Modeling, Specifying and Forecasting Space Weather

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2020 CEDAR Distinguished Lecture
Presented June 2021

UtahStateUniversity

Outline

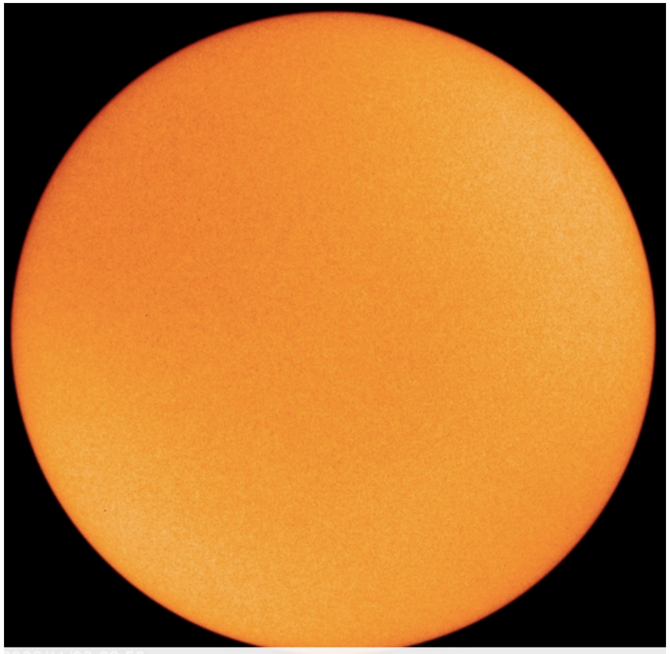
1. What is Space Weather
2. Physics-Based Ionosphere and Thermosphere Models
3. Upper Atmosphere-Ionosphere Weather Models
4. Multi-Model Ensemble Prediction System (MEPS)
5. Ensemble Averaging of Data Assimilation Models

1. Space Weather

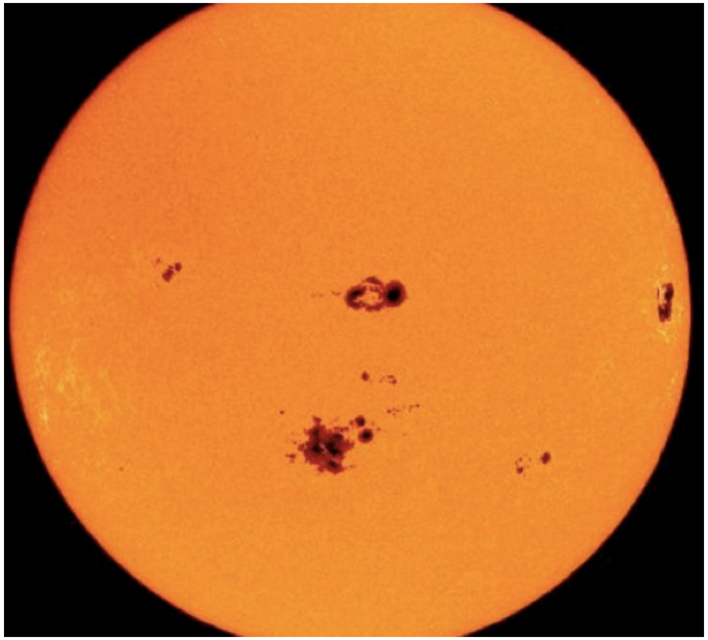
Causes of Space Weather:

- **Solar Weather**
  - **Changes in the Solar Wind**
  - **Solar Flares**
  - **Coronal Mass Ejections**
- **Plasma Instabilities in the Ionosphere**
- **Waves from the Lower Atmosphere**

Sunspots



Quiet



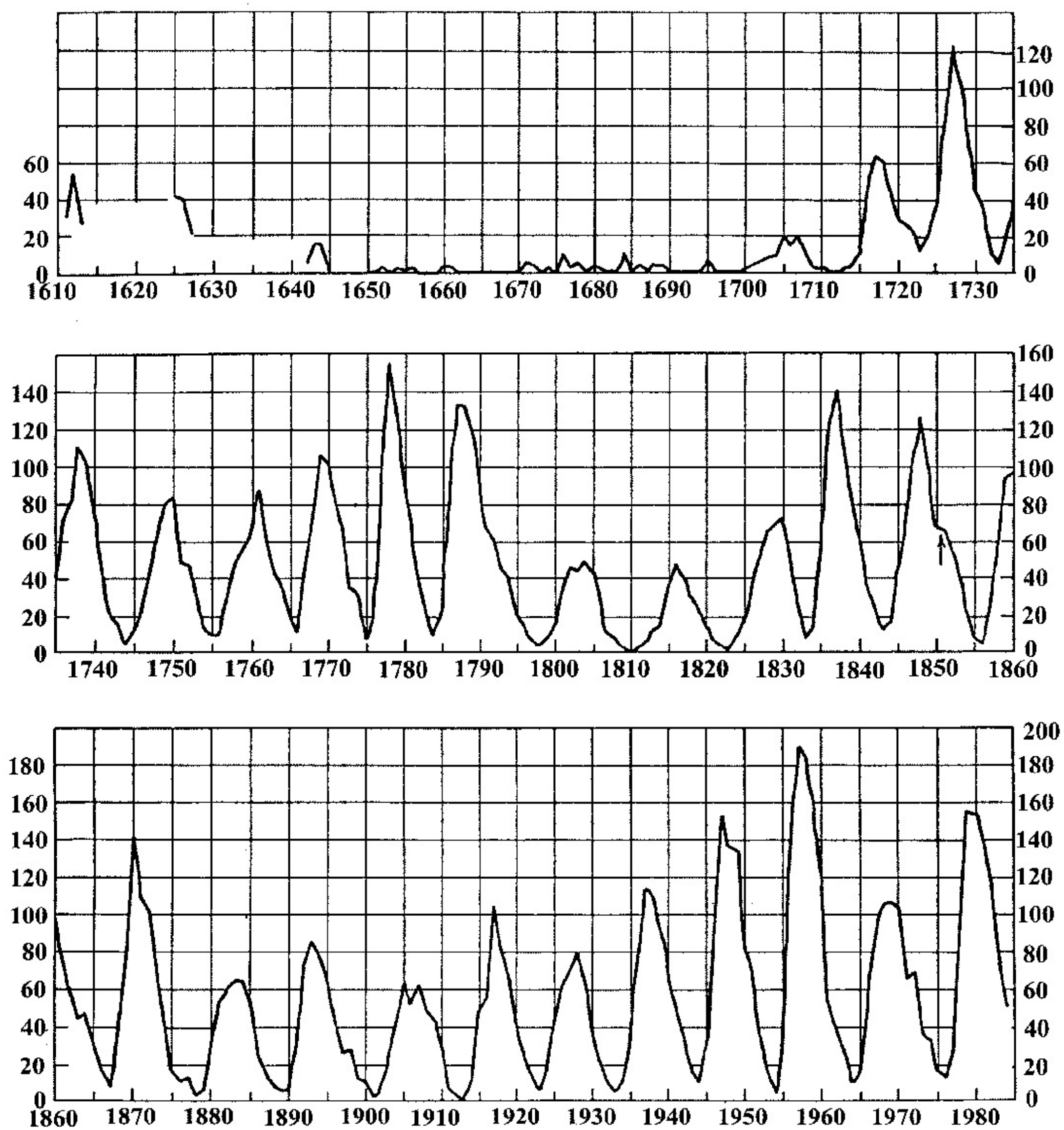
Active

Dark regions in the Sun's lower atmosphere
Cooler than the surrounding region
Associated with Space Weather disturbances

