Session: *International Forum for Space Weather Capabilities Assessment I*

Medium Range Thermosphere-Ionosphere Storm Forecasts

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Aaron Ridley, U Michigan
The Model Development Community

Government sponsorship acknowledged: NASA/NSF Partnership for Collaborative Space Weather Modeling

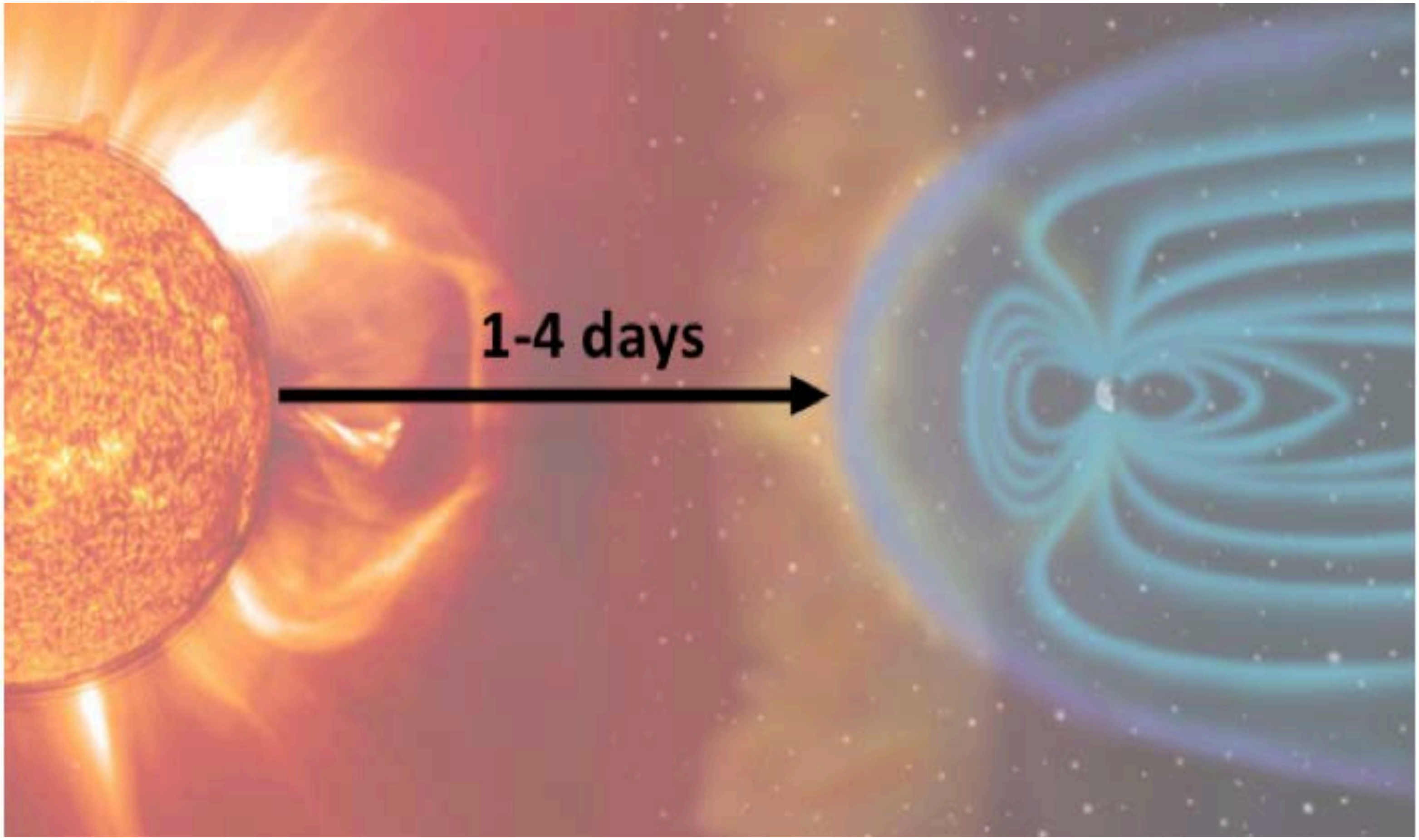
Overview

- The vision: forecasting as a *scientific frontier*
- Understanding thermosphere-ionosphere storm forecasts
- The Space Weather Forecast Testbed (SWFT)

- Acknowledgement: Lutz Rastaetter, Ja Soon Shim and Michelle Mendoza of CCMC

- Web interface to SWFT and custom "forecast mode" runs

Medium-Range Forecast



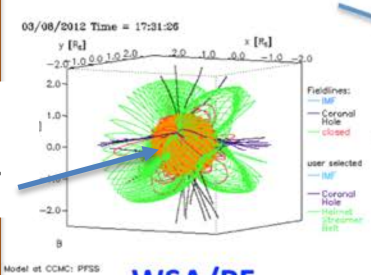
- The applied community has clearly stated a need for forecasts with such lead times
- Contrast to lead times based on ACE data (satellite at L1) of about 1 hour

Exploring "Sun to Mud" Forecasts

- Center for Integrated Space Weather Modeling (2000's), LWS TR&T, NSF, MURI, etc.
- NASA/NSF Partnership for Collaborative Space Weather Modeling (2013-)

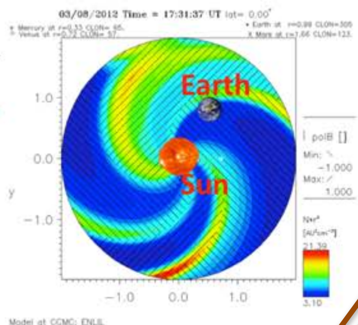
Solar Corona

Solar Interior



WSA/PF

Heliosphere



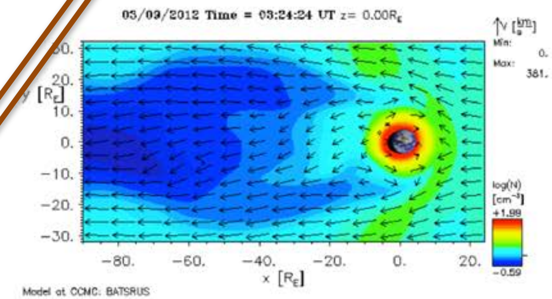
ENLIL

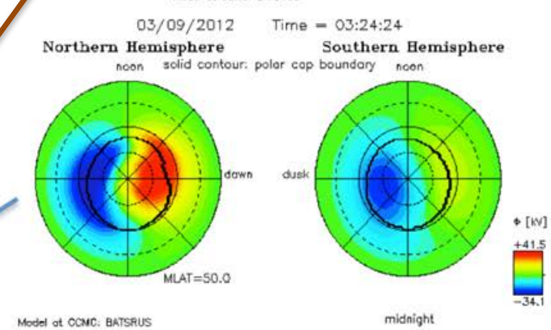
Current solar wind collaborators:
CSEM (U Michigan)
CCMC

Operational

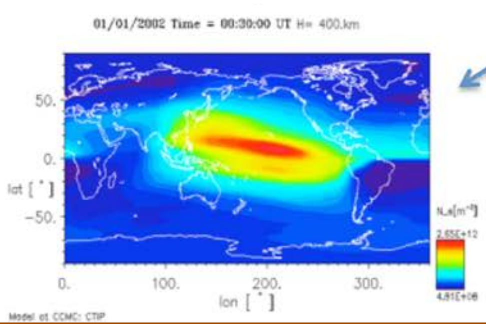
Magnetosphere

Our focus





Global thermosphere-ionosphere storm



High latitude convection pattern

Non-MHD:

- Particle precipitation/ aurora (empirical model)
- Shielding currents (Rice Convection M)

Ionosphere-Thermosphere Forecasts: A Scientific Frontier

- **Existing simulations of the IT contain the essential physics of a global ionospheric storm**
- **Forecasts constitute the most rigorous tests of the simulations**
  - **Learn the implications of poorly observed simulation parameters**
- **In what ways do existing simulations differ from the output of a perfect simulation (aka observations*)?**
  - **What physics is insufficiently represented?**
  - **What are the impacts of poorly specified boundary conditions?**
  - **Forecasting context – useful!**

