Implications of Forecasting Thermosphere-Ionosphere Conditions After Initiation of an Eruptive Solar Event

Anthony Mannucci[1], Bruce Tsurutani[2], Olga Verkhoglyadova[1], Xing Meng[1], Ryan McGranaghan[2], Chunming Wang[3], Gary Rosen[3], Surja Sharma[4], and Ja-Soon Shim[5]

[1]Jet Propulsion Laboratory
[2]NASA Jet Propulsion Laboratory
[3]University of Southern California
[4]University of Maryland College Park
[5]Catholic University of America

November 23, 2022

Abstract

An objective of the solar and space physics communities has been to predict the behavior of the interconnected physical systems that bring space weather to Earth. One approach is to use first-principles models that may predict behavior of the various space plasma regimes from the magnetized solar corona to Earth's upper atmosphere. We focus on space weather forecasts in the thermosphere-ionosphere (T-I), with lead time based on the period following a solar eruption. There are generally 1-4 days lead time before the interplanetary coronal mass ejection (ICME) reaches the Earth's magnetopause. Forecasting the behavior of the T-I with such multi-day lead times requires new ways of using and assessing first principles models, which are capable of predicting many details of the T-I response, including the time history of the global electron density distribution, neutral densities and neutral winds. All facets of the complex T-I system response must be predicted based on input solar and interplanetary parameters. Another influence on the forecast is the condition of the T-I at the time a forecast is produced (e.g. shortly after the CME eruption epoch). However, the role of such pre-conditioning is not well understood for lead times of a few days. To improve our understanding of these forecasts, we have submitted more than 120 multi-day simulation periods to NASA's Community Coordinated Modeling Center, spanning three coupled T-I models. Approximately 40 T-I storms have been simulated, driven by solar wind and EUV parameters alone. We will present an analysis that characterizes how T-I models respond to the information content of the solar wind, mediated through climatological models of high latitude forcing, and the possible influence of pre-existing conditions. Smoothing across mesoscale variability is inevitable in this scenario. Analyzing the response across events and across models reveals critical information about the predictability of the T-I system as an ICME approaches.

Implications of Forecasting Thermosphere-Ionosphere Conditions After Initiation of an Eruptive Solar Event

Jet Propulsion Laboratory
California Institute of Technology

A. J. Mannucci[1], B. T. Tsurutani[1], O. P. Verkhoglyadova[1], X. Meng[1], R. McGranaghan[1], C. Wang[2], G. Rosen[2], S. Sharma[3], J. Shim[4]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA
[2]University of Southern California, Los Angeles, CA —— [3]University of Maryland, College Park, MD
[4]Goddard Planetary Heliophysics Institute, University of Maryland Baltimore County, NASA Goddard Space Flight Center, Greenbelt, MD

AGU 100 FALL MEETING Washington, D.C. | 10–14 Dec 2018

Poster No. SM31E-3554
Wednesday Dec 12, 2018

Overview

- **Detection of a CME at the sun can be used to initiate forecasts of solar wind conditions at Earth and then the response of the global thermosphere-ionosphere (TI) storm, using first-principles models**
- **We assessed custom forecastable-mode simulations of three models running at CCMC: TIE-GCM, GITM and CTIPe**
- **Forecastable-mode simulations are driven by the measured solar wind parameters and short-term (~few day) F10.7 index forecasts**
- **We developed forecast metrics that define positive phase (*increased TEC*) and negative phase (*decreased TEC*) storm features – relative to quiet background**
- **We compared data-driven TEC maps to simulations using *binary evaluation criteria*: are "observed" storm-time *features* matching simulations?**
- **What factors limit TI forecasts initiated after CME detection?**

Approach: Metrics for Global Ionospheric Storms Based on Total Electron Content (TEC)

TEC metric definition

- For GIM (GPS TEC data)

$$dTEC_{GIM}(UT,lon,lat) = \frac{TEC_{GIM}(UT,lon,lat) - TEC_{GIM,pre\text{-}storm}(UT,lon,lat)}{variability\ of\ TEC_{GIM,quiet}(UT,lon,lat)}$$

