Science Highlight #6
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Medium Range Thermosphere-Ionosphere Storm Forecasts

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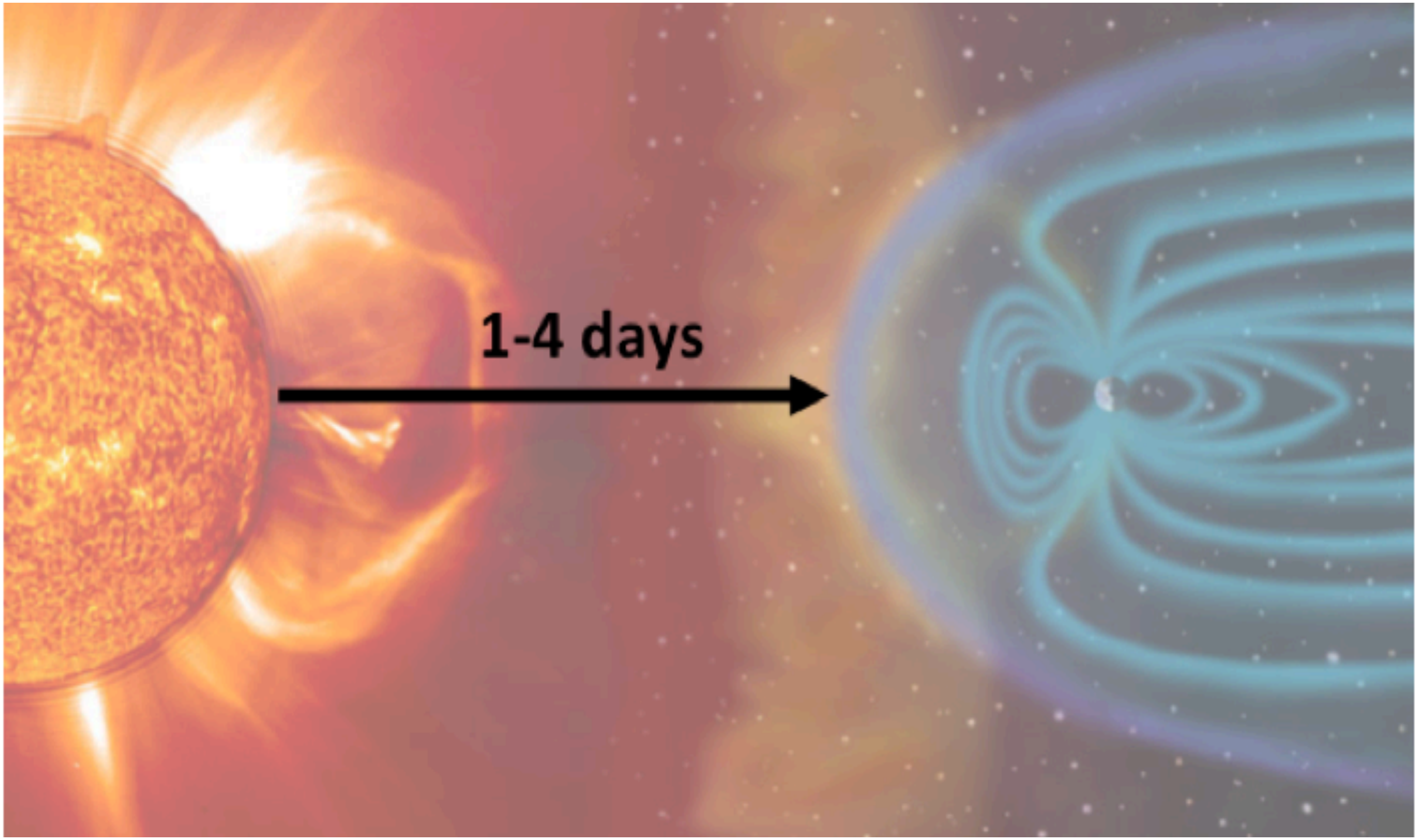
Collaborators:
Angelos Vourlidas, William Lotko, …

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

Objective

- ***“An orientation towards forecasting research is valuable to our scientific efforts”***

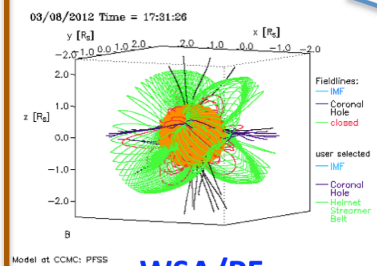
A medium-range forecast is a forecast of about 3 days lead time

IT = Ionosphere-Thermosphere

Explore "Sun to Mud" Forecasts

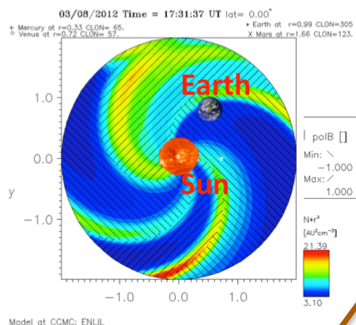
- Center for Integrated Space Weather Modeling (2000's), LWS TR&T, NSF, MURI, etc.
- NASA/NSF Partnership for Collaborative Space Weather Modeling (2013-)