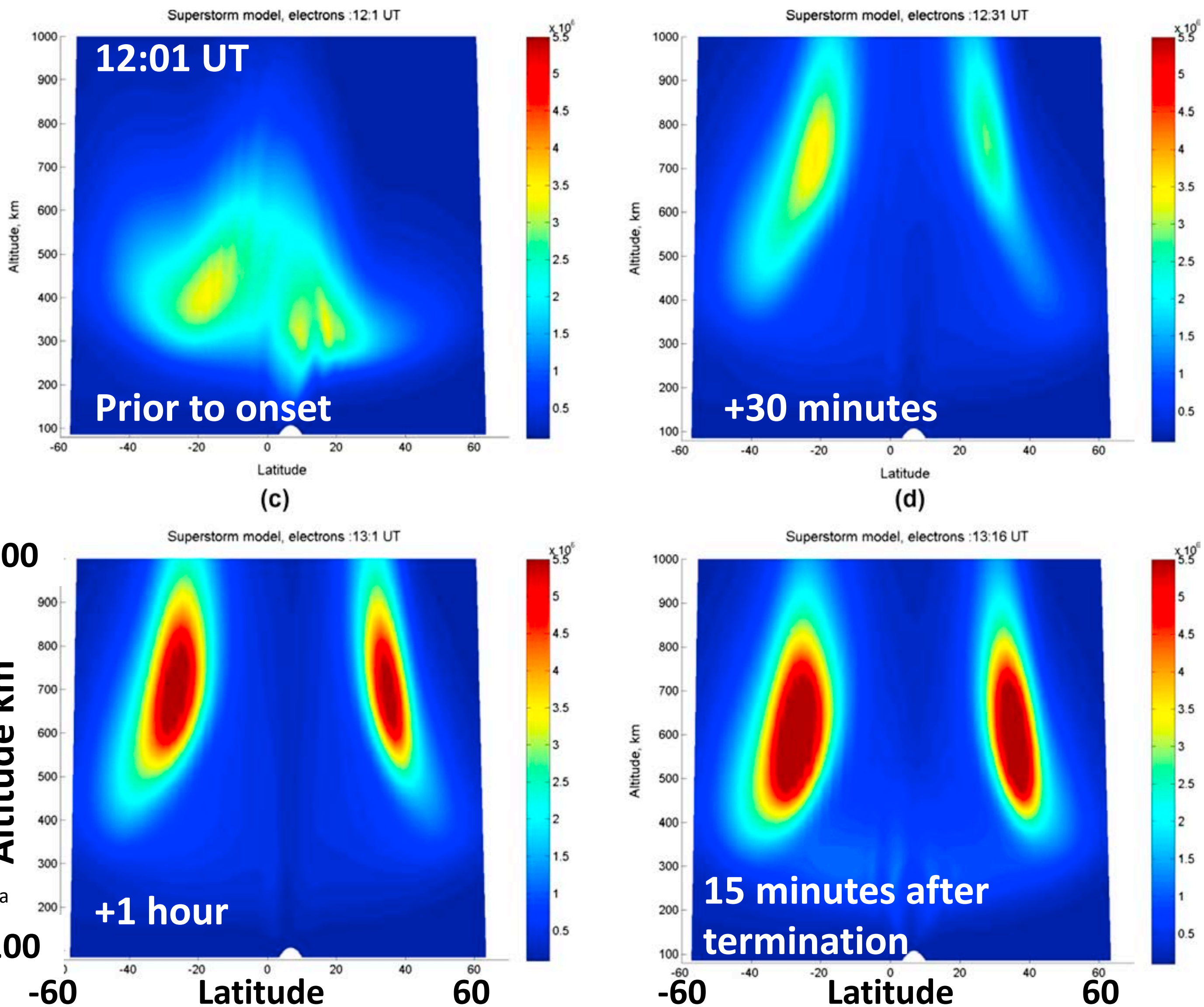
*Filtered and noise added

Simulating the Positive Phase of a Global Ionospheric Storm

20 mV/m for 1 hour

Estimate based on inner magnetosphere estimate/ extrapolation

SAMI-2: neutral wind and composition unchanged from quiet time



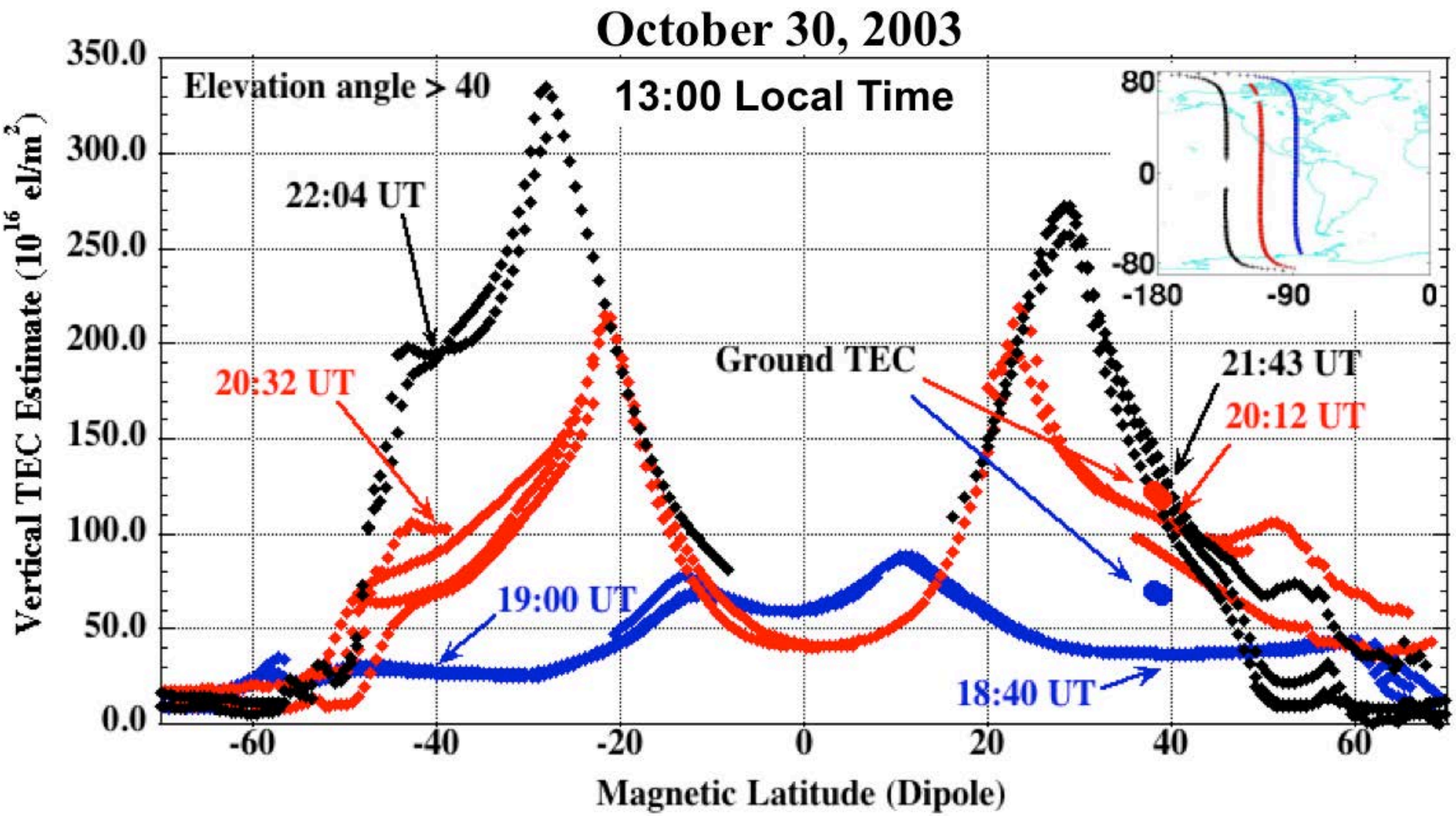
Winds are "nominal" poleward

5.5e6 el/cm^3

0 el/cm^3

Tsurutani, B. T, O. P. Verkhoglyadova1, A. J. Mannucci, G. S. Lakhina, and J. D. Huba (2012) Extreme changes in the dayside ionosphere during a Carrington-type magnetic storm, J. Space Weather Space Clim. doi: 10.1051/swsc/2012004.

The 2003 Halloween Superstorm



CHAMP altitude: 400 km

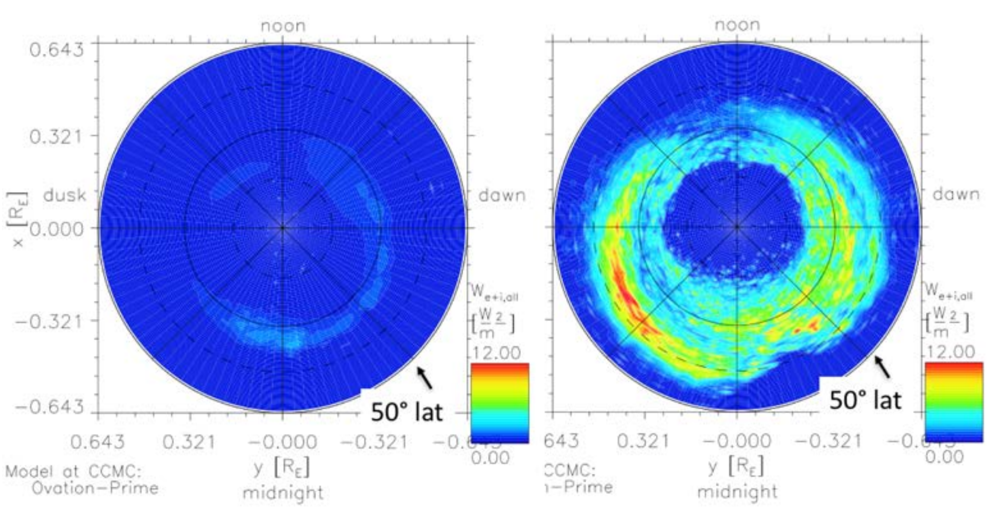
Mannucci et al., "Dayside global ionospheric response …" *GRL* 2005

Forecast Mode Runs

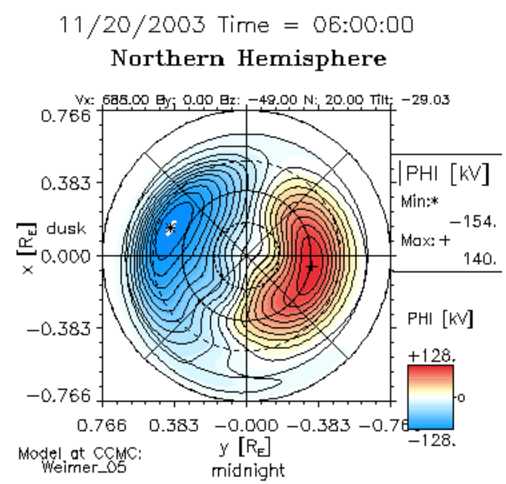
Example: Forecasting global ionospheric total electron content (TEC) – one of the simplest ionospheric quantities to forecast.