NOAA

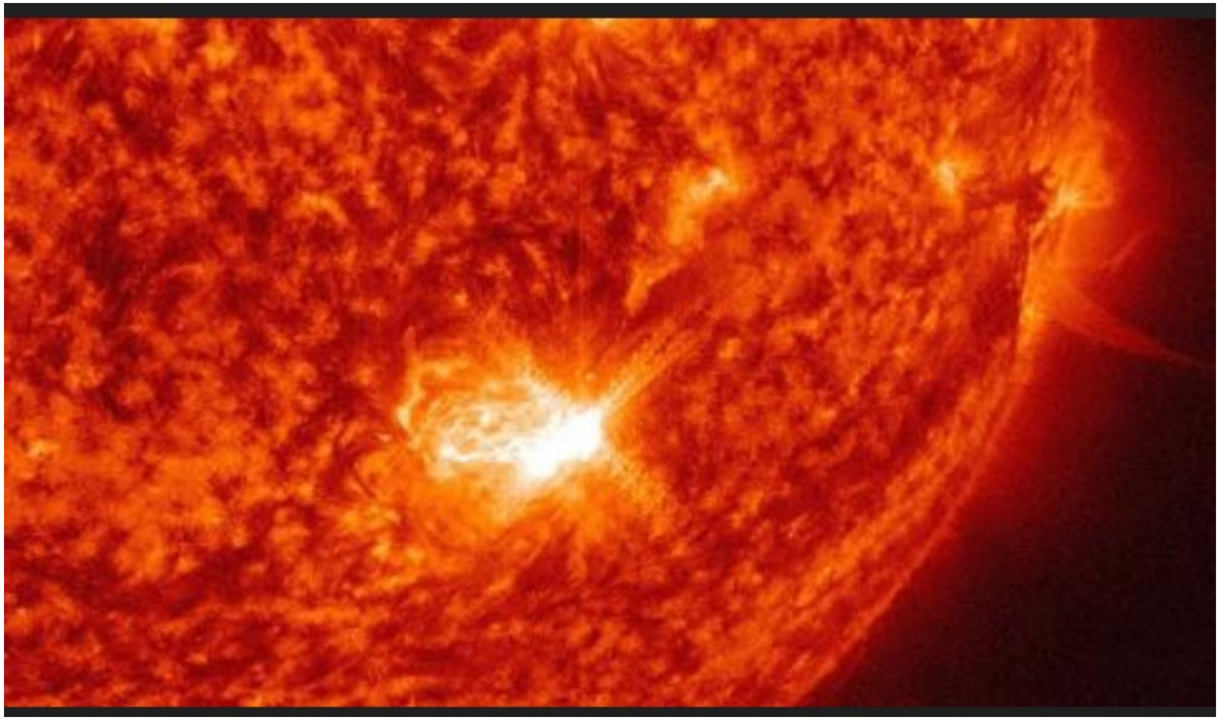
Sunspot Numbers

- **11-Year Solar Cycle**
- **Annual Averages**
- **Maunder Minimum**
  Period 1645-1715



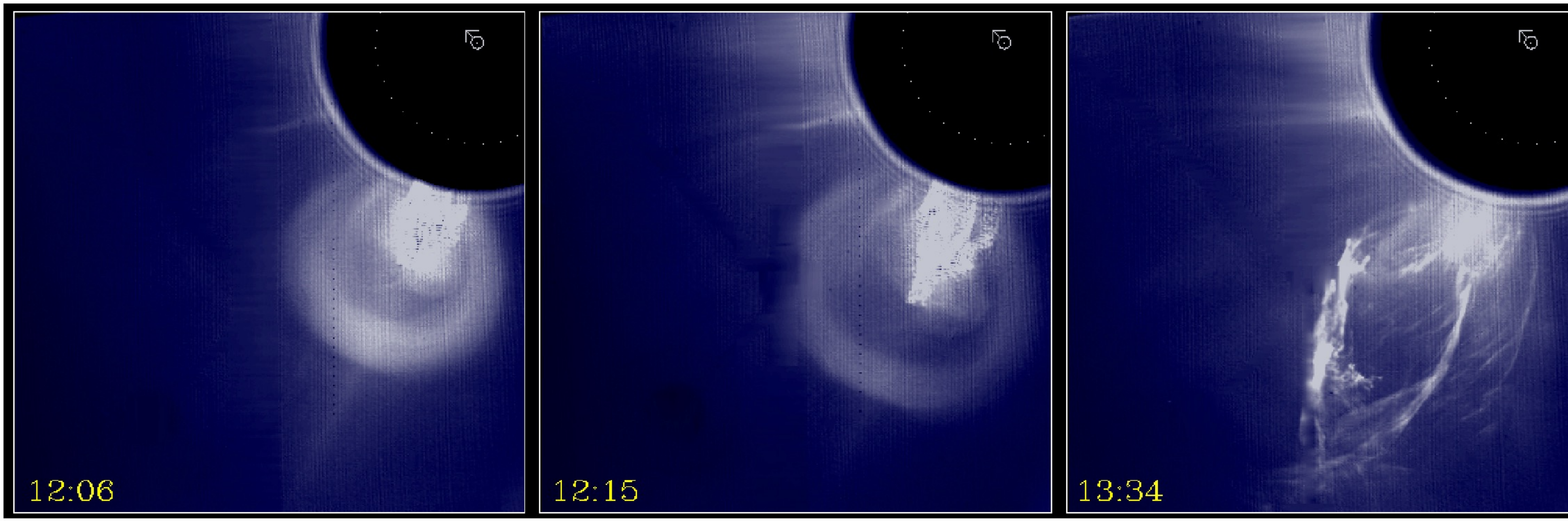
Eddy (1976)

Solar Flare



A sudden explosion of intense electromagnetic radiation
from the Sun's surface
Can enhance Ionospheric densities in the D-region
Can affect radio waves and communications