Solar Corona



WSA/PF

Heliosphere



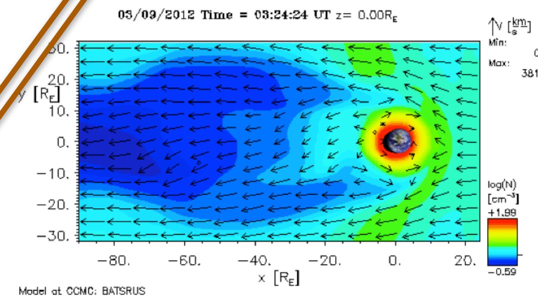
ENLIL

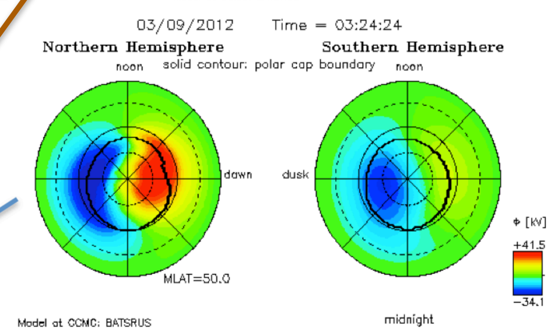
Current solar wind collaborators:
CSEM (U Michigan)
CCMC

Operational

Magnetosphere

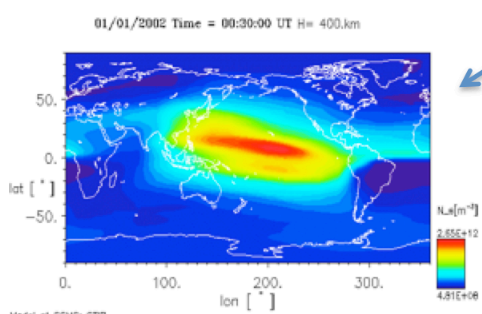
Our focus





High latitude convection pattern

Global thermosphere-ionosphere storm



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

The Role of IMF B_y in Large Geomagnetic Storms

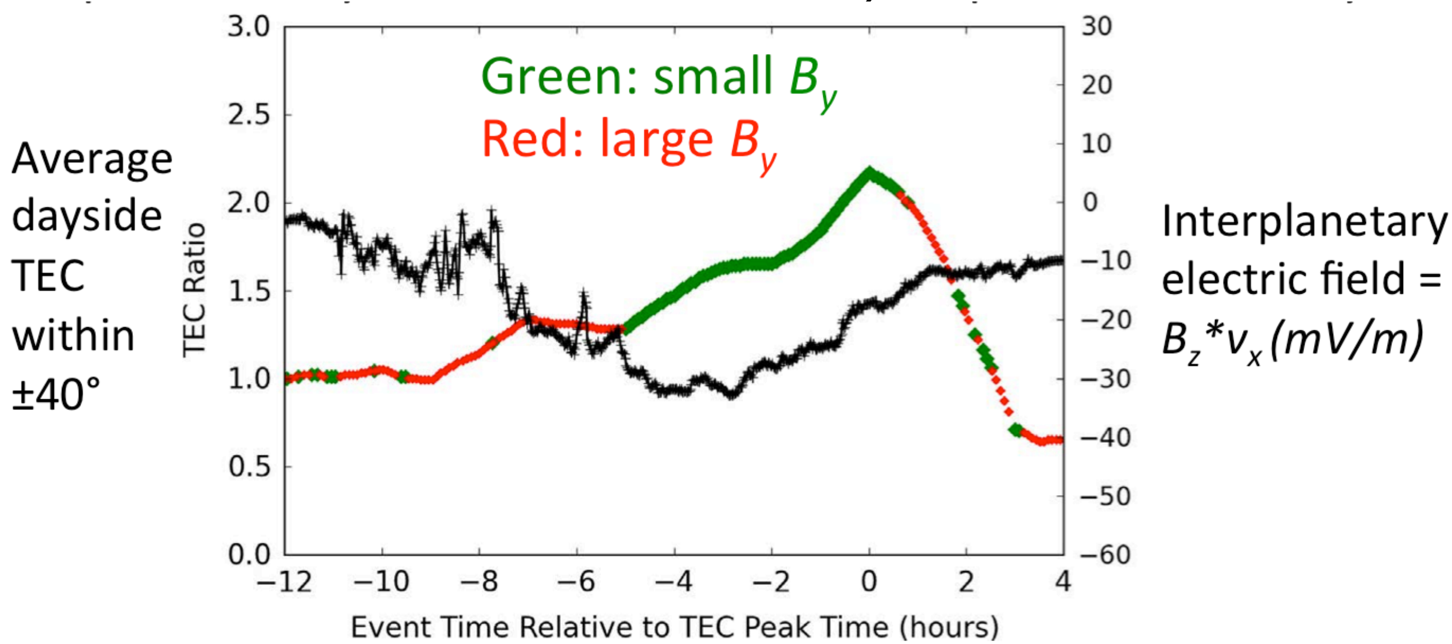
Study 8 superstorms spanning 2000-2004

Prompt penetration electric field ->

global dayside TEC response ->

response delayed for the 20 Nov 2003 superstorm -> Why?