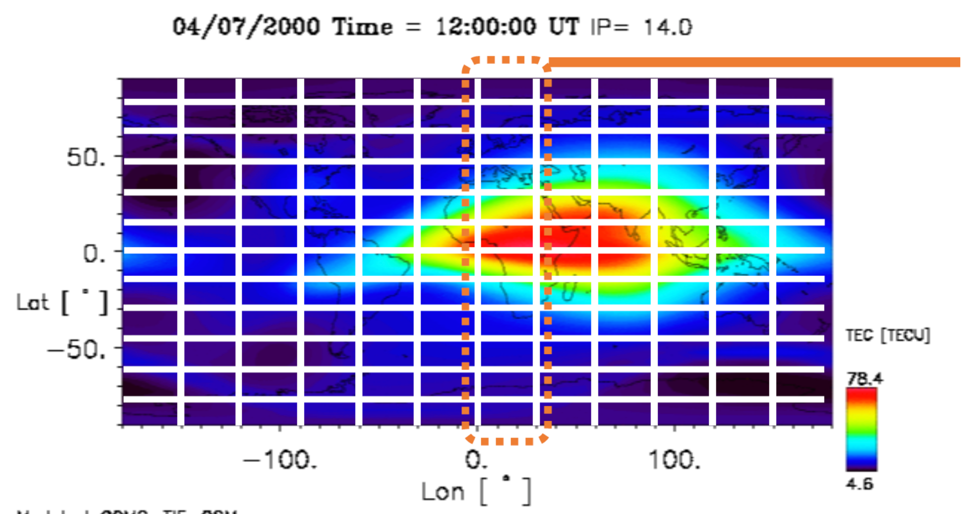
- For Model (TIE-GCM, GITM, CTIPe)

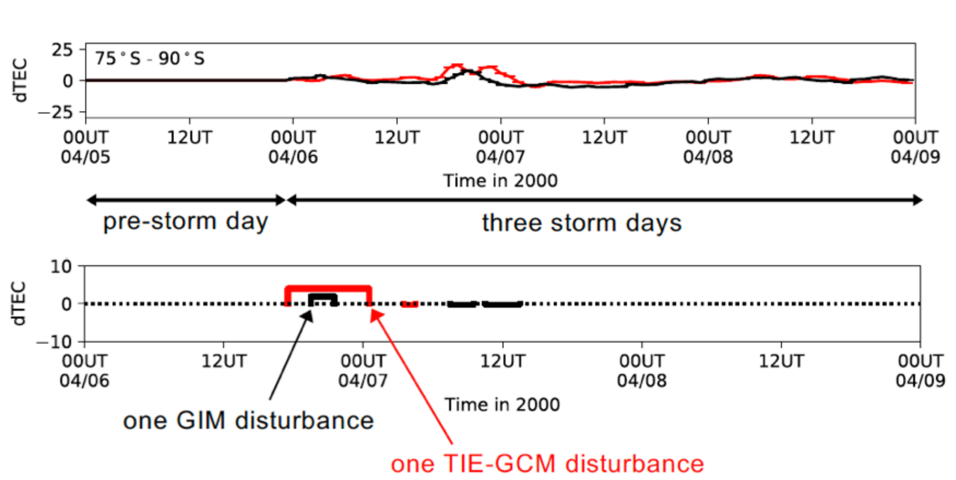
$$dTEC_{Model}(UT,lon,lat) = \frac{TEC_{Model}(UT,lon,lat) - TEC_{Model,pre\text{-}storm}(UT,lon,lat)}{variability\ of\ TEC_{GIM,quiet}(UT,lon,lat)}\ Scale(UT)$$

$$Scale(UT) = \frac{median\left(TEC_{GIM,pre\text{-}storm}(UT,lon,lat)\right)}{median\left(TEC_{Model,pre\text{-}storm}(UT,lon,lat)\right)}$$

- $TEC(UT,lon,lat)$: the mean TEC within a **30° x 15°** grid box centered at (lon,lat) and at a given **UT hour** for either GIM or Model

TIE-GCM Simulated TEC for 12UT on 7 April 2000





Simulated Forecast: Success Rate and False Alarm Rate

Forecast Success: for a given GIM disturbance, Model predicts a disturbance that starts +/- 3 hours of the GIM disturbance starting time and ends +/- 3 hours of the GIM disturbance ending time

(see previous panel for definition of "disturbance")