"Forecast mode" inputs:

- **F10.7 EUV proxy**
- **Solar wind from OMNI data or ENLIL, CORHEL, SWMF heliosphere model runs**
- **Weimer 2005 empirical model of ionospheric electrodynamics**
- **Ovation Prime empirical auroral patterns**

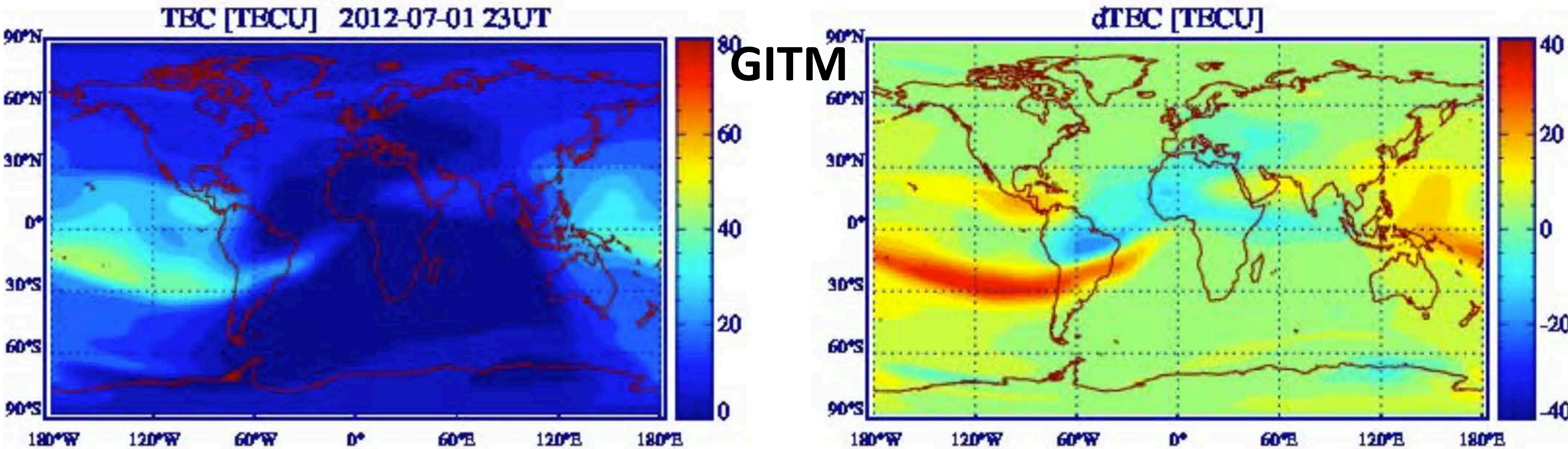


Ovation Prime particle precipitation model

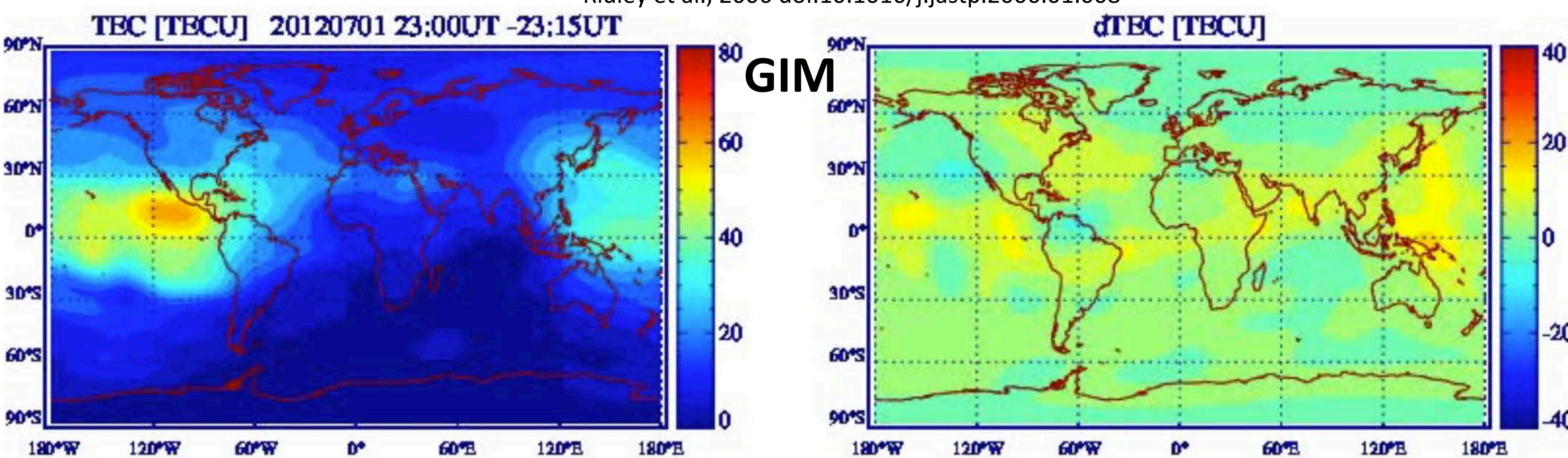


Weimer potential (convection)

Basis For Evaluation: Global Ionospheric Maps

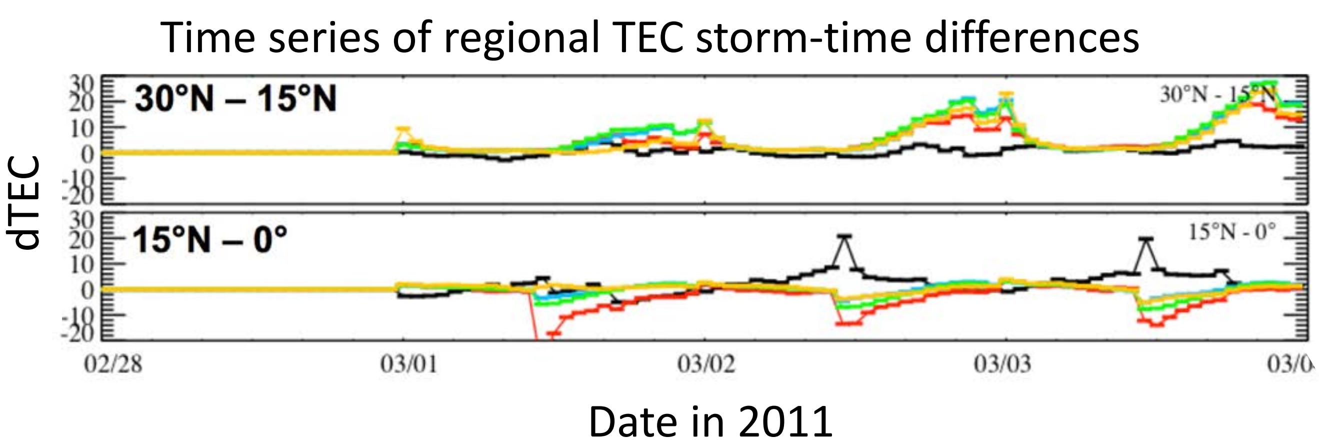


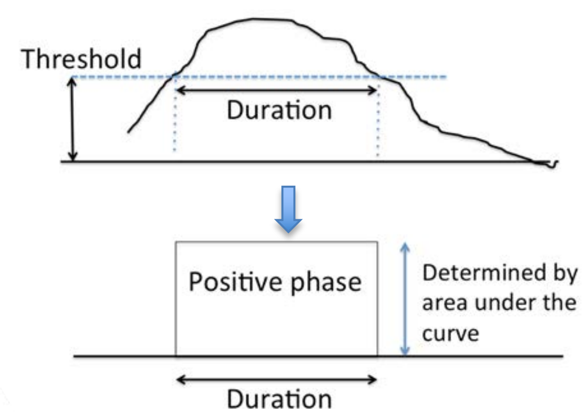
Ridley et al., 2006 doi:10.1016/j.jastp.2006.01.008



Physically Meaningful Model Output: "Forecast Variables"

- **Capture regional "positive" (TEC increases) and "negative" (decreases) *TEC changes* relative to quiet time (dTEC)**
- **Statistical significance based on quiet time variability**
- **Define a threshold level**
- **Take duration into account**
- **Compare global TEC map ("data") to GITM output**

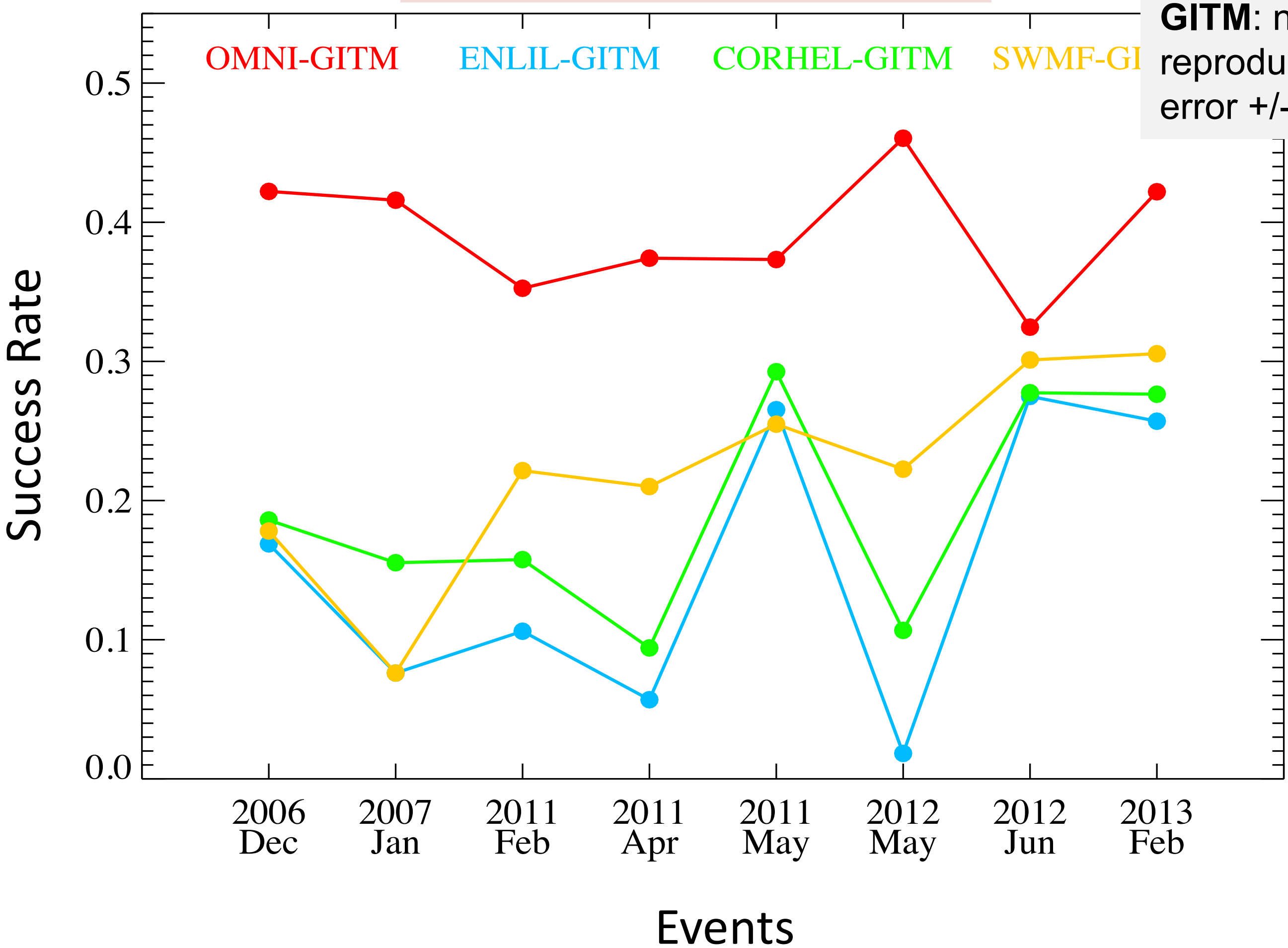




See Meng et al., 2016, doi:10.1051/swsc/2016014

Solar Wind Driven “Forecasts”

Forecast Performance

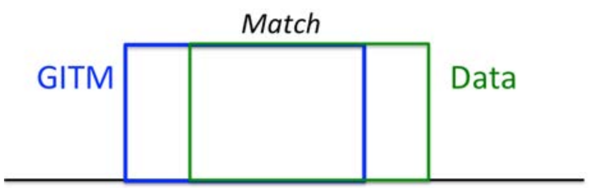


TEC data (GIM): number of all TEC disturbances with |dTEC| > 4
GITM: number of GIM TEC disturbances reproduced by the simulations, with time error +/- 3 hours at most

Forecast Success Rate:

$$\frac{\text{\#GITM Matches}}{\text{\#GIM TEC Disturbances}}$$

- Forecast variables are useful and will continue to be refined Including adaptive location, thresholds, scaling, etc.