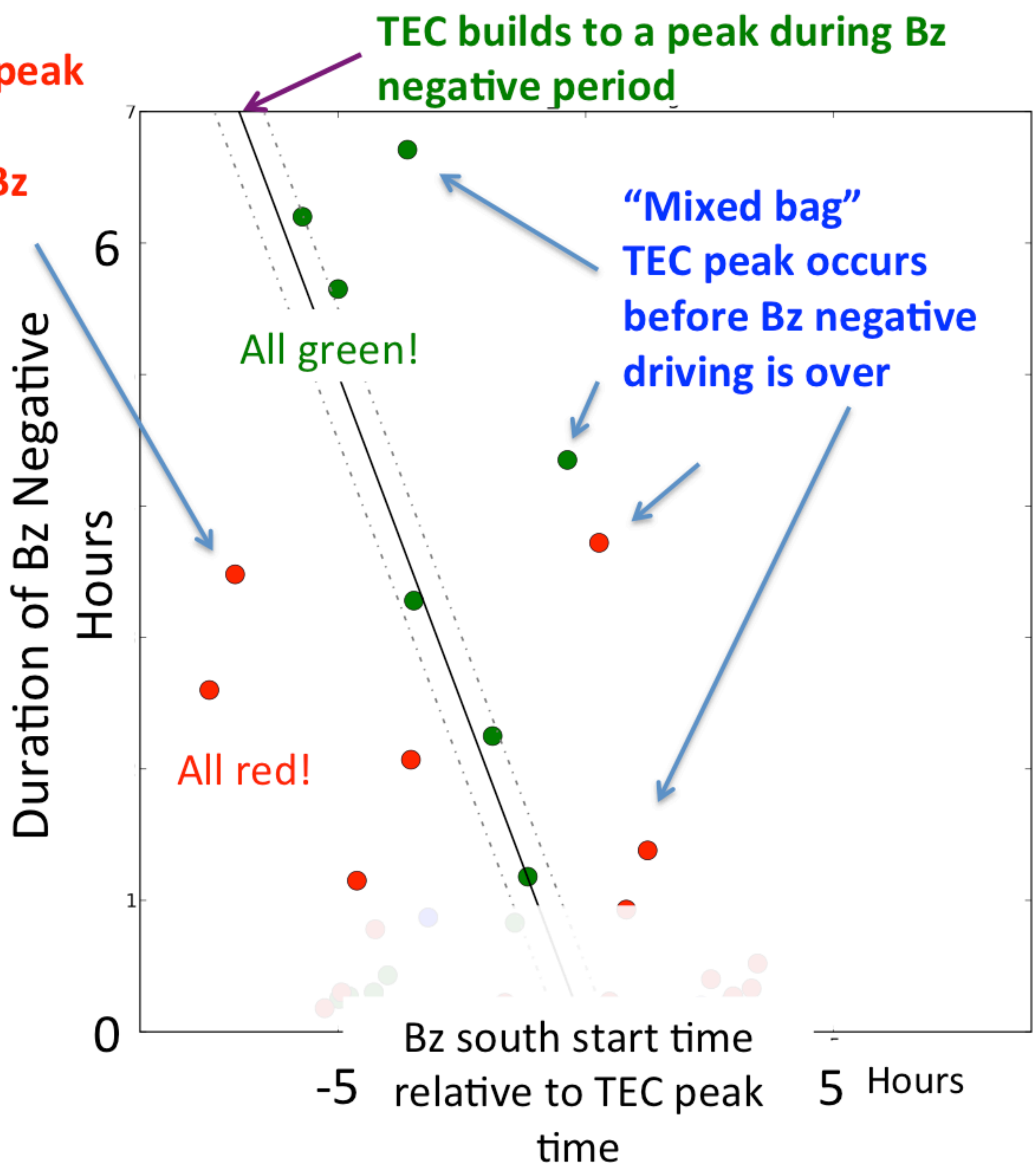
Answer: IMF B_y ?



Mannucci et al., 2014, doi:10.1016/j.jastp.2014.01.001

Analyzed 8 largest superstorms spanning 2000-2004

The TEC peak occurs outside Bz negative period



Each circle represents a prolonged large B_z negative period

Green: By/Bz < 0.7

Red: By/Bz > 0.7

“Events” based on Bz < -10nT
One TEC peak time/storm

Time resolution ~30 minutes

What Should We Forecast?

