LWS Heliophysics Science Technical Interchange Meeting
May 20-22 2014

# Medium Range Thermosphere-Ionosphere Storm Forecasts

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**Barbara Emery, NCAR High Altitude Observatory**
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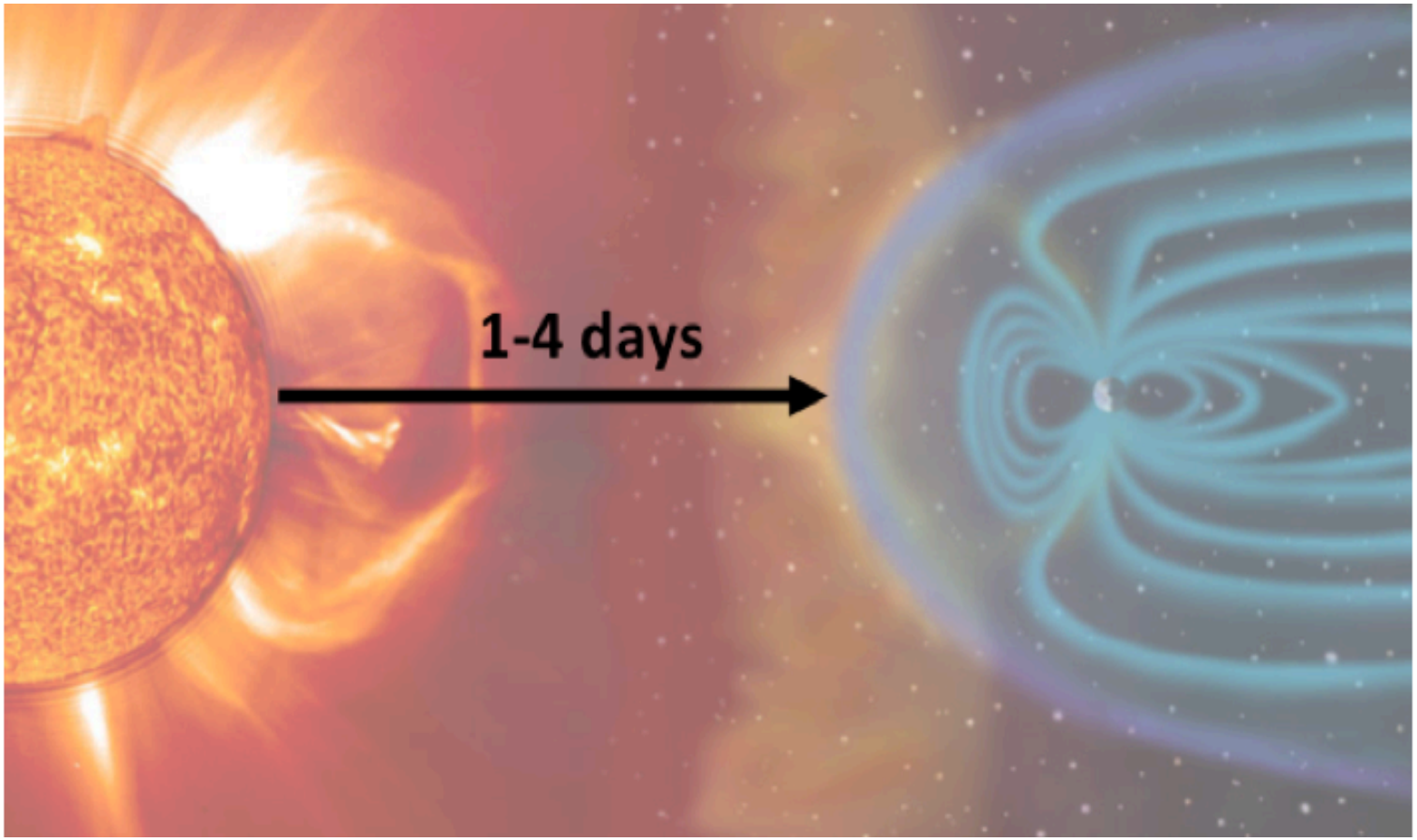
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# Overview of this session

- **Forecasts of High Speed Solar Wind Streams**
  - **Already shown**
- **Medium Range Thermosphere-Ionosphere Forecasts**
  - **Overview, model introduction and detailed analysis**
- **Statistical Characterization of Model Forecast and Uncertainties**
- **Prediction of Ionospheric Activity from the AL Index Time Series Using the Ensemble Transform Kalman Filter**
  - **Data driven forecasting**
  - **Overcoming some limitations of sun-to-Earth heliospheric modeling**

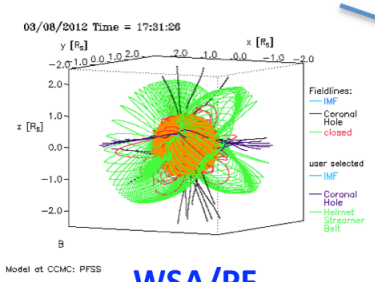
# Forecasting Lead Time for a Global Thermosphere-Ionosphere Storm




- The applications 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

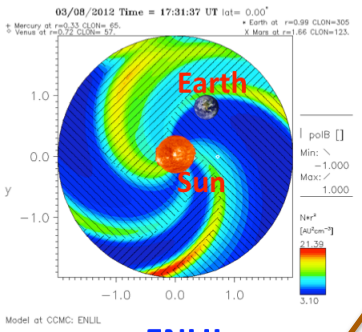
# The Modeling Chain

Solar Corona




WSA/PF

Heliosphere

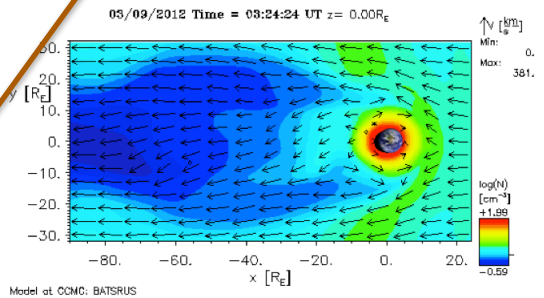


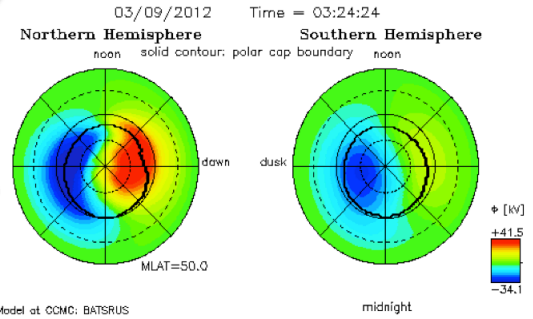

ENLIL

Operational

Our focus

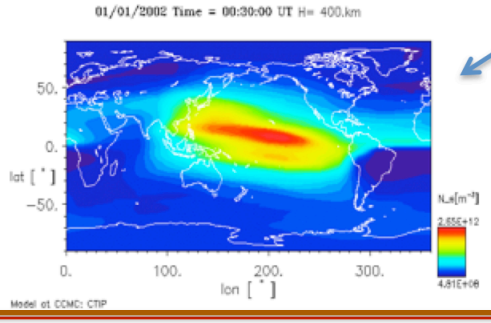
Magnetosphere




High latitude convection pattern

Global thermosphere-ionosphere storm



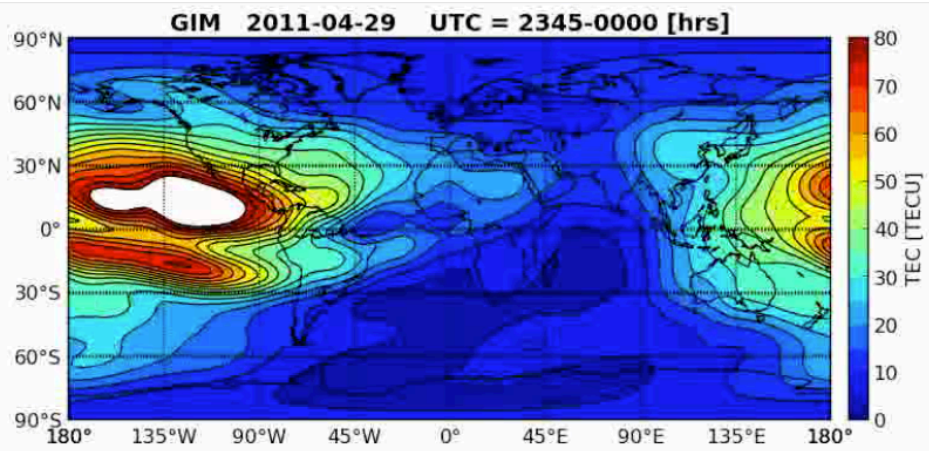

Non-MHD:

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

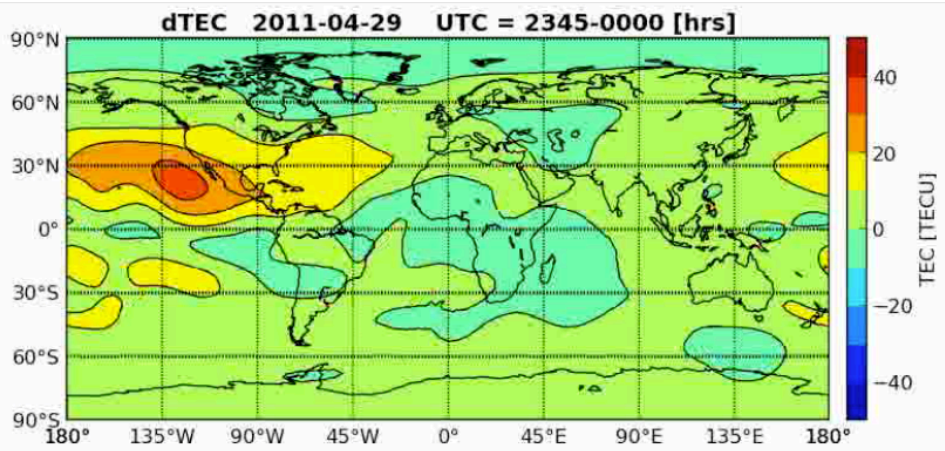
# Defining “Ionospheric Weather”

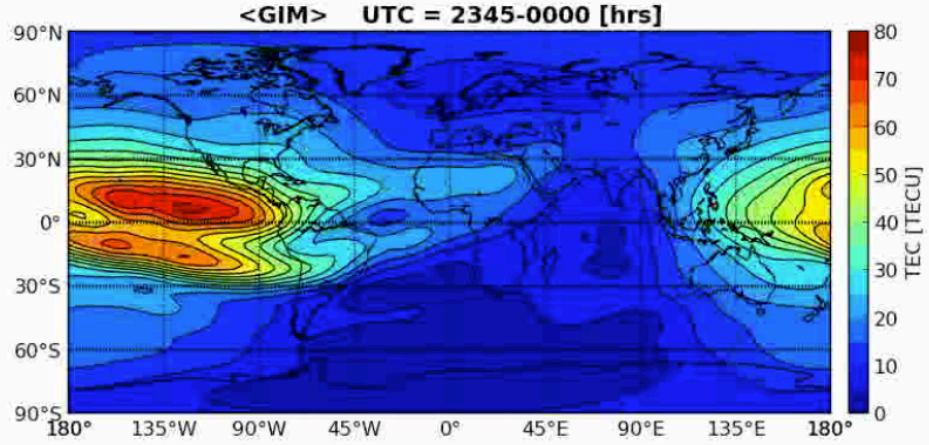
Global ionospheric maps: Data-driven space-time interpolations of ionospheric total electron content (TEC)

TEC estimate

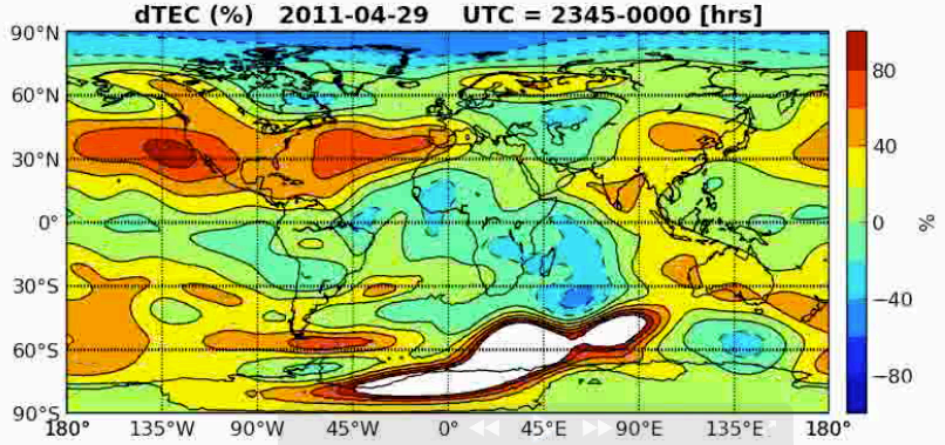



Absolute difference wrt quiet time average



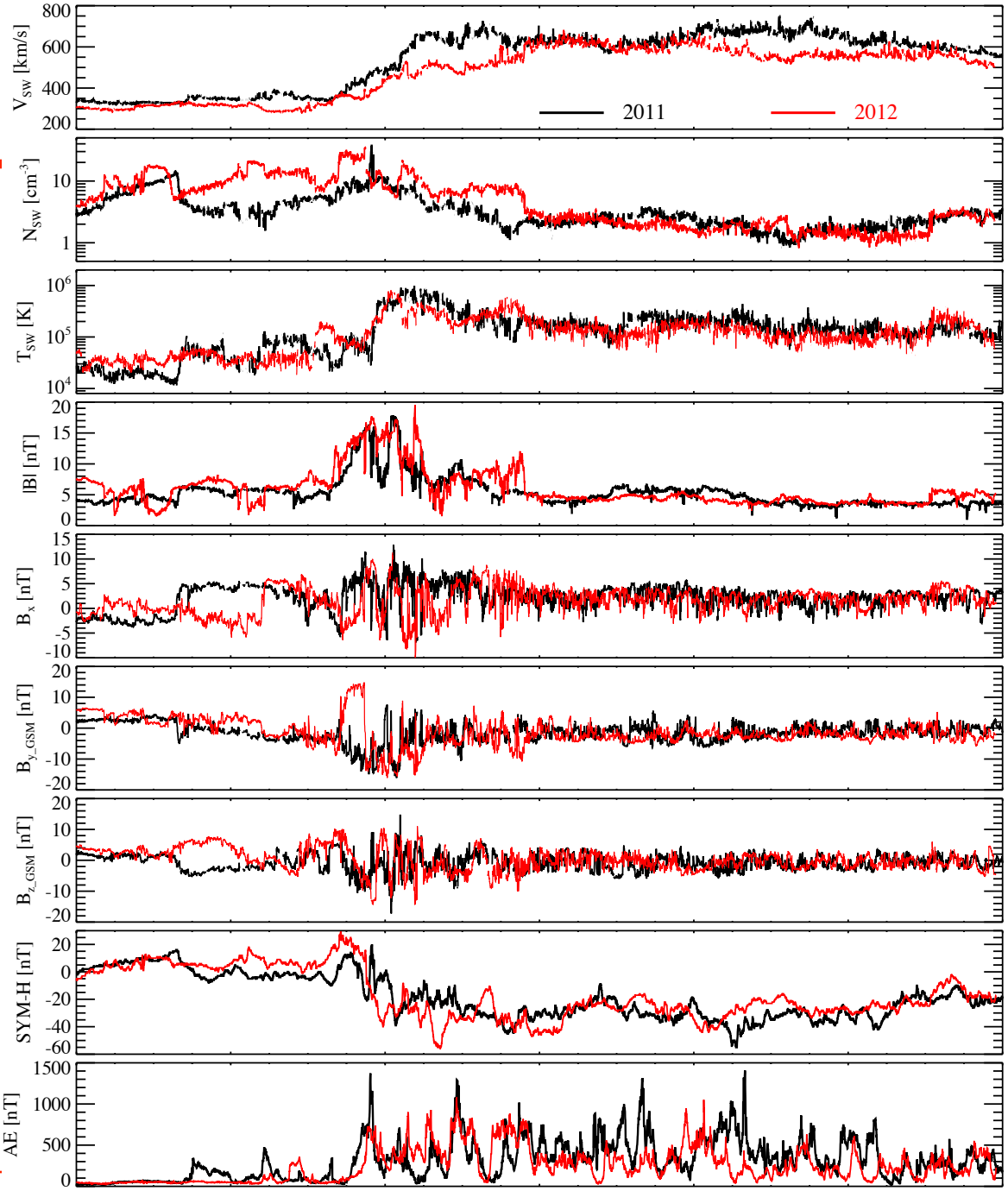




Quiet time average




Fractional difference

Case study: two corotating interaction regions/high speed streams



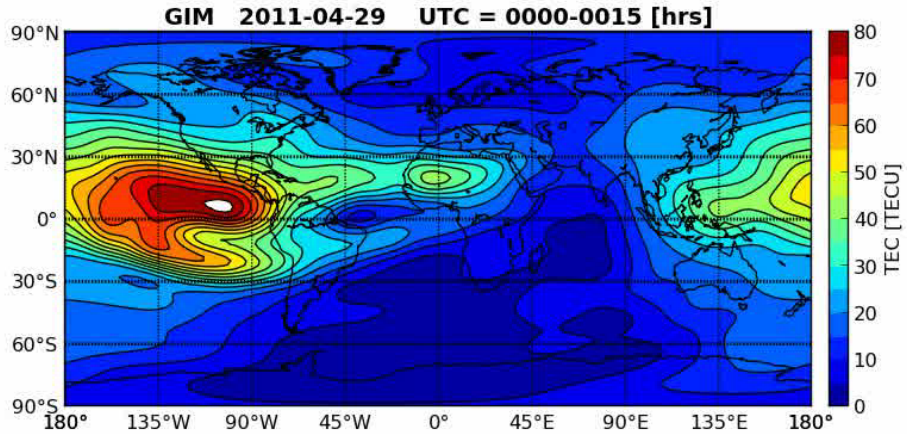

ACE solar wind data

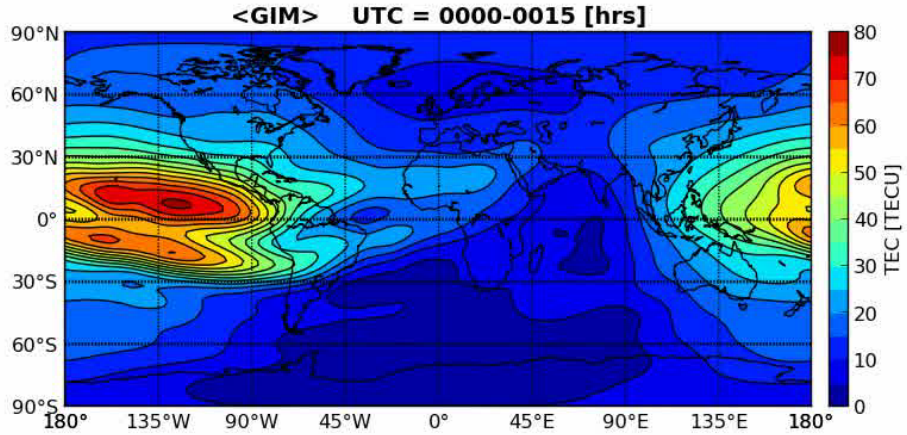
What are similarities and differences in the ionospheric response?