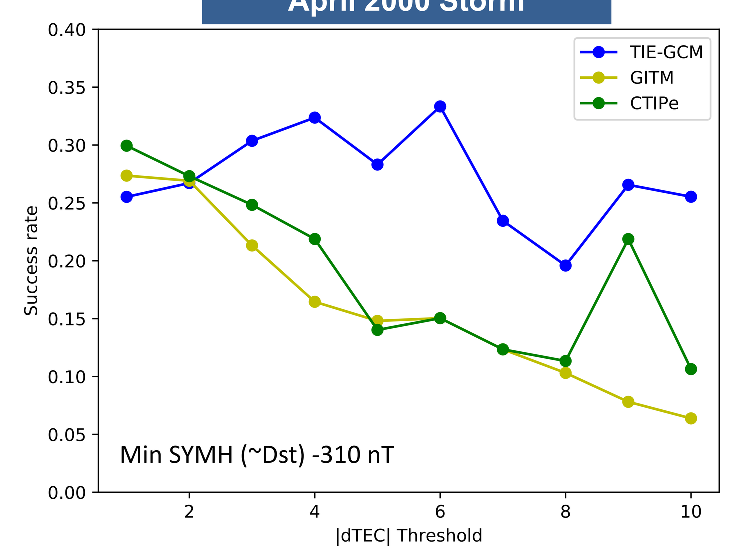
Forecast Success Rate

$$= \frac{number\ of\ disturbances\ that\ are\ \text{"}Forecast\ Successes\text{"}}{number\ of\ GIM\ disturbances\ (over\ the\ globe\ and\ across\ three\ storm\ days)}$$

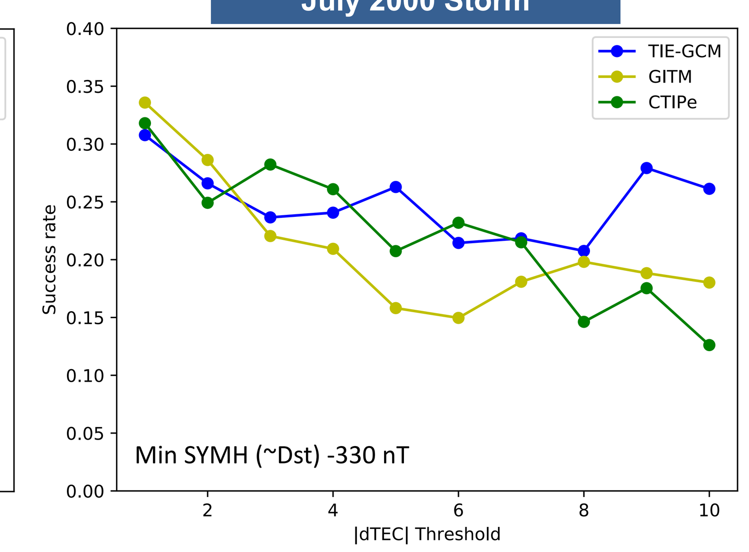
Forecast False Alarm Rate

$$= \frac{number\ of\ disturbances\ that\ are\ not\ \text{"}Forecast\ Successes\text{"}}{number\ of\ Model\ disturbances\ (over\ the\ globe\ and\ across\ three\ storm\ days)}$$