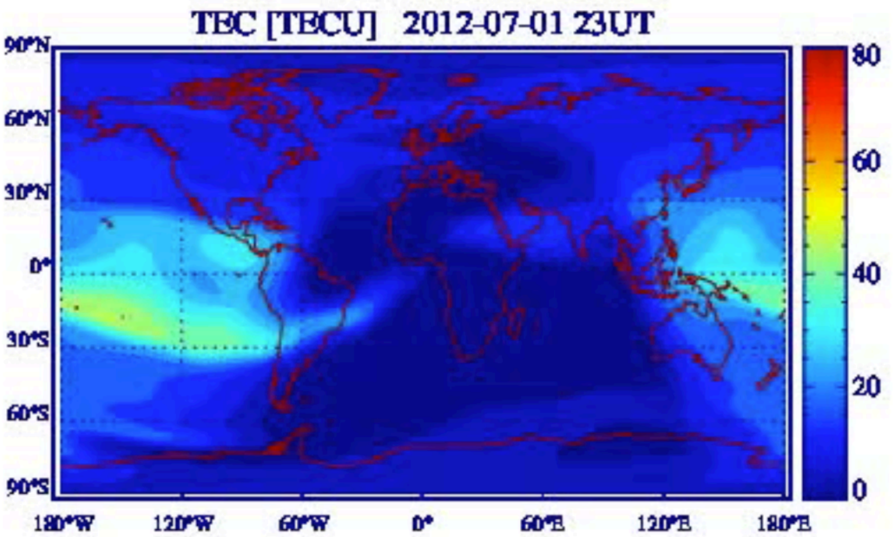
- Philosophy: Walk Before You Run
- A forecast is the output of a model stepped forward in time
- Drive the model with a solar wind forecast
- The model produces lots of output
- Extract 2D TEC maps from the model – simplify
- TEC: lots of validation data

Global Ionosphere Thermosphere Model (GITM) Output

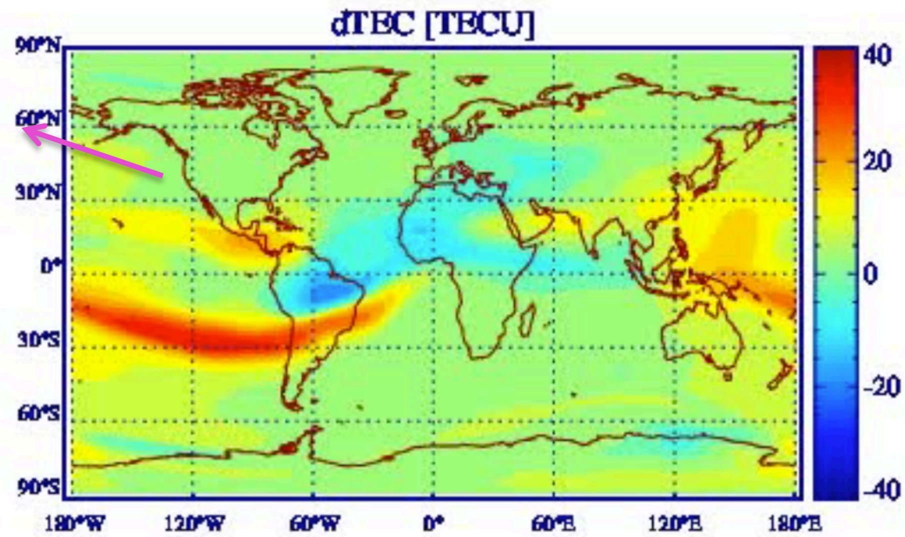
Ridley et al., 2006 doi:10.1016/j.jastp.2006.01.008