What are the causes?

# April 29, 2011

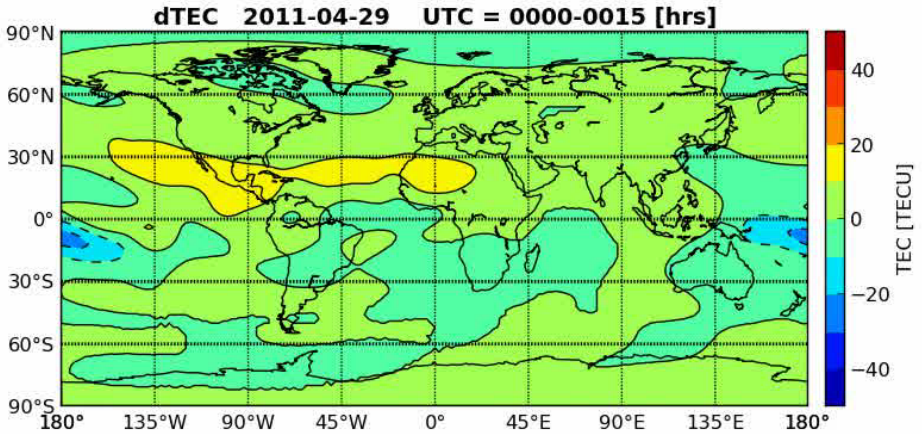
TEC estimate

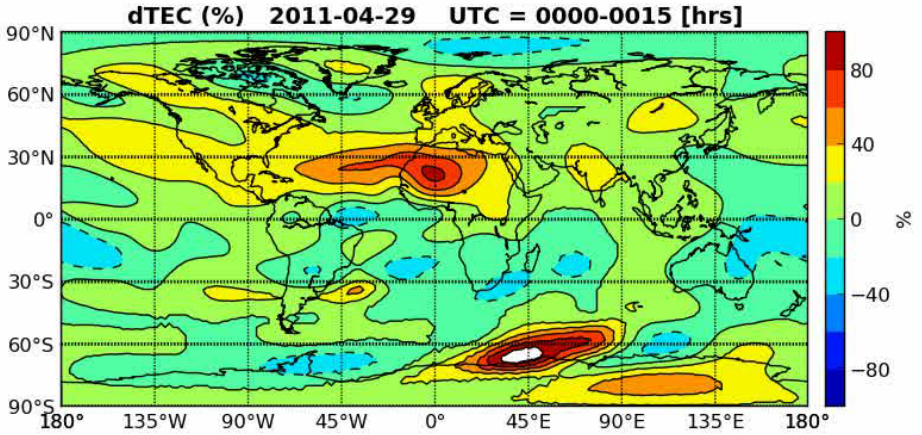



Quiet time average

Absolute difference wrt quiet time average

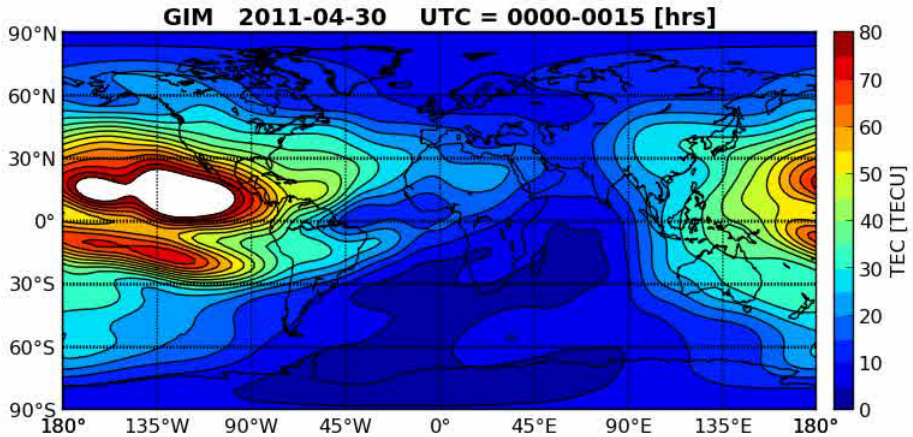


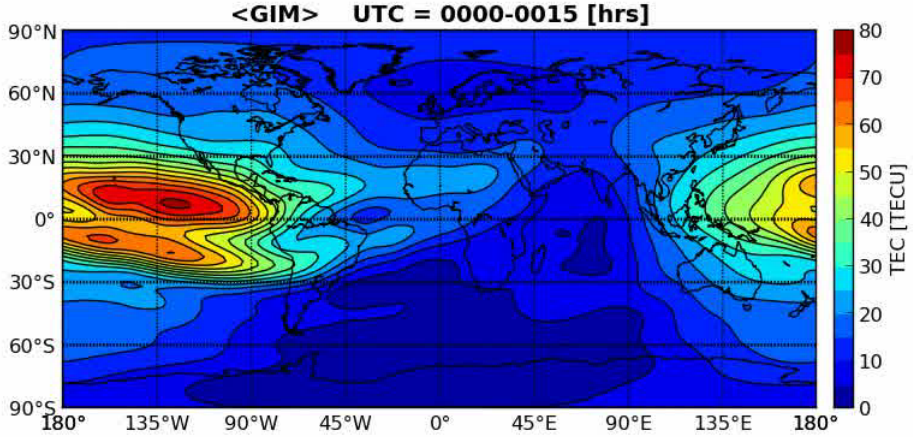




Fractional difference

# April 30, 2011

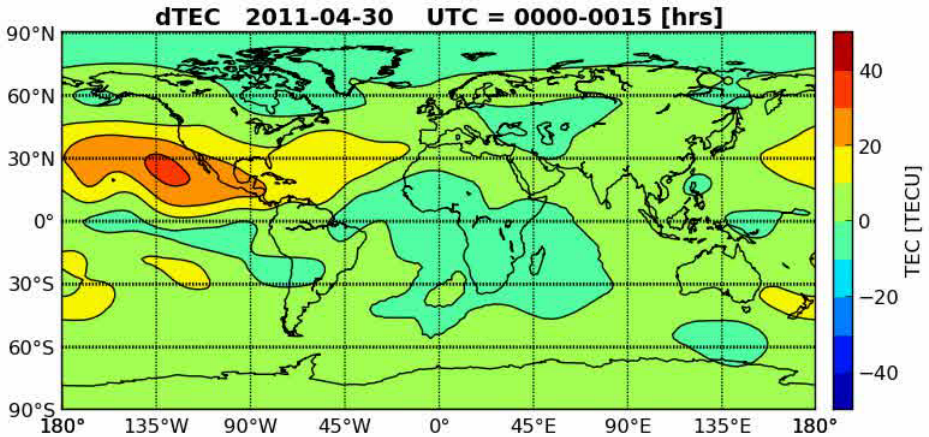
TEC estimate

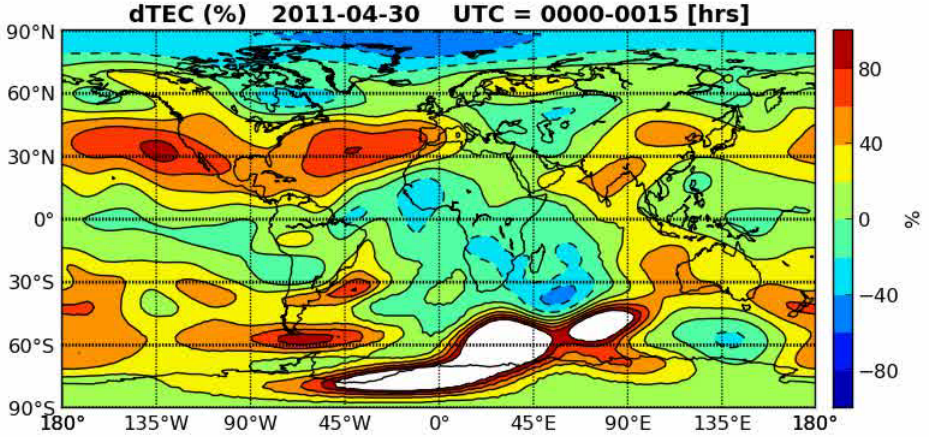



Quiet time average

Absolute difference wrt quiet time average

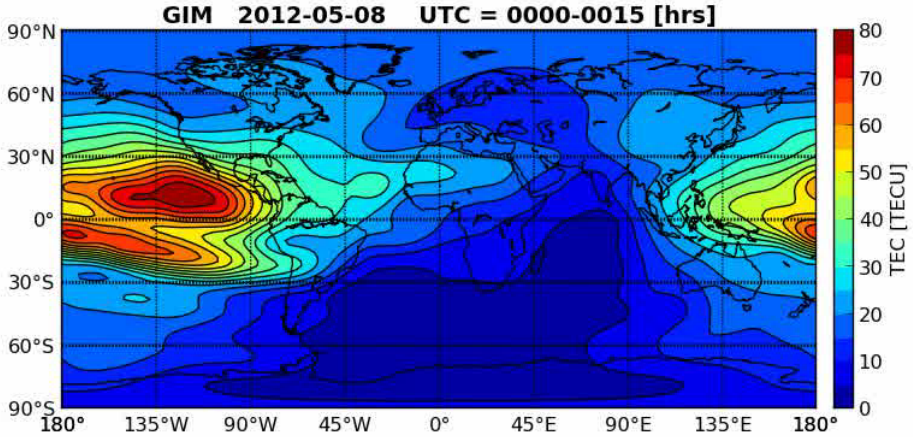


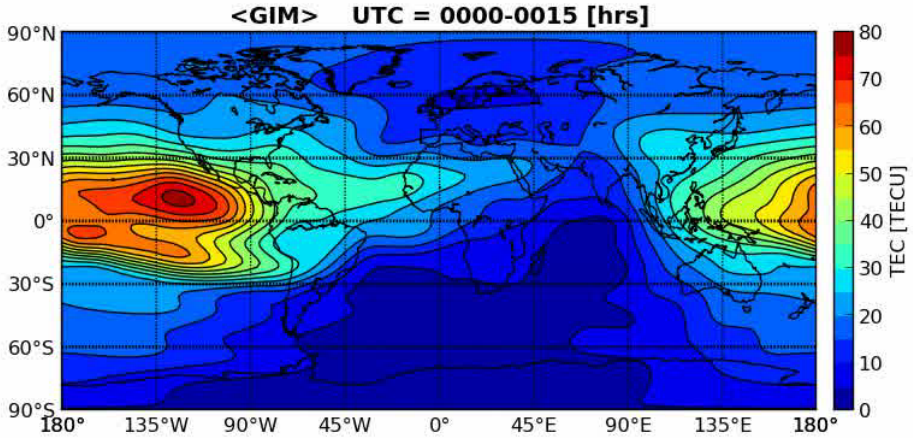




Fractional difference

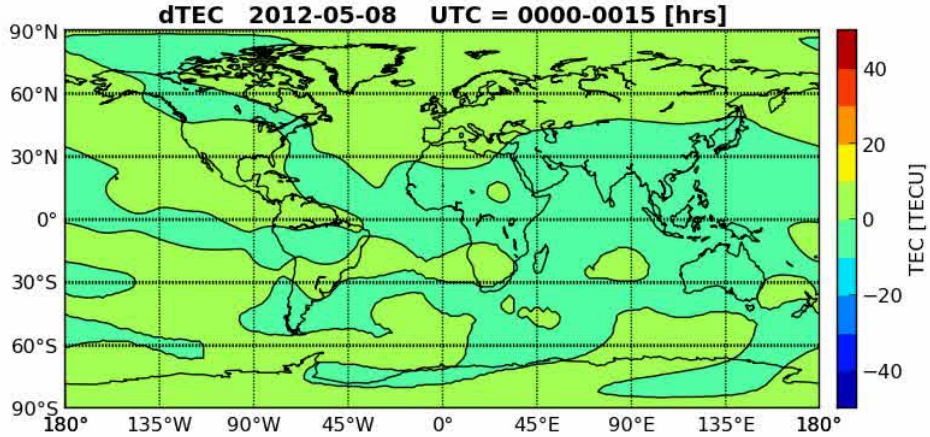
# May 8, 2012

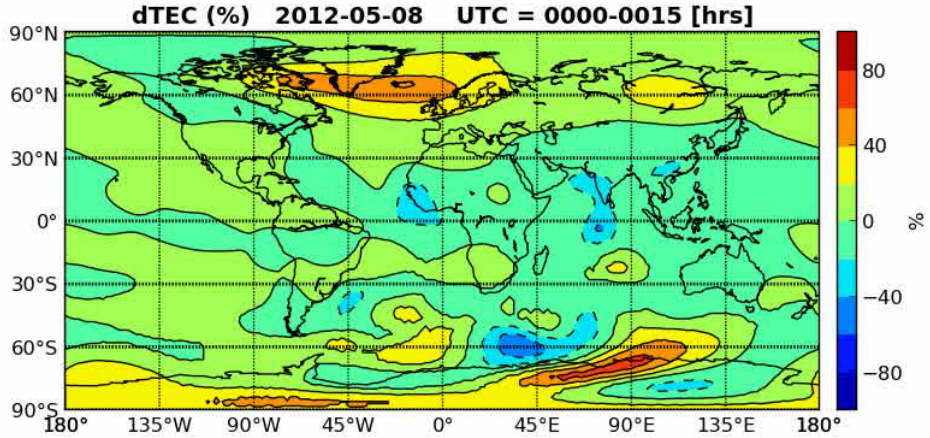
TEC estimate




Absolute difference wrt quiet time average



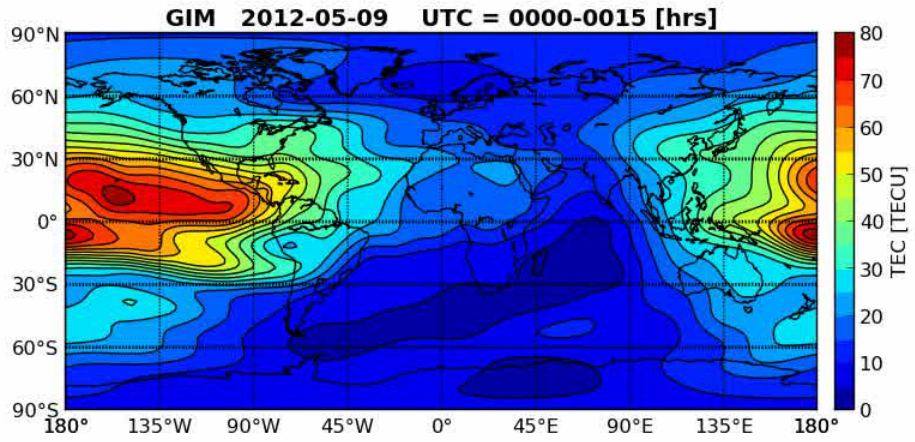



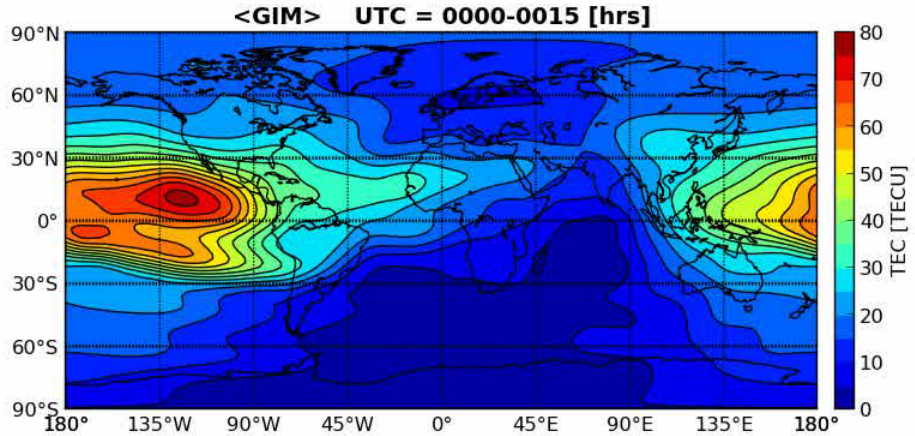

Quiet time average

Fractional difference

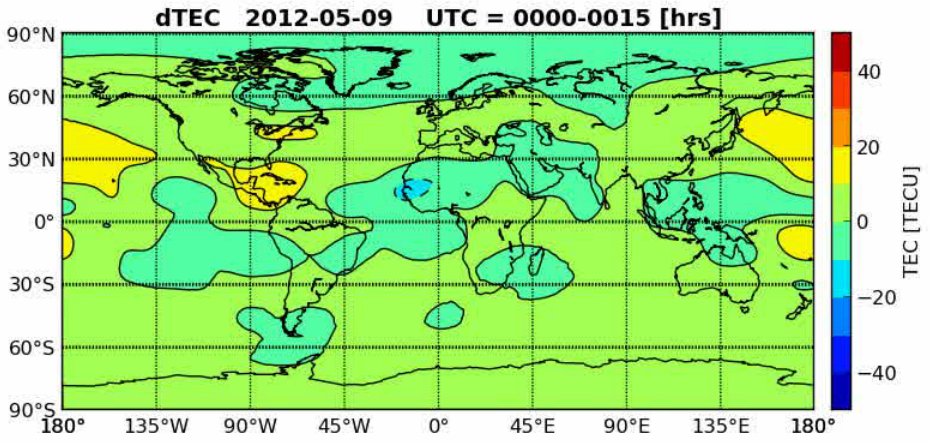
# May 9, 2012

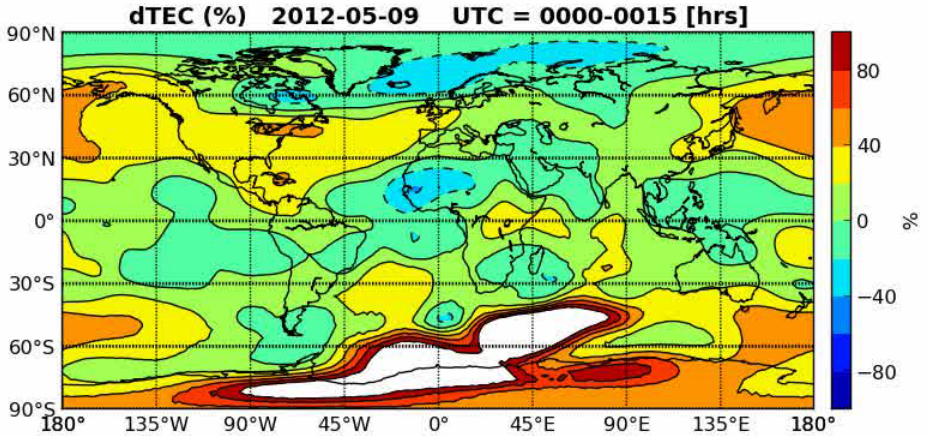
TEC estimate




Absolute difference wrt quiet time average

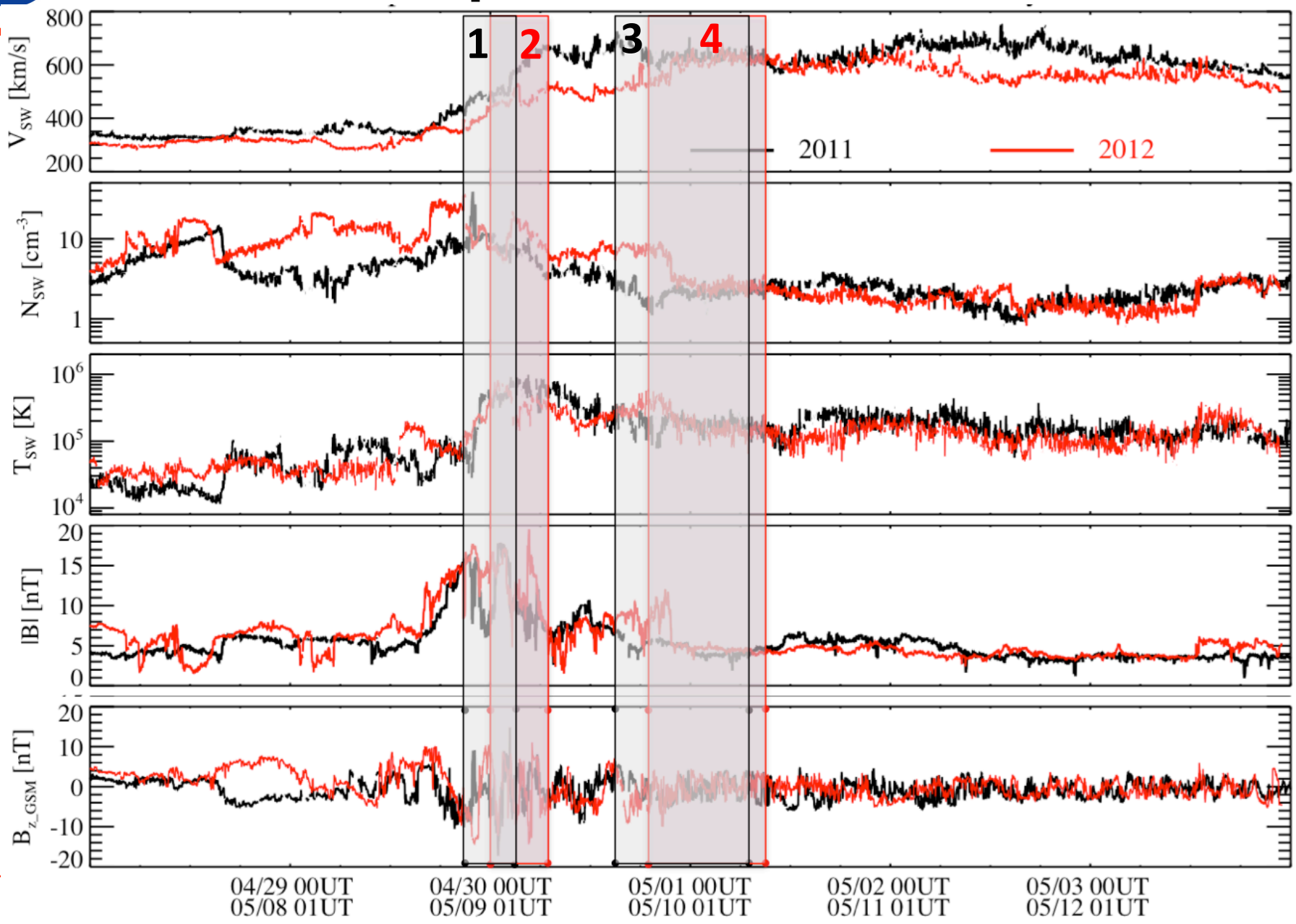



Quiet time average

Fractional difference

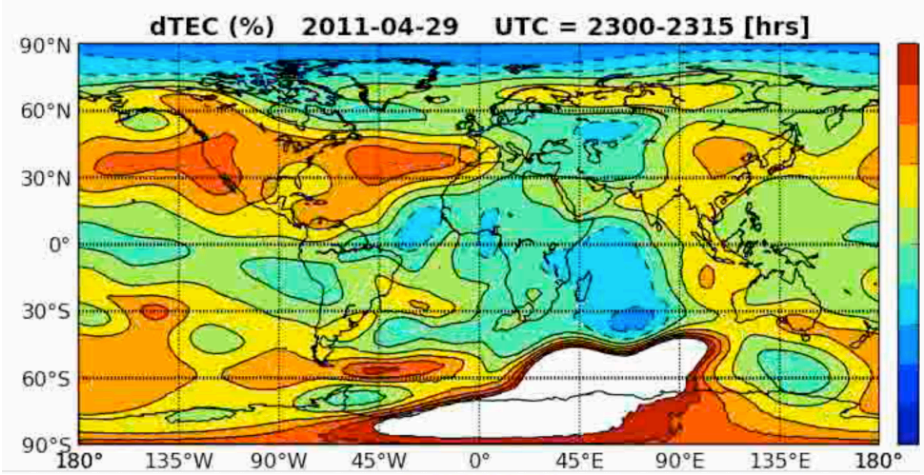