NASA I[illegible]ge
weather.com

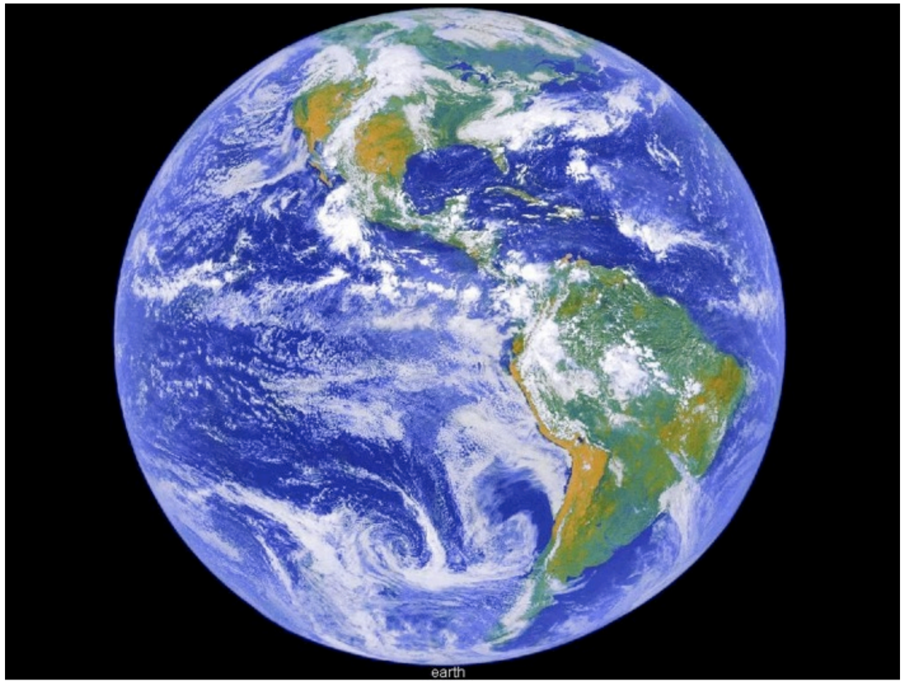


Coronal Mass Ejection

Speed = 1000 km/s (2 million mph)
Mass = 100 billion kg (220 billion lbs)
Explosion = 1 billion hydrogen bombs

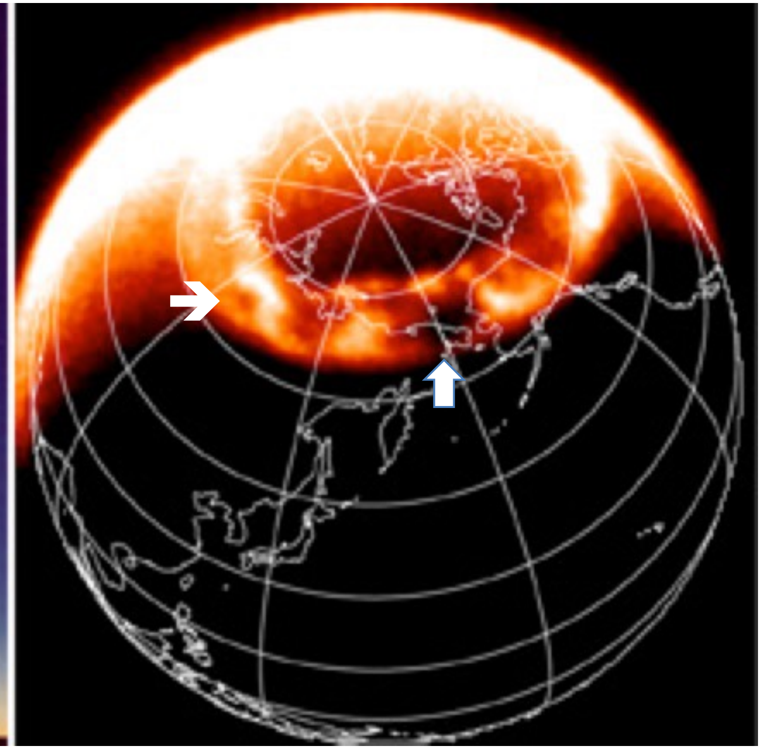
High Altitude Observatory

Solar Wind



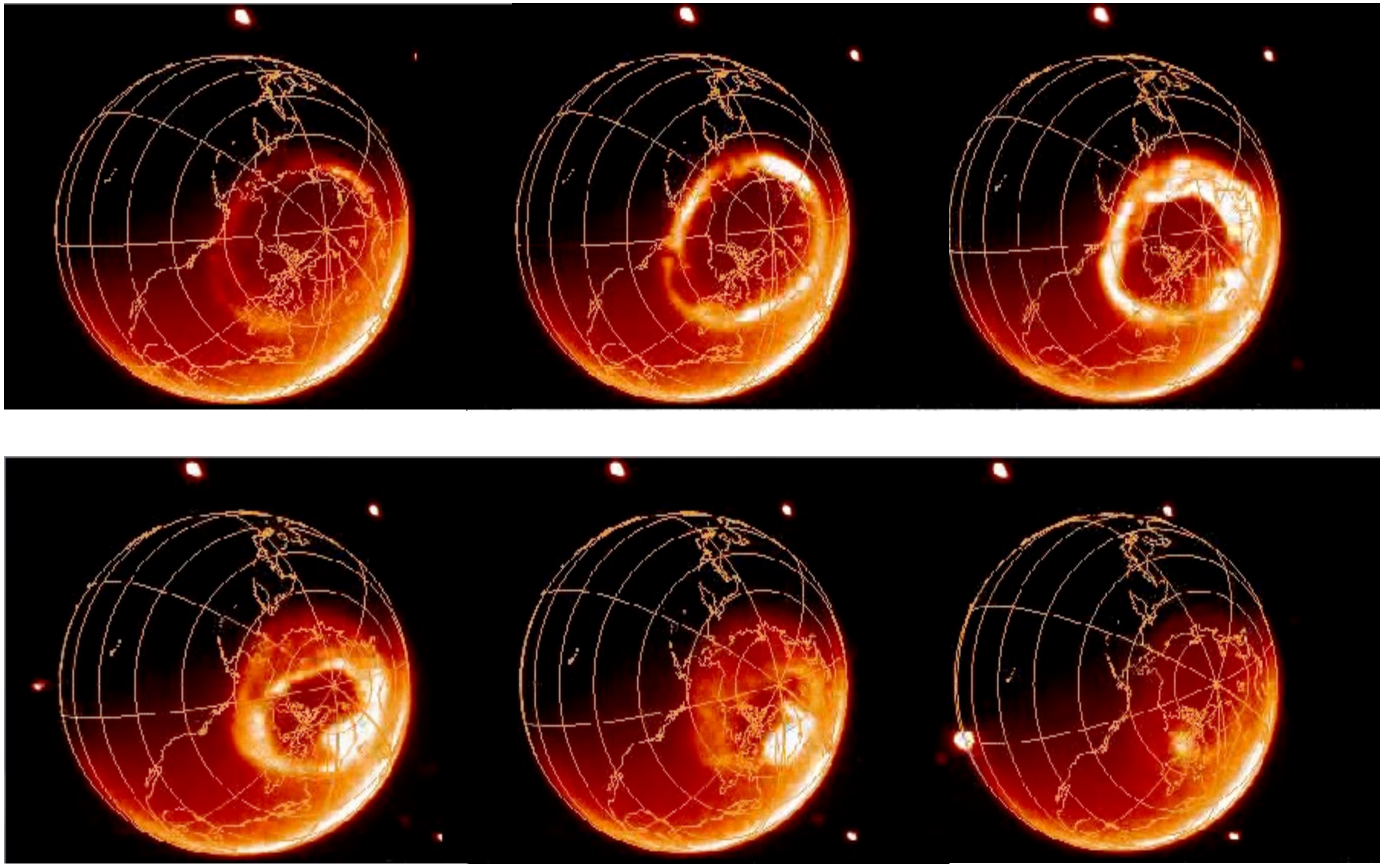
Earth location = 217 Solar Radii from Sun (150 million km)
Light takes 500 sec to reach Earth
Solar Wind takes 2-3 days to reach Earth and at Earth:
Speed = 200-900 km/s
Density = 1-80 cm^{-3}
Temperature = 100,000 K