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

TEC Map From a GITM Run



TEC "Difference" Map vs Quiet

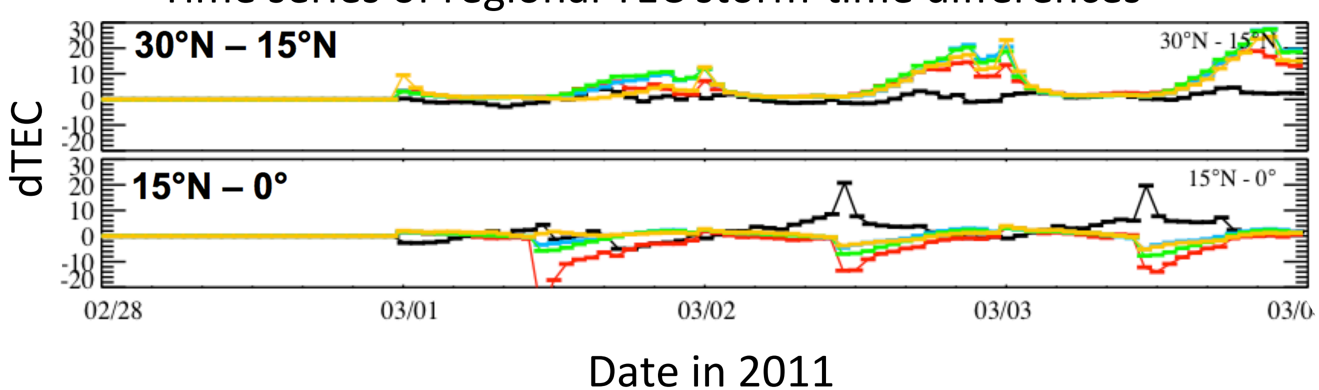


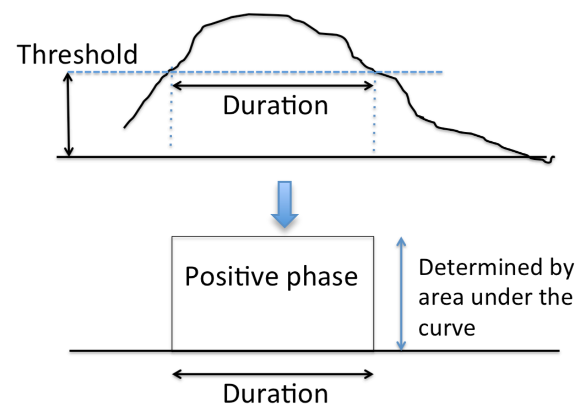
- "Forecast mode" runs (CTIPe, TIEGCM, GITM) have been defined and started at CCMC: all model inputs driven by solar wind variables and F10.7 forecasts (short-term and 81-day)

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**

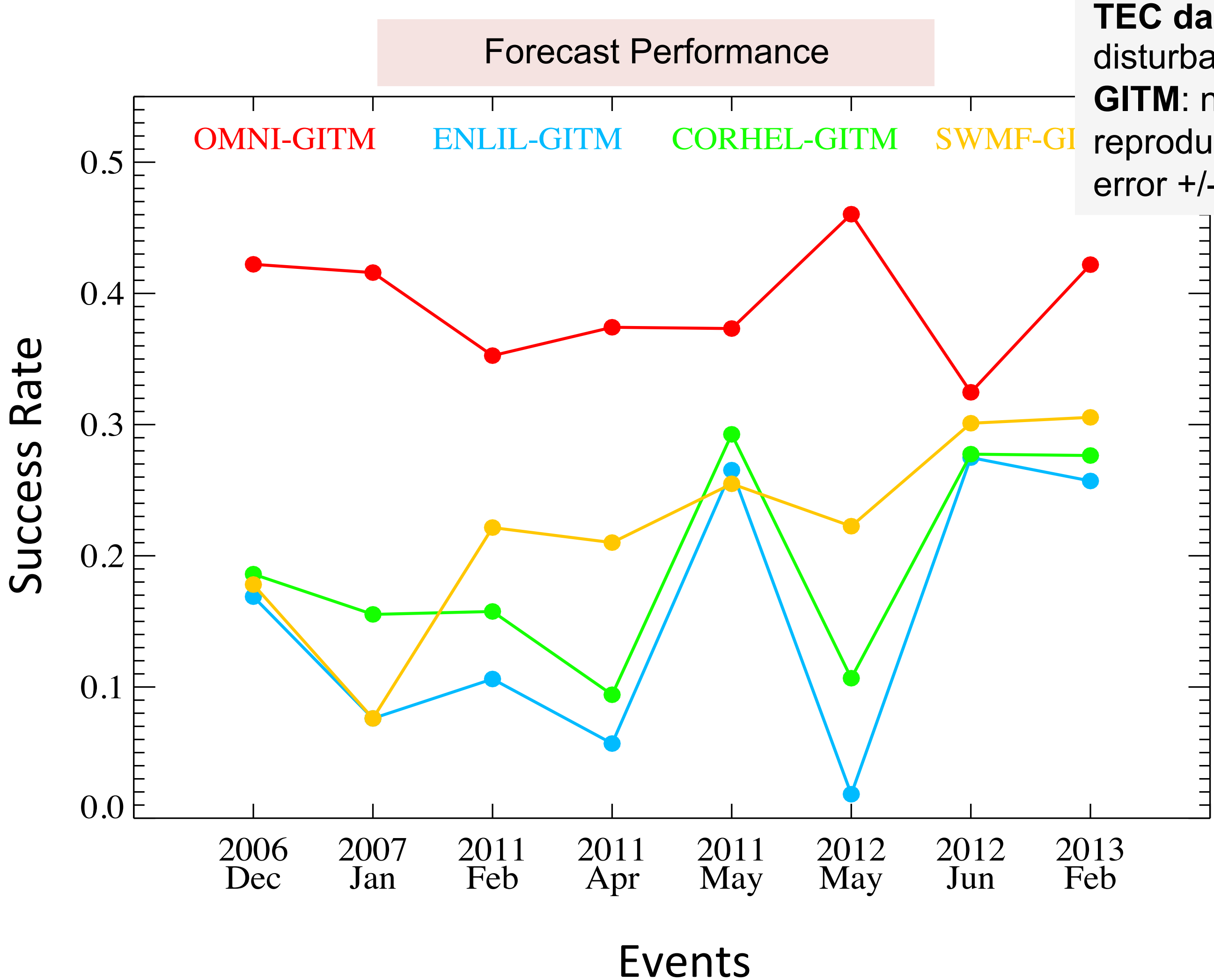
Time series of regional TEC storm-time differences





