means of developing data-driven methods that accurately forecast time series of geospace parameters that are overly smoothed by global models.

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