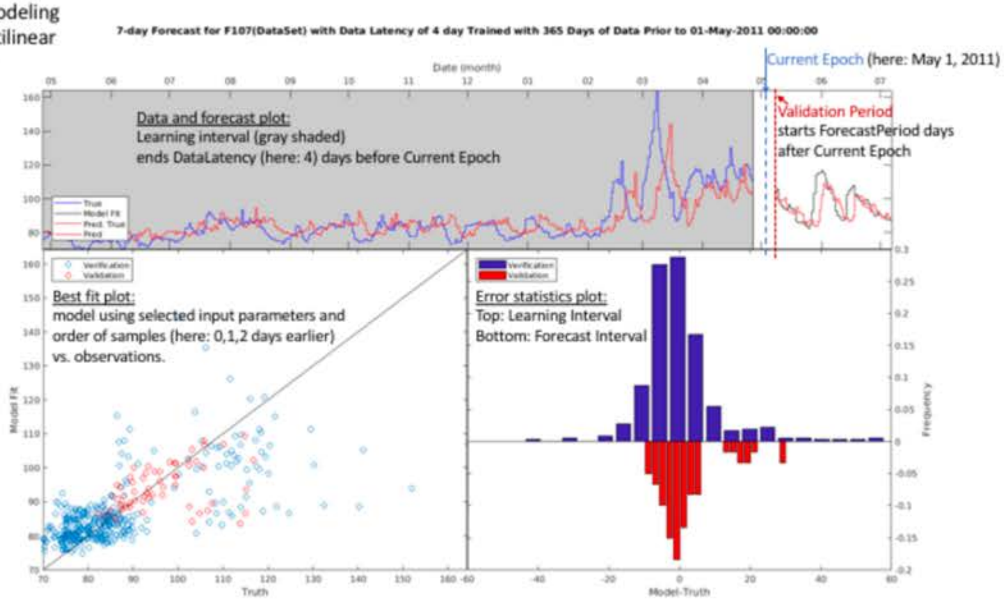
The Space Weather Forecast Testbed

- The Space Weather Forecast Testbed (SWFT) is a platform for assessing space weather forecast strategies
- Three key components of SWFT are:
  - Repository of 12 years of solar, interplanetary, geomagnetic, ionosphere data and indices at 3 hour resolution
  - Matlab scripts that prepare data for forecast strategy training experiments
  - CCMC developed web-portal to allow web access and computation support
- SWFT is currently at the beta stage

Planned implementation as CCMC "Instant Run"

Sample plot of SWFT modeling and multilinear analysis

SWFT modeling and multilinear analysis



Instant Run interface for SWFT

(The example shows the different time periods. The resulting forecast model can be inproved.)

SWFT model instant run submission

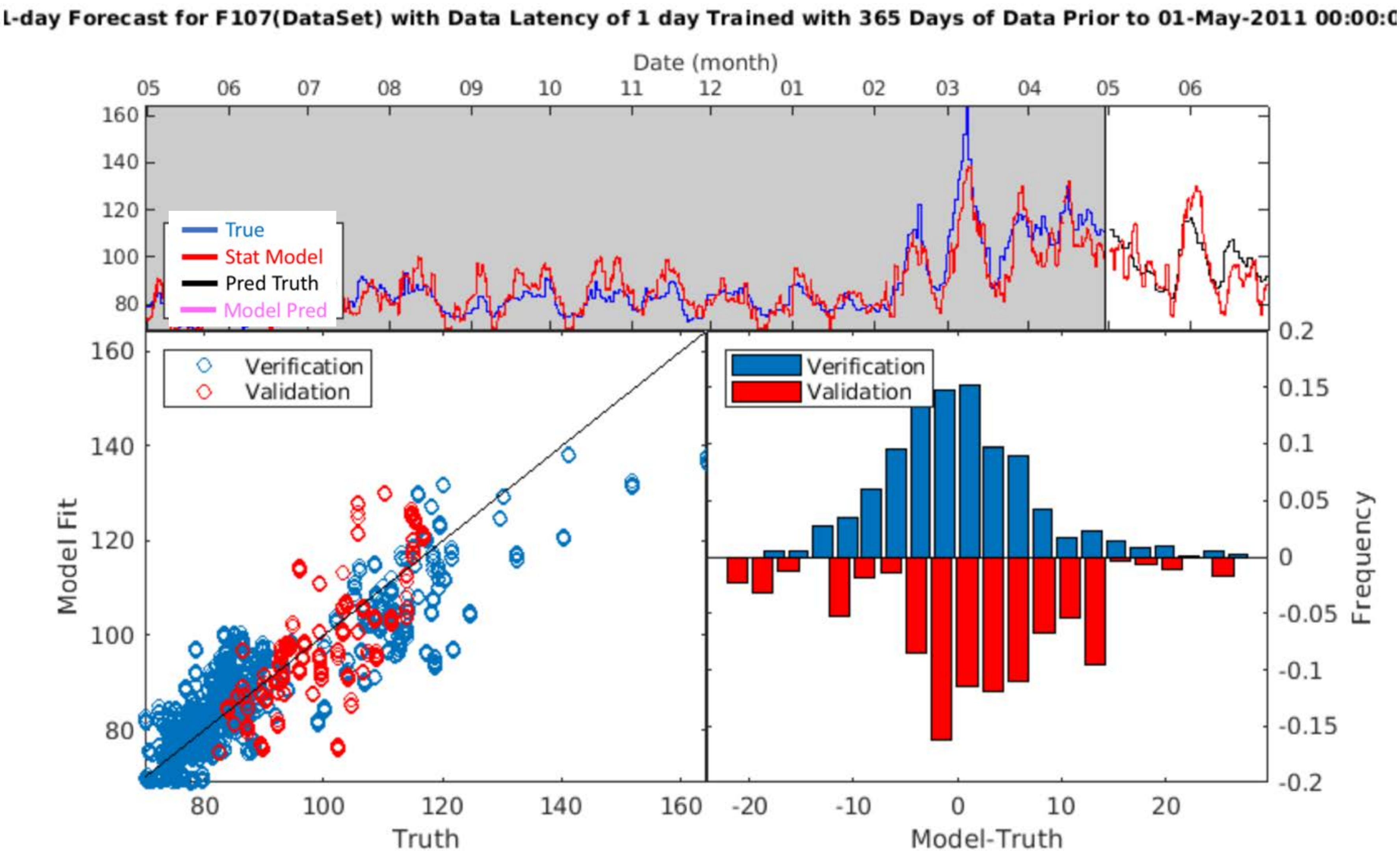
Current Epoch (the start of the learning interval through the end of the forecast period must be between 2000/08/01 01:00 UT and 2012/12/31 23:59 UT):

- Year: 2011
- Month: 5
- Day: 1

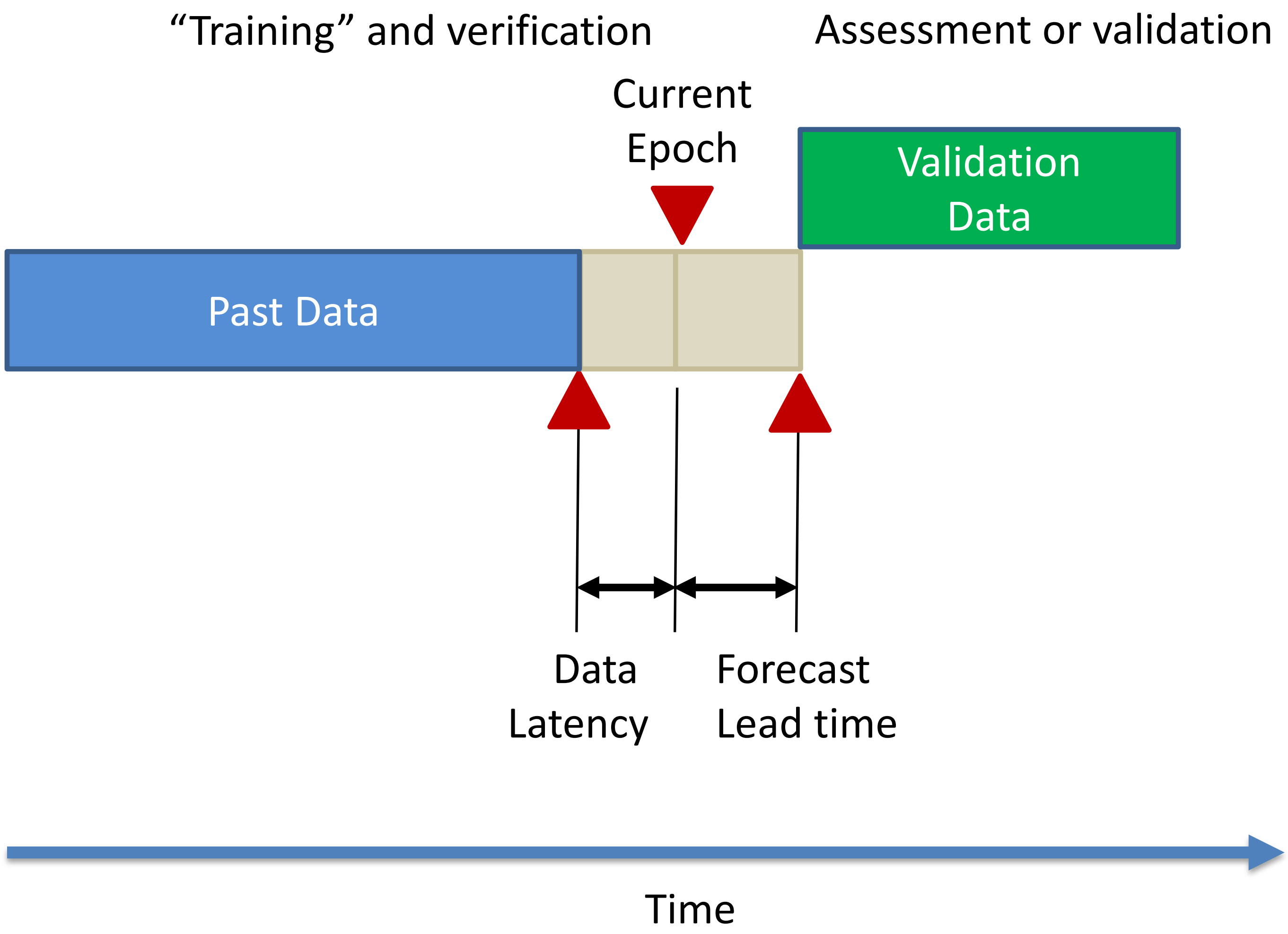
Data latency [days] (day of latest available data before current day during forecast): 4