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

Solar Wind Driven "Forecasts"

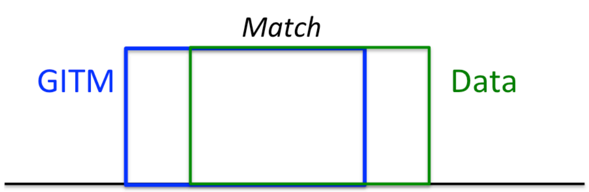


TEC data (GIM): number of all TEC disturbances with |dTEC| > 4
GITM: number of GIM TEC disturbances reproduced by the simulations, with time error +/- 3 hours at most

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.



What is the Scientific Value of Forecasting Research?

Why Forecast?

Contingency Table

Model Output

Observation

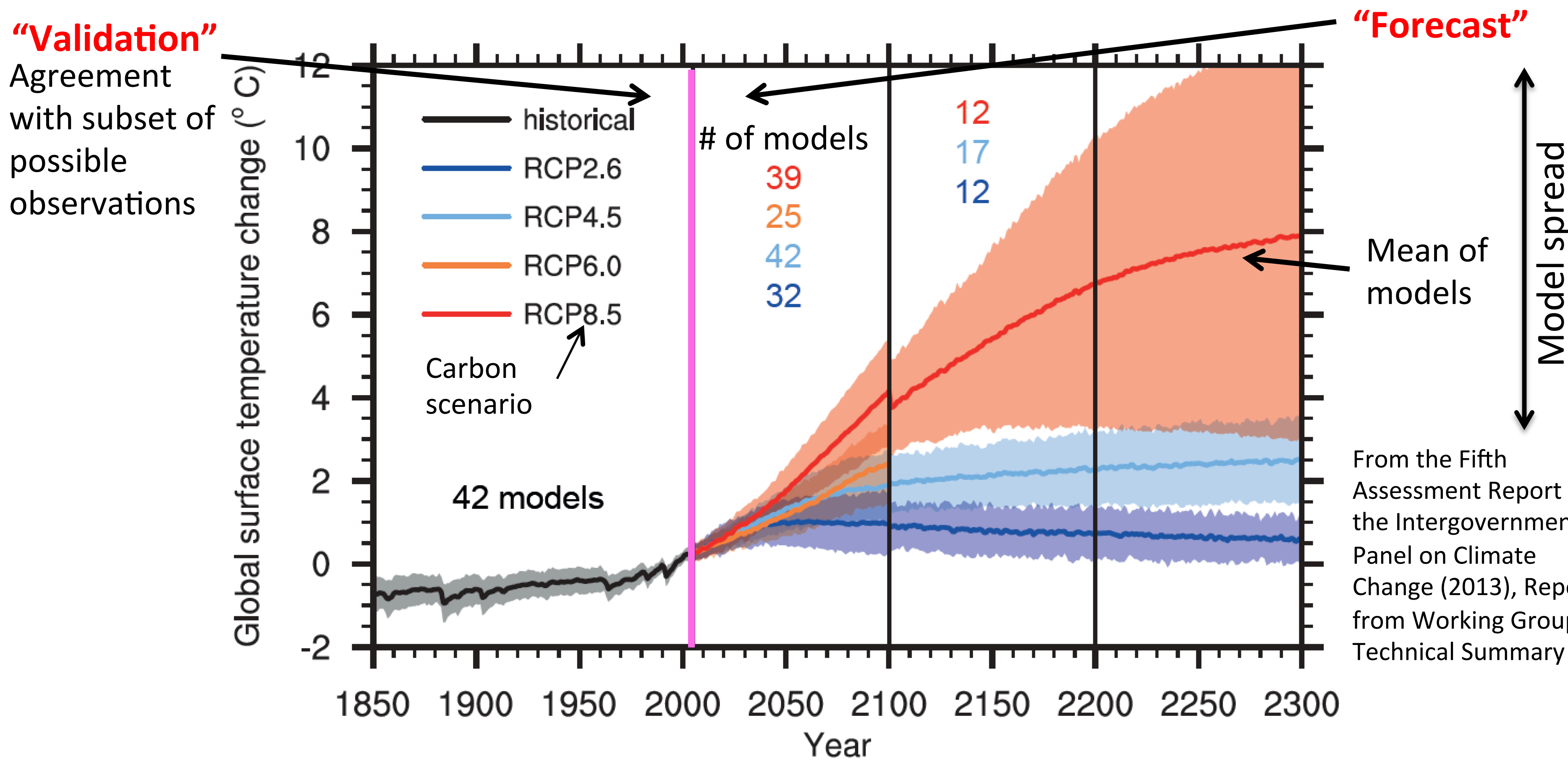
	Feature is reproduced in the model	**Feature is not reproduced by model**
Feature is observed	Many publications Validation	Fewer publications
Feature is not observed	Fewer publications	Validation