Satellite Images



- Ground Photograph by Jan Curtis.
- FUV Image from the IMAGE Satellite.

Satellite Images

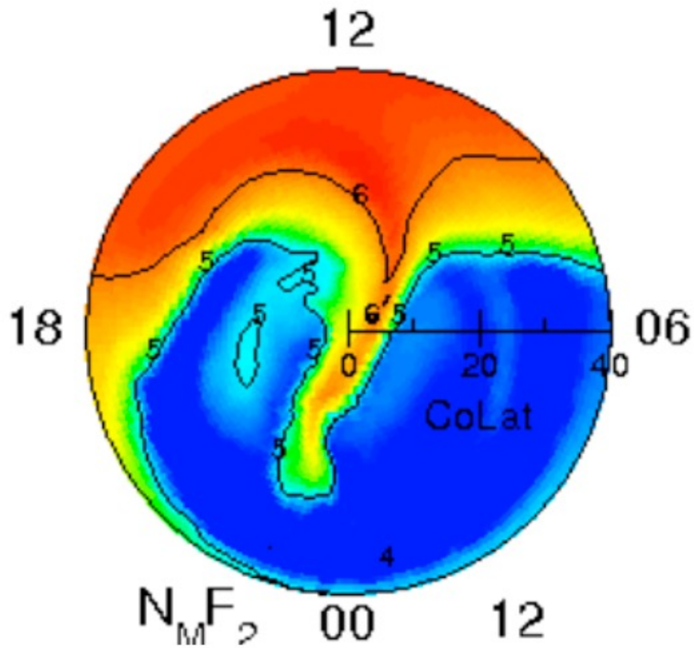


Burch, J. L., *Scientific American, 284*, 72-80, 2001

- **Bastille Day Storm**
- **July 14-15, 2000**
- **Snapshots During a 1-Hour Period**

Space Weather – High Latitudes

Tongue of Ionization



Winter Polar Region

Southward Interplanetary Magnetic Field

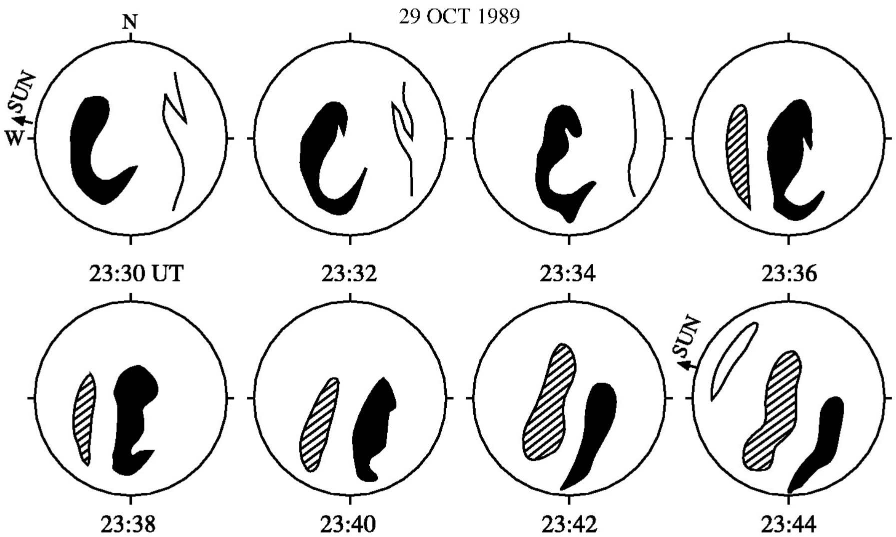
Forms in sunlight in the cusp region

Anti-sunward plasma convection extends the high-density plasma across the dark polar cap, forming the Tongue

Density of the Tongue can be more than a factor of 2 higher than the background plasma density

Space Weather – High Latitudes

Propagating Plasma Patches



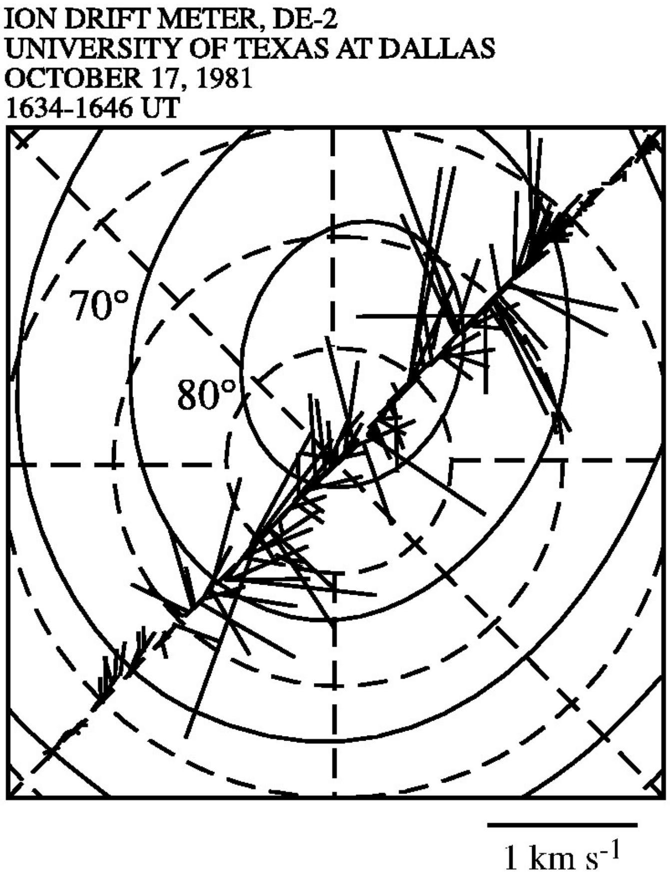
Propagating plasma patches observed at Qaanaaq, Greenland, on October 29, 1989. The dials represent a digitization of all-sky images (630-nm) taken at 2-minute intervals.

