NASA–NSF Space Weather Modeling Collaborations
Kick-off Meeting May 1, 2013

Medium Range Thermosphere-Ionosphere Storm Forecasts

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Acknowledgement to:
The community of scientists/model developers and program managers who made this possible…

Take-Away Messages

- Now is the time to start T-I forecasts
- Forecasts require specialized mathematical techniques that work in concert with physics based modeling
- Forecasting will lead to scientific advances
- Forecasting requires a community effort

What's in a name?

World Meteorological Organization Designations

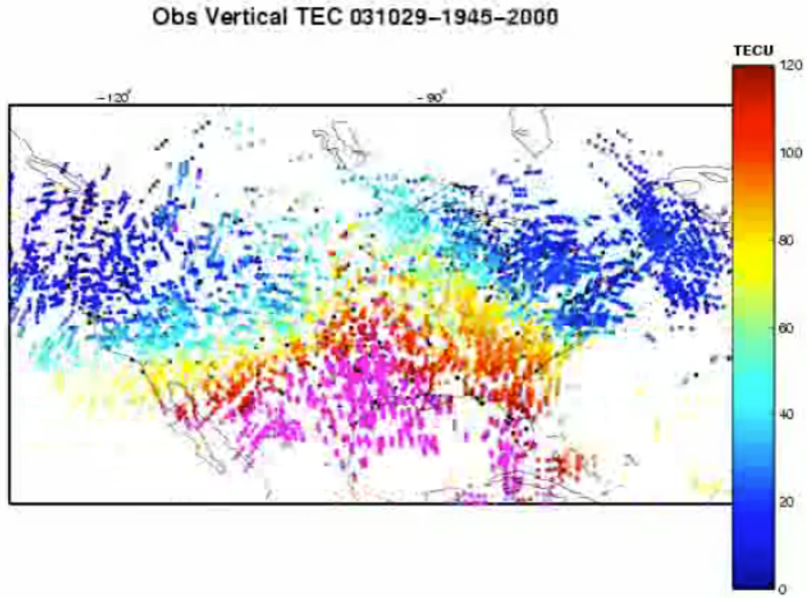
Short-range: ½ – 3 days
Medium-range: 3-10 days
Extended-range: 10-30 days

Overview

- What is a thermosphere-ionosphere storm?
- Why the interest in forecasting space weather?
- Solar wind as the cause of T-I storms
- The forecasting challenge
- Goals
- Summary

Ionospheric Storm: October 29, 2003

October 29, 2013
1945 UT



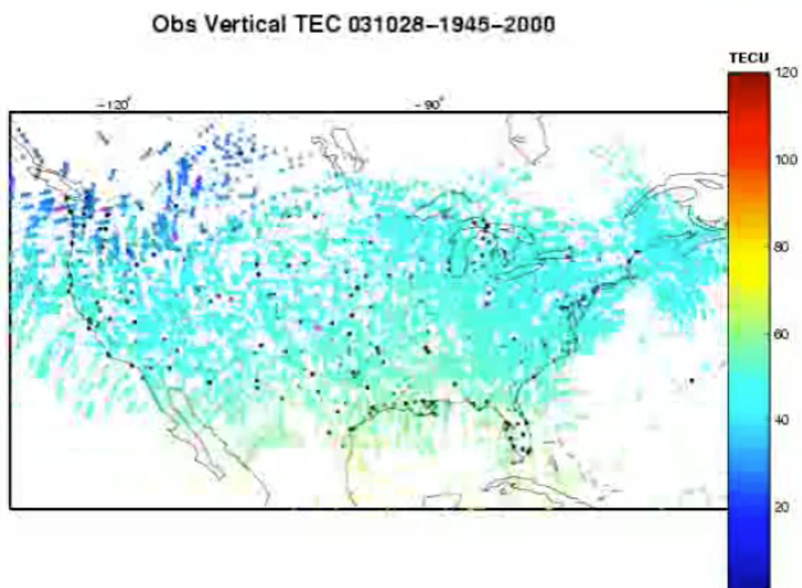
120 TECU

Purple > 120 TECU

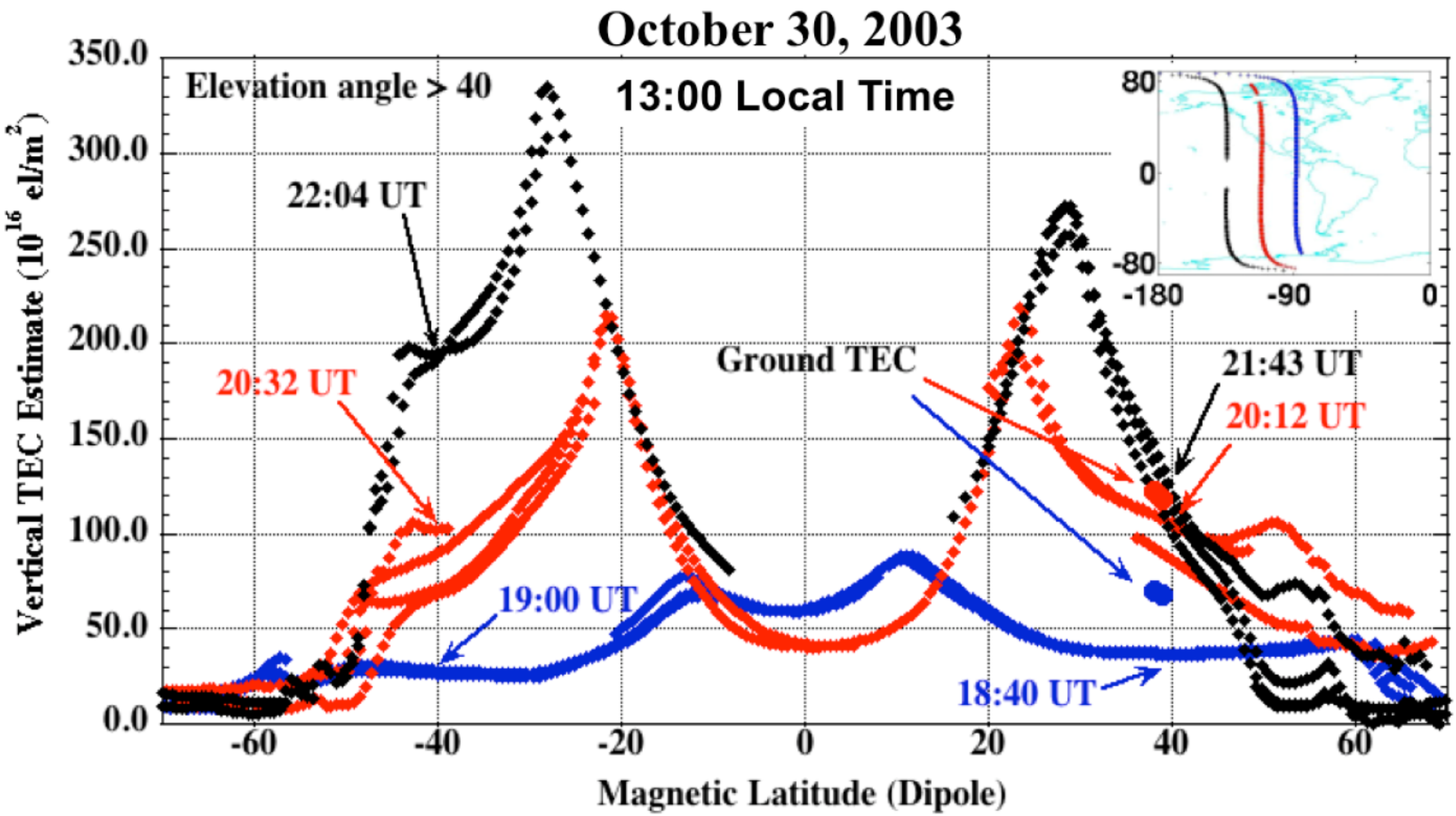
Measurements of ionospheric total electron content over the US using GPS technology

0 TECU

October 28, 2013
1945 UT



Global Perturbations



CHAMP altitude: 400 km

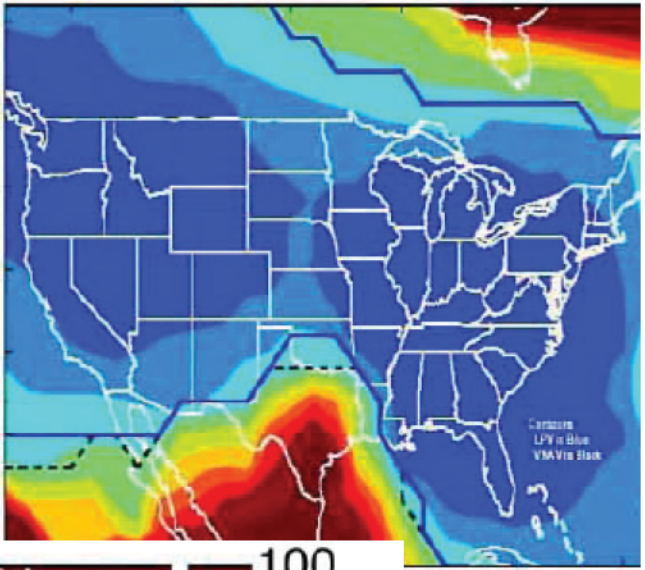
Mannucci et al., "Dayside global ionospheric response …" *GRL* 2005

Availability of Aircraft Navigation

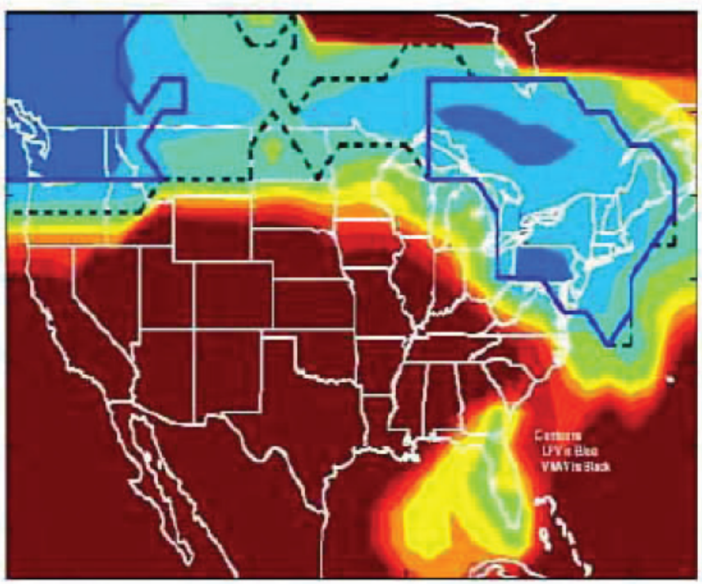
Source: FAA provided materials in "Severe Space Weather Events Understanding Societal and Economic Impacts: A Workshop Report", National Research Council 2009