A *forecasting research* orientation will increase the number of publications in these quadrants

Reference: H. Rishbeth, "Ionoquakes: Earthquake Precursors in the Ionosphere?" EOS 87(32), 2006

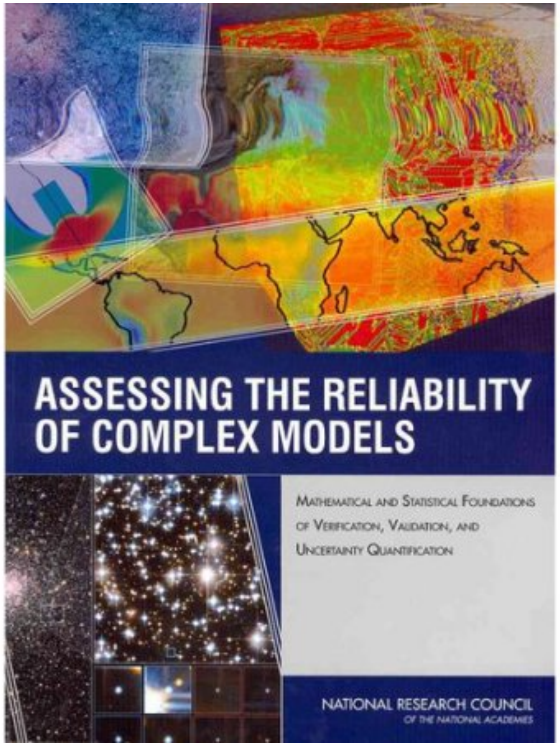
Cautionary Tale: Climate Modeling

Output **(global surface temperature)** from 42 climate models for different carbon scenarios
Inter-model agreement with the past is much closer than inter-model spread projected into the future



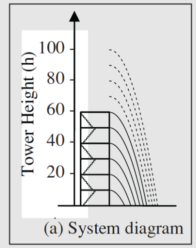
From the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2013), Report from Working Group I, Technical Summary

Forecasting: A Stringent Test of our Scientific Understanding



NRC, 2012

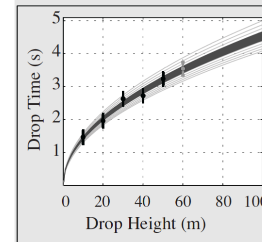
Dropping ball problem – NRC's prototype



(a) System diagram

Box 1.1
Dropping a Bowling Ball from a Tower

The time that it takes for a bowling ball to fall from a tower 100 meters (m) high will be predicted by using experimental drop times obtained from a 60-m tower (Figure 1.1.1(a)). Drop times are recorded for heights of 10, 20, . . . , 50 m, and a validation experiment of dropping a ball from 60 m is also conducted. The uncertainty in the measured drop times is normally distributed about the true time with a standard deviation of 0.1 seconds (s). The quantity of interest (QOI) is the drop time for the bowling ball at a height of 100 m. Since the tower is only 60 m high, a computational model



(b) Ball drop time by height

$$\frac{d^2x}{dt^2} = g$$

Physical law does not determine a unique trajectory

$$x = x_{Fit} + \dot{x}_{Fit}t + \frac{1}{2}gt^2$$

Best agreement between model and observations occurs if I have all the observations in advance

$$x = x_{OBS} + \dot{x}_{OBS}t + \frac{1}{2}gt^2$$

More difficult to obtain agreement with observed constants of integration

"Strategic Capability"

- **What is our "deliverable"?**

Space Weather Forecast Testbed

- Our deliverable to CCMC for community use
- System for exploring forecasting scenarios using observations and first-principle model output
- Currently contains 10+ years of TEC maps, derived TEC properties, solar wind variables, solar proxies, geomagnetic indices, etc. at 3-hour cadence
- Data mining algorithm: multi-variable regression
- Rigorously separates training data sets from test data sets, and does so continuously in time, user selectable
- Helps the community understand the forecasting implications of our research and scientific understanding

Multi-Linear Regression

- Regression consists of finding optimal coefficiets for a linear model of the form