- Winter Polar Region
- Southward Interplanetary Magnetic Field
- Forms in sunlight equatorward of the auroral zone
- Patches can be circular or cigar-shaped
- Patch density can be up to a factor of 100 above background plasma density
- Plasma patches drift in an anti-sunward direction with the background plasma
- Figure shows cigar-shaped plasma patches drifting in an anti-sunward direction across Greenland
- Dimensions of the patches are 200 x 1000 km
- Velocity of the patches is about 730 m/s

Fukui et al., 1994

Space Weather – High Latitudes

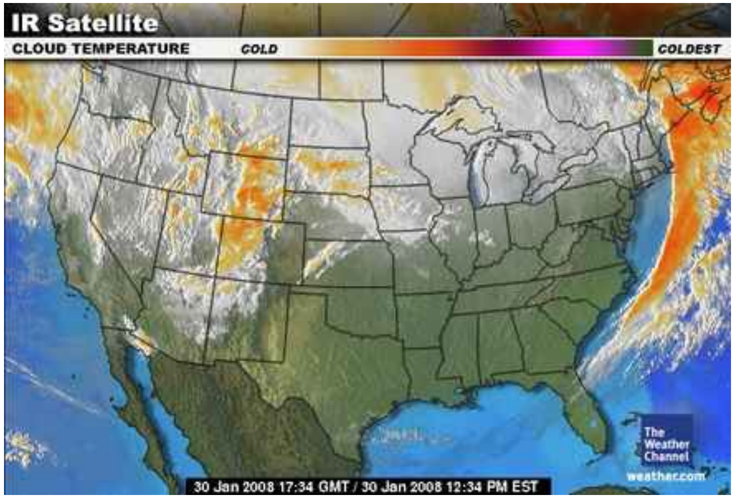
Plasma Drift Velocities



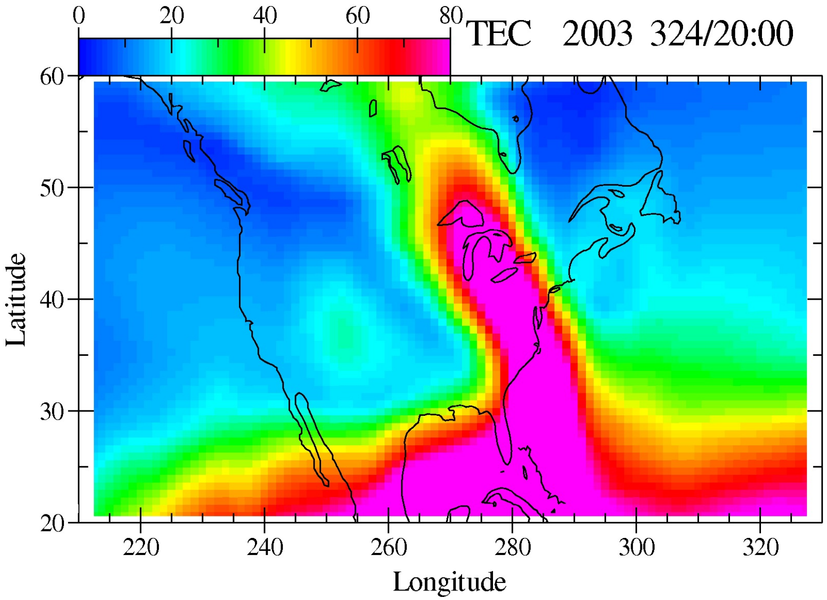
- Northern Polar Region
- Northward Interplanetary Magnetic Field
- Plasma Drift Velocities
- Pattern appears to be turbulent
- Satellite traversal was only 12 minutes
- Probably spatial structure
- Nine reversals in the flow direction

Frank, 1986

Space Weather – Mid-Latitudes



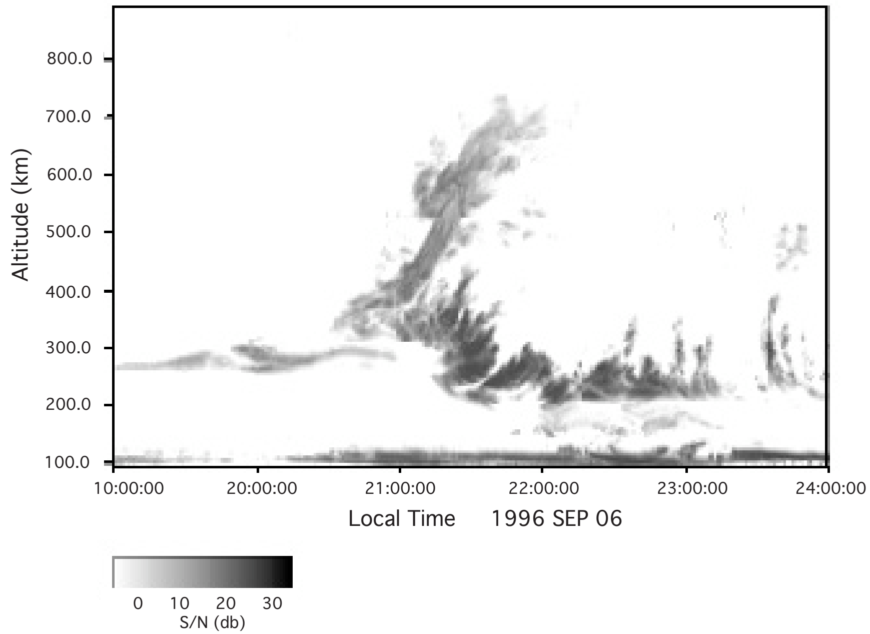
Snowstorm in the Lower Atmosphere



Solar Storm in the Upper Atmosphere-Ionosphere

Spread F/Equatorial Bubbles

JULIA Coherent Scatter Radar



Spread-F event seen by the JULIA coherent scatter radar near Lima, Peru, on September 6, 1996. Plot of coherent backscatter signal-to-noise ratios versus time.