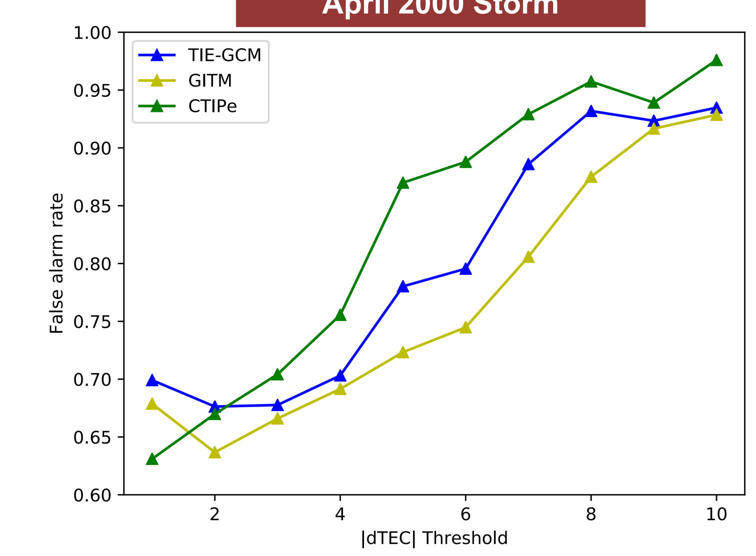
Forecast Success Rate April 2000 Storm



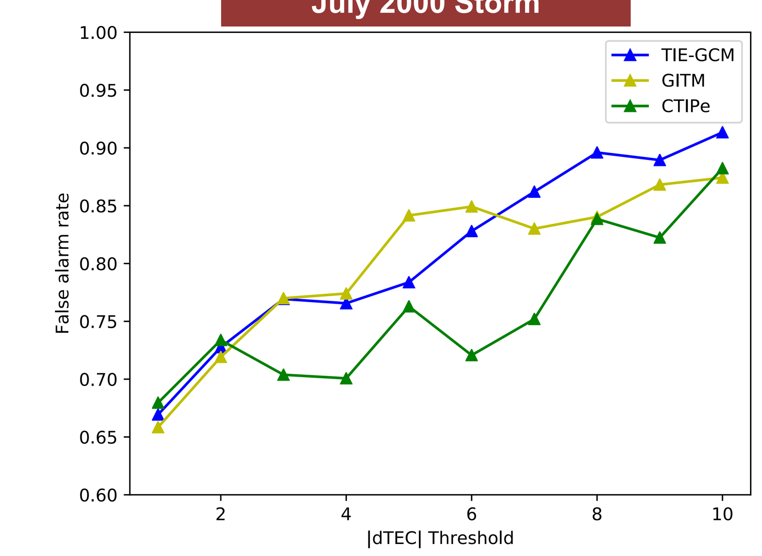
Forecast Success Rate July 2000 Storm



Forecast False Alarm Rate April 2000 Storm



Forecast False Alarm Rate July 2000 Storm



Key points

- Rates are threshold dependent
- Models below 35% success rate
- One model has clearly higher success rate in April 2000
- False alarm rate increases with threshold – models can overestimate increasingly larger (and fewer) features
- Forecasting the complex TI response using only solar wind and F10.7 inputs is very challenging
- What are the factors determining forecast success rates and false alarm rates?

All three models are coupled thermosphere-ionosphere (TI) first-principles models

X. Meng, A. J. Mannucci, O. P. Verkhoglyadova, B. T. Tsurutani, "Assessing an Approach to Ionospheric Total Electron Content Forecasting using Physics-based Models" No. MT-401, Session PSW.1, 42nd General Assembly COSPAR Pasadena CA July 2018

Simulated Forecast: Skill Scores

Model Output

Observation	Contingency Table	Feature is reproduced by the model	Feature is not reproduced by the model
	Feature is observed	True Positive (TP)	False Negative (FN)
	Feature is not observed	False Positive (FP)	True Negative (TN)

True Skill Statistic (TSS) approach to TEC-based metric

$$TSS = \frac{TP}{TP+FN} - \frac{FP}{FP+TN}$$

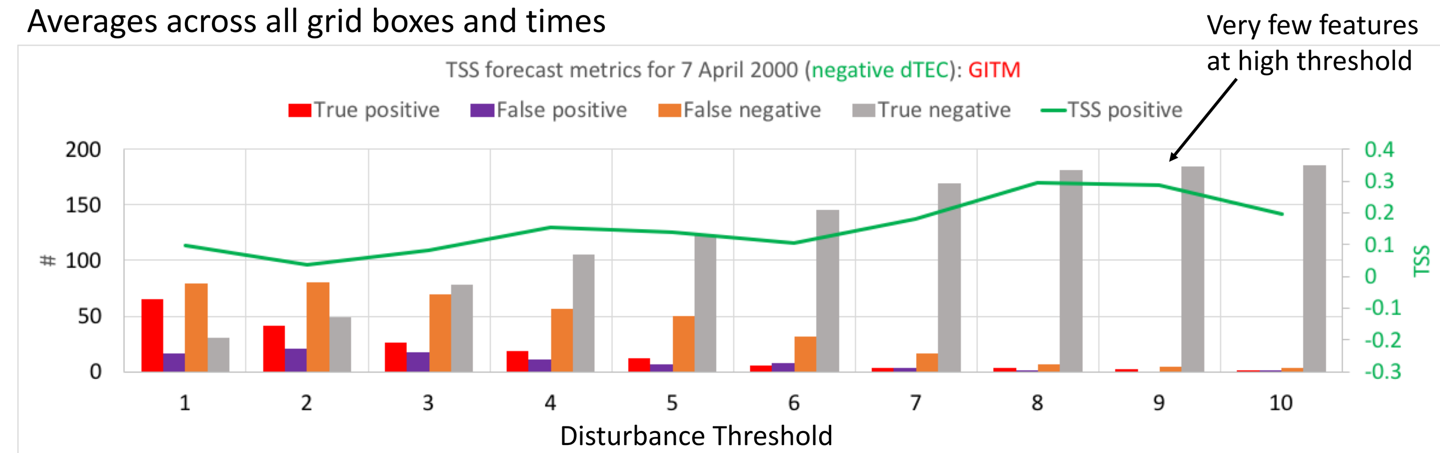
Steps to calculate the metric:

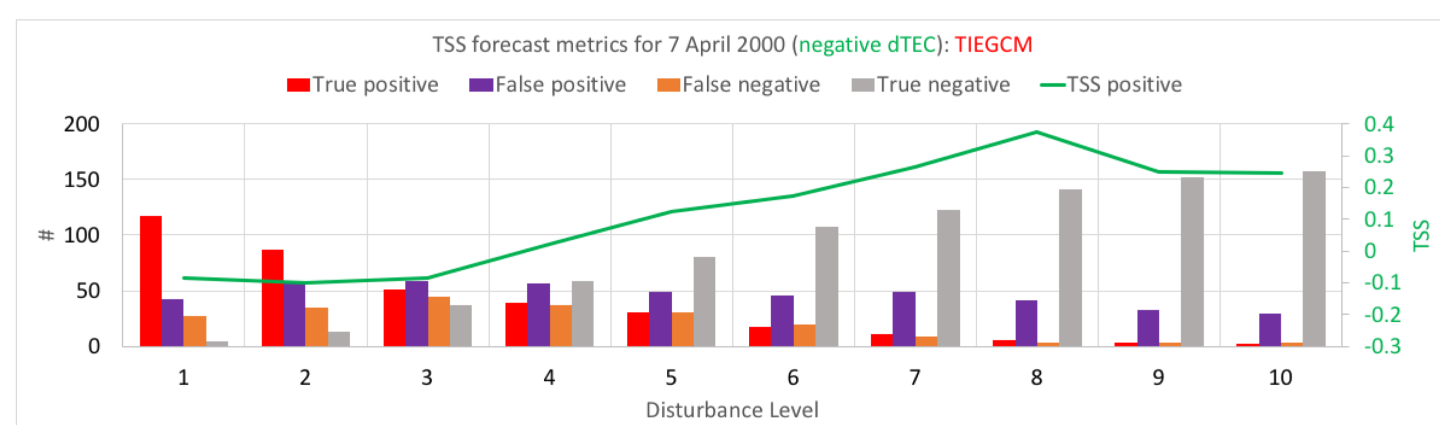
- Find occurrences when dTEC reaches a threshold (level) for each grid box within successive 3 hour windows
- Do separately for observation (GIM) and simulation within each time window
- Define TP, FP, FN and TN based on if threshold is reached at any time within each time window
- Compute separately for positive (+) and negative (-) dTEC