October 29, 2003

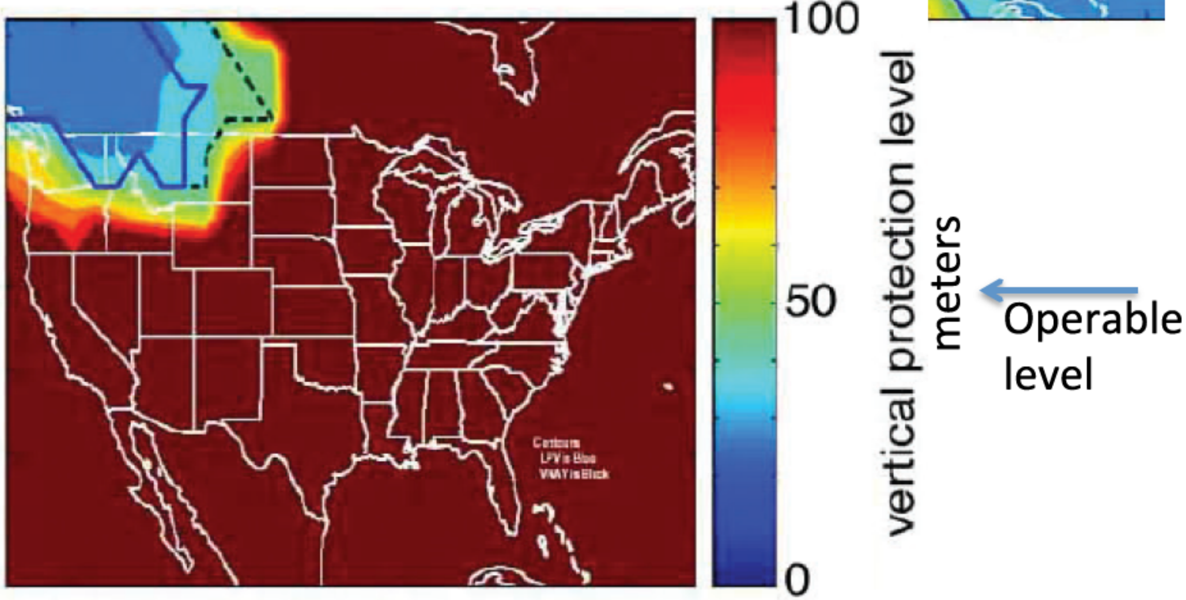
16:44 UT



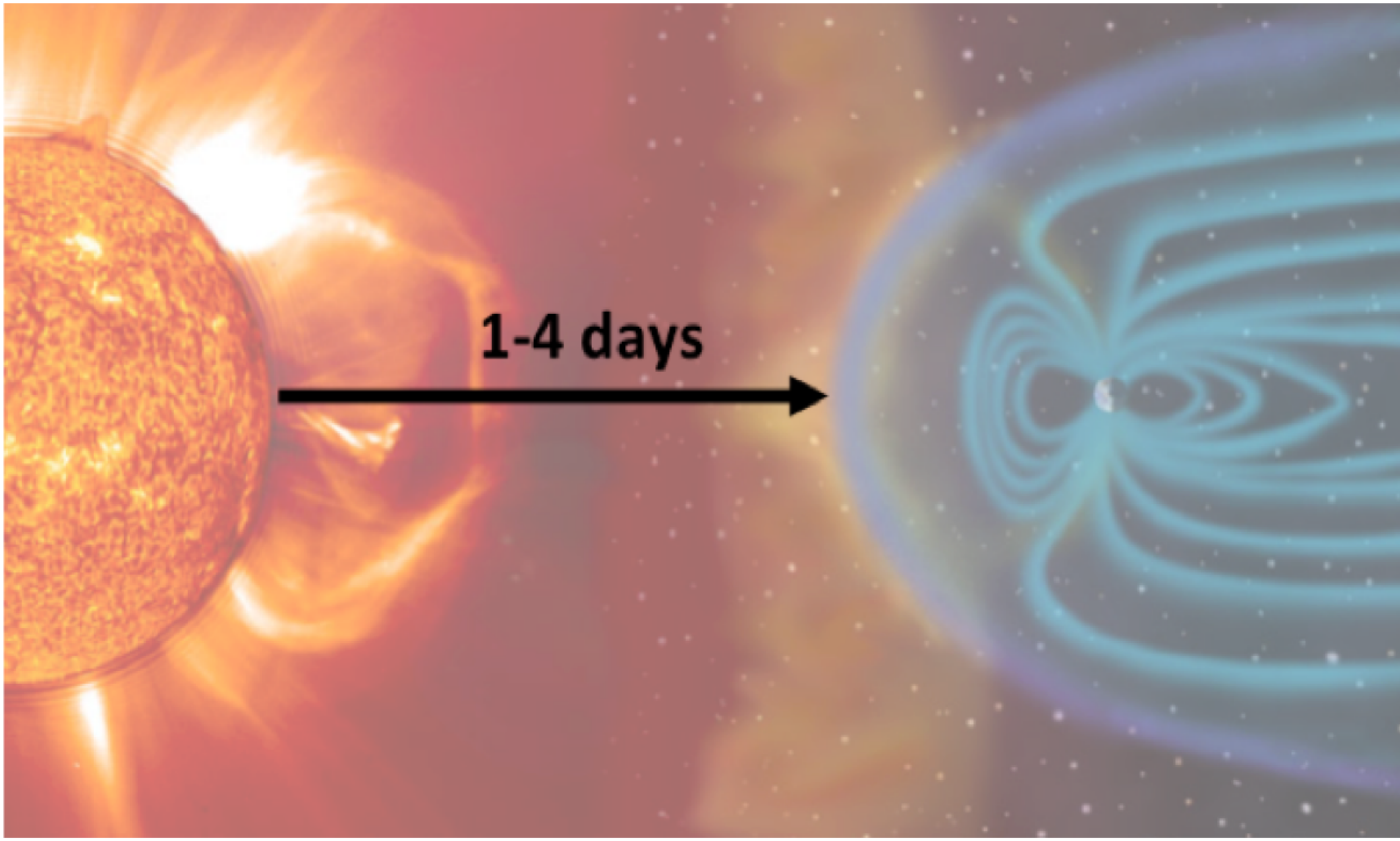
17:48 UT



19:06 UT

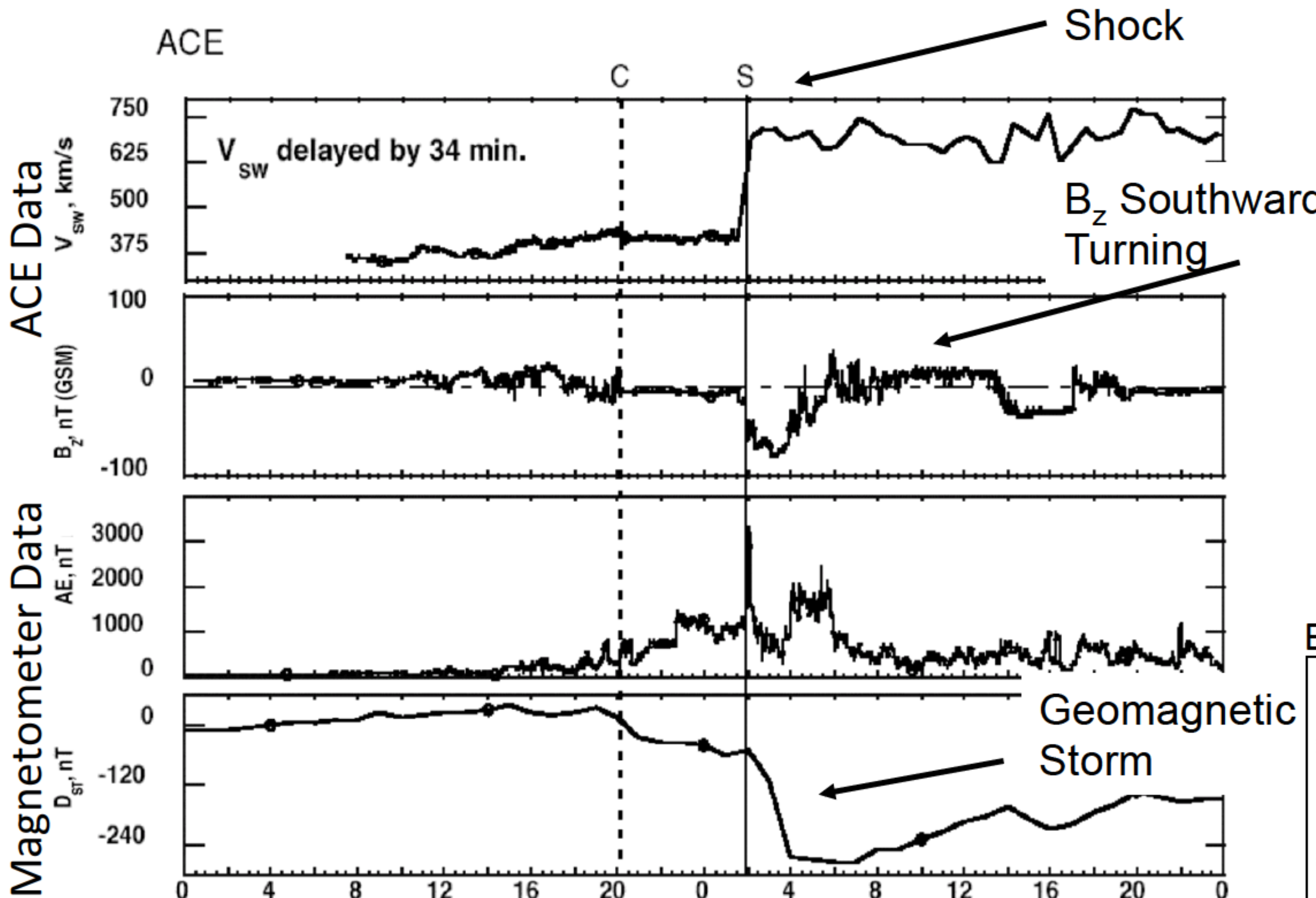


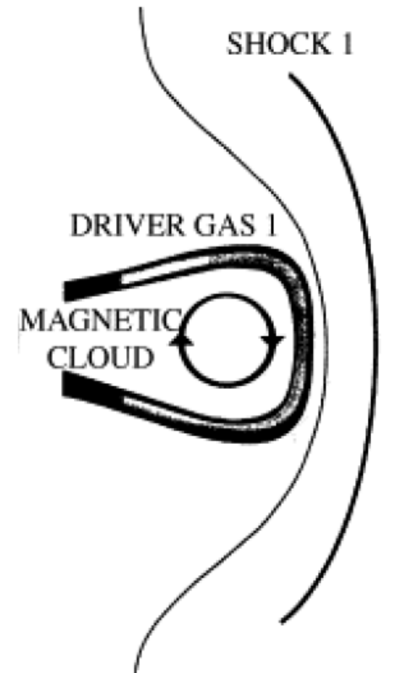
Forecasting Lead Time for a Global Thermosphere-Ionosphere Storm