Learning Interval [days]: 365

SWFT Output – F10.7 Forecast



Time Scales for Forecast Experiments



SWFT Casts the Forecast Problem into a Statistical Framework

What quantities does the physics correlate?
What quantities are inherently more predictable?
What limits forecasts of the ionosphere-thermosphere?

- **Supervised machine learning trains a general regression model of the form**

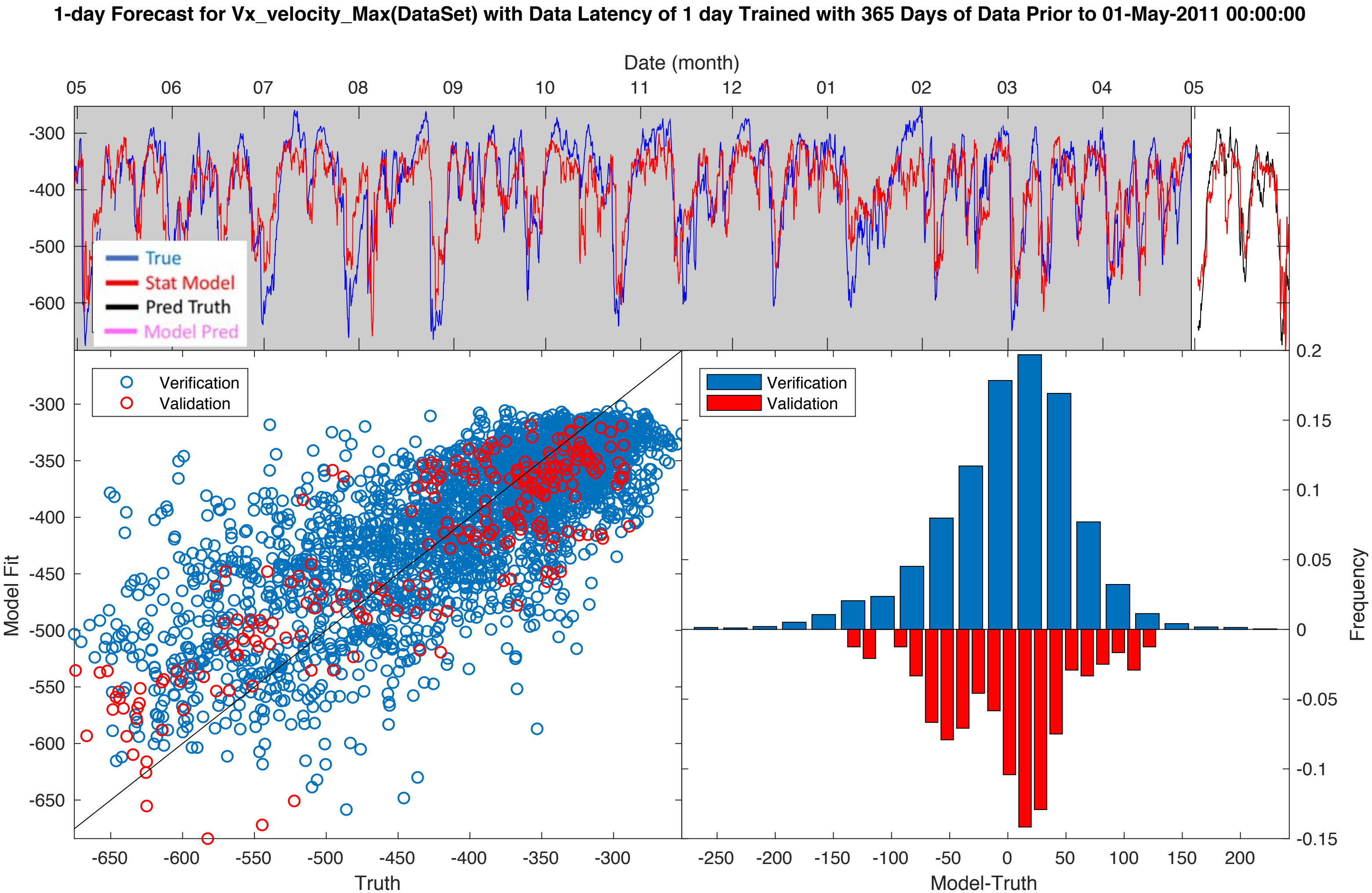
$$y = f(x; w), x \in \mathbb{R}^n, y \in \mathbb{R}^m, w \in \mathbb{R}^d,$$

  - Vector x is called independent the variable
  - Vector y is called dependent variable. In forecast applications, vector y is to be predicted using x.
  - Vector w represents model parameter
- **A collection of matched pairs** $\{(x_k, y_k), k = 1, \cdots, N\}$ **is used to train the model to achieve optimal performance.**

Steps in Developing a Forecast Experiment

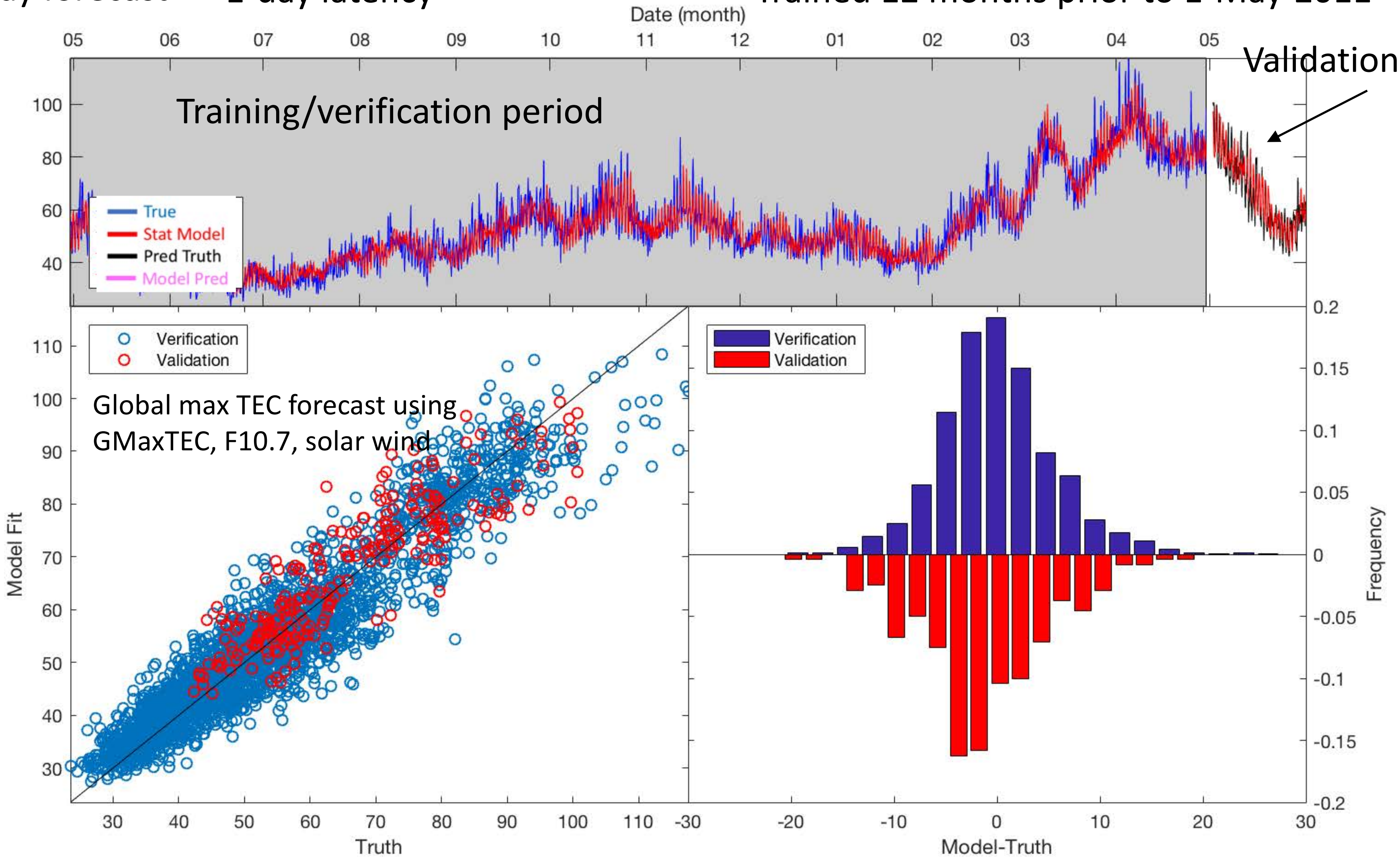
- **Step 1: Decide on which variable to forecast.**
- **Step 2: Select independent variables:**
  - Select the variables and time history to be used.
- **Step 3: Select length of training data set and validation period:**
  - Decide what is the data latency and forecast lead time
  - Select current date
- **Step 4. Select methodology for the forecast**
  - Multilinear, logistic, random decision forest