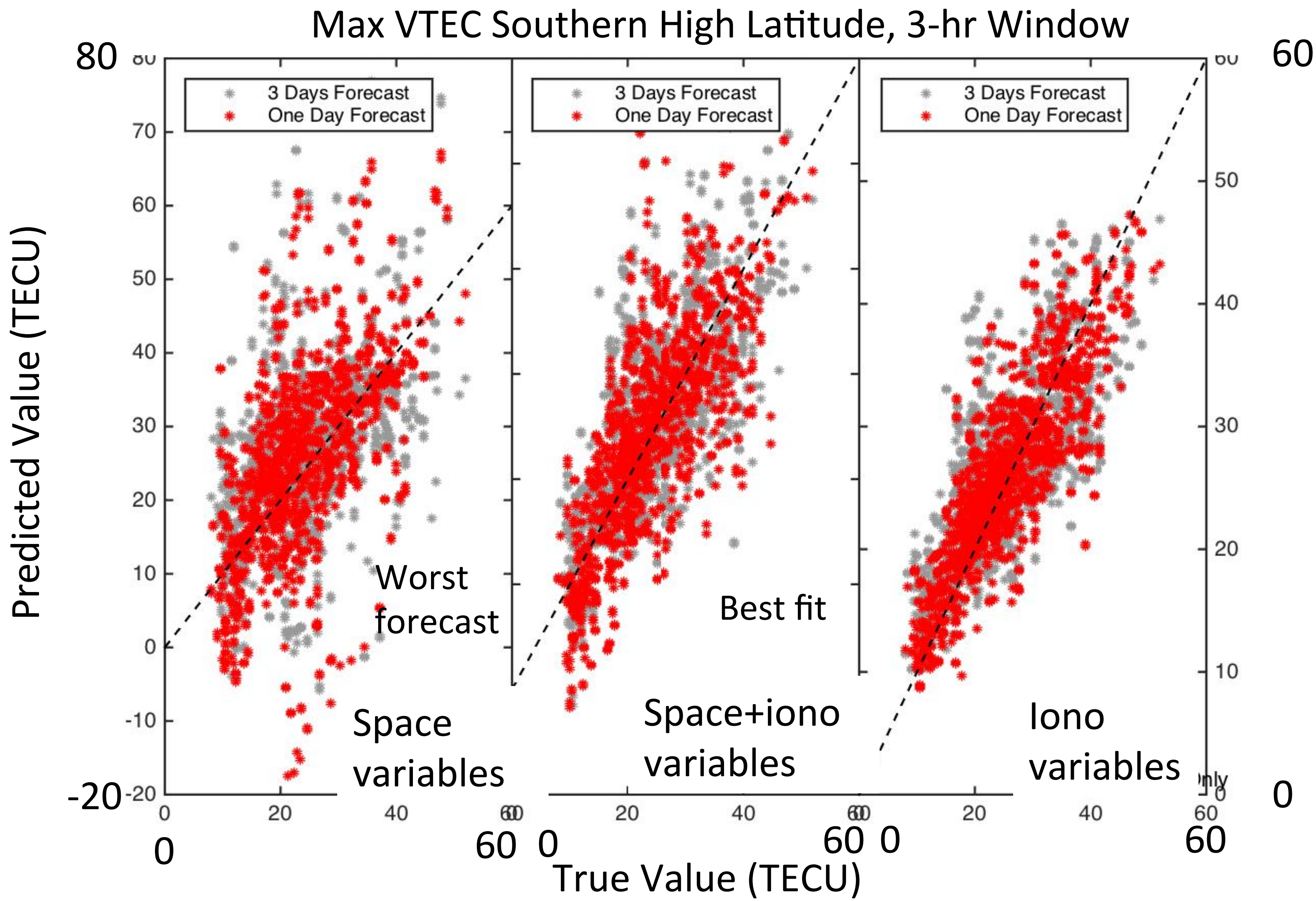
$$v_X(t) = T\begin{pmatrix} \vec{u}(t-d) \\ \vdots \\ \vec{u}(t-d-m) \end{pmatrix}, \vec{u}(t) = \begin{pmatrix} v_X(t) \\ \vdots \\ B_X(t) \\ \vdots \\ n_{SunSPot}(t) \end{pmatrix}.$$

- Optimization for T consists of solving the least square minimization problem using historic data

$$\min_T \sum_{k=1}^{N} \left| v_X(k) - T\begin{pmatrix} \vec{u}(k-d) \\ \vdots \\ \vec{u}(k-d-m) \end{pmatrix} \right|^2 .$$

- "Fitting" step: generate regression coefficients and covariances
- "Forecast" step: evaluate the linear model using data not used in the fitting step

Example: TEC Forecast (data only)



Exploration Using SWFT

- **Relative forecast improvement of storm-time TEC using:**
  - **Solar wind variables such as interplanetary electric field**
  - **Solar EUV variables**

- **Forecast TEC variables based on models**
  - **First-principles ionosphere**
  - **First-principles coupled thermosphere-ionosphere**
  - **IRI**

- **Forecast High latitude indices and derived products**

Wanted: the output of first-principle model runs

Items I Could Not Cover

- Science result: “coherent” wave-particle interactions
- Science result: supersubstorms (AE > 2500 nT) occurring during geomagnetic quiet
- Solar wind work EEGGL and ADAPT
- Objective identification of ionospheric “anomalies” – understanding seasonal patterns
- AE index forecasts based on dynamical systems theory

Summary

- **Solar wind-ionosphere coupling via prompt penetration electric fields – the role of B_y**
- **Forecast simplified quantities, not a full TEC map**
- ***Forecasting research advances scientific understanding***
- **A new tool is coming to the community: Space Weather Forecast Testbed**
  - **Exploring forecast capabilities of data-driven and first-principles models**
- **Timing of when the CME hits the magnetosphere is critical (3-4 hours)**
  - **Approaches are under active development**
- **Happy coincidence: the faster the CME, the lower the uncertainty in arrival time**