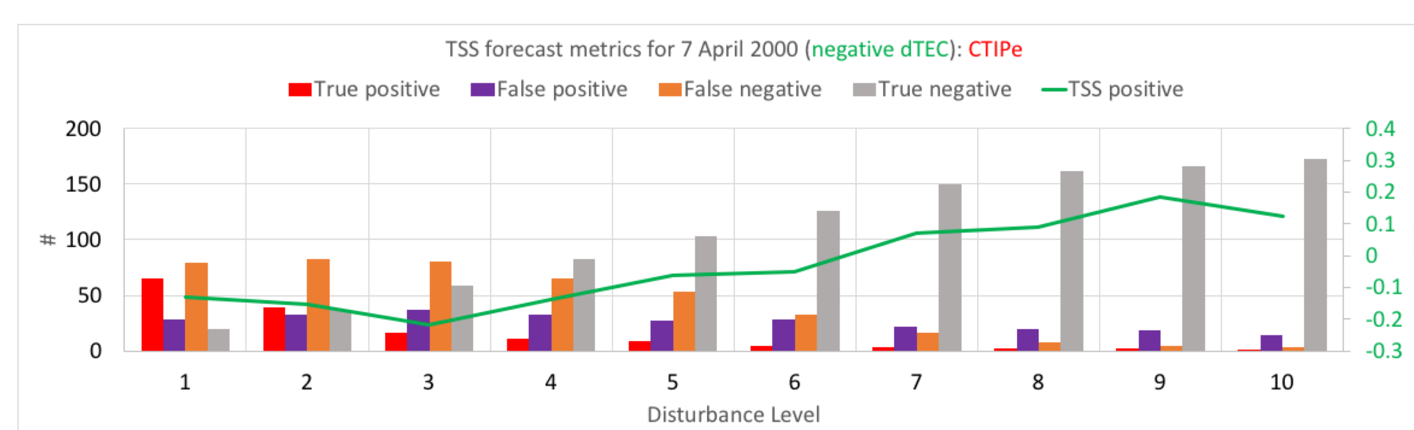
TSS: Bloomfield et al., 2012

Averages across all grid boxes and times

Very few features at high threshold







Negative storm features analyzed (*TEC decreases*)

Not to be confused with T/F Negative!

Key points

- All models show some skill
- One model is most consistently positive TSS
- Another model reaches a higher peak TSS
- A particular TSS value weakly represents underlying contingency table
- Recommend analyzing all four contingency table values according to location, time and local time

See McGranaghan et al., 2018

References

Bloomfield, D. S., P. A. Higgins, R. T. J. McAteer, and P. T. Gallagher (2012), TOWARD RELIABLE BENCHMARKING OF SOLAR FLARE FORECASTING METHODS, ApJ, 747(2), L41–7, doi:10.1088/2041-8205/747/2/L41.
Meng, X., A. J. Mannucci, O. P. Verkhoglyadova, and B. T. Tsurutani (2016), On forecasting ionospheric total electron content responses to high-speed solar wind streams, J. Space Weather Space Clim., 6, A19–11, doi:10.1051/swsc/2016014.
Mannucci, A. J., M. E. Hagan, A. Vourlidas, C. Y. Huang, O. P. Verkhoglyadova, and Y. Deng (2016), Scientific challenges in thermosphere-ionosphere forecasting – conclusions from the October 2014 NASA JPL community workshop, J. Space Weather Space Clim., 6, E01–10, doi:10.1051/swsc/2016030.
Mannucci, A. J., and B. T. Tsurutani (2017), Ionosphere and Thermosphere Responses to Extreme Geomagnetic Storms, in Extreme Events in Geospace: Origins, Predictability and Consequences, edited by N. Buzulukova, pp. 493–511, Elsevier.
Deng, Y., C. Sheng, B. T. Tsurutani, and A. J. Mannucci (2018), Possible Influence of Extreme Magnetic Storms on the Thermosphere in the High Latitudes, Space Weather, 16(7), 802–813, doi:10.1029/2018SW001847.
McGranaghan, R. M., A. J. Mannucci, B. Wilson, C. A. Mattmann, and R. Chadwick (2018), New Capabilities for Prediction of High-Latitude Ionospheric Scintillation: A Novel Approach With Machine Learning, Space Weather, 16, doi:10.1029/2018sw002018.

Acknowledgments

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, and supported by Living With A Star Targeted Research and Technology NASA/NSF Partnership for Collaborative Space Weather Modeling Program. The authors sincerely acknowledge Masha Kuznetsova, Ja-Soon Shim, Anne Michelle Mendoza, and the rest of the CCMC team for accommodating the model runs and preparing the outputs customized to our needs.

Contact information: Anthony J. Mannucci: Anthony.J.Mannucci@jpl.nasa.gov

Conclusions and Future Work

- We have developed ionospheric storm metrics that are valuable to assess how first-principles simulations may perform for forecasts initiated after CME eruption (1-4 day lead time)
- Storm-feature based metrics can be further refined to understand how simulations capture basic features of the storm (positive and negative phases), not necessarily exact details of the TEC behavior
- The forecast scenario – driving by solar wind conditions alone – is challenging given the complexities of storms
- These simulated forecasts are "optimistic" and do not account for errors in a solar wind ensemble forecast
- Approximately 40 storm periods have been run at CCMC with three models, available for further statistical analysis
- The community needs improved tools to determine factors limiting such forecasts