Example of Using SWFT



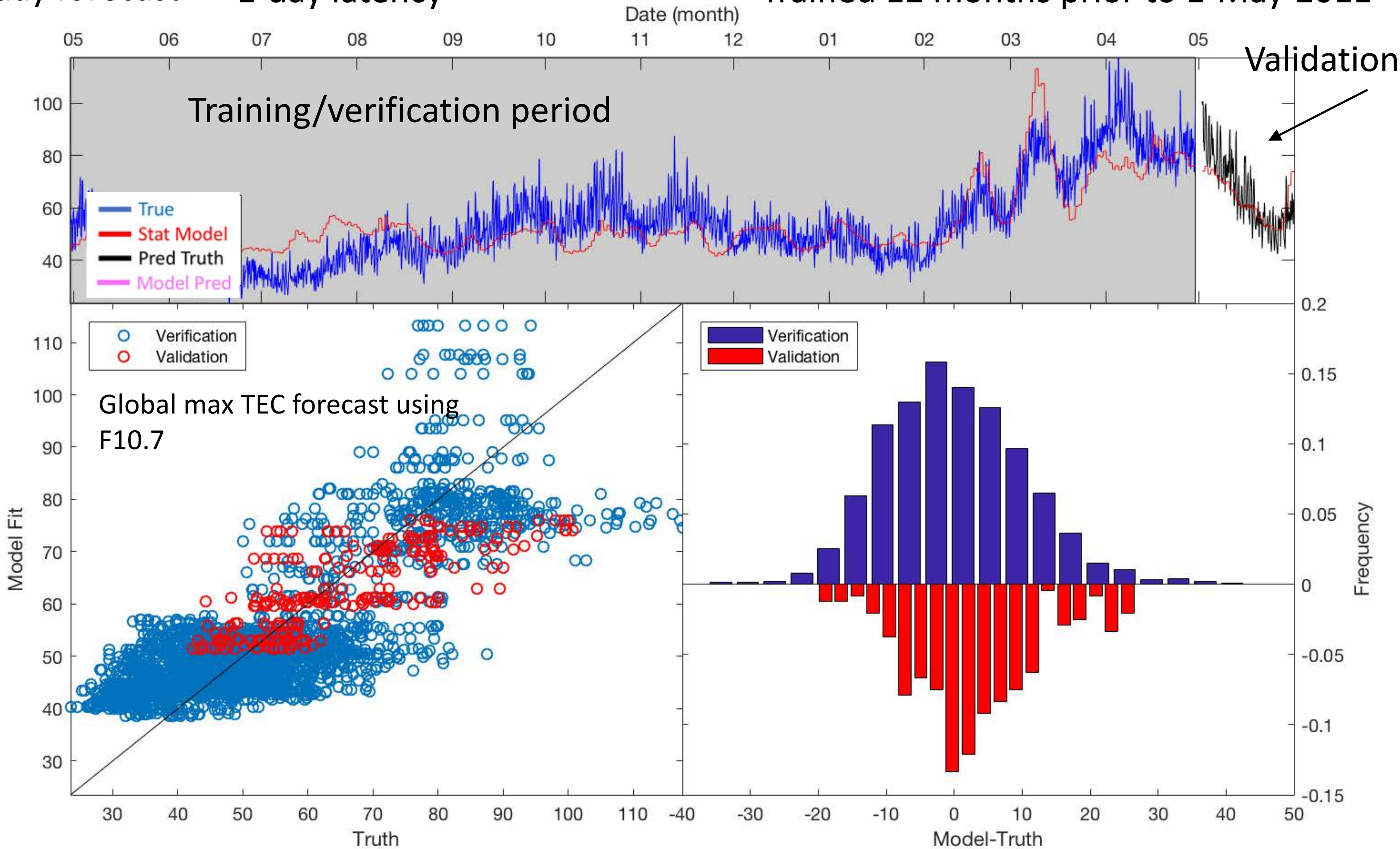
SWFT Output – Global Maximum TEC Forecast using GMaxTEC, F10.7, Solar Wind

1-day forecast   1-day latency   Trained 12 months prior to 1-May-2011



SWFT Output – Global Maximum TEC Forecast using F10.7

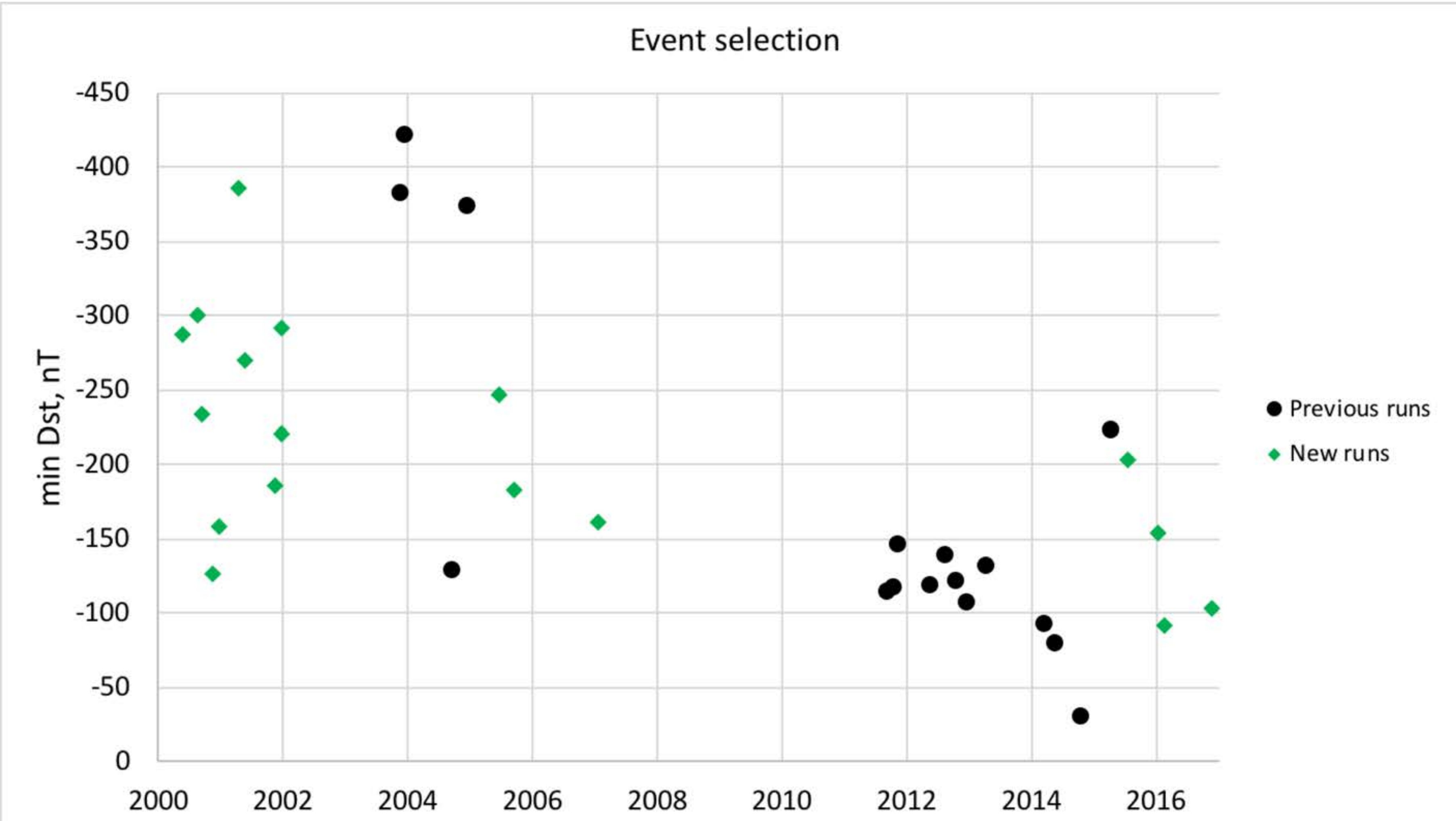
1-day forecast 1-day latency Trained 12 months prior to 1-May-2011



SWFT Future Development

- Additional statistical/machine learning models
- Addition of simulation output
- Addition of near solar data
  - Flare and CME events, solar wind structure ID
- Balancing training data
- More options including non-linear form of variables, hybrid variables
- Community involvement is critical
  - New data set preparation
  - Experiments with forecast strategies
  - Sharing experiences (wiki)

Generating Simulation Statistics



Summary

- CCMC has been a great partner in advancing our understanding of medium-range ionosphere-thermosphere storm forecasts
- Web-interface to beta version of Space Weather Forecast Testbed is implemented
- Forecast-mode runs using three IT models at CCMC
  - GITM, TIEGCM, CTIPe
- Continuing work on ionosphere-thermosphere forecast algorithms
  - Implementation into SWFT
- Goal: SWFT improves the community's understanding of Heliophysics simulations
- Look forward to SWFT growing organically and being of interest to a broad community
  - Physics-based community (IT and others…)
  - Statistical/machine learning community

