Medium Range Thermosphere-Ionosphere Storm Forecast

Anthony Mannucci, Bruce Tsurutani, Olga Verkhoglyadova, Attila Komjathy, Mark Butala, Xiaoping Pi, Brian Wilson, JPL/Caltech
Aaron Ridley, Ward Manchester, Bart van der Holst, U Michigan
Chunming Wang and Gary Rosen, University of Southern California
Surja Sharma, Eugenia Kalnay, Kayo Ide, E Lynch, U Maryland
Ja Soon Shim, Masha Kuznetsova, CCMC/Goddard Space Flight Center

Angelos Vourlidas, Peter MacNeice, William Bristow, Dave Hysell, William Lotko

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

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

October 29, 2013
1945 UT

October 28, 2013
1945 UT
Global Perturbations

October 30, 2003
13:00 Local Time

Vertical TEC Estimate (10^{16} \, \text{el/m}^2)

Magnetic Latitude (Dipole)

22:04 UT
20:32 UT
19:00 UT
18:40 UT
21:43 UT
20:12 UT

Elevation angle > 40

CHAMP altitude: 400 km

Mannucci et al., “Dayside global ionospheric response …” GRL 2005
Availability of Aircraft Navigation


October 29, 2003

16:44 UT

17:48 UT

19:06 UT

vertical protection level

Operable level
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

ACE Data

V_{sw} delayed by 34 min.

B_z Southward Turning

Geomagnetic Storm

Earth’s magnetic shield

Magnetometer Data

May 1 2013  Mannucci/JPL
Mechanism for Dayside TEC Increase: Ionospheric Uplift

Solar Wind

\[ \mathbf{E}_{\text{SW}} \]

\[ \mathbf{B} \leftrightarrow \mathbf{v}_{\text{sw}} \]

Dawn-to-dusk directed

\[ \mathbf{V}_{\text{iono}} \sim 100 \text{ m/s} \]

\[ \mathbf{V} = \mathbf{E} \times \mathbf{B} \]

Plasmasheet

N S
SAMI2 Model Run

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

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

Tsurutani et al., Ann Geo 2007

SAMI-2 runs with added electric field
Why Consider Forecasting Thermosphere-Ionosphere Storms?

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

Solar Corona

Heliosphere

Magnetosphere

WSA/PF

ENLIL

Operational

Coupled Thermosphere-Ionosphere

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

High-latitude potential field
Field-aligned currents

May 1 2013
Mannucci/JPL
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

Adjustment based on scientific principles or observations.

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”
Figure adapted from AFWA map (Air Force Weather Agency)
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

“Classical” view of the solar cycle

ISES Solar Cycle F10.7cm Radio Flux Progress
Observed data through Jan 2013

- Maximum
- Minimum

Lika Guhathakurta’s view
(my interpretation)

Equatorial*
active regions
Equatorial coronal
holes
High latitude
 coronal holes

Proxy for UV radiation

See Guhathakurta and Philips, Space Weather, 2013

*Solar latitude
SOHO Images – Solar Cycle

Early declining phase

Halloween storm

Declining phase

Active regions
Coronal holes

Solar maximum
Solar minimum

EIT 195
Fe XII
1x10^6 K

2003-01-01
2003-10-28
2006-01-29
2002-12-01
2010-01-01
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”

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

Lorenz system for atmospheric convection, 1963

\[ X' = -\sigma X + \sigma Y, \]  
\[ Y' = -XZ + rX - Y, \]  
\[ Z' = XY - bZ. \]
Model Validation Versus Forecast

This difference is related to our ability to use the model for scientific inference.
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, Cols

- **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

ECMWF model forecast performance
Anomaly correlation % of 500 hPa height forecasts

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