# Ionospheric “Features”

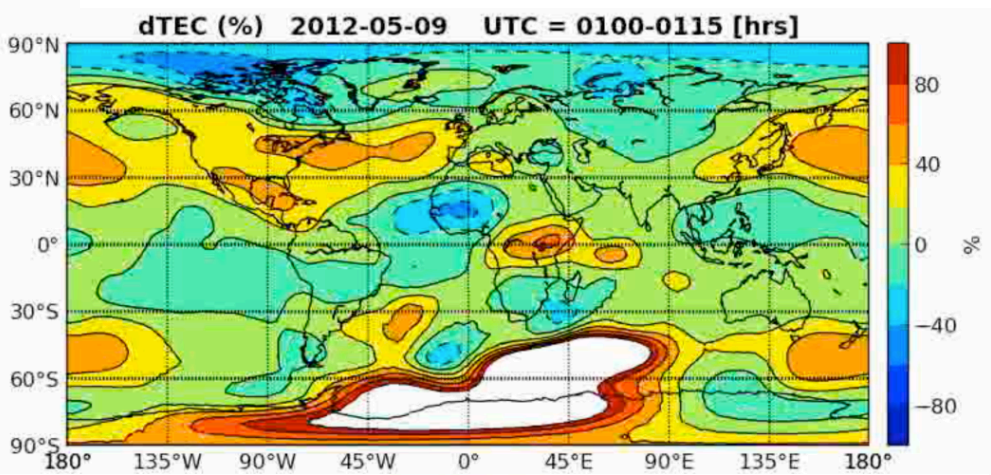


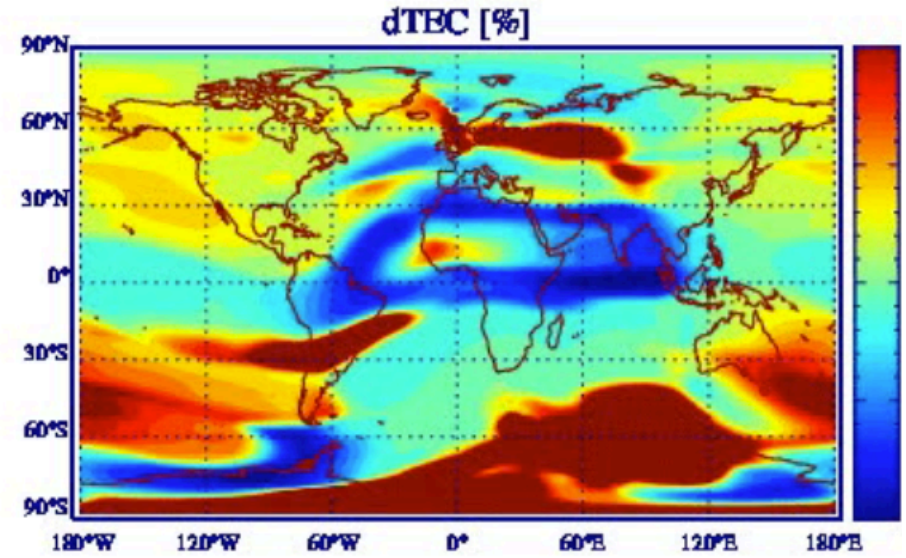
# Feature Identification

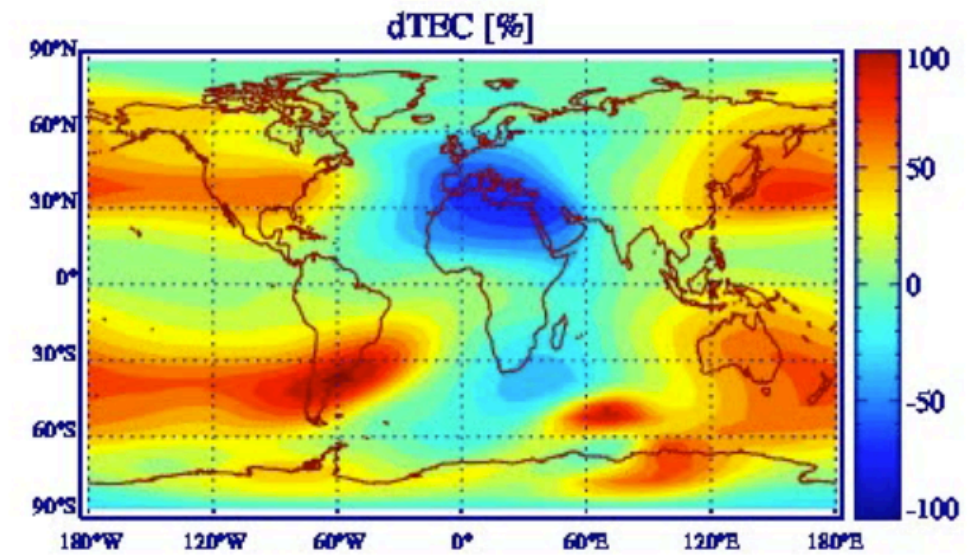
1. 2011 – localized, larger increase ~ 6 hours duration
2. 2012 – broader, smaller increase ~ 7 hours
3. 2011 – localized, lower latitude increase ~ 16 hours
4. 2012 – localized, lower latitude decrease ~ 14 hours

# Modeling Results: GITM and TIEGCM



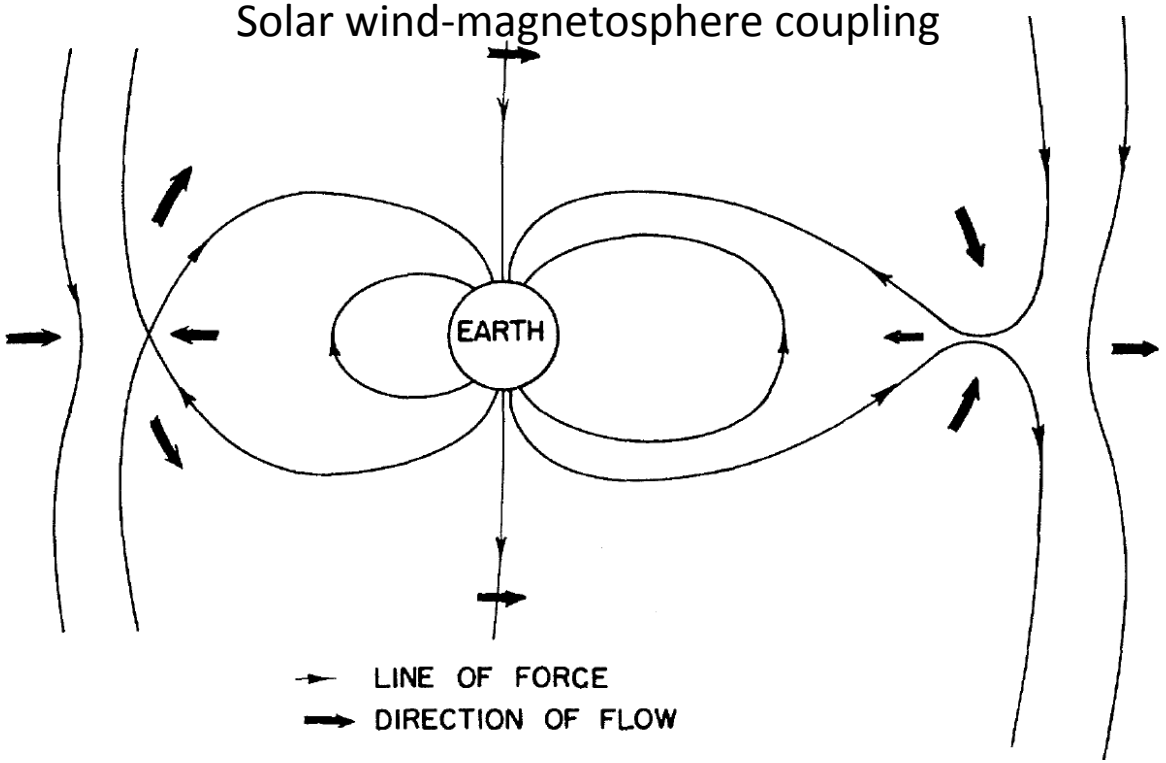




SWMF -> GITM

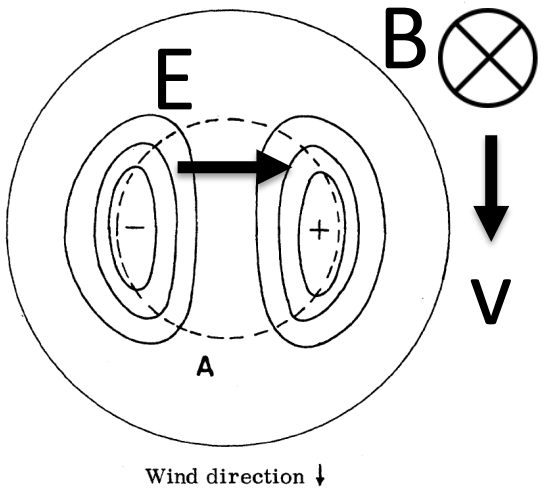
Weimer -> TIEGCM

# High Latitude Convection, Frictional Heating

Solar wind-magnetosphere coupling




"hydromagnetics" Dungey, 1961




Simulated version: SWMF MHD

Drives GITM

GITM thermal balance equation

$$\mathcal{Q} = Q_{\mathrm{EUV}} + Q_{\mathrm{NO}} + Q_{\mathrm{O}} + \frac{\partial}{\partial r}\left((\kappa_{\mathrm{c}} + \kappa_{\mathrm{eddy}})\frac{\partial T}{\partial r}\right)$$

$$+ N_e \frac{\overline{m}_{\mathrm{i}}\overline{m}_{\mathrm{n}}}{\overline{m}_{\mathrm{i}} + \overline{m}_{\mathrm{n}}} \nu_{\mathrm{in}} (\mathbf{v} - \mathbf{u})^2$$

Frictional heating (ions and neutrals)