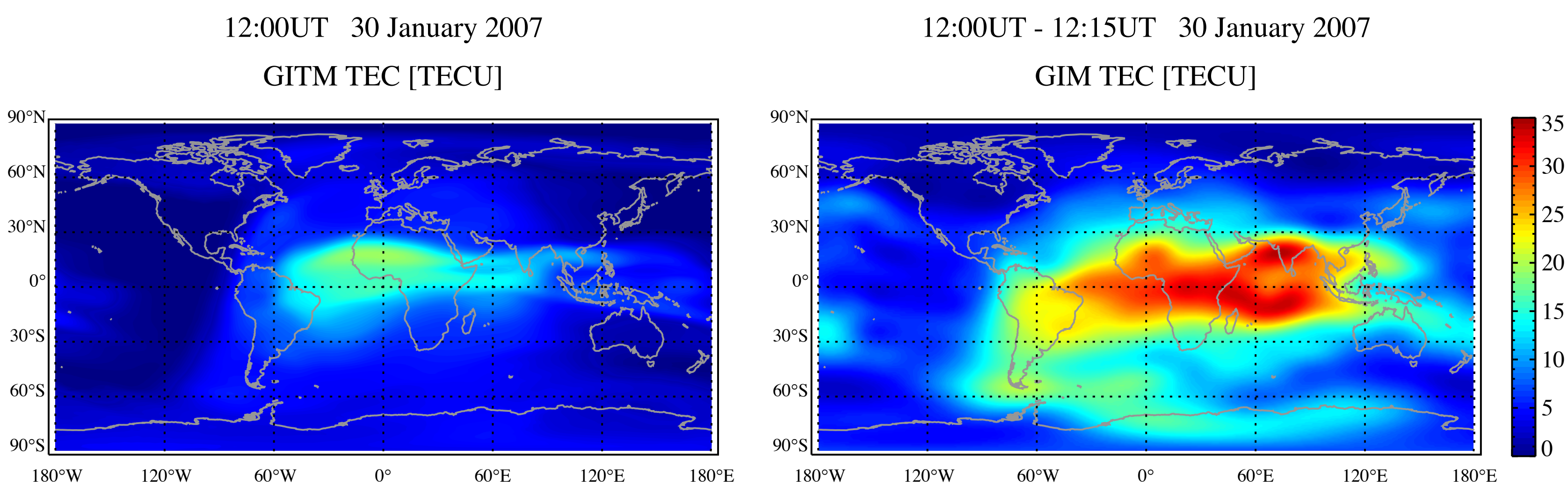
BACKUP

Ionosphere "Storm" Forecasts

- **Based on Global Ionosphere-Thermosphere Model (GITM) [Ridley et al. 2006]**
- **"Forecast mode": inputs are F10.7, solar wind from OMNI data or ENLIL, CORHEL, SWMF predictions for the heliosphere, driving Weimer 2005 ionospheric electrodynamics**
- **Alternative high latitude driving: SWMF magnetosphere and ionospheric electrodynamics**
- **Data product: Global Ionospheric Maps (GIM) [Mannucci et al. 1998] based on GPS-derived TEC data.**

GITM: hourly TEC maps

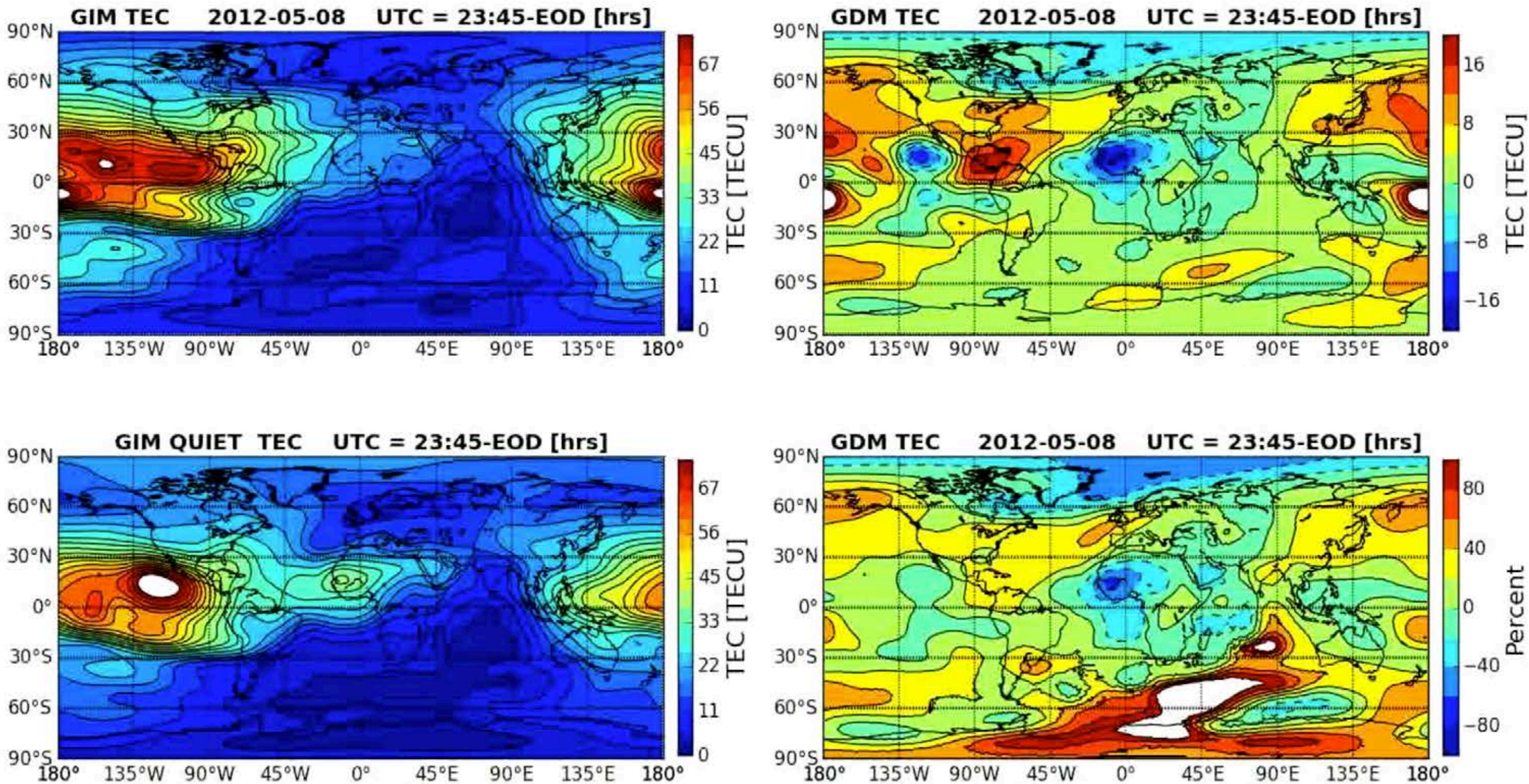
GIM: averaged TEC for the first 15 minutes of every hour



TEC maps from OMNI-driven **GITM** and **GIM** for the January High Speed Stream 2007 storm

GITM "TEC" is integrated electron density between 100 km – 600 km altitudes.

Developing Forecast Variables



Forecast Variables Definition

- **Step 1: Divide the globe into grid boxes of size 30° (longitude) x 15° (latitude)**
- **Step 2: Compute the mean TEC within each grid**
- **Step 3: For each day, define and calculate the TEC perturbation as**

GIM TEC Metric

$$dTEC_{GIM}(UT, lon, lat) = \frac{TEC_{GIM}(UT, lon, lat) - TEC_{GIM,quiet}(UT, lon, lat)}{\sigma_{TEC,GIM,quiet}(UT, lon, lat)}$$

GITM TEC Metric

$$dTEC_{GITM}(UT, lon, lat) = \frac{TEC_{GITM}(UT, lon, lat) - TEC_{GITM,quiet}(UT, lon, lat)}{\sigma_{TEC,GIM,quiet}(UT, lon, lat)} * Scale(UT)$$

where $$Scale(UT) = \frac{median(TEC_{GIM,quiet}(UT, *, *))}{median(TEC_{GITM,quiet}(UT, *, *))}$$

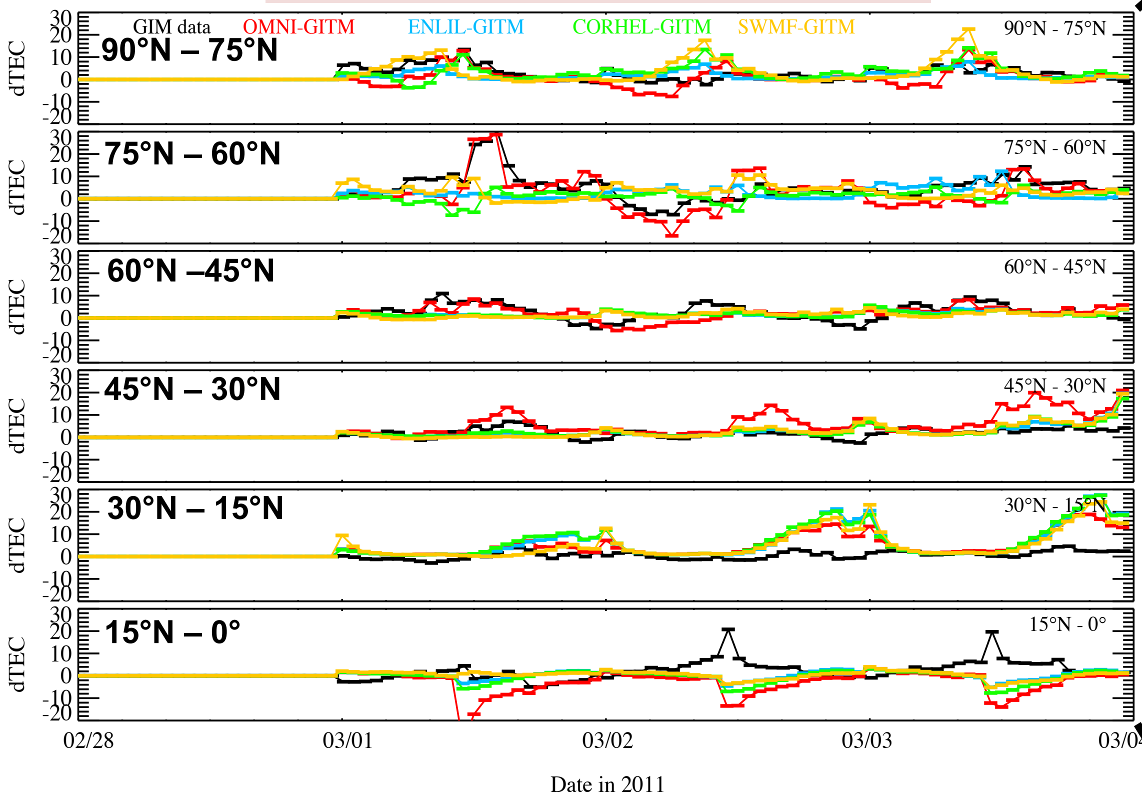
- **The quiet day is selected from the days before each storm event with daily Ap < 6**
- **Final output: hourly *dTEC* for every 30° x 15° grid box**
- **May require modification for CMEs (superstorms)**