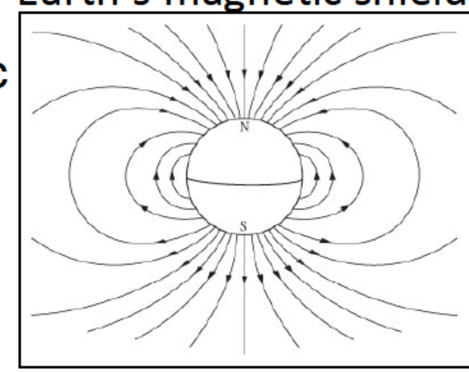
- The applied community has clearly stated a need for forecasts with such lead times
- Contrast to lead times based on ACE data (satellite at L1) of about 1 hour

Solar Wind/Interplanetary Drivers

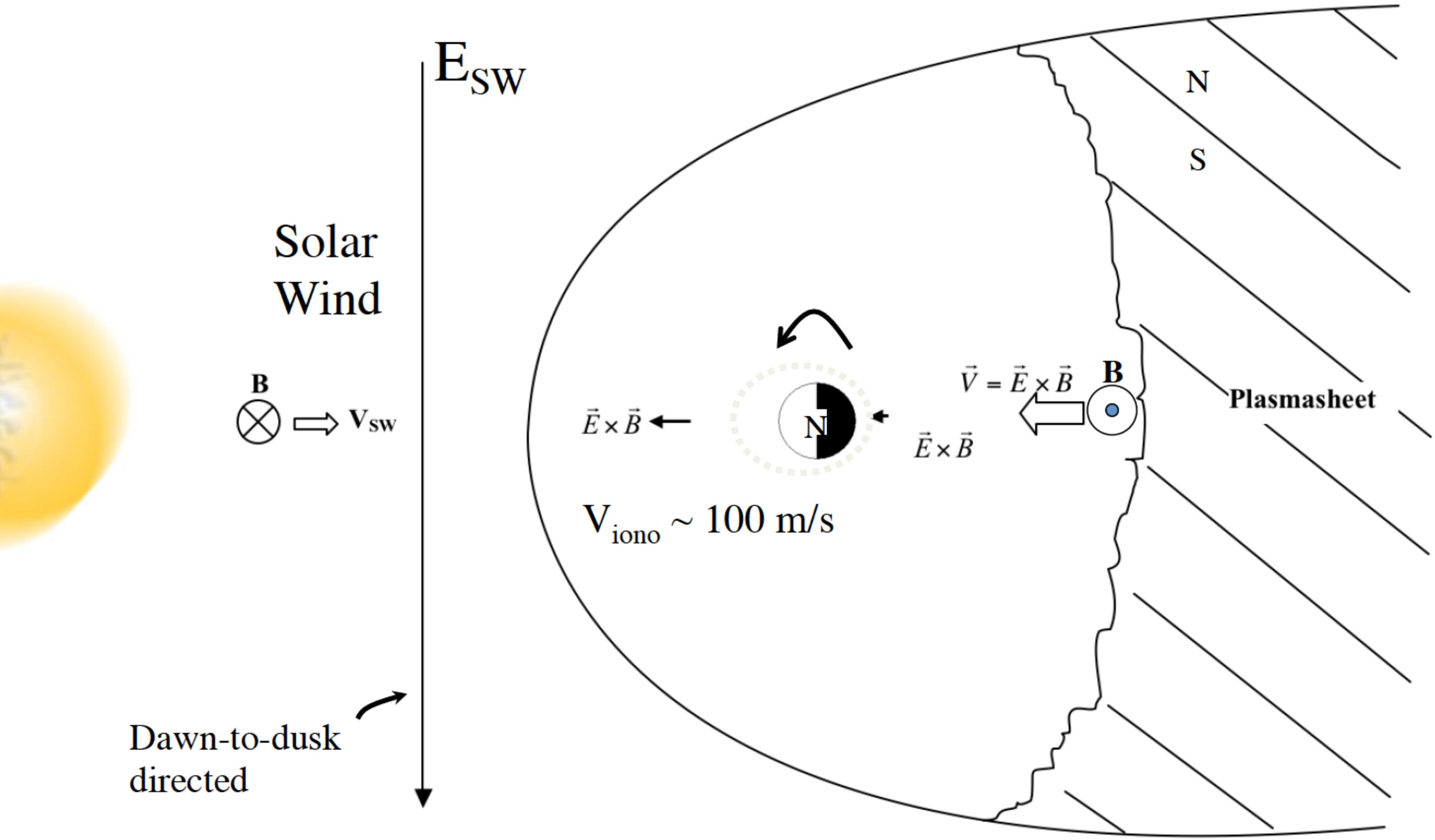




Earth's magnetic shield



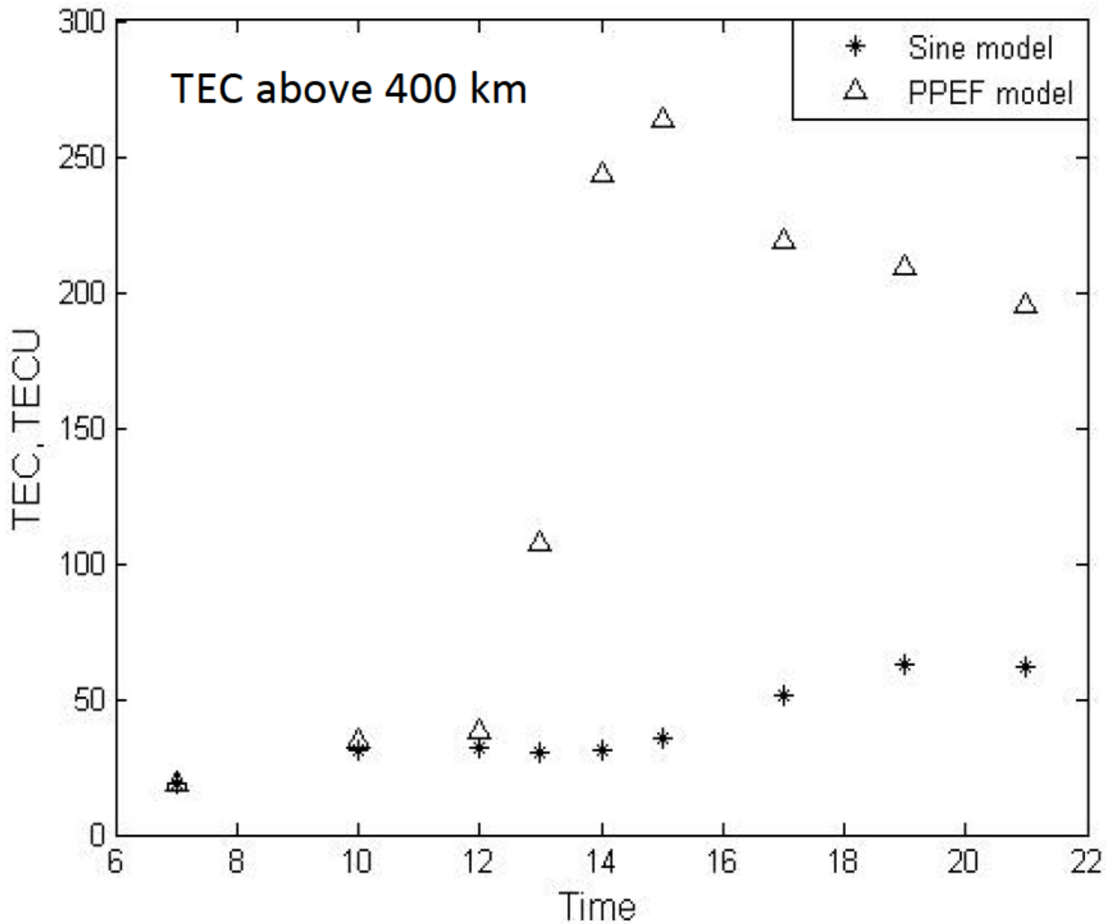
Mechanism for Dayside TEC Increase: Ionospheric Uplift



SAMI2 Model Run

Electric field estimate using CHAMP magnetometer data: **4 mV/m**

Ann. Geophys., 25, 569–574, 2007



LT

Background sinusoid 0.5 mV/m

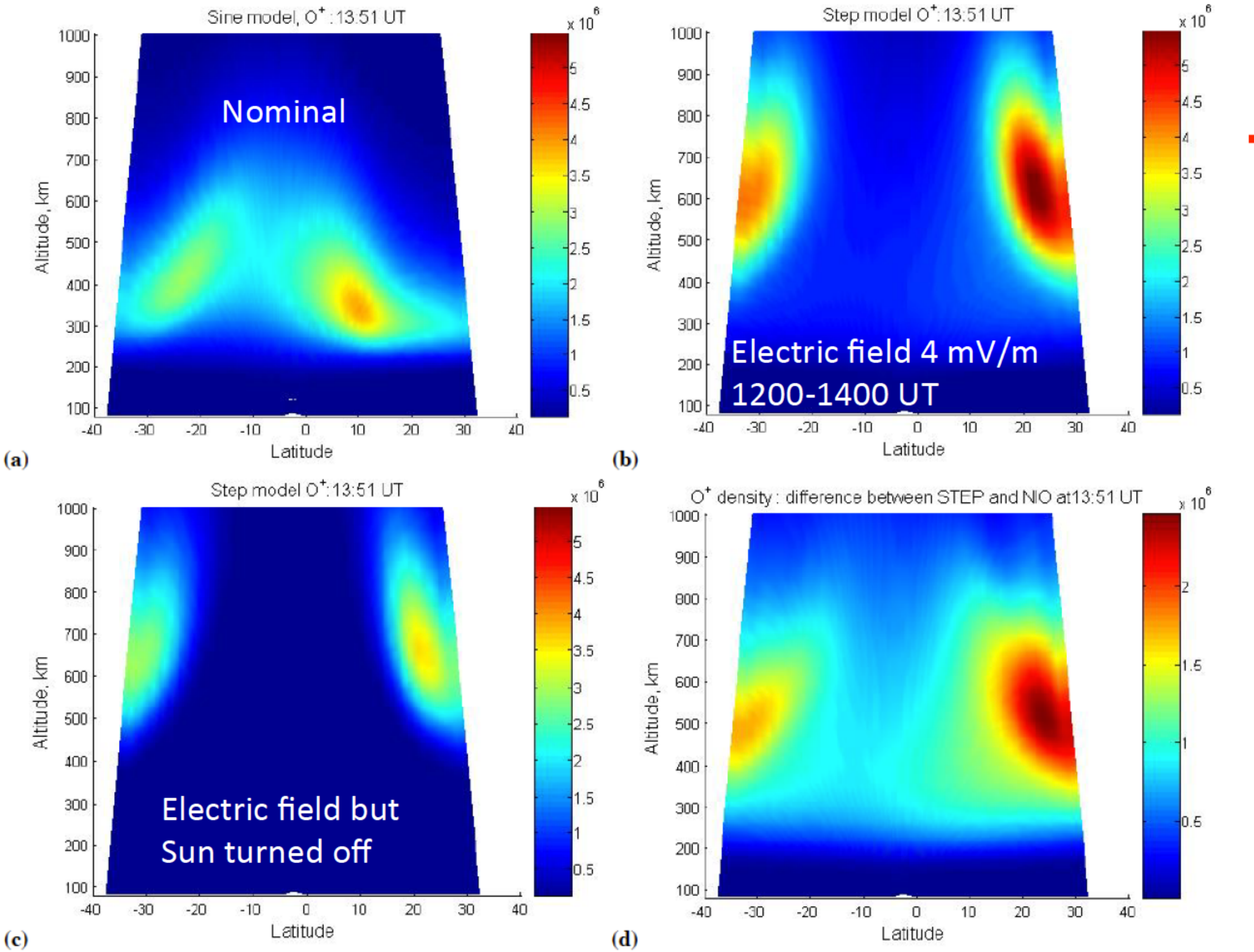
Enhanced electric field
12 - 14 LT
(single longitude model)