Ridley, Deng, Toth (2006) "The global ionosphere-thermosphere model", JASTP

**v** is ion velocity
**u** is neutral velocity

# High Latitude Inputs to GITM: Driven by the Solar Wind

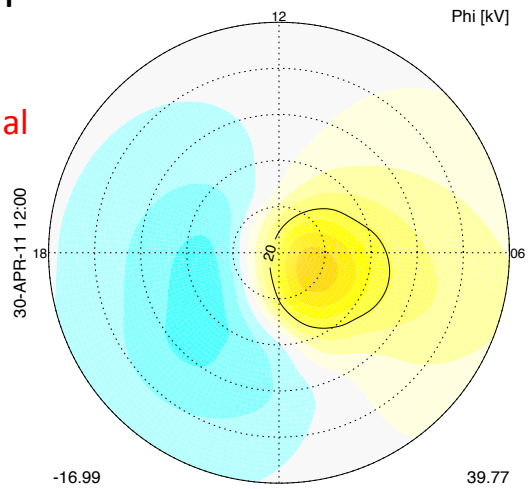
30 April 2011
12 UT

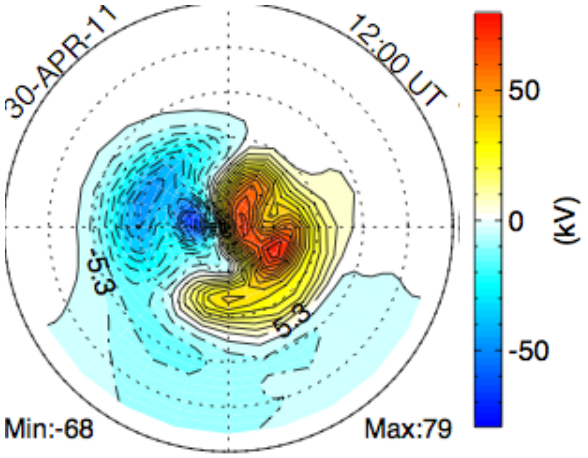
SWMF

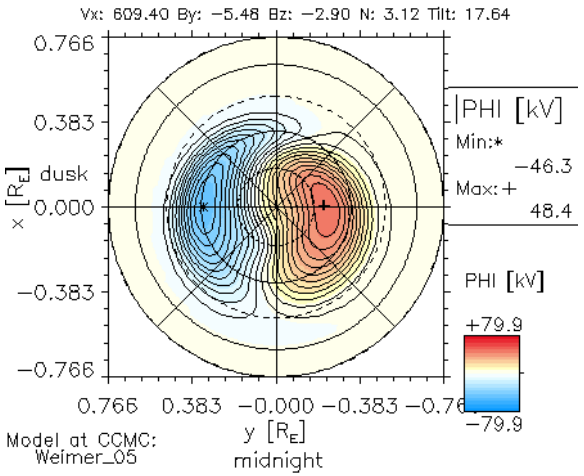
AMIE

Weimer

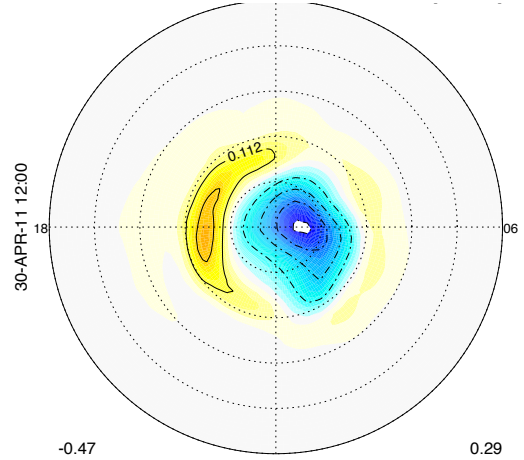
Potential

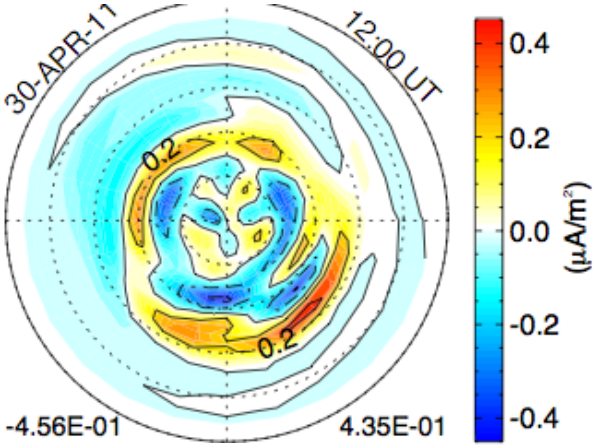


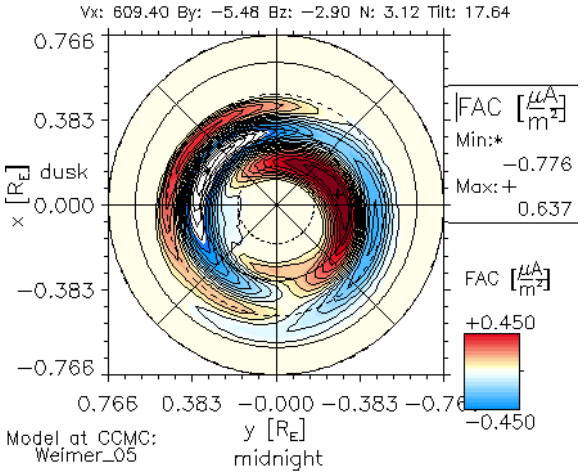



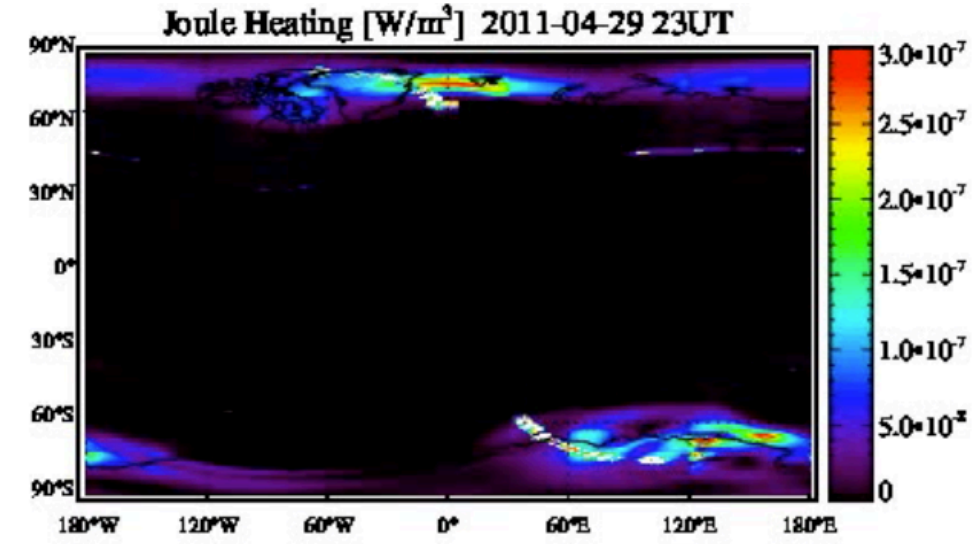

FAC

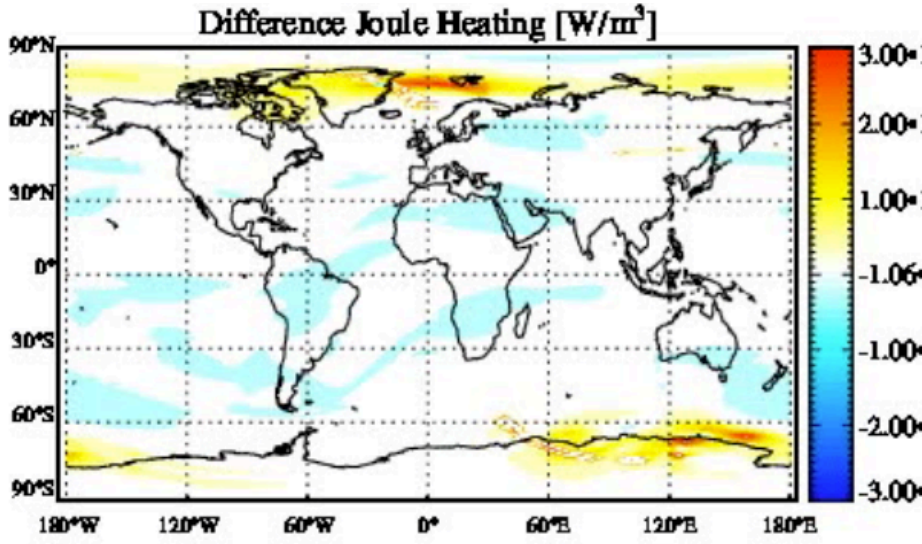


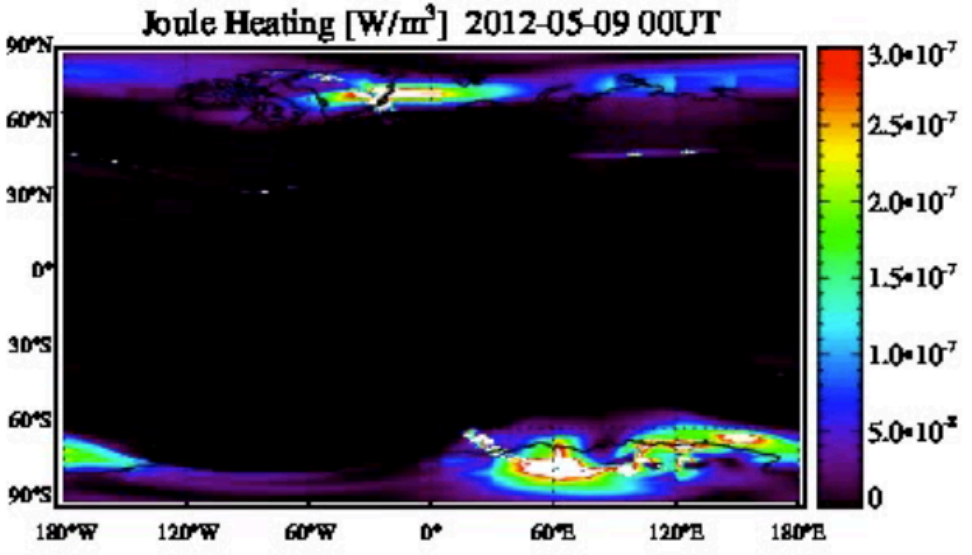



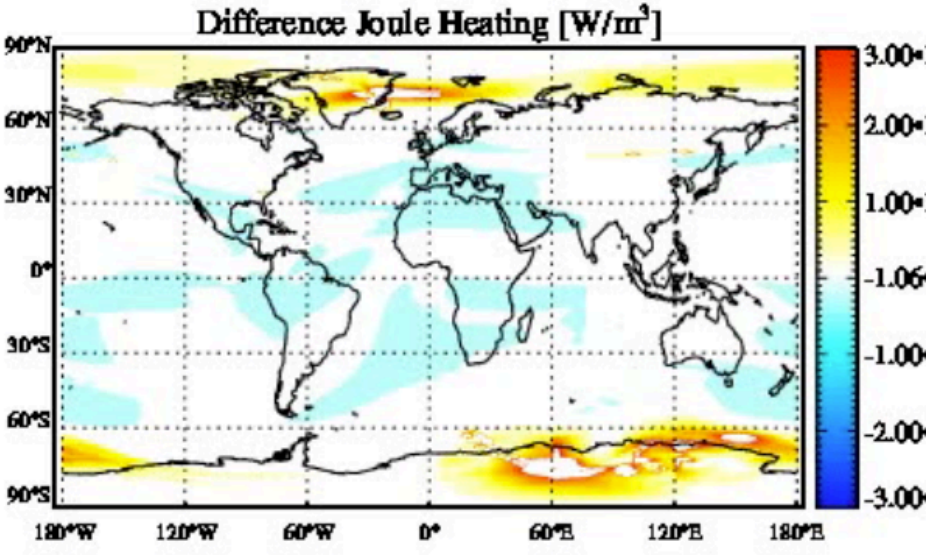



# Joule Heating Comparison: SWMF Driving GITM



# Non-MHD: Particle Precipitation

- Electron precipitation dramatically changes ionospheric conductivity, and thus the convection pattern and Joule (frictional) heating
- Electron precipitation is an additional heating source
- Significant challenges: requires MHD and kinetic effects modeling
- Connection to solar wind less direct
- "Shielding" of penetration electric fields also falls in the category of requiring combining MHD with kinetic effects
- More on that in the next segment

# Towards Predictive Capability for Space Weather Models

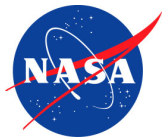
"***A primary goal of the LWS Program should be the development of first-principles-based predictive and specification models for the coupled Sun-Earth system***…predictive capabilities require a systems approach with cross-disciplinary modeling…" LWS SDT report 2003

"While metrics provide a means for the objective assessment of **long-term model improvement**, model validation…is required for identifying and documenting model strengths and weaknesses." Spence et al., JASTP 2004

- **Transition from "proof of concept" to predictive capability**
- **Degree of agreement between models and data is objectively determined**
- **Model agreement and disagreement with data are on equal footing**
- **Model uncertainty estimates are crucial**
  - **Multi-model comparisons**
- **Any and all data are valuable, potentially providing critical insights towards model improvement**
  - **Global models are globally correlated**
- ***Understanding is improved* as predictive capability is developed**
  - **Not just algorithm improvement**

# Summary

- Forecasting distinct ionospheric features caused by solar wind disturbances
- What limits forecast accuracy?
  - How does the magnetosphere-ionosphere-thermosphere respond as an interconnected system?
  - Multiple models and inputs, driver observations are key
- HSS is easier to forecast on the solar side, but may be more dependent on initial conditions
  - Collaboration w/ Schunk/MEPS effort
- Next step: forecasts w/ uncertainties
- Significant improvement expected following launch of GOLD and ICON missions
  - GOLD's global view will revolutionize our understanding of global thermosphere-ionosphere storms

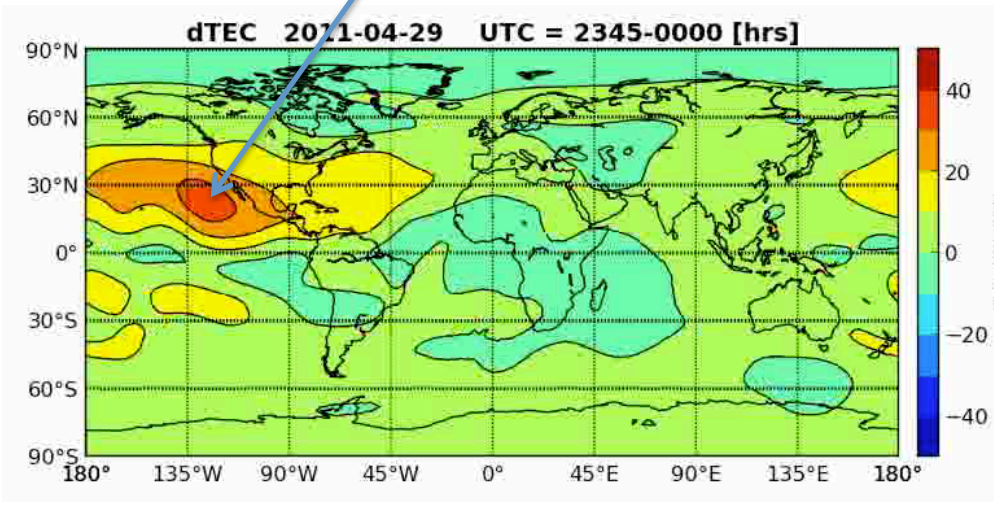


# BACKUP SLIDES

# Defining an Ionospheric Forecast

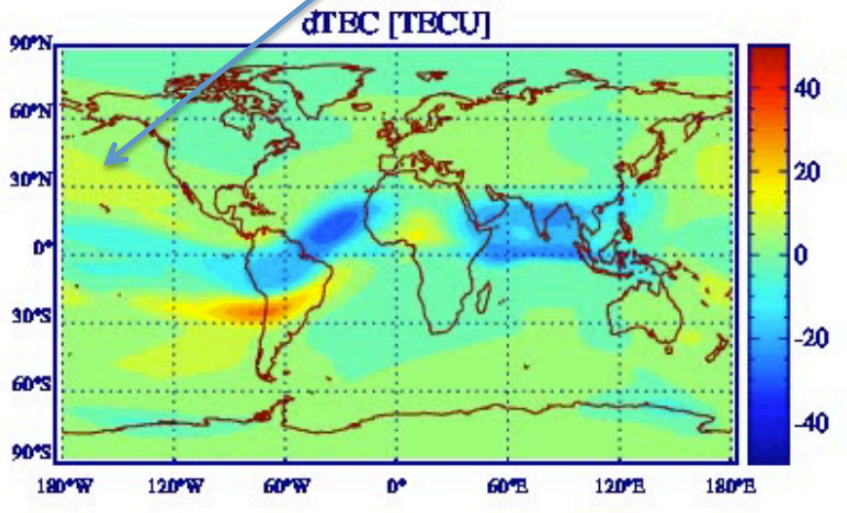
Solar wind ➔ Storm Phase ➔ TEC “feature”

Location 1




TEC Difference Map

Location 2




GITM (Weimer input)

# 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

# Overview/Notes

- HSS solar wind -> storm phase -> TEC feature
- What caused the Lu supersubstorm where winds dominated? Preconditioning?
- The solar wind “zoo”
- Multi-model approaches and why they are important
  - Theoretical basis
- The forecasting challenge: validation vs forecast mode
- Case studies

# 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

# Bizarre

- **Things that reduce forecast accuracy:**
  - **Adding more physics**
  - **Keeping more data**
- **Things that improve forecast accuracy:**
  - **Using contradictory physical representations of the same phenomenon**

- **"What does it all mean?"**
  - **I.e. what does model agreement with data mean, and what does disagreement mean in a scientific sense?**