Initial forecasts will be for integrated density between 100-600 km

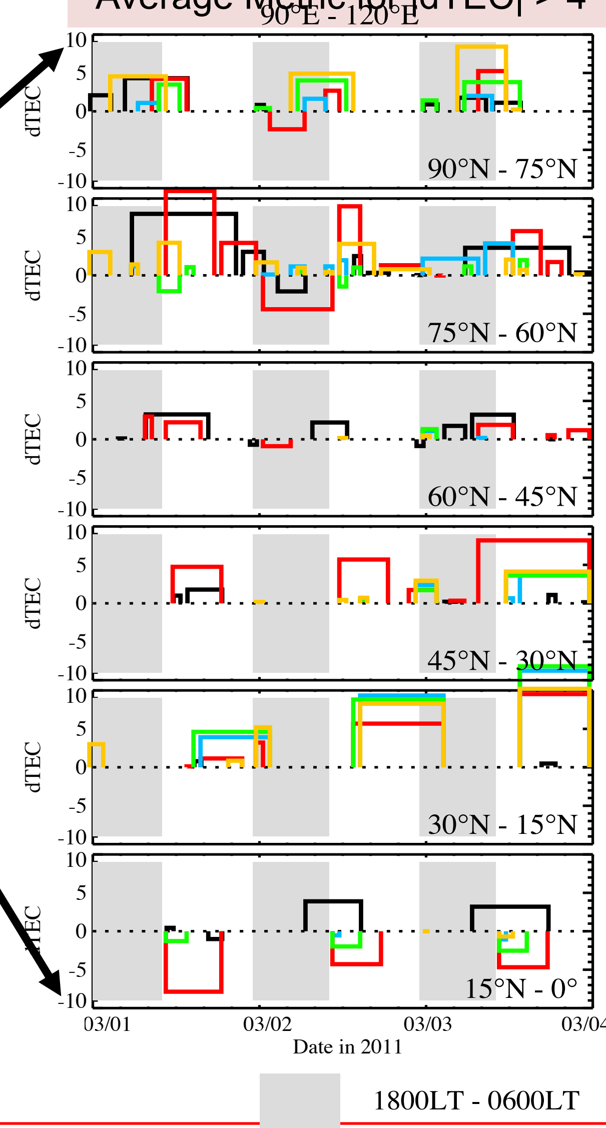
Forecast Variables Example

OMNI-GITM
ENLIL-GITM
CORHEL-GITM
SWMF-GITM

TEC Metric for the **Feb 2011** Event
Longitude **90°E - 120°E**



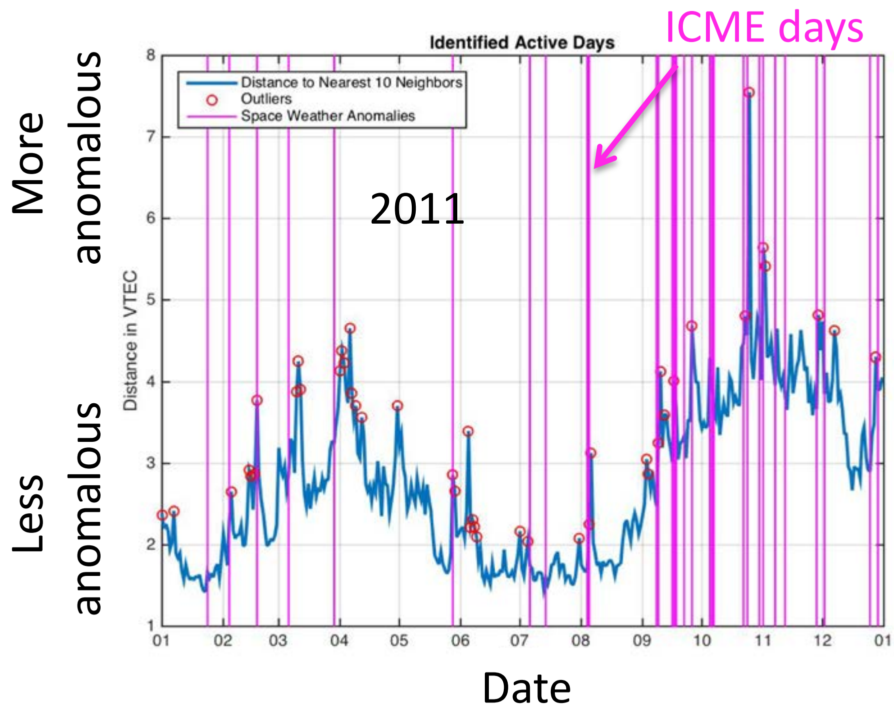
Average Metric for |dTEC| > 4



Average Metric: indicates for how long and by how much |dTEC| exceeds a certain level.

Objective Analysis of "Ionospheric Anomalies"

- **Cluster analysis of TEC maps identifies anomalies independently of geomagnetic conditions**
- **Bounds what can be achieved by solar wind driven forecasting**



Wang, C., I. G. Rosen, B. T. Tsurutani, O. P. Verkhoglyadova, X. Meng, and A. J. Mannucci (2016), Statistical characterization of ionosphere anomalies and their relationship to space weather events, *J. Space Weather Space Clim.*, *6*, A5–16, doi:10.1051/swsc/2015046.

CCMC Implementation

- **Establish baseline modeling chain**
  - **Path towards real-time implementation**
  - **Variants to baseline could be implemented to produce multiple forecasts per event**
- **Historical forecast runs**
  - **EEGGL+AWSOM, Ansatz+ENLIL and OMNI (data) for CMEs**
  - **ENLIL, CORHEL, SWMF and OMNI (data) for HSS**
- **Community accessible TEC forecast variables and assessment data**
- **Updated as new events occur**

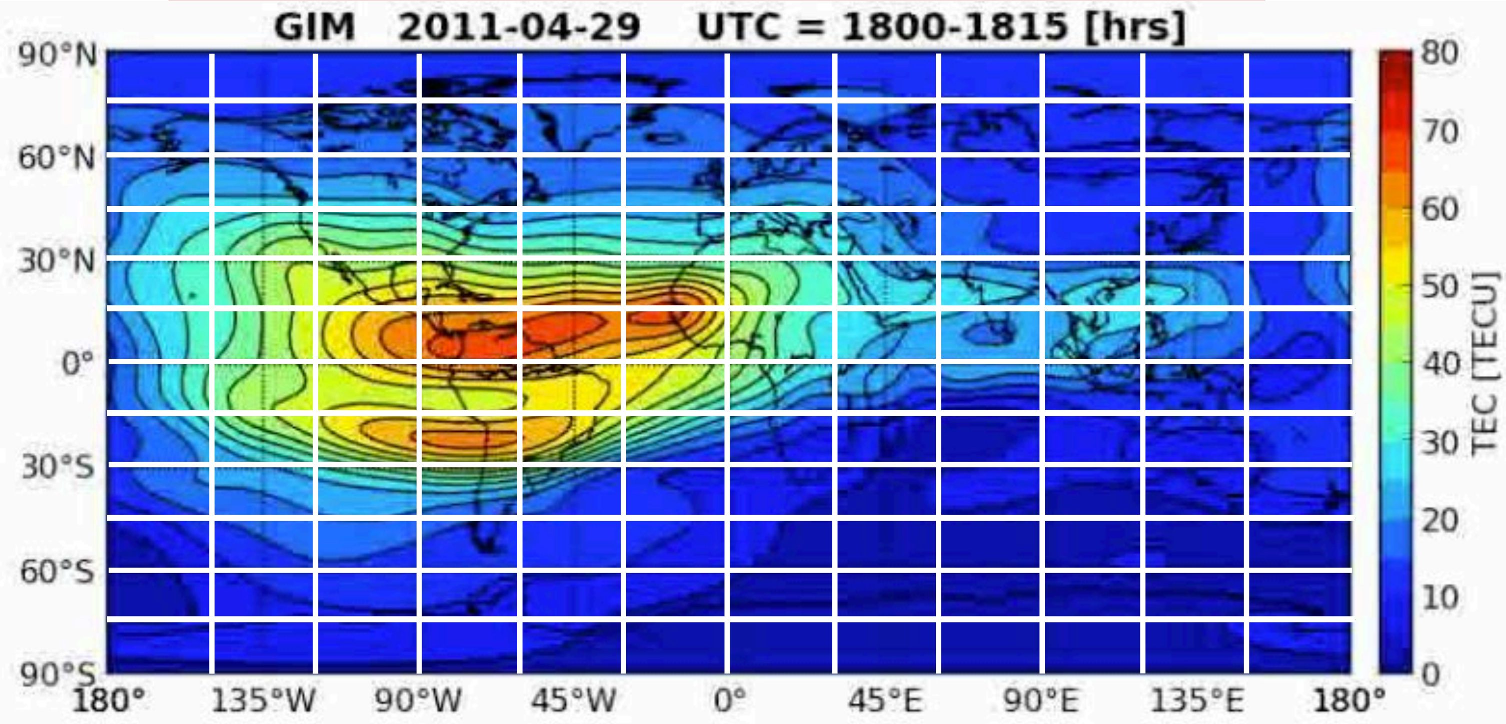
We will deliver forecast variables and related algorithms to facilitate such a capability at CCMC

Acknowledgement: CCMC provided solar wind model runs (ENLIL, CORHEL, SWMF, ENLIL+Cone) and TIEGCM runs
See http://ccmc.gsfc.nasa.gov/community/LWS/lws_medrangestorms.php

Data-Driven Methods

Initial Approach: Focus on Total Electron Content over a Coarse Grid

A typical Global Ionospheric Map (GIM) TEC
"Data Product"



Step 1: Divide the globe into longitude-latitude grids of size 15° x 30° lat/lon

Step 2: Develop time series of TEC metrics in each grid cell. Observations vs model

- ***Reduces the number of "predictions" from ~1x10^5 (3D model) to 144 (coarse TEC grid) at each time step (e.g. hourly)***
- ***Remains complex, but is more manageable***