25° Latitude

CHAMP value ~230 TECU

CCMC Version: sinusoidal E with peak value specified

Verkhoglyadova et al., in Coupling Processes in the Equatorial Atmosphere Symposium Proceedings, March 2007

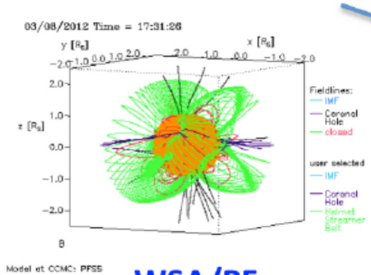


Tsurutani et al., Ann Geo 2007

SAMI-2 runs with added electric field

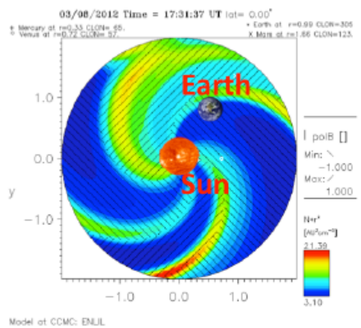
Why Consider Forecasting Thermosphere-Ionosphere Storms?

Solar Corona



WSA/PF

Heliosphere

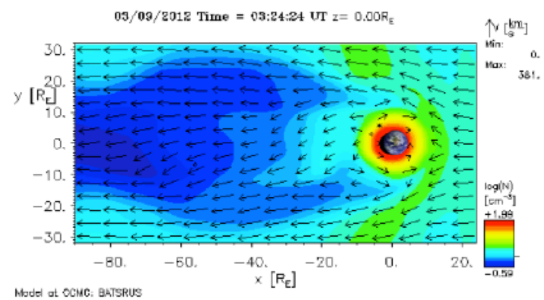


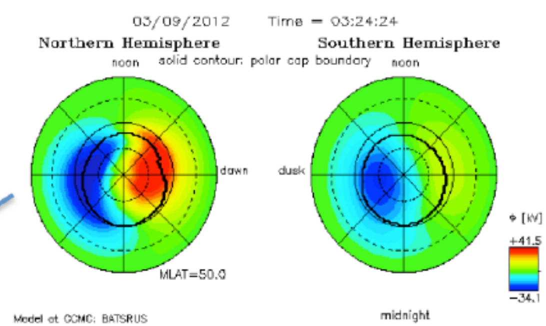
ENLIL

Operational

- Existing modeling chain at Community Coordinated Modeling Center–GSFC/NASA

Magnetosphere



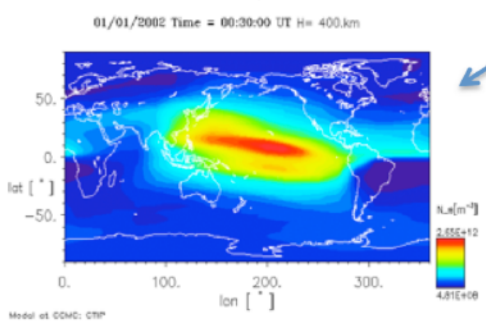


High-latitude potential field
Field-aligned currents

Non-MHD:

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

Coupled Thermosphere-Ionosphere

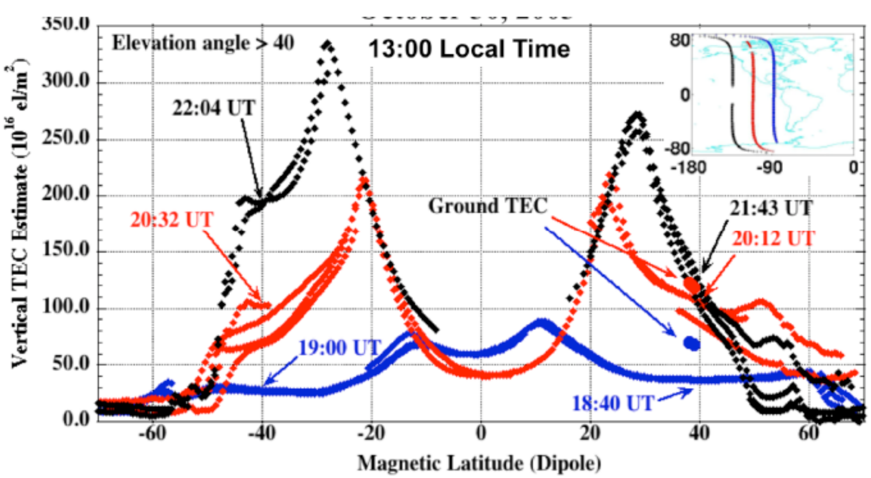


Approach

- Solar wind forecasts – Space Weather Modeling Framework (Antiochos & Gombosi)
- Thermosphere-ionosphere forecasts
- Model development – GITM + plasmasphere
  - Global Ionosphere Thermosphere Model SWMF
- Ensemble forecast system
  - Rigorously determined probabilistic forecasts
- Data driven model development
- Science investigations
- Implementation at CCMC

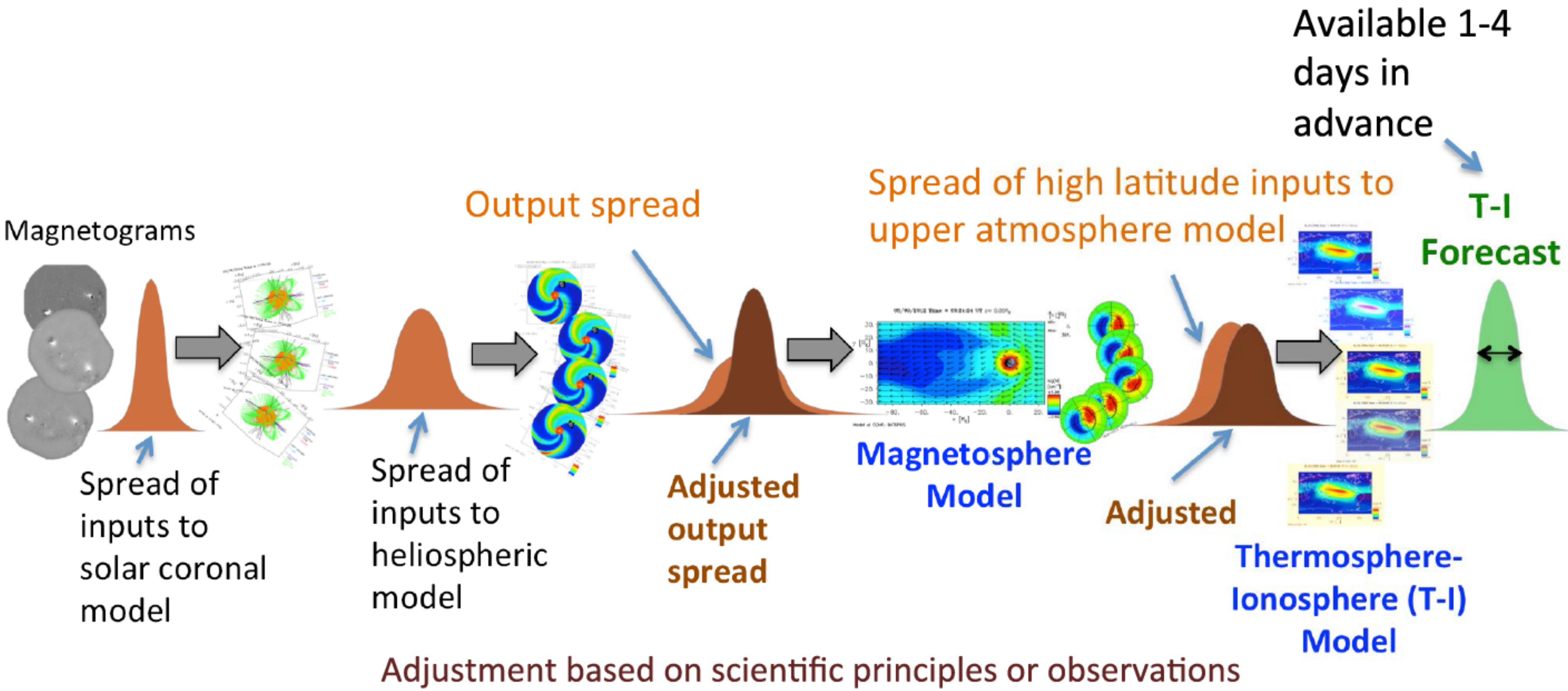
Ensemble Forecast System

- **Database of model runs and validation data**
  - We will forecast measured quantities that are relatively straightforward to evaluate
  - Observations across the modeling chain will permit us to evaluate driver realism
- **Initial goal: insight, not accuracy**
  - We will use existing models in most cases
  - Multiple models of the same domain could be used



What will the vertical TEC be at lat/lon 30°/225° at 2200 UT? What is uncertainty?

Multiple Domains



Creating a probabilistic forecast for global thermosphere-ionosphere storms using the modeling chain at CCMC, developed by a multi-disciplinary team of scientists, applied mathematicians, and numerical weather prediction experts.