Hysell and Burcham (1998)

- **Plasma instabilities in F-region can lead to Spread-F**
- **In the Equatorial region, spread-F can lead to Plasma Bubbles**
- **Bubble wedge region extends north-south along B-field with an apex altitude as high as 1500 km**
- **East-west extent of the bubble wedge can be several 1000 km**

2. Physics-Based Ionosphere and Thermosphere Models

Time Dependent Ionosphere Model (TDIM)

- Global Physics-Based Ionosphere Coupled to Global Empirical Thermosphere (MSIS Model)
- High Latitudes -- Convection E-Field and Auroral Precipitation Specified
- Equatorial E-Field Specified

Ionospheric Forecast Model (IFM)

- Same as TDIM but Modified to Run Faster Than Real Time

Ionosphere Plasmasphere Model (IPM)

- Global Physics-Based Ionosphere-Plasmasphere Coupled to Global Empirical Thermosphere

IPM-Global

- Global Physics-Based Ionosphere-Plasmasphere Extended to Include High Latitudes
- Ionosphere at High Latitudes Similar to TDIM but Includes Polar Wind Outflow

Global Thermosphere Model (GTM)

- Global Physics-Based Thermosphere can be Coupled to Global Empirical, Physics-Based, or Data Assimilation Ionosphere

Ionosphere – Plasmasphere Model (IPM)

- 90-30,000 km
- Altitude, Latitude, Longitude Grids Set by User
- Six Ion Species (NO^+, O_2^+, N_2^+, O^+, H^+, He^+)
- Realistic Magnetic Field (IGRF)
- Some of the Physical Processes included in IPM:
  - Field-Aligned Diffusion
  - Cross-Field Electrodynamic Drifts
  - Thermospheric Winds
  - Neutral Composition Changes
  - Energy-Dependent Chemical Reactions
  - Ion Production due to:
    - Solar UV/EUV Radiation
    - Auroral Precipitation
    - Star Light

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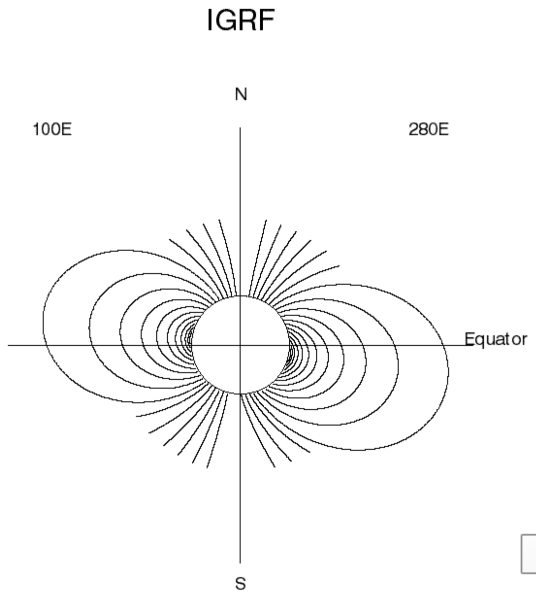
IPM-Global

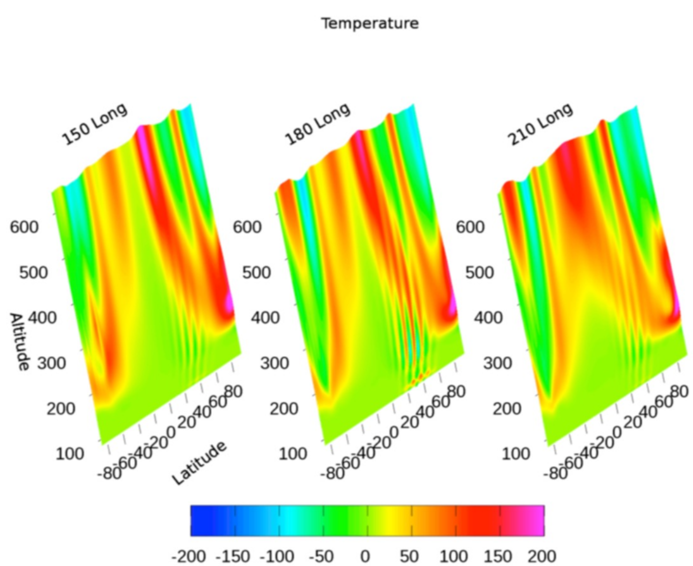
- The Model is Composed of an Ionosphere-Plasmasphere Model (IPM) that Covers Low and Mid-Latitudes and an Ionosphere-Polar Wind Model that Covers High Latitudes.
- 90-30,000 km at Low-Middle Latitudes
- 90-10,000 km at High Latitudes
- Altitude, Latitude, Longitude Grids Set by User
- Output Parameters:
  - NO^+, O_2^+, N_2^+, O^+, H^+, He^+
  - T_e, T_i
  - $u_{||}$, $u_{\perp}$

As the High Latitude Region Expands and Contracts due to Geomagnetic Storms, the B-field Lines Open and Close Accordingly



Global Thermosphere Model (GTM-Ionosphere)

- 40-800 km
- Altitude, Latitude, Longitude Grids Set by User
- Neutrals (N_2, O_2, O)
- Non-hydrostatic, Non-linear Flows
- Planetary, Tidal, Gravity, and Sound Waves
- Subsonic, Transonic and Supersonic Winds
- Wave Breaking in the Lower Thermosphere
- Can be Coupled to a Global Empirical, Physics-Based, or Data Assimilation Ionosphere



GTM-Ionosphere simulation of an equatorward propagating Traveling Atmospheric Disturbance interacting with an upward propagating gravity wave from the lower atmosphere (*Gardner and Schunk, 2011b*).

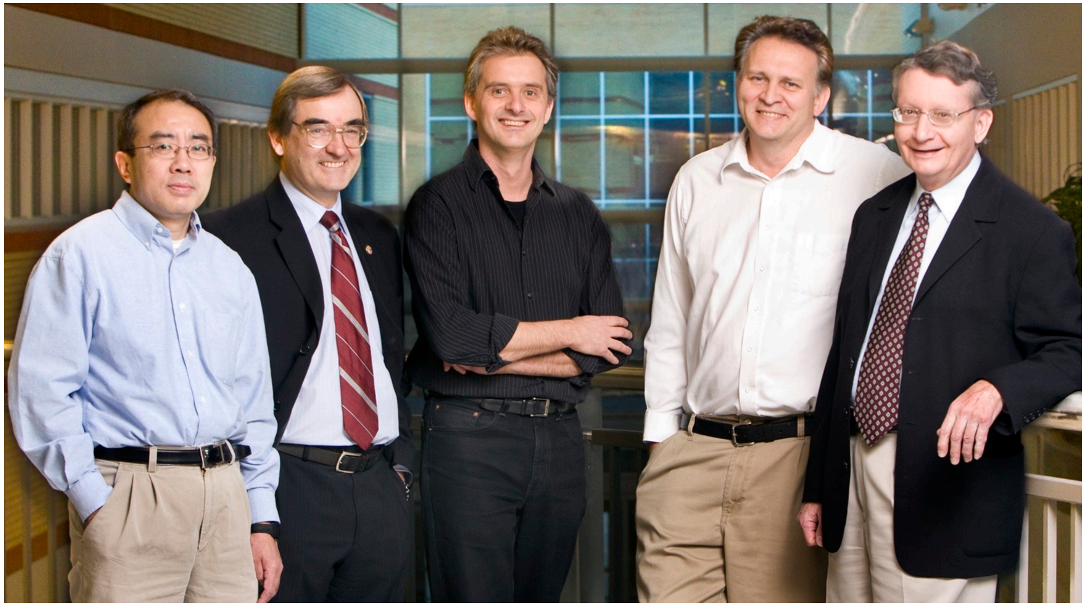
3. Upper Atmosphere-Ionosphere Weather Models