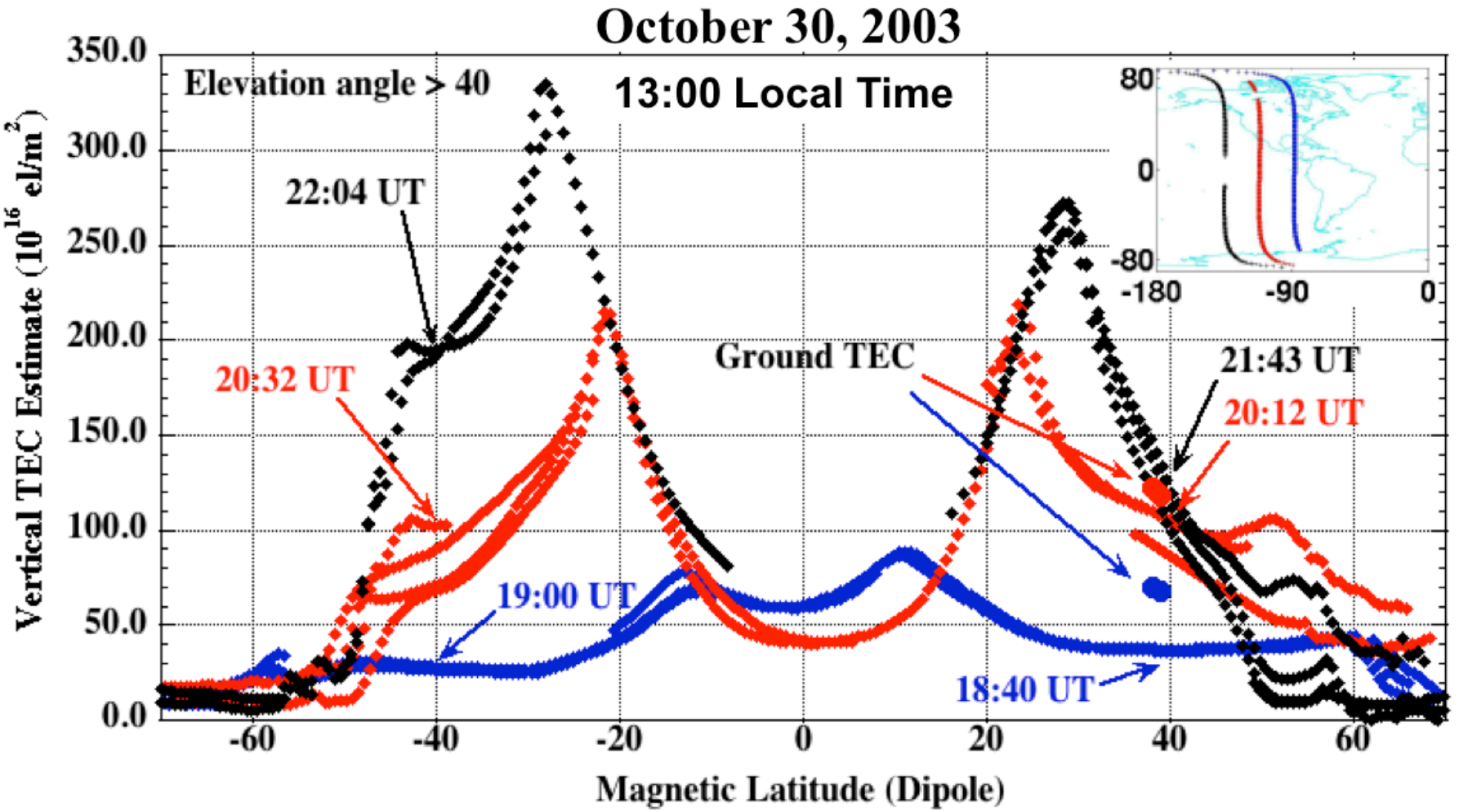
# Model Assessment

- What does "good agreement" between a model and observation mean?
- Start with a functional definition based on a forecast you want to make: E.g. TEC to 20%
  - E.g. if we could forecast TEC in the mid-latitude ionosphere to 20% accuracy 3 days in advance, that would be considered a major accomplishment
  - Even if it were just TEC changes to 20%
- As a physics-based model, an accurate forecast already implies a number of physical inputs are forecast accurately as well
- "Good agreement" means the physical drivers agree with observations such that we can derive 20% TEC agreement

# Model Assessment (2)

- As a model “validator” you are answering the “there exists” question
- As a forecaster you are trying to break the model

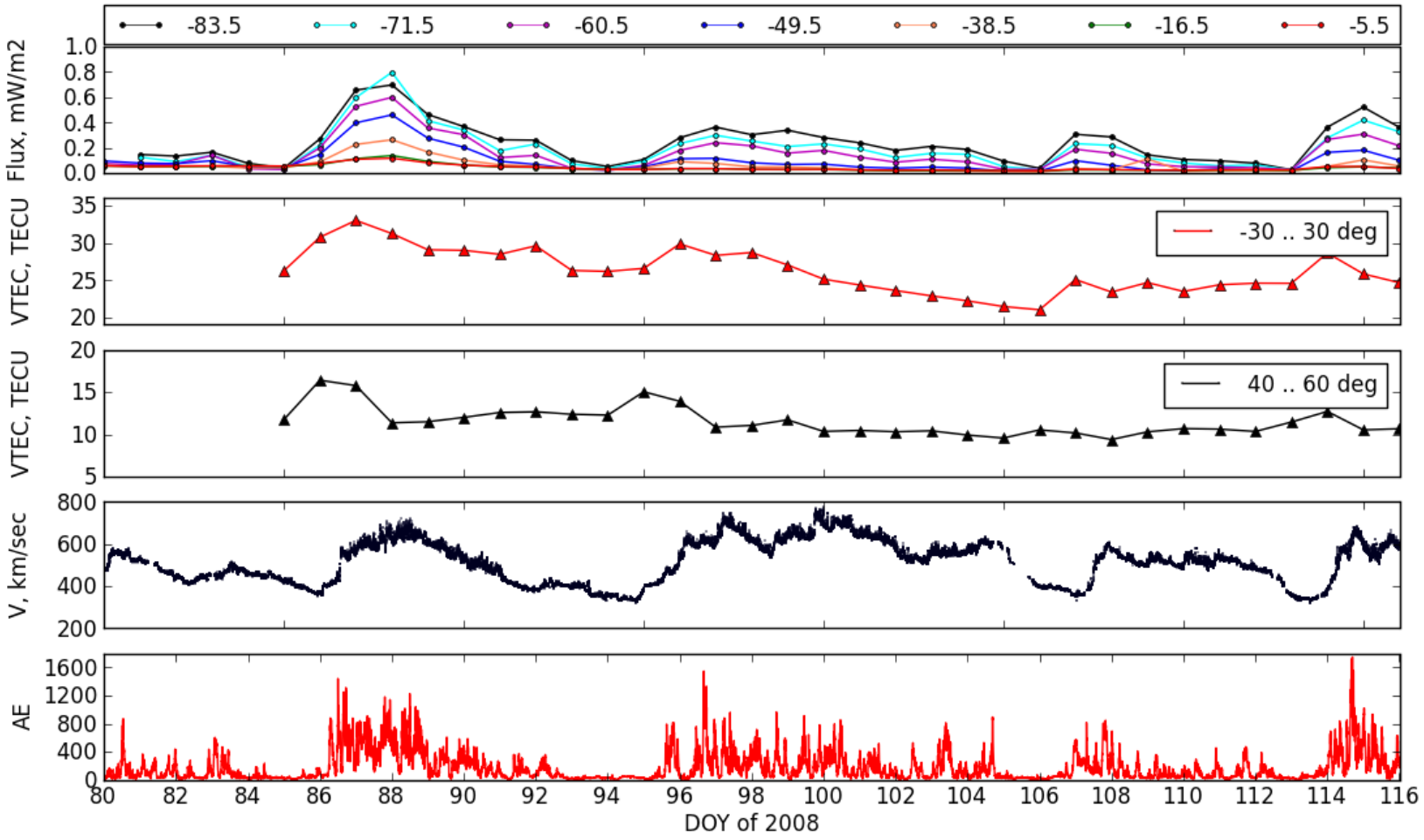
# Global Perturbations




CHAMP altitude: 400 km

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

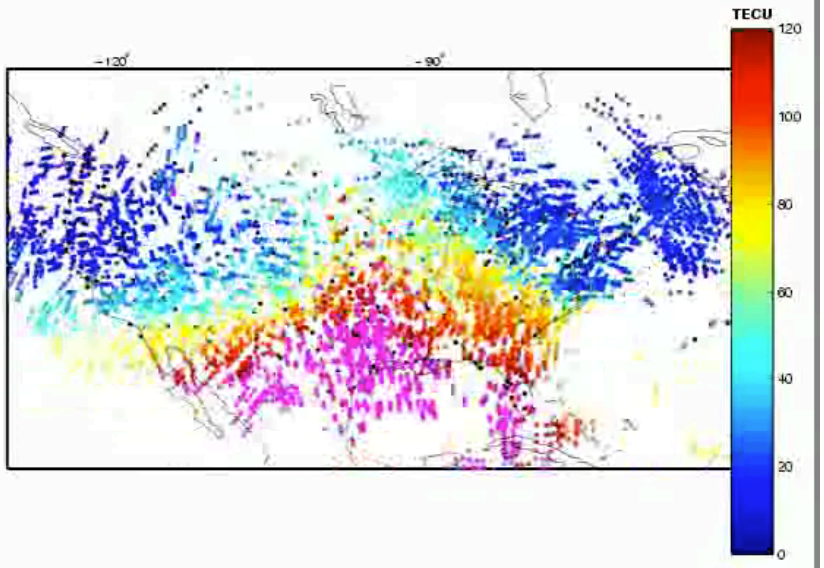
# Recurrent Activity – High Speed Streams




Ionospheric impacts are less than for CME storms

# Ionospheric Storm: October 29, 2003

October 29, 2013
1945 UT



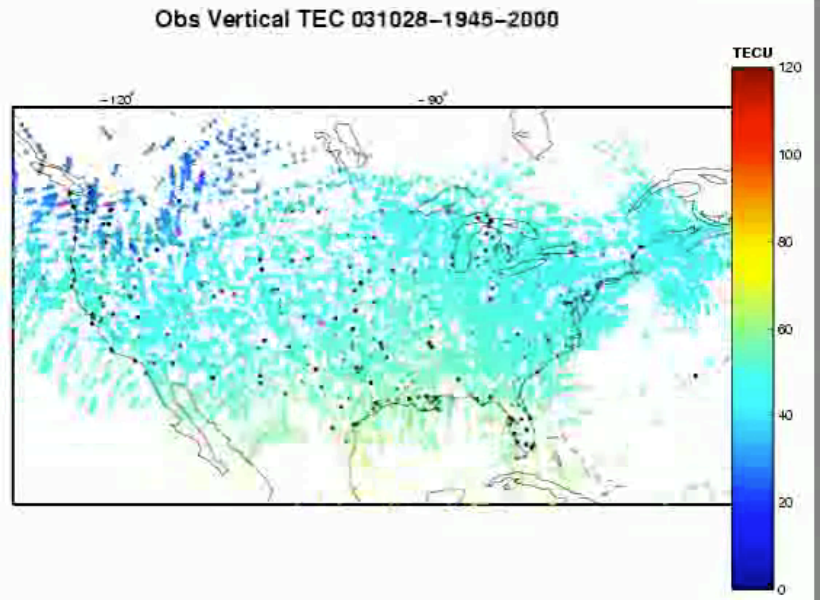

120 TECU

**Purple > 120 TECU**

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

0 TECU

October 28, 2013
1945 UT

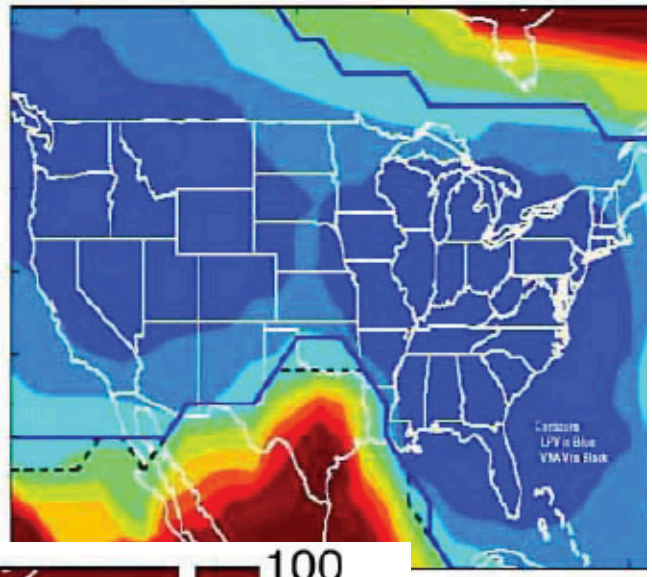


# Availability of Aircraft Navigation

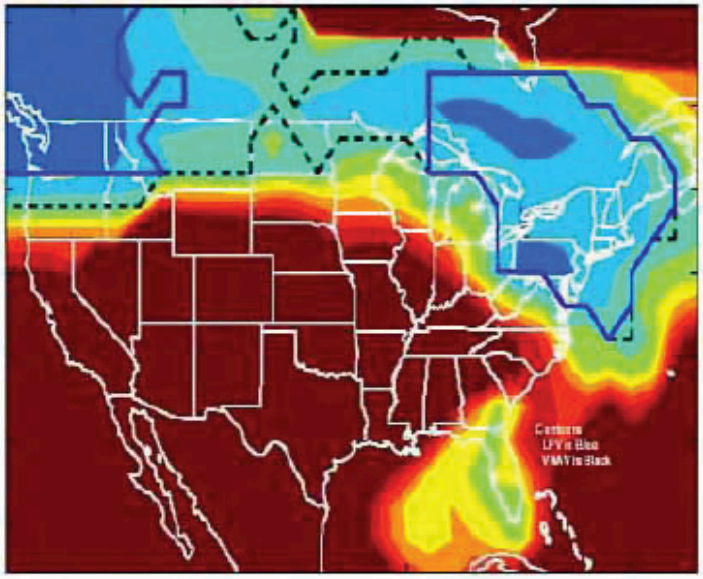
Source: FAA provided materials in “Severe Space Weather Events Understanding Societal and Economic Impacts: A Workshop Report”, National Research Council 2009

October 29, 2003

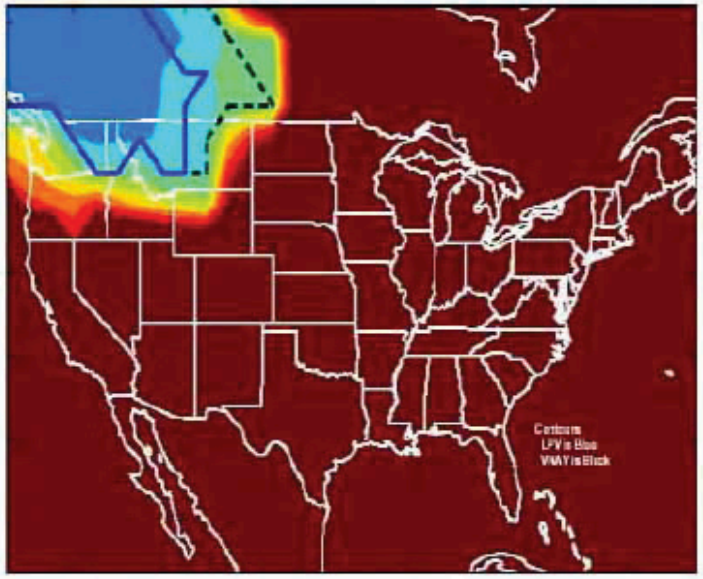
16:44 UT

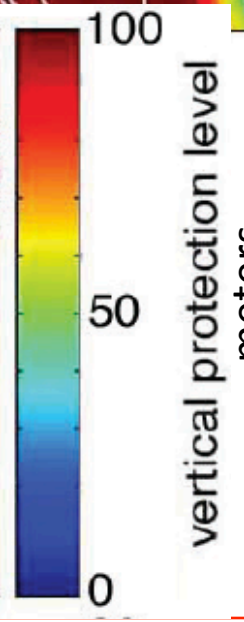


17:48 UT



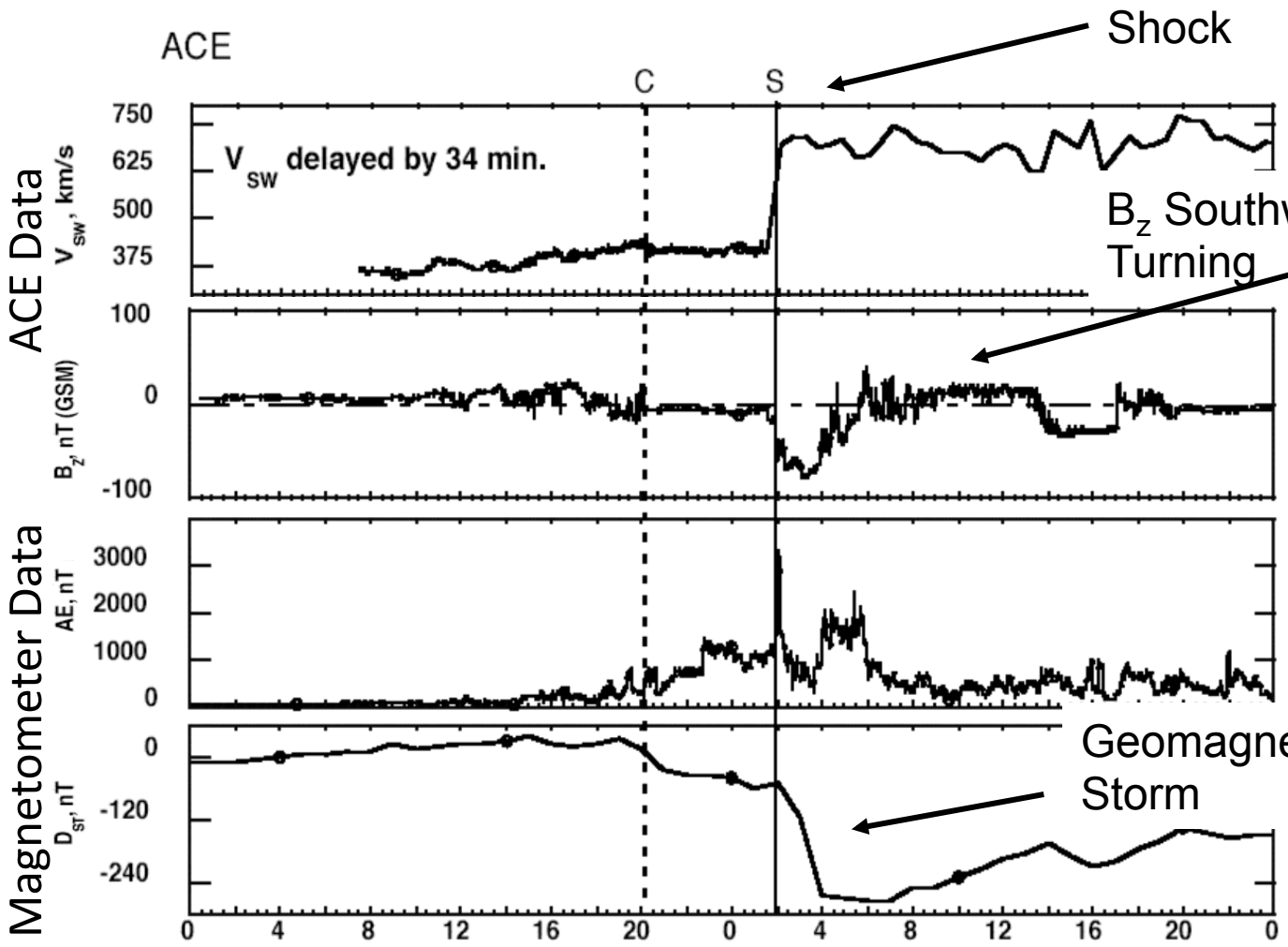
19:06 UT

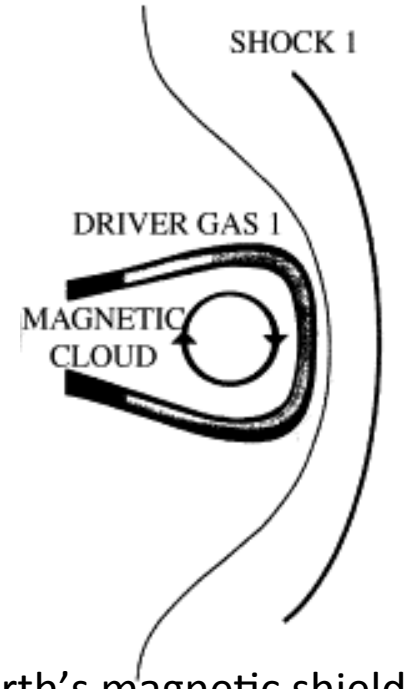




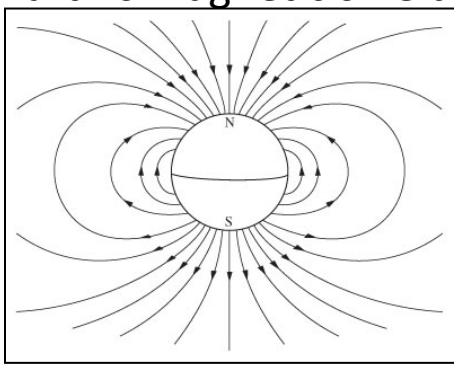

Operable level

# Solar Wind/Interplanetary Drivers

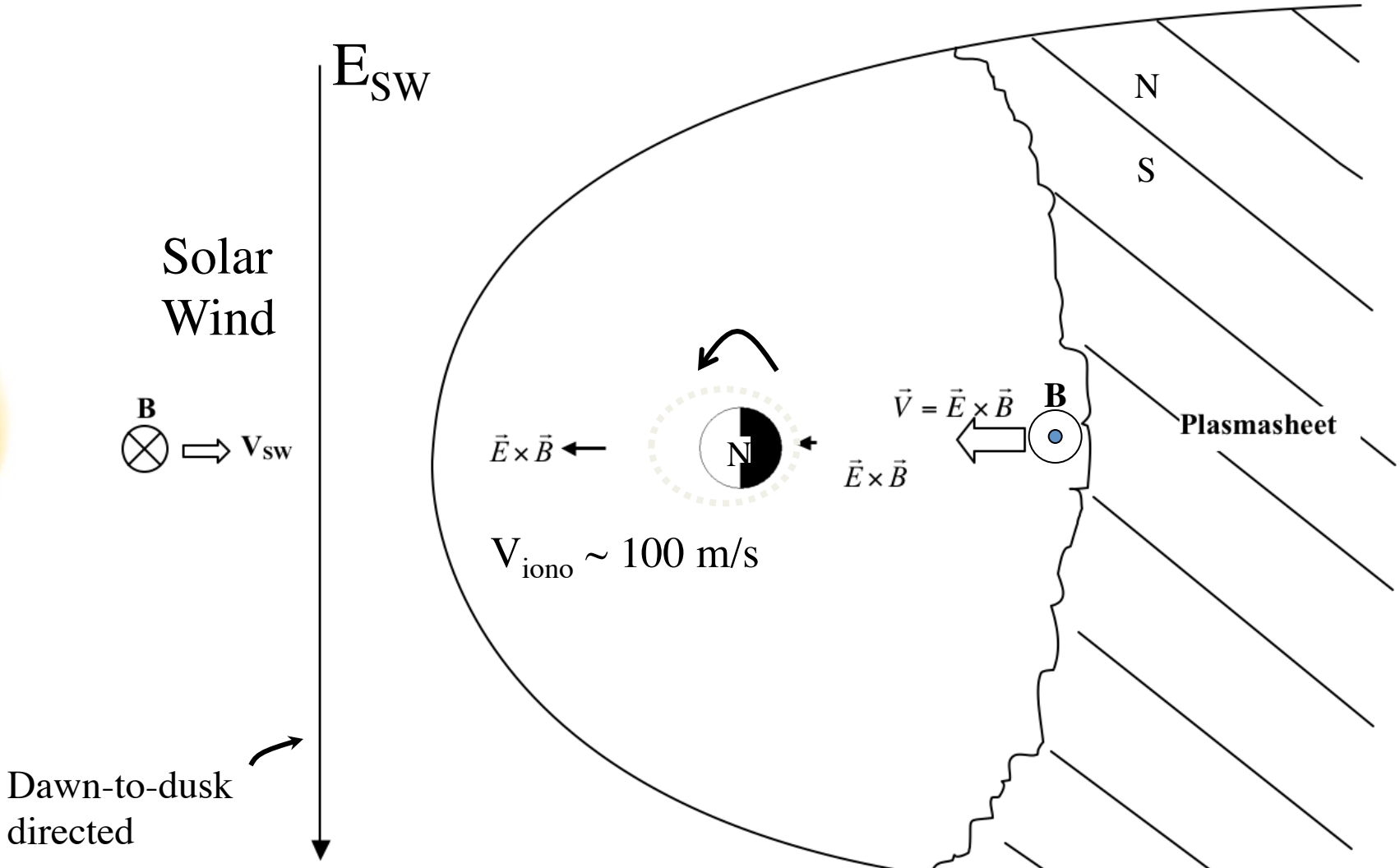



Earth's magnetic shield

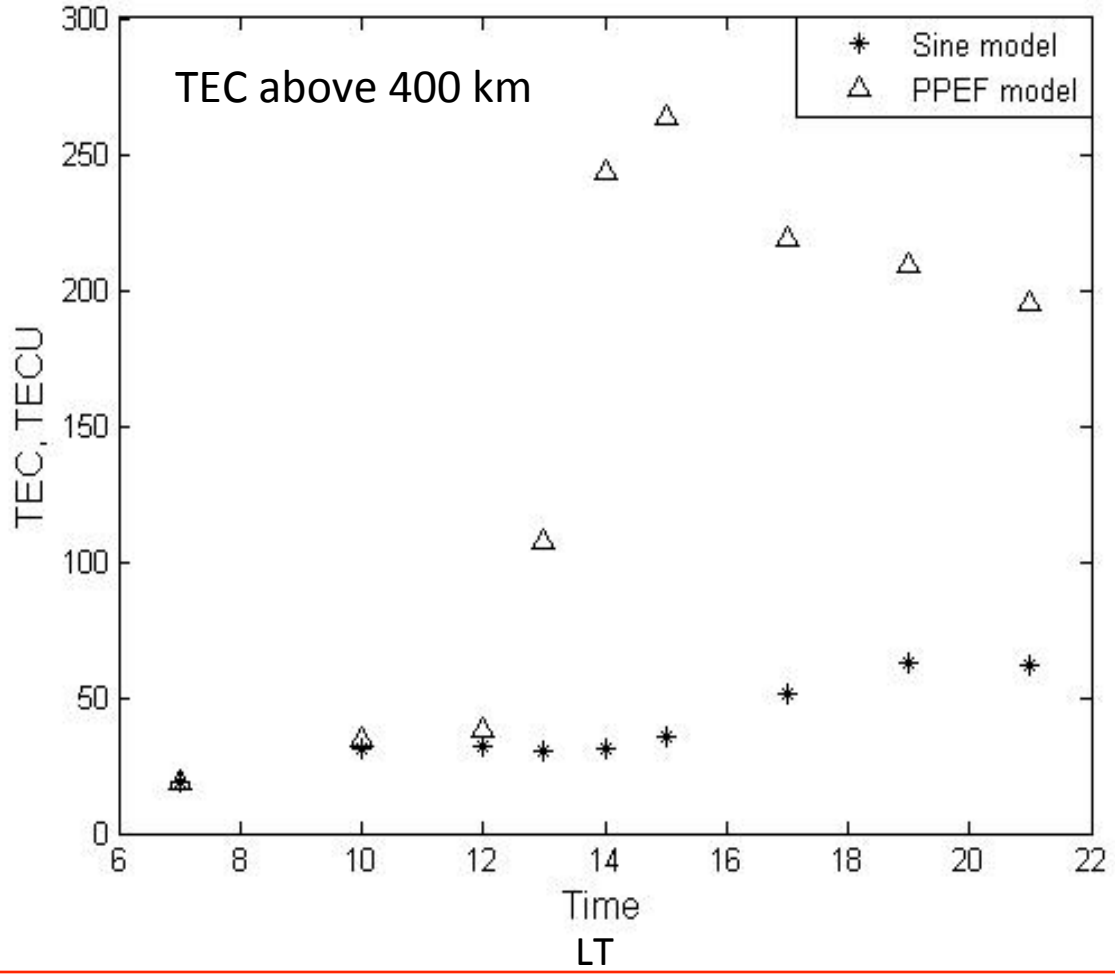


# Mechanism for Dayside TEC Increase: Ionospheric Uplift



# SAMI2 Model Run

Electric field estimate using CHAMP magnetometer data: **4 mV/m**
Ann. Geophys., 25, 569–574, 2007




Background sinusoid 0.5 mV/m

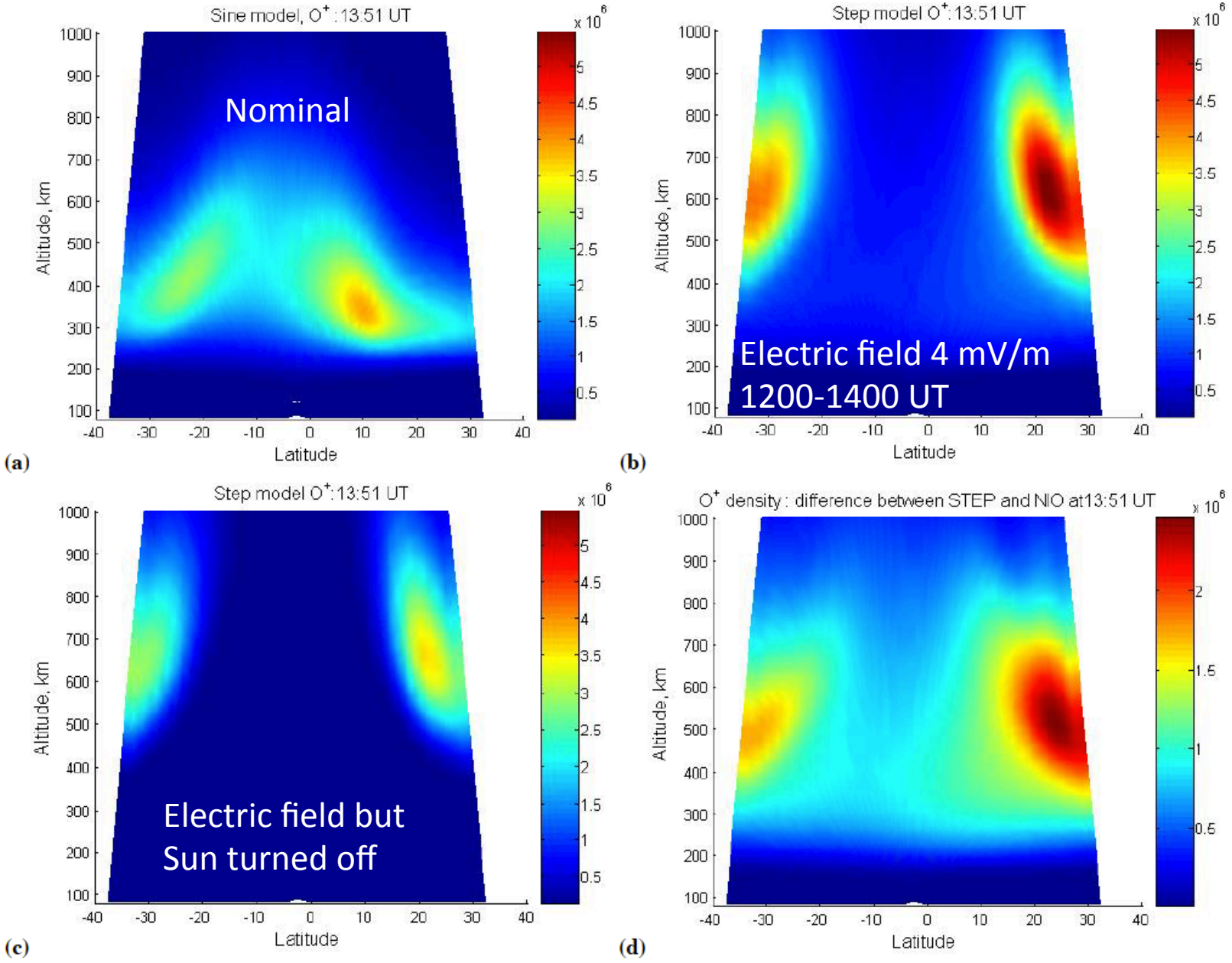
Enhanced electric field
12 - 14 LT
(single longitude model)