GTIS = "Global Thermosphere-Ionosphere Storm"

Forecast Uncertainty Regions

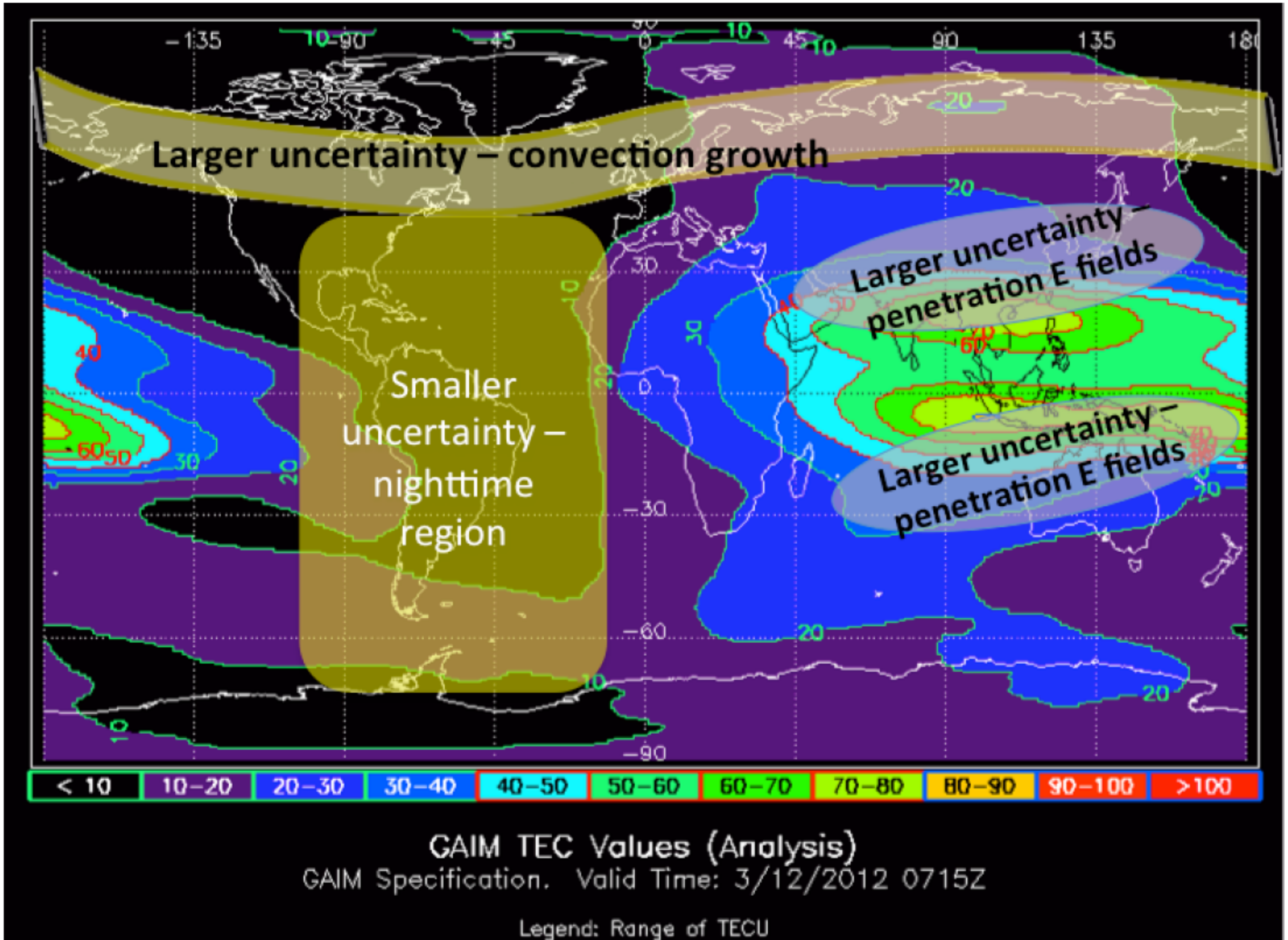
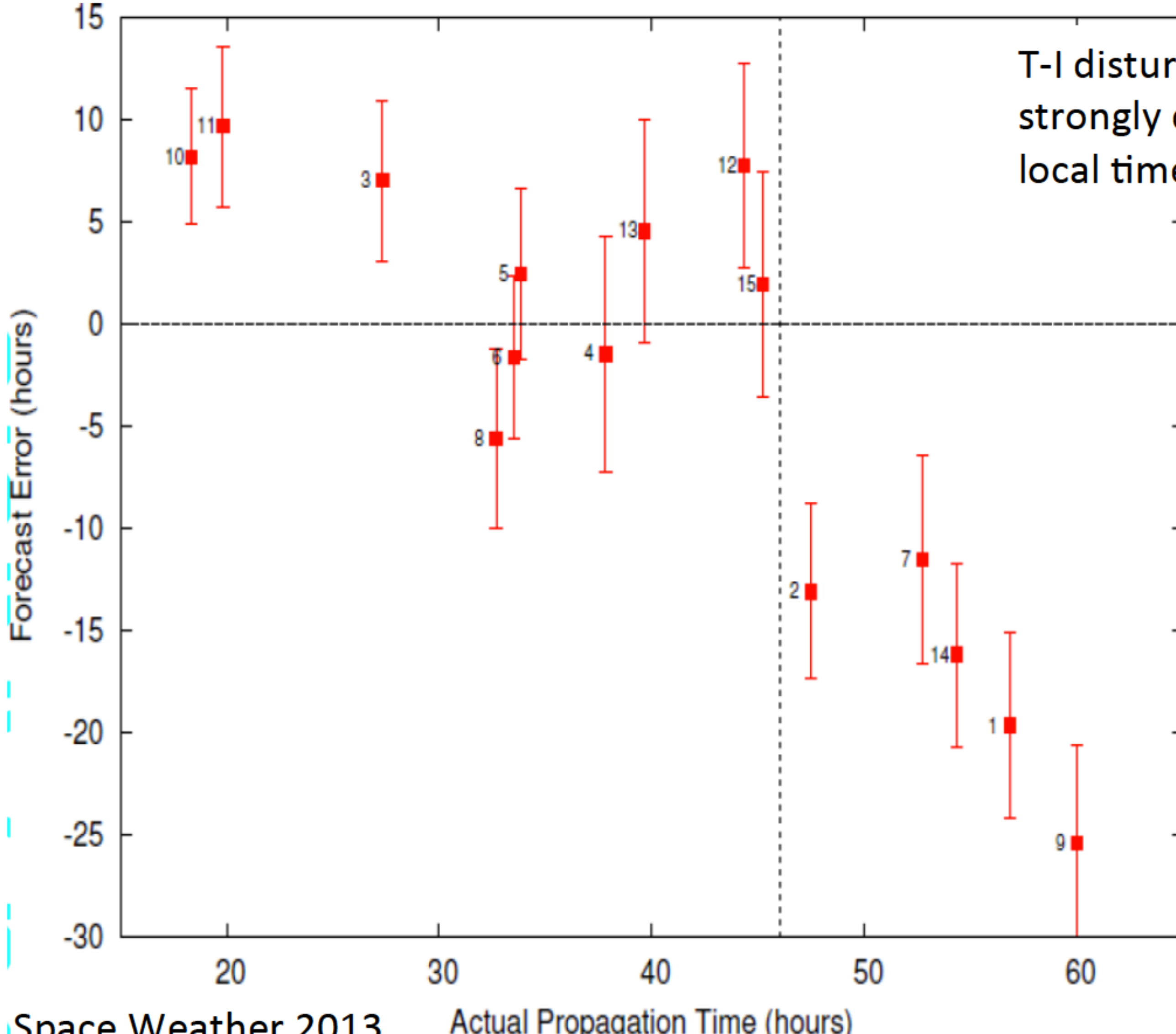


Figure adapted from AFWA map (Air Force Weather Agency)

WSA-ENLIL + CONED Model: Disturbance Arrival Time



T-I disturbances are strongly dependent on local time

Emmons et al., Space Weather 2013

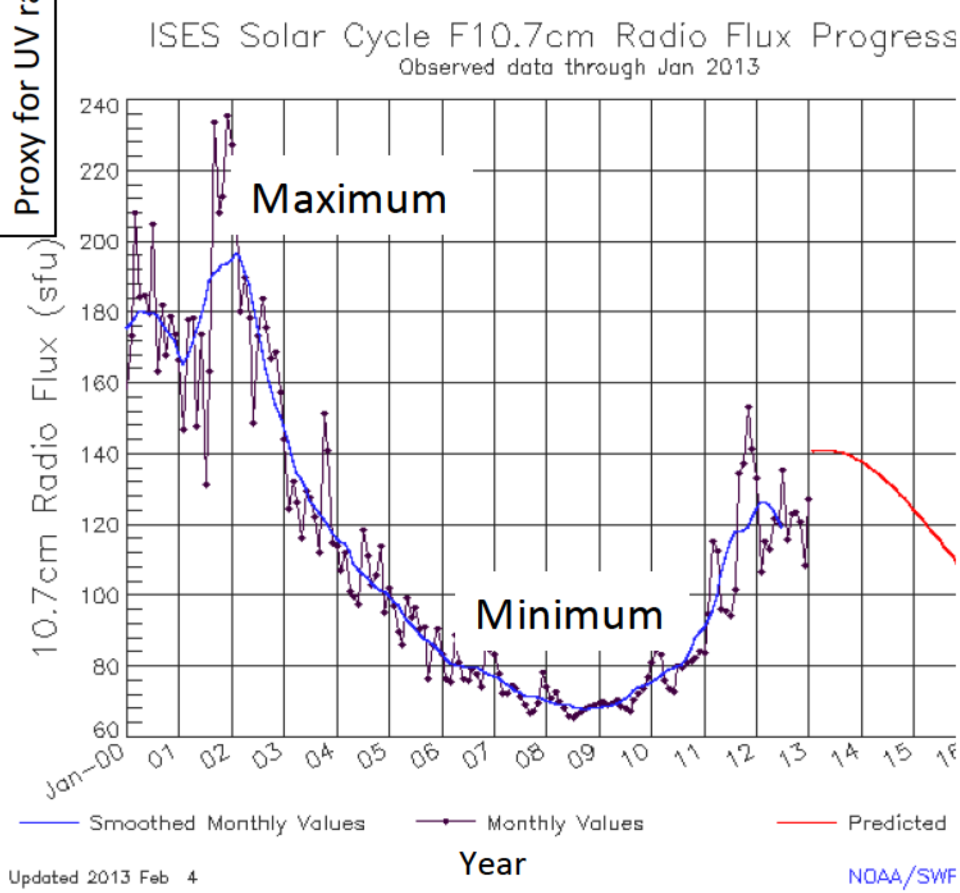
Solar Wind Forecasts

- Forecasting the geoeffective component of a coronal mass ejection is a major focus of this collaboration
- Forecasting arrival time of CME is critical
- Observations at L5 (upstream) may help significantly
- Forecasting a disturbance due to coronal holes is much more tractable
  - Coronal hole persistence
  - Solar rotation period of 27 days

Disturbances Throughout the Solar Cycle

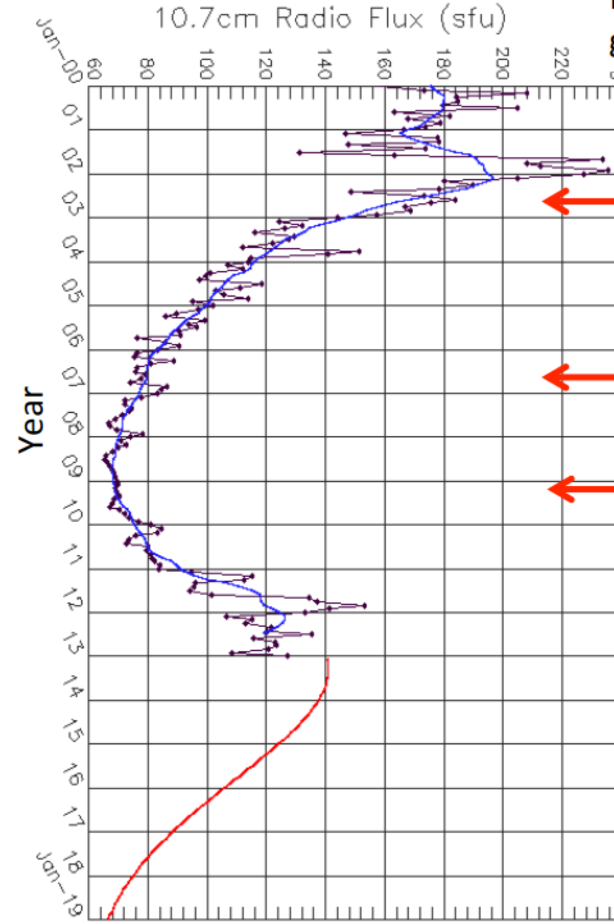
Proxy for UV radiation

"Classical" view of the solar cycle



http://www.swpc.noaa.gov/SolarCycle/

Lika Guhathakurta's view (my interpretation)



Dominant causes geoeffectiveness

Equatorial* active regions

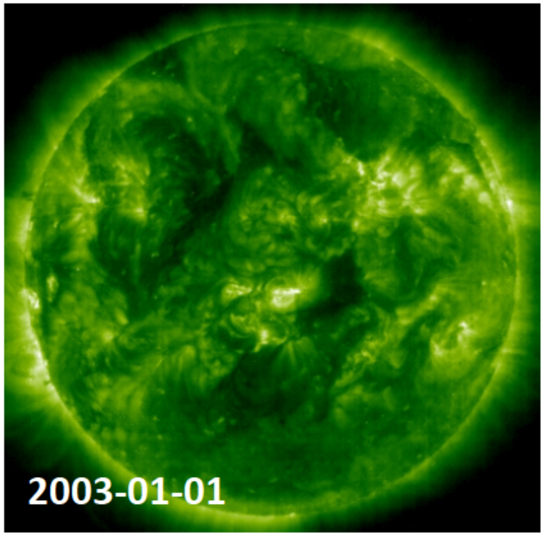
Equatorial coronal holes

High latitude coronal holes

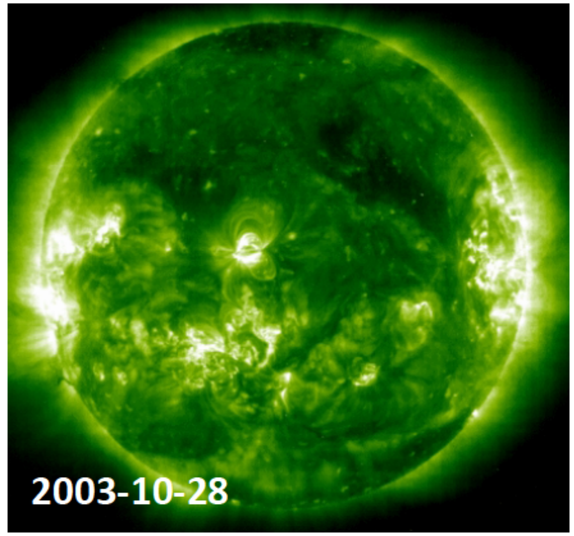
See Guhathakurta and Philips, Space Weather, 2013

*Solar latitude

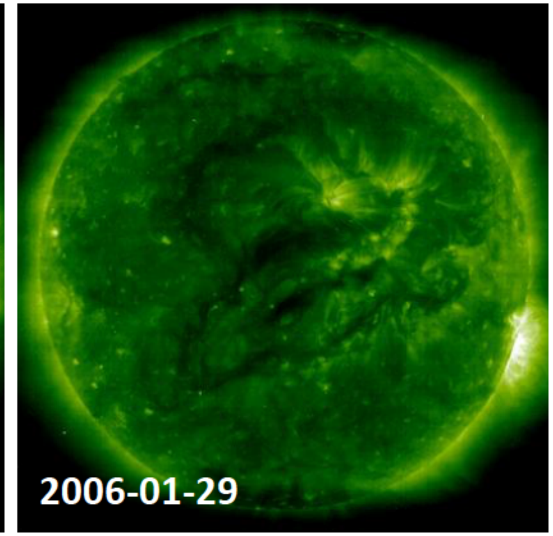
SOHO Images – Solar Cycle



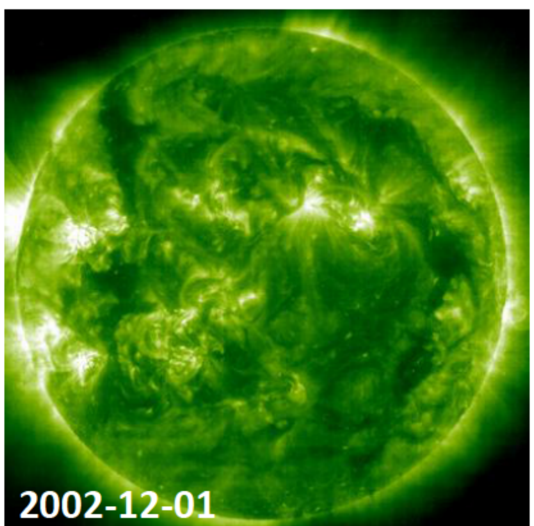
Early declining phase



Halloween storm



Declining phase

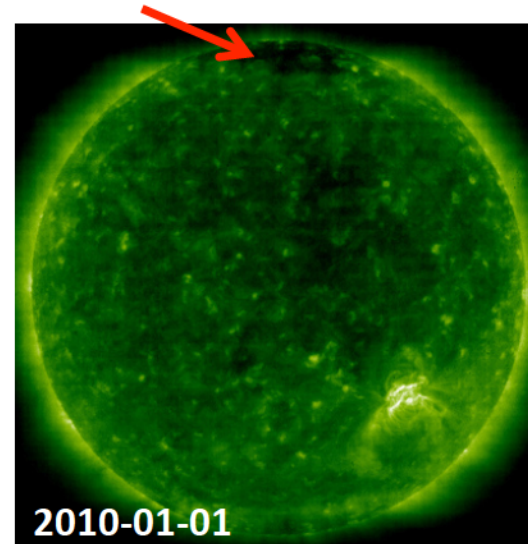


Active regions
Coronal holes

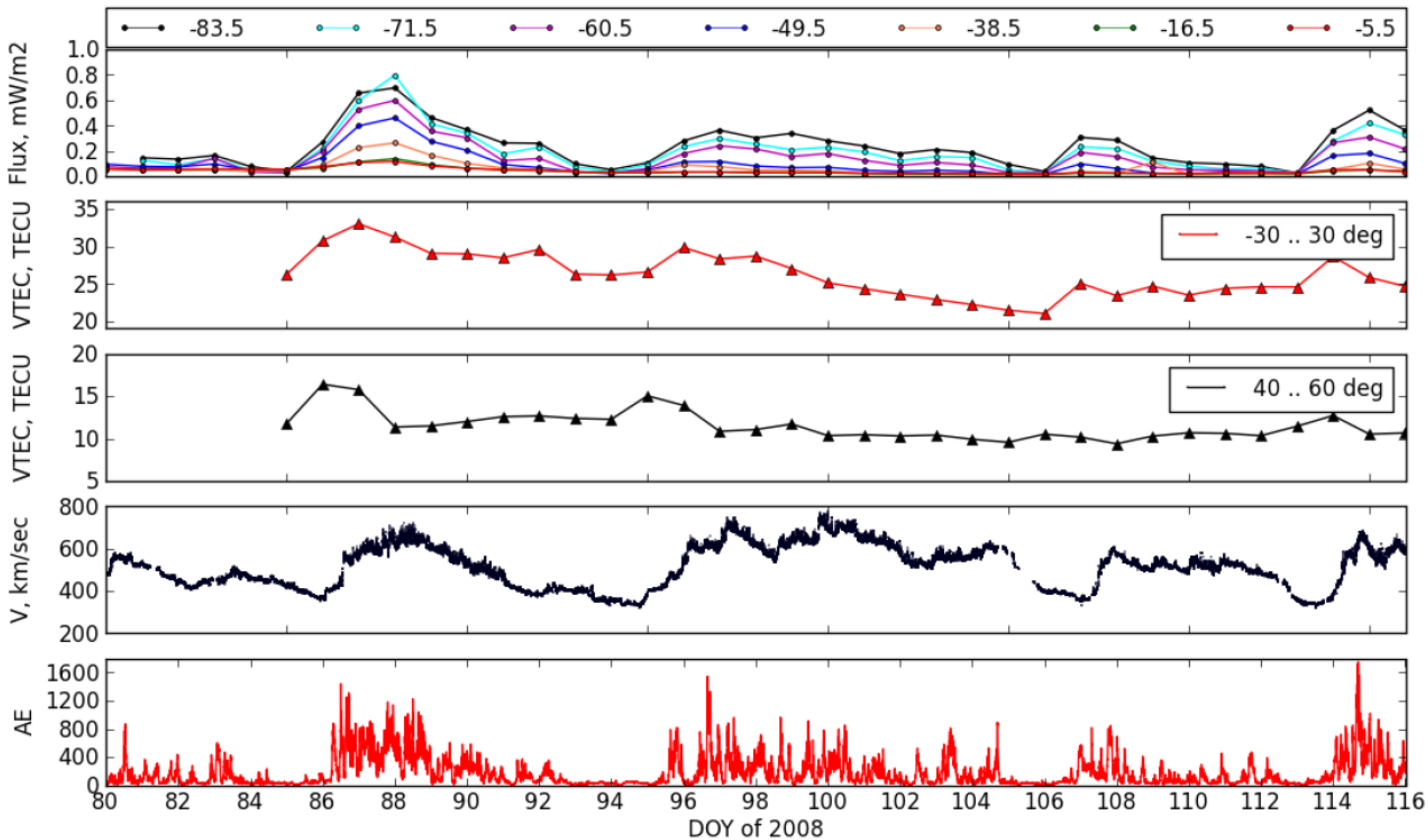
EIT 195
Fe XII
1×10^6 K

Solar maximum

Solar minimum

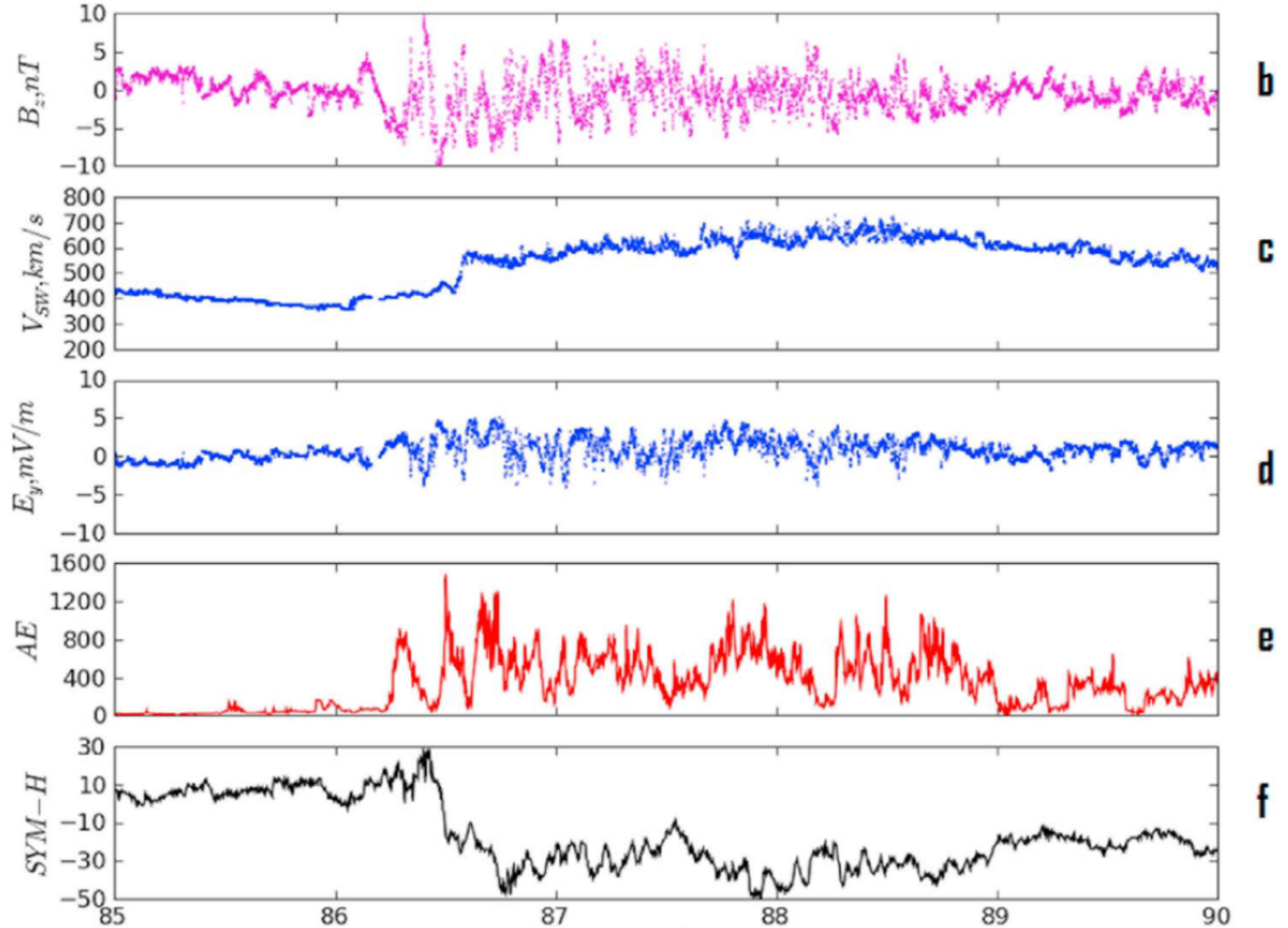


Recurrent Activity – High Speed Streams



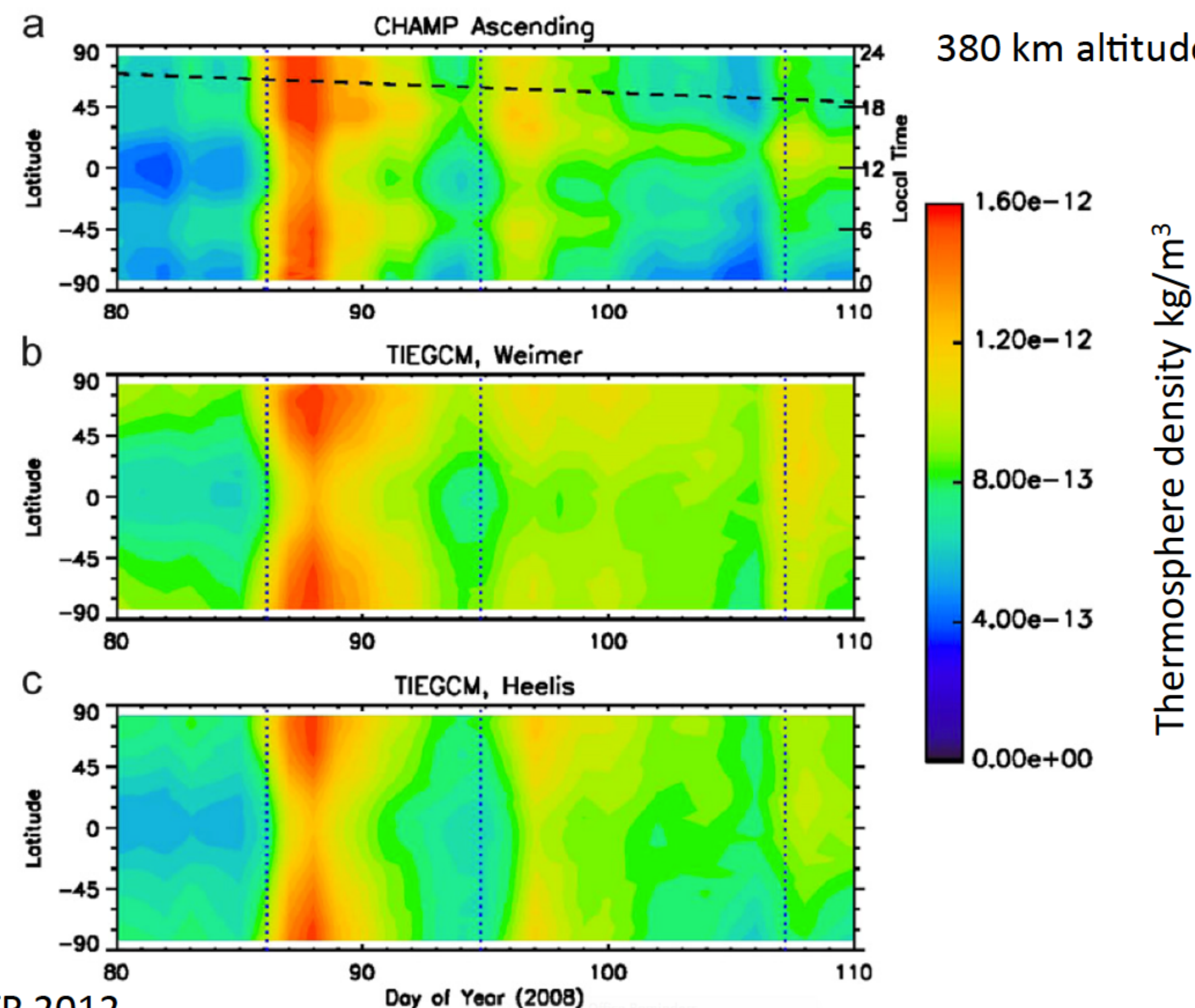
Ionospheric impacts are less than for CME storms

Interplanetary Parameters – Whole Heliospheric Interval



Verkhoglyadova et al., JGR 2011 DOY 2008

Modeling Study of High Speed Streams



Two different high latitude inputs driven by solar wind parameters

Heating at high latitudes leads to thermospheric density increases at S/C altitude

Burns et al., JASTP 2012

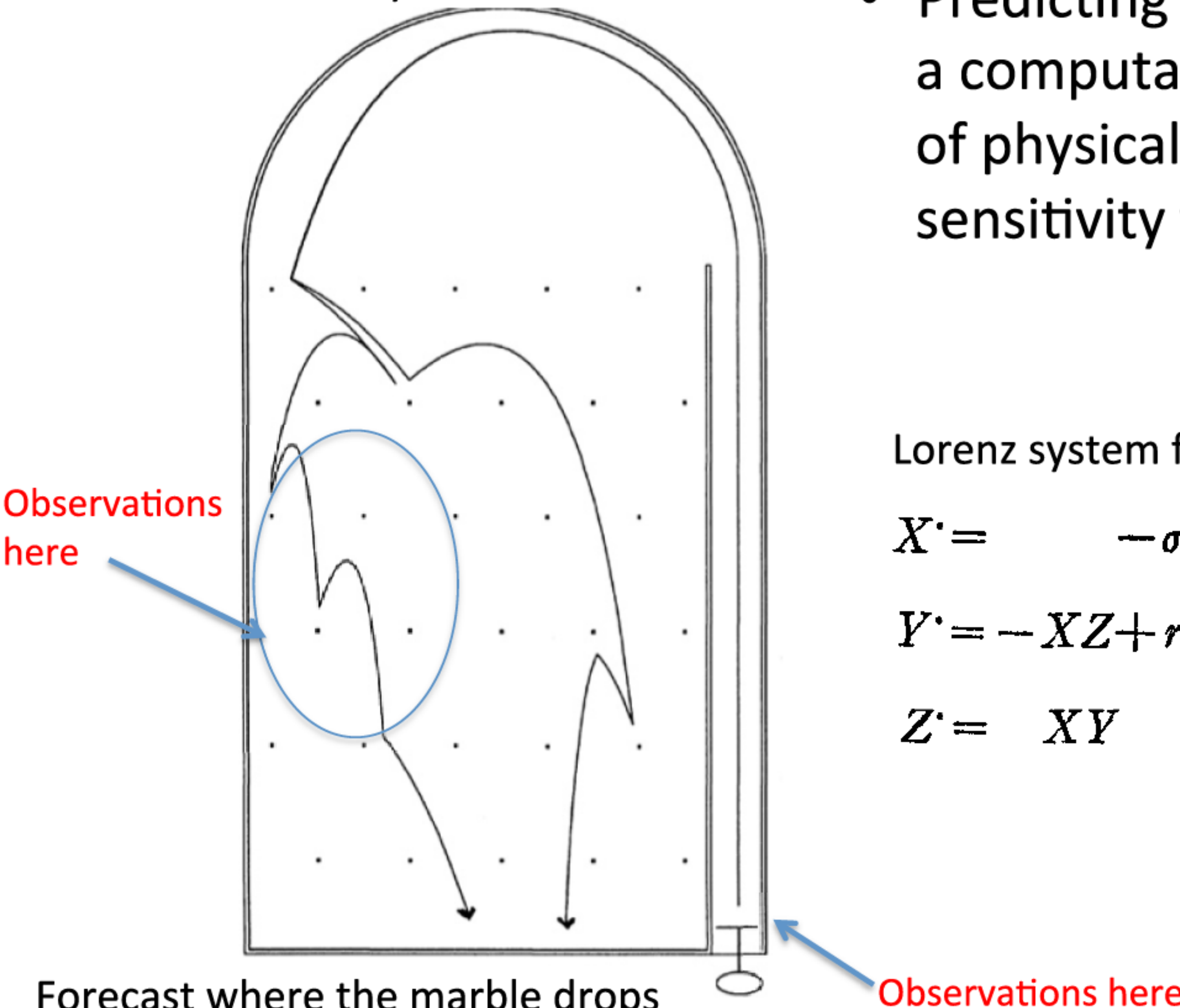
The Forecasting Challenge

- Forecasting represents a significant new challenge to modeling the coupled Sun-Earth system
- Improving forecasts will lead to new scientific insights when modeling is an important component of the scientific inference chain
- Forecasting depends on the characteristics of physical system and the computation
  - Stability and sensitivity to initial conditions
  - Must account for "missing physics"

Chaos: Sensitivity to Initial Conditions

"Lorenz 1963: Deterministic Nonperiodic Flow"

Sensitivity to initial conditions



Forecast where the marble drops

- Predicting the future depends on a computational representation of physical knowledge and sensitivity to initial conditions

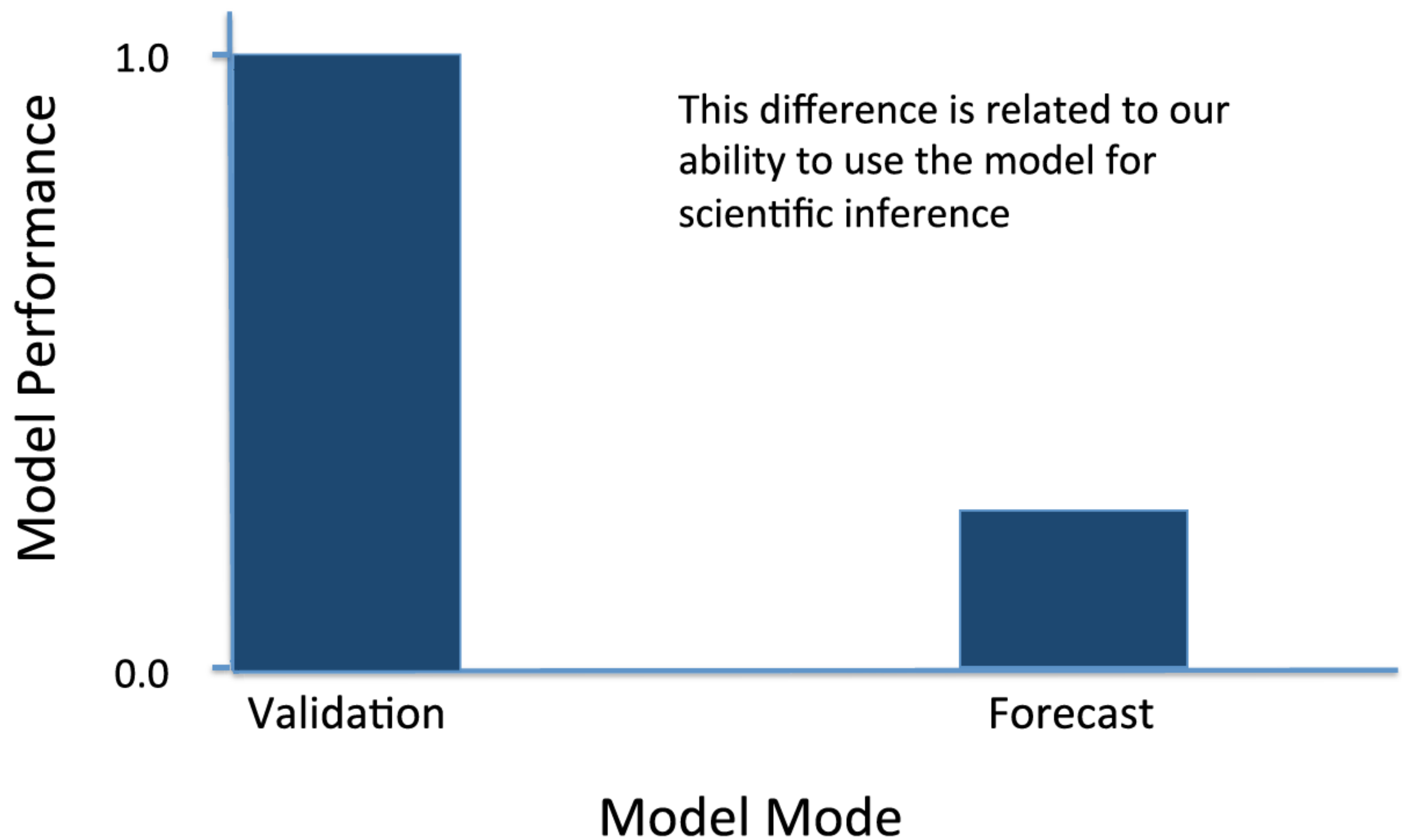
Lorenz system for atmospheric convection, 1963

$$\dot{X} = -\sigma X + \sigma Y, \quad (25)$$

$$\dot{Y} = -XZ + rX - Y, \quad (26)$$

$$\dot{Z} = XY - bZ. \quad (27)$$

Model Validation Versus Forecast



The Forecasting Challenge

- In typical model-data comparisons, several model outputs are available to compare with data, without likelihood ranking
- In a forecast, a more limited number of model outputs is available, ranked in terms of likelihood
- It is advantageous where possible to compare forecasts using different models

Proposal Team PIs, CoIs

- JPL/Caltech: A J Mannucci, BT Tsurutani, O Verkhoglyadova, A Komjathy, M Butala, X Pi
  - Overall direction and science
- U Michigan: A Ridley, B van der Holst, W Manchester
  - Global Thermosphere Ionosphere Model (GITM)
  - Solar & Heliosphere, Space Weather Modeling Framework
- U Southern California: C Wang, G Rosen
  - Ensemble forecast system
  - Statistical methods
- U Maryland: S Sharma, E Lynch, E Kalnay, K Ide
  - Data-driven methods
  - Ensemble forecast system
  - Statistical methods
- CCMC: Ja Soon Shim, Masha Kuznetsova, Peter MacNeice
  - Ensemble forecast system

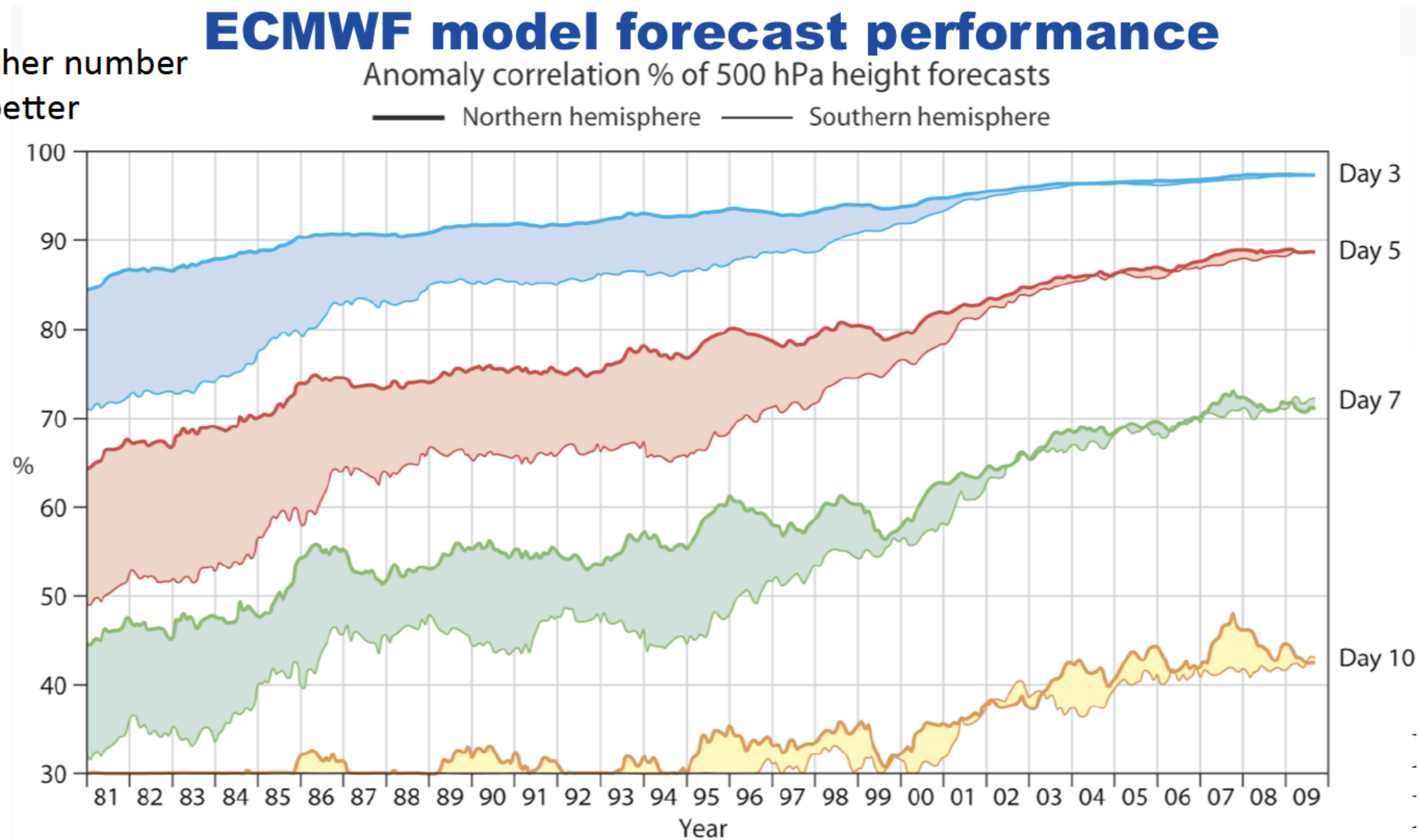
Angelos Vourlidas – NRL: Solar-heliosphere

Science Questions

- **How do variations in solar forcing across the solar cycle affect the thermosphere-ionosphere from lower to sub-auroral latitudes?**
- **What is the time history of ionospheric and thermospheric forcing (at different latitude ranges and local times), and how does this differ between HSS and CME storms?**
- **How does the thermosphere-ionosphere respond to the variable electrodynamics in response to solar wind forcing? *Do we fully understand the physics of prompt penetration electric fields and the role of shielding in this response?* Are magnetospheric currents modeled accurately?**
- **How well do models reproduce the high latitude electrodynamics over the range of storm intensities?**
- **Does the physics behind T-I response differ substantially between average and extreme cases of solar forcing? What new physics emerges during the more intense storms?**
- **What is the role of O+ ions in determining storm effects, and how well is this captured by first principles models?**
- **What is the altitude response of a ICME storm?**

Weather Forecasting Example – Improvement Over Time

Higher number is better



Long-term objective: improved forecasts result from improved scientific understanding and new observations

Summary

- Is the community ready for a medium-range forecasting effort? *Yes*
- Medium-range forecast is a clearly recognized need
- An effort in this area will focus attention on key gaps in our understanding
- Provides justification for the critical observations
  - Solar wind
  - Thermosphere-ionosphere
- Improved forecasts over time is an important indication that knowledge is being gained
- Significant science benefits

Coordination – Forecasting Solar Wind

- **Arrival time of CME or CIR/HSS**
- **B_z primarily, but B_y is important also**
- **Duration of large magnitude B_z (or large B?)**
- **Characteristics of IMF in a HSS**
- **Role of sheath?**
- **Aiding by observations (e.g. at L5) – forecasting *changes***