Global Assimilation of Ionospheric Measurements (GAIM)

R. W. Schunk, L. Scherliess, L. C. Gardner,
D. C. Thompson, V. Eccles, J. J. Sojka, and L. Zhu

Similar to Tropospheric Weather Models

GAIM Team



Zhu, Sojka, Scherliess, Thompson, Schunk, Eccles, Gardner

USU Physics-Based Data Assimilation Models

Global Assimilation of Ionospheric Measurements

- **Gauss-Markov Model (GAIM-GM)**

  Air Force Operational Model 2006 – 2020

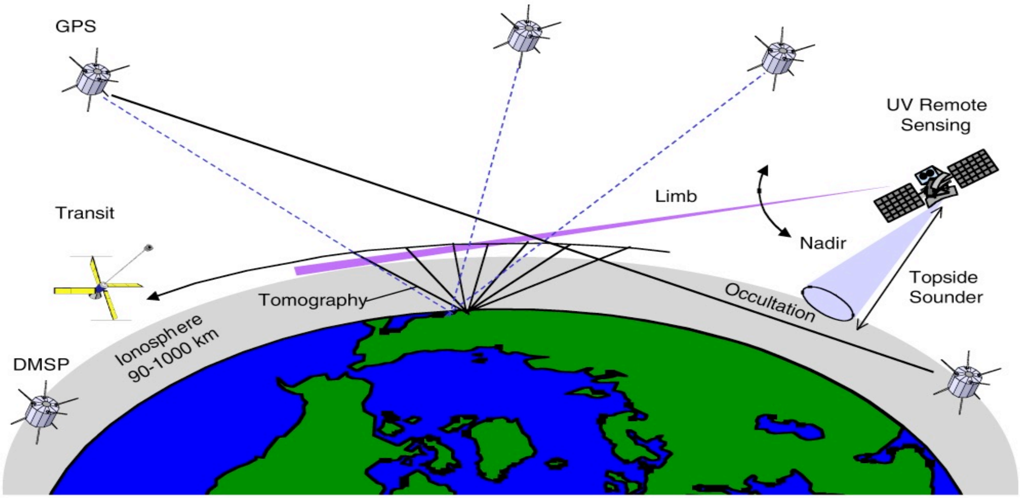
- **Full Physics Model (GAIM-FP)**

  Air Force Operational Model 2020

Ensemble Kalman Filter Model for High-Latitude Ionosphere Dynamics & Electrodynamics (IDED-DA)

Currently a Science Model

GAIM-GM and GAIM-FP Assimilate Multiple Data Sources



Data Assimilated Exactly as They Are Measured

- **Bottomside N_e Profiles from Digisondes (200)**
- **Slant TEC from more than 1000 Ground GPS Receivers**
- **N_e Along Satellite Tracks (4 DMSP satellites)**
- **Integrated UV Emissions (LORAAS, SSULI, SSUSI, TIP)**
- **Occultation Data (CHAMP, IOX, SAC-C, COSMIC, C/NOFS)**
- **Data Assimilated at Low and Mid-Latitudes**

GAIM
"Bringing The Pieces Together"

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GAIM-GM Model

- **Ionosphere Forecast Model (IFM)**
- **Global physics-based model for background ionosphere**
- **90 - 1400 km**
- **15 - minute output cadence**
- **O^+, H^+, NO^+, N_2^+, O_2^+, T_e, T_i**
  - **Only uses N_e**

- **Kalman Filter solves for deviations from background electron density distribution**

- **GAIM-GM does not provide information about ionospheric drivers (electric fields, neutral winds, etc.)**

G A I M
"Bringing The Pieces Together"

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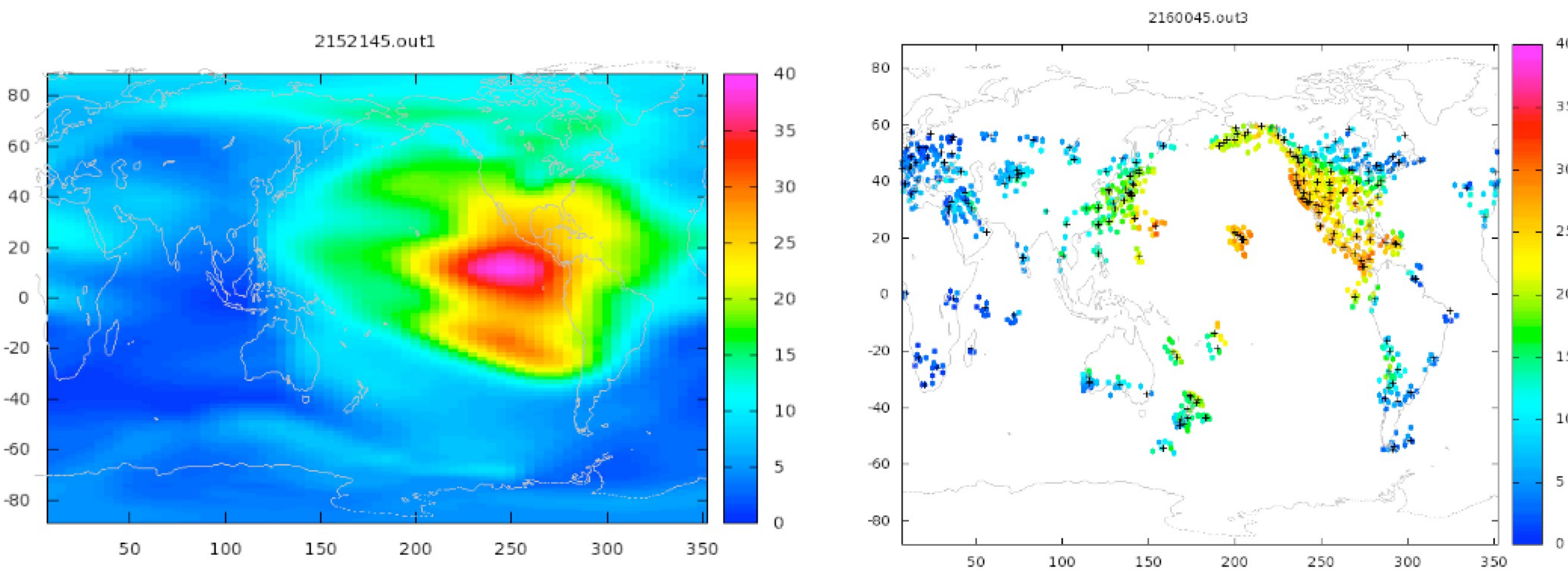
GAIM-GM global Run

- 357 global TEC stations (IGS network) used in real-time at USU Space Weather Center
- Up to 10,000 measurements assimilated every 15- min



Vertical TEC versus Geographic Latitude (left) and Longitude (right)

"Bringing The Pieces Together"