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

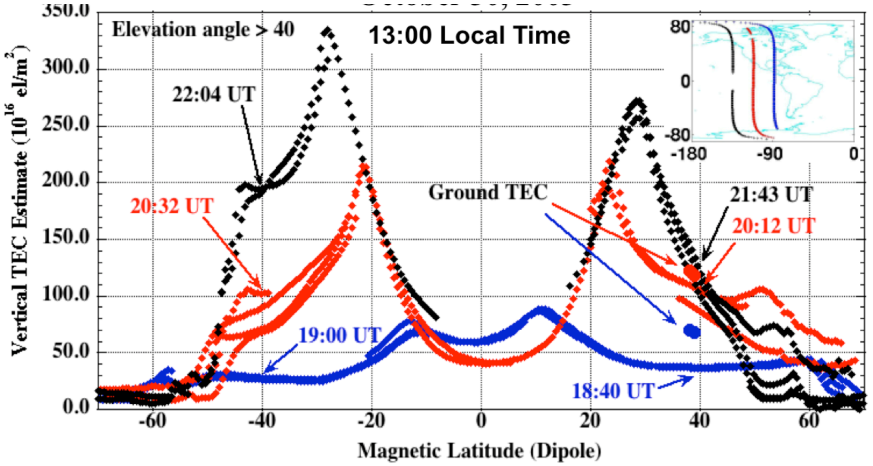



Tsurutani et al., Ann Geo 2007

SAMI-2 runs with added electric field

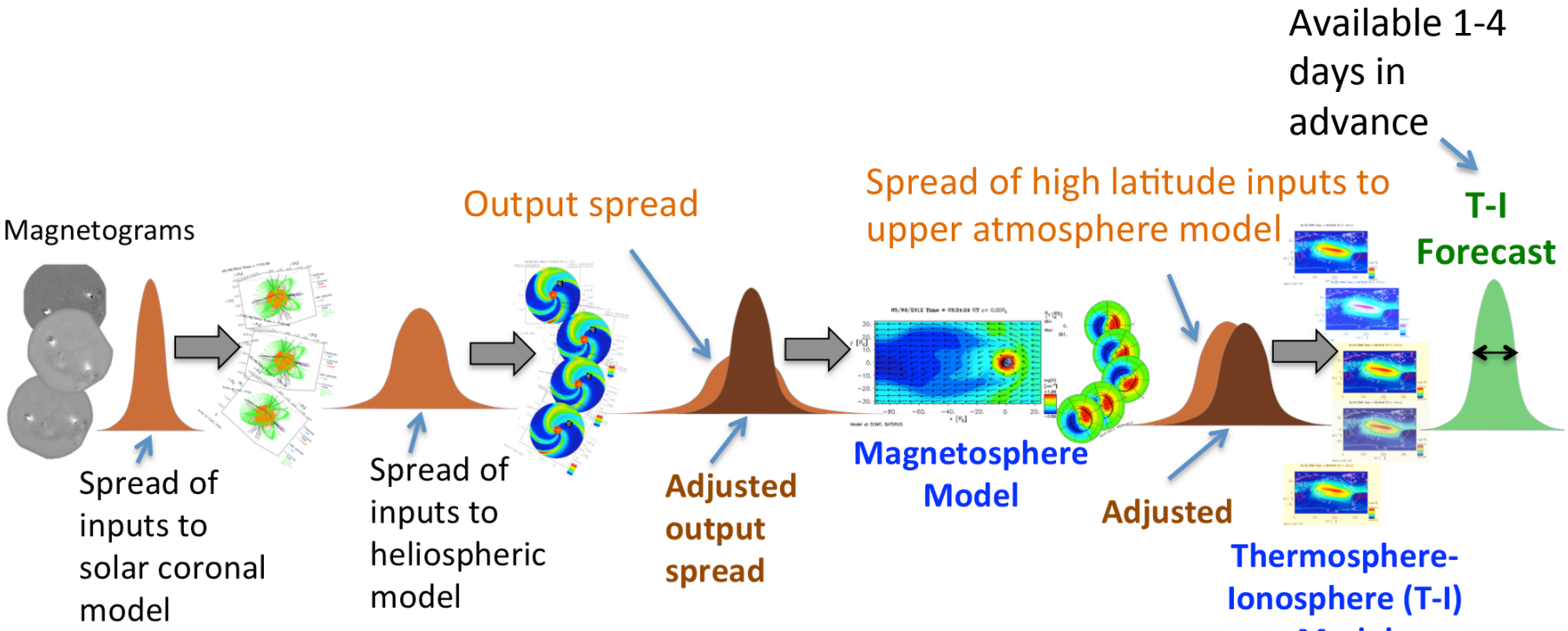
# Ensemble Forecast System

- **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

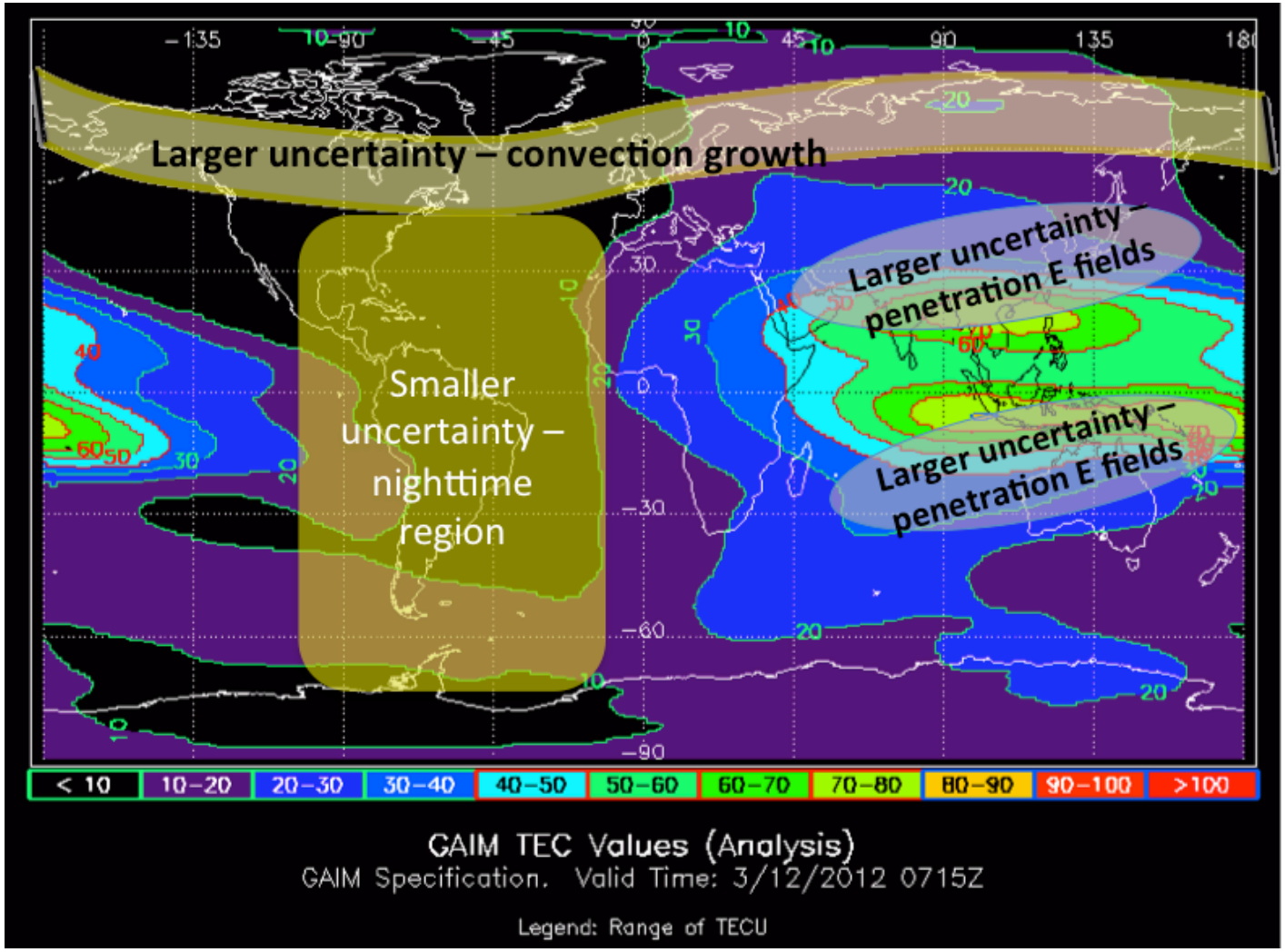
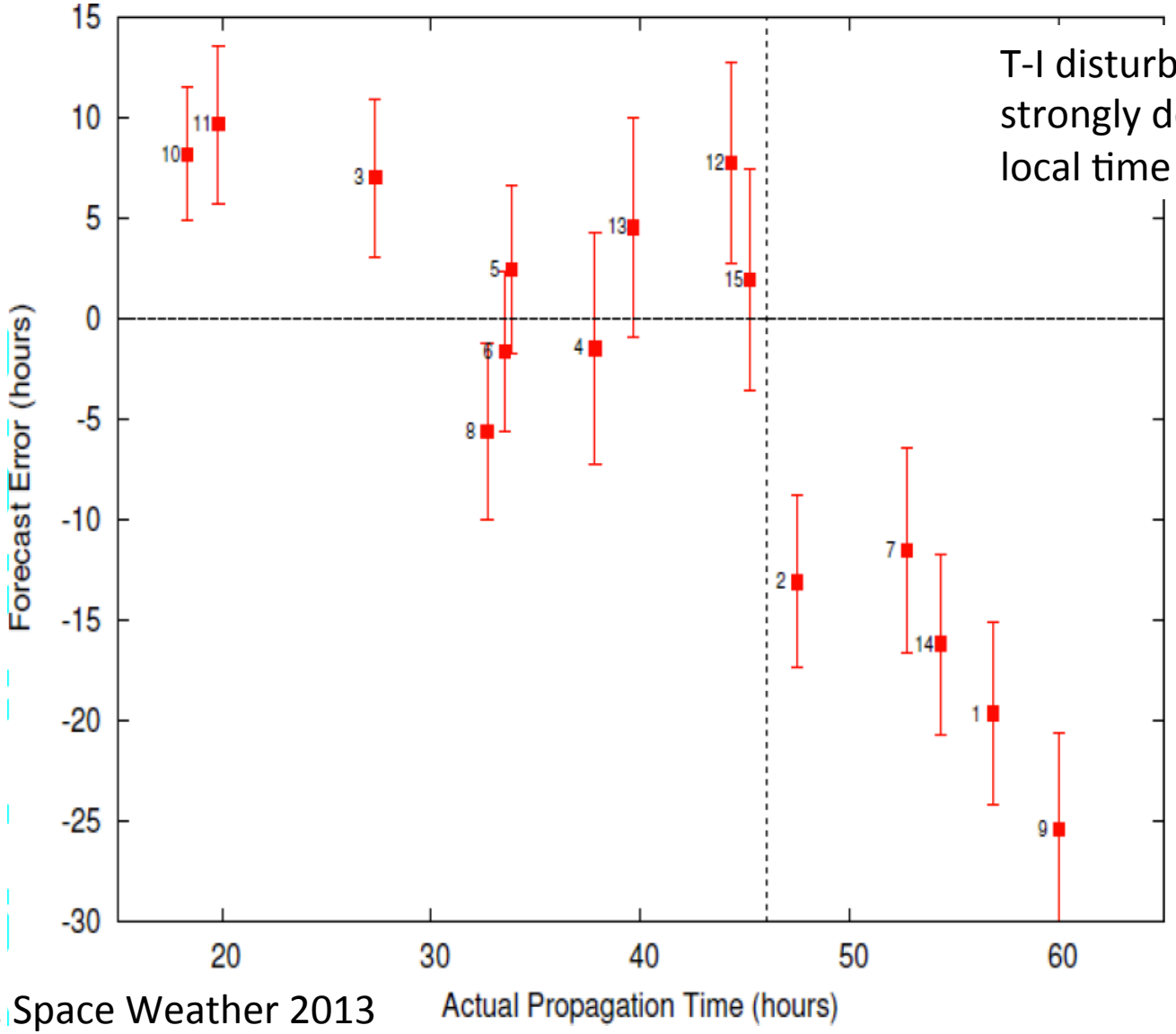



Figure adapted from AFWA map (Air Force Weather Agency)

# WSA-ENLIL + CONED Model: Disturbance Arrival Time




T-I disturbances are strongly dependent on local time

Emmons et al., Space Weather 2013

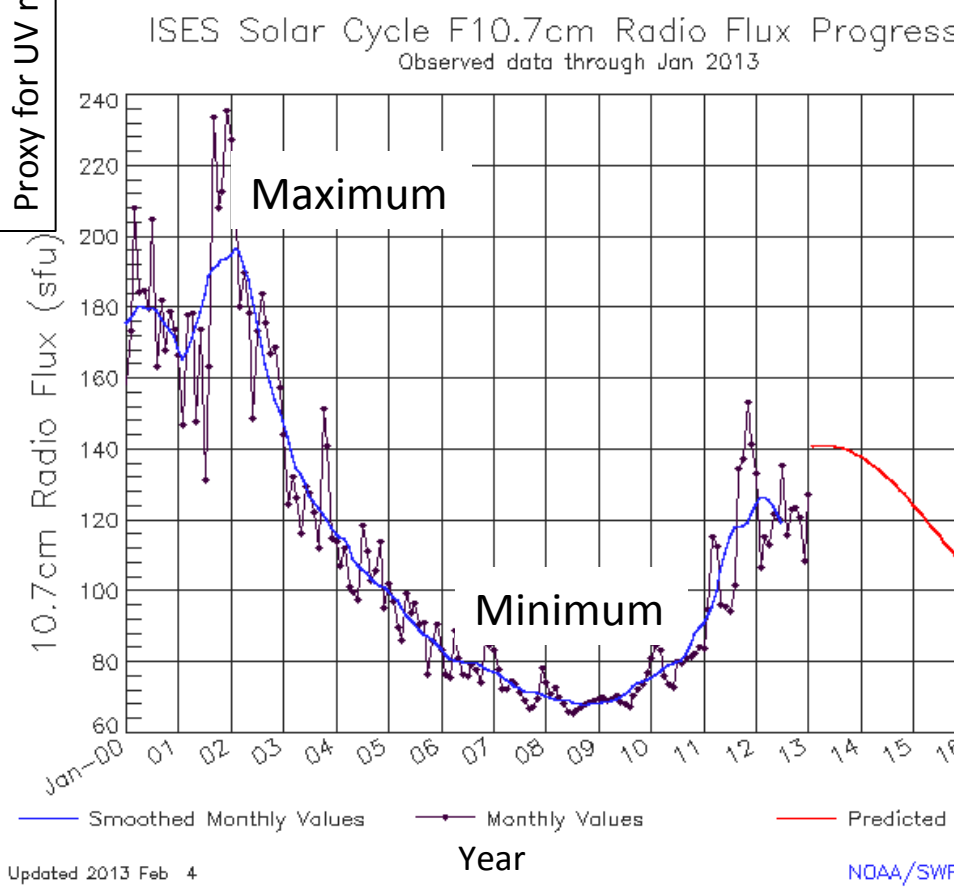
# Solar Wind Forecasts

- 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

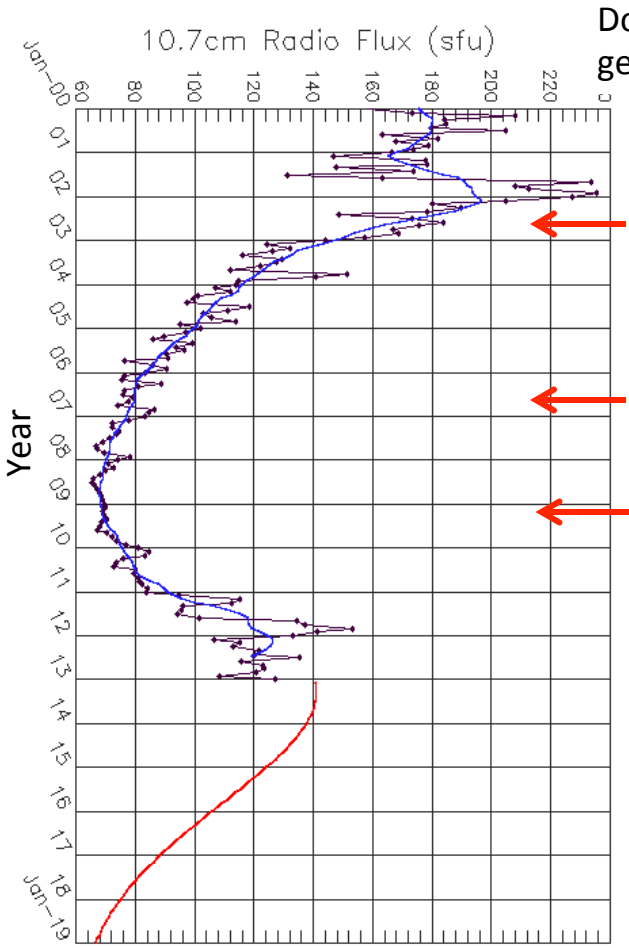
Proxy for UV radiation

"Classical" view of the solar cycle




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

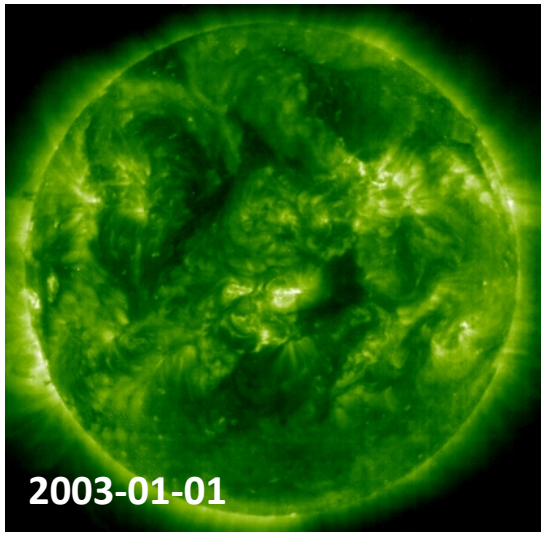
Lika Guhathakurta's view
(my interpretation)



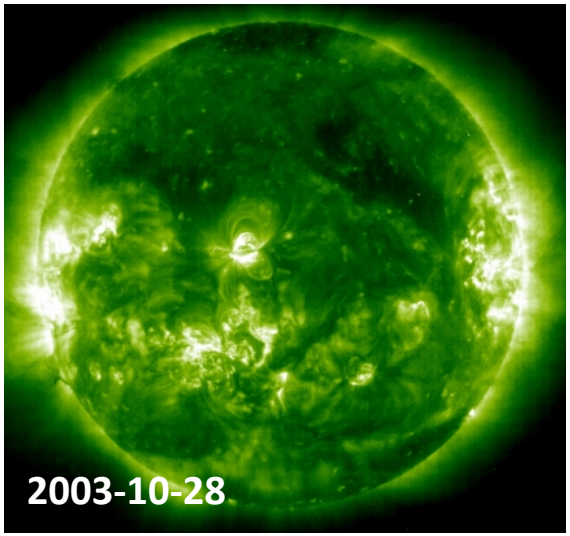

*Solar latitude

See Guhathakurta and Philips, Space Weather, 2013

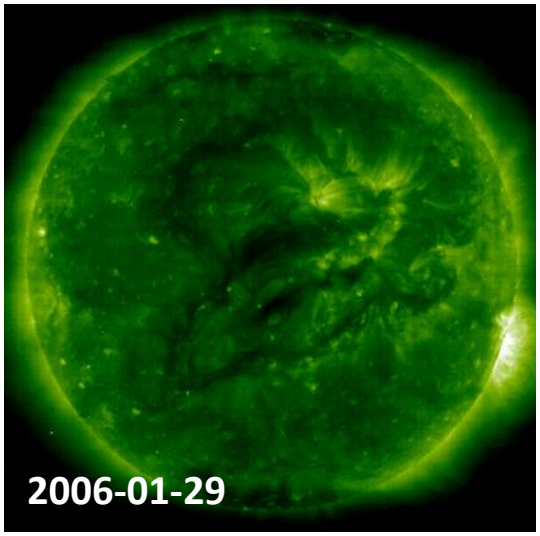
# SOHO Images – Solar Cycle



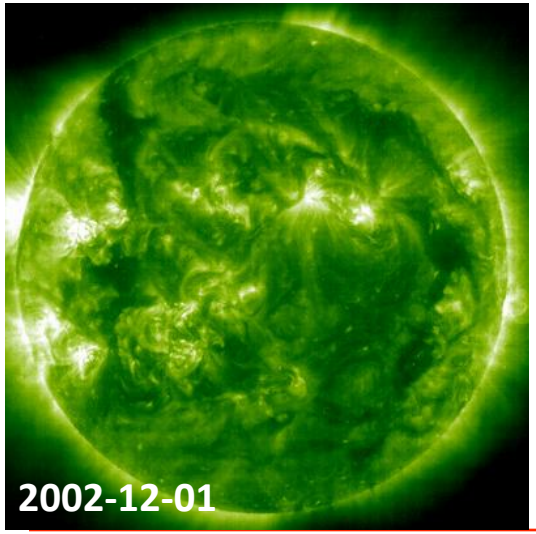

Early declining phase




Halloween storm




Declining phase

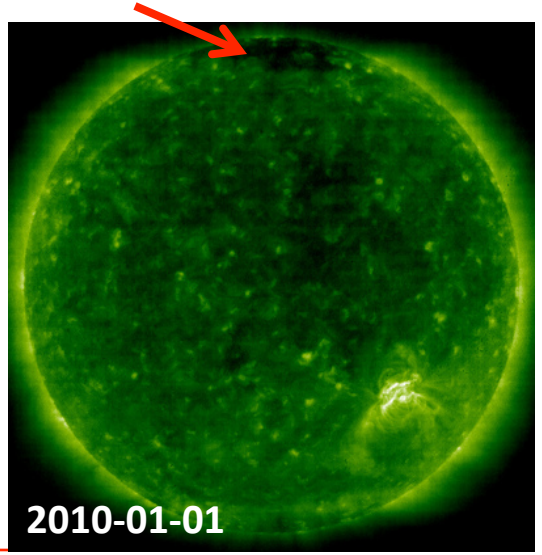



Solar maximum

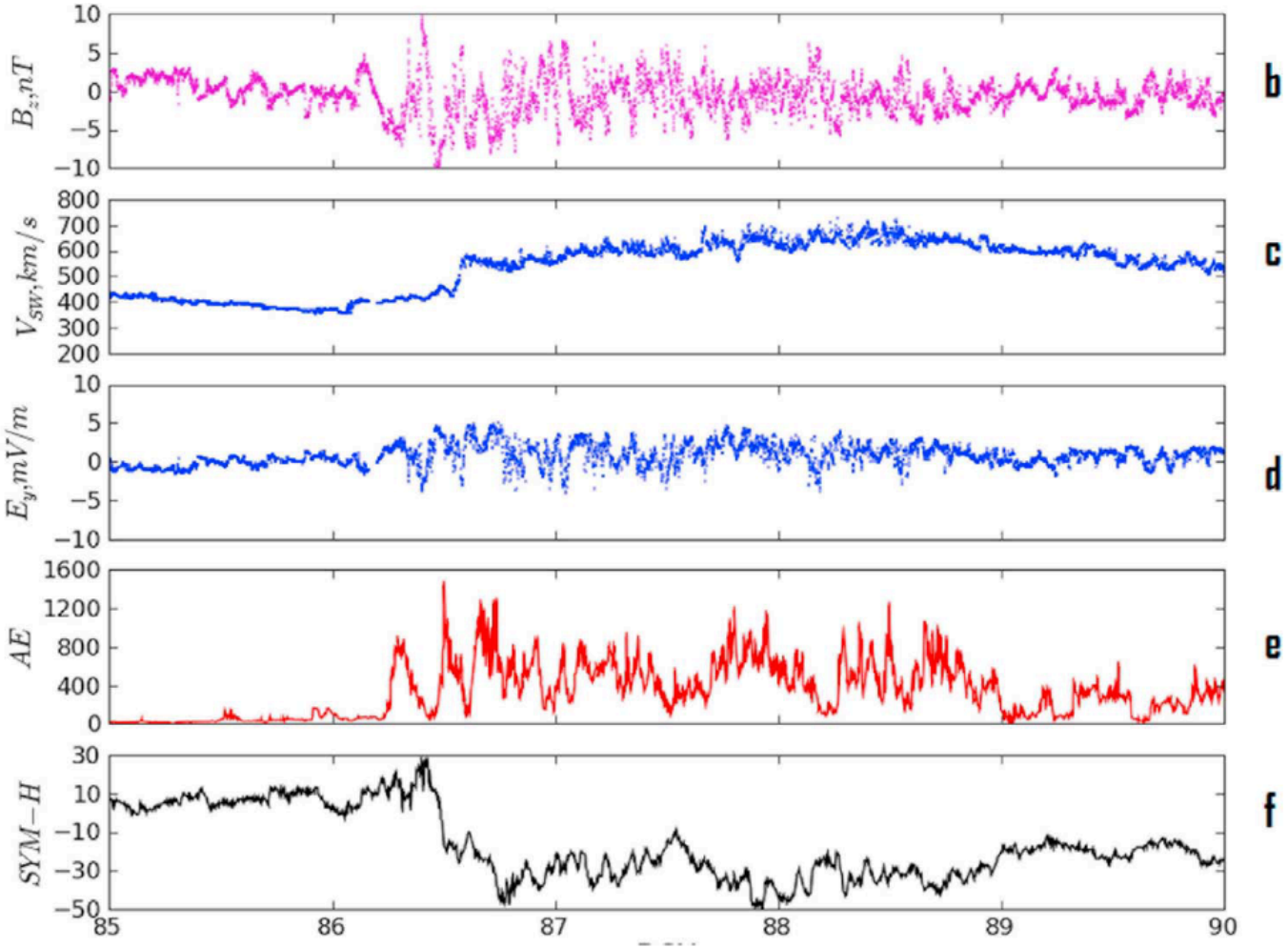
Active regions
Coronal holes

EIT 195
Fe XII
$1x10^6$ K

Solar minimum

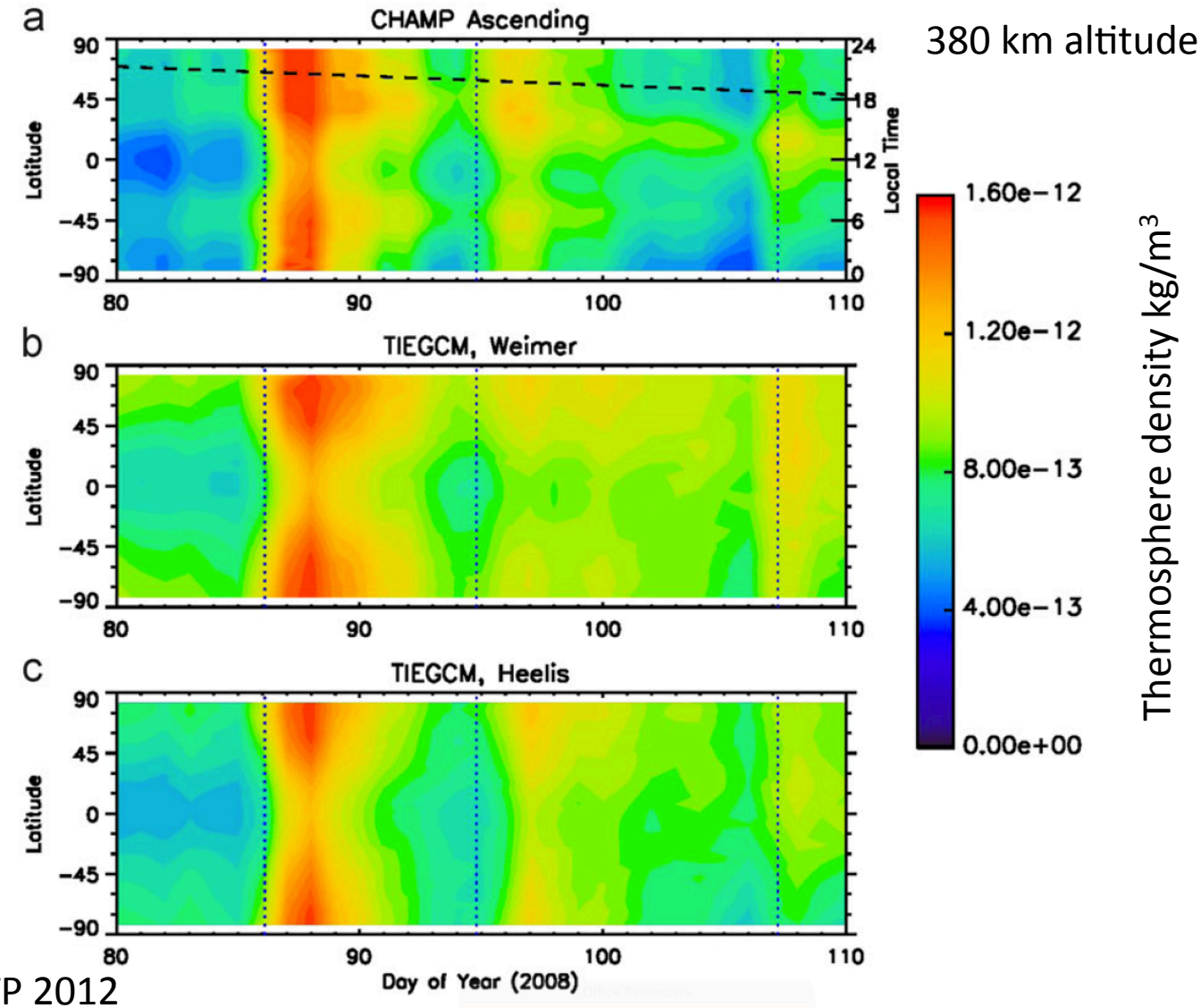


# Interplanetary Parameters – Whole Heliospheric Interval




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

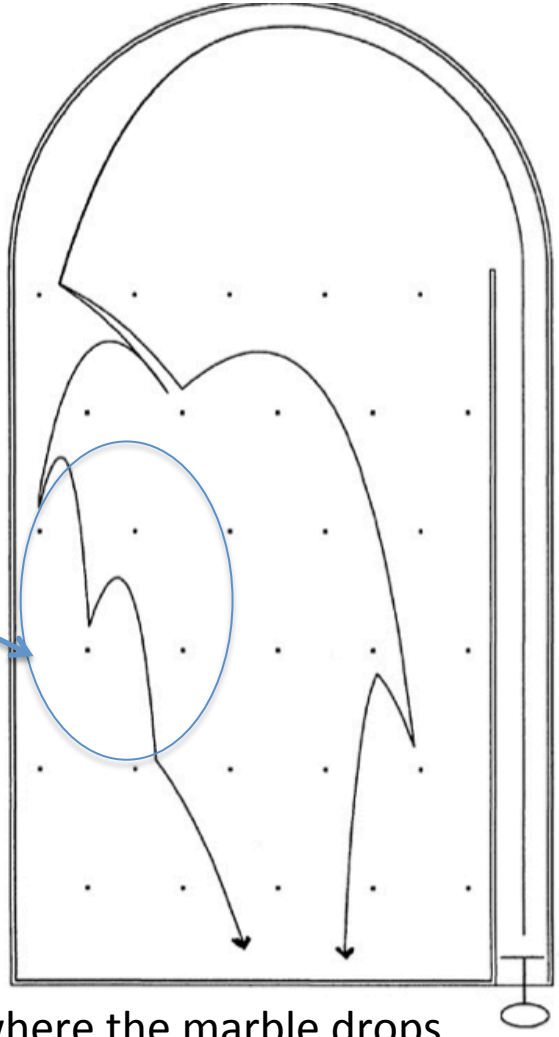
# The Forecasting Challenge

- **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



Observations here

Forecast where the marble drops

Observations here

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

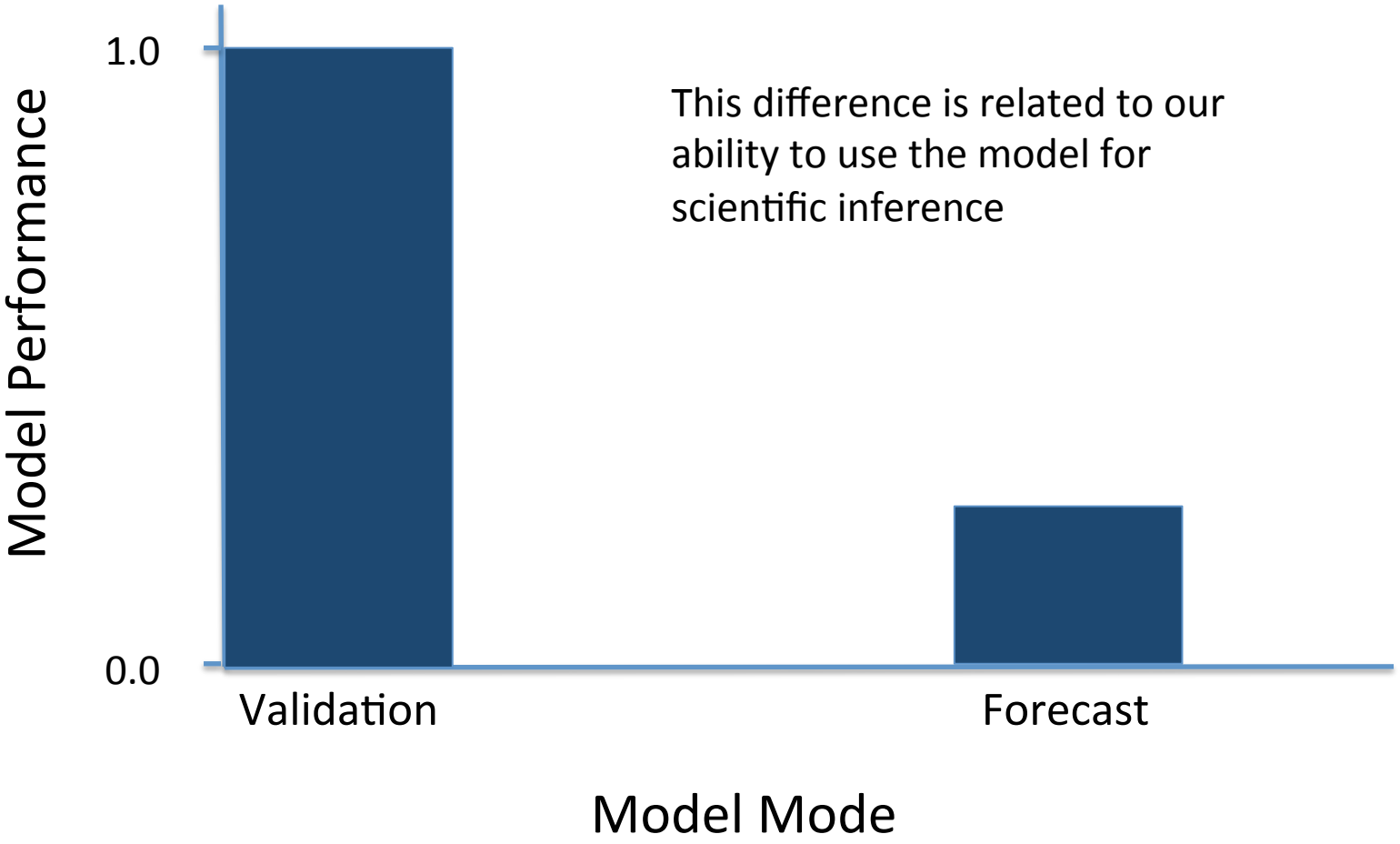
Lorenz system for atmospheric convection, 1963

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

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

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

# 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**

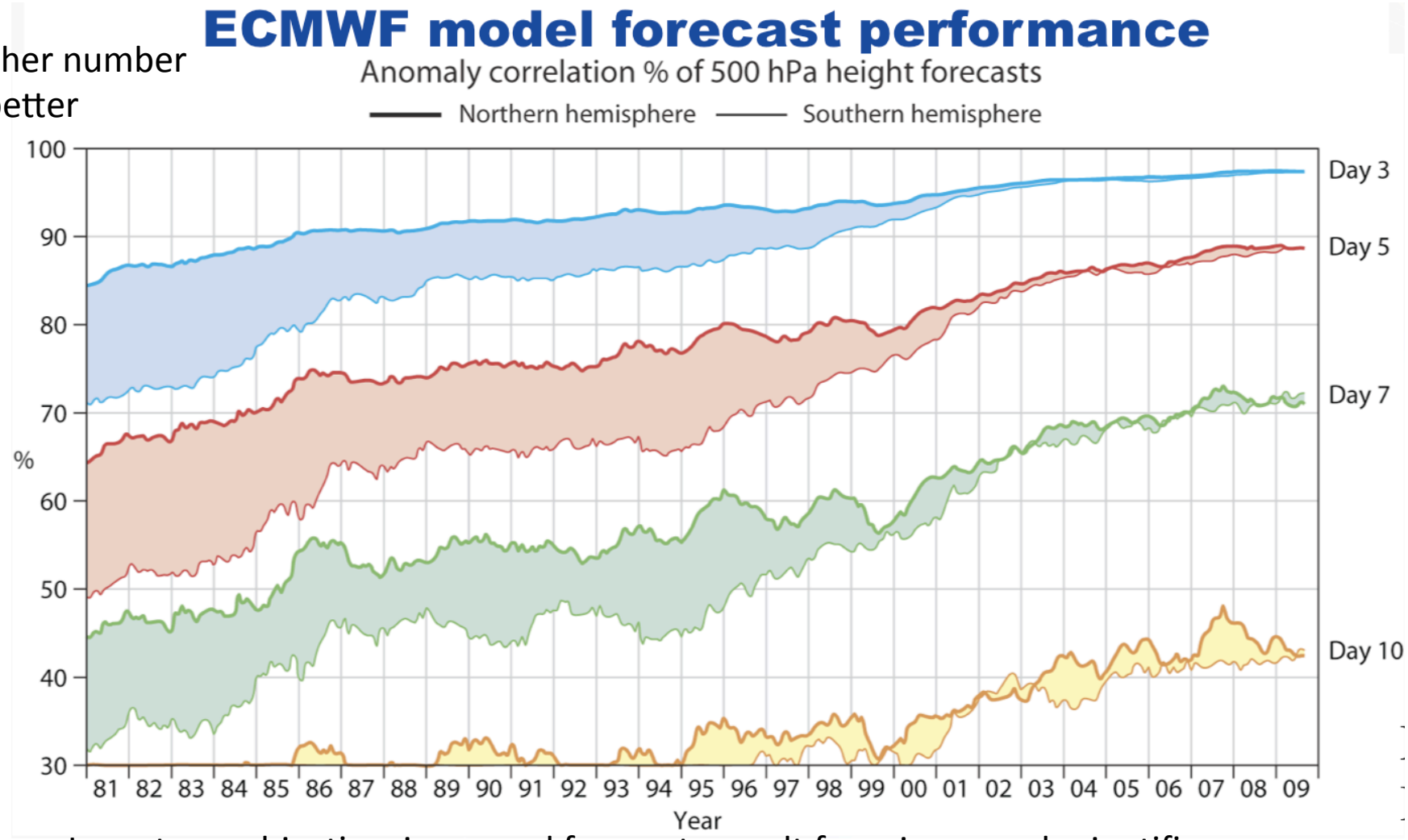
Angelos Vourlidas – NRL: Solar-heliosphere

# 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

# 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*