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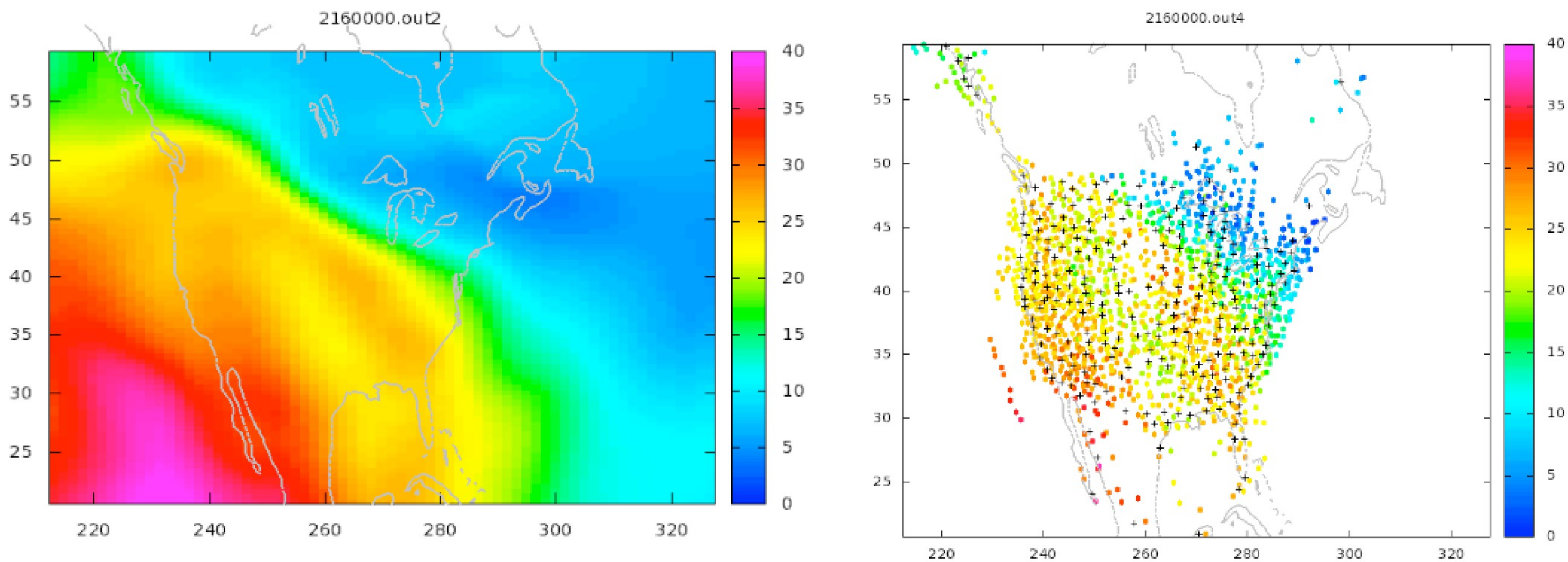
GAIM-GM regional (High Resolution) Run:

- 424 USTEC stations (CORS network) used in real-time at USU Space Weather Center
- Up to 10,000 measurements assimilated every 15-min



Vertical TEC versus Geographic Latitude (left) and Longitude (right)

"Bringing The Pieces Together"

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GAIM-FP

- Ensemble Kalman Filter (24-30 CPU/Cores)
- Physics-based Ionosphere-Plasmasphere Model (IPM)
- Incorporates Ionospheric Physics in the Data Assimilation
- Can Assimilate the 5 Data Sources shown in a Previous Slide
- Altitude, Latitude, Longitude Grids Set by User
- Ionospheric Specifications, Forecasts and Drivers
    - Electric Field
    - Neutral Wind
    - Neutral Composition

G A I M
"Bringing The Pieces Together"

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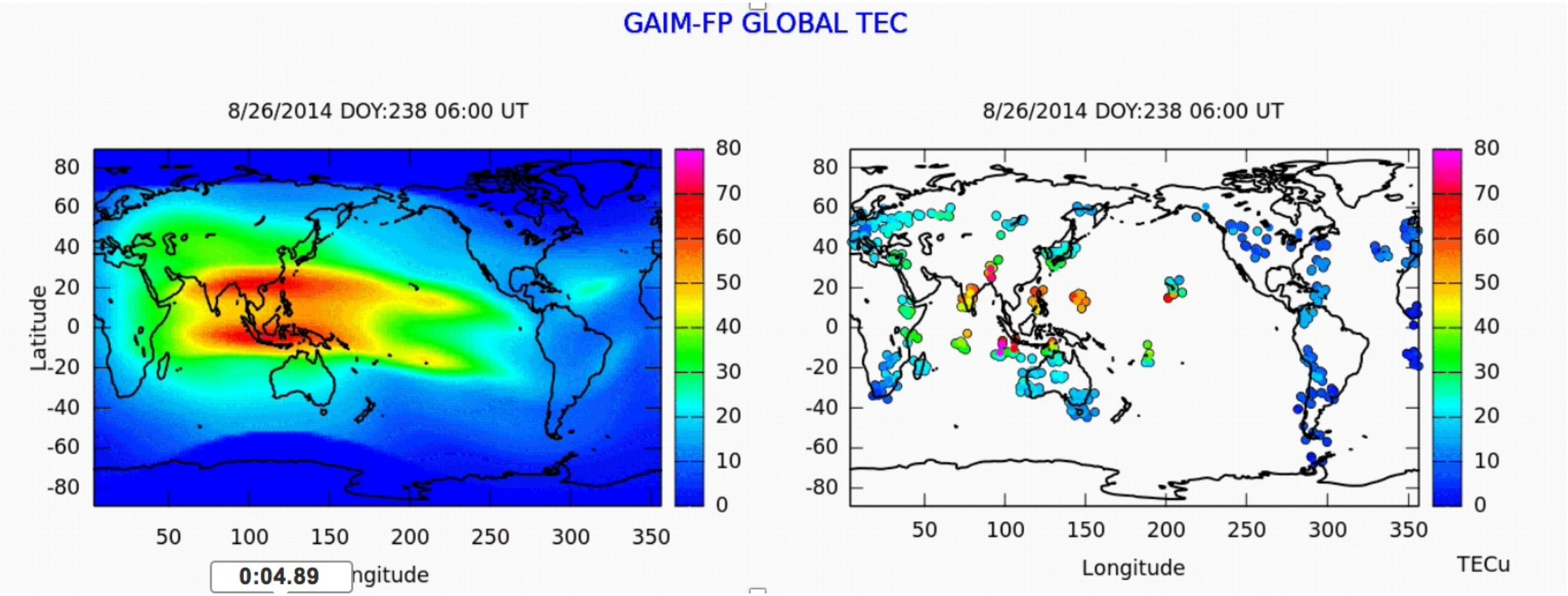
GAIM-FP Global Run

- 400 global TEC stations (IGS network) used in real-time at USU Space Weather Center
- Up to 10,000 measurements assimilated every 15- min
- 40-50 Ionosondes/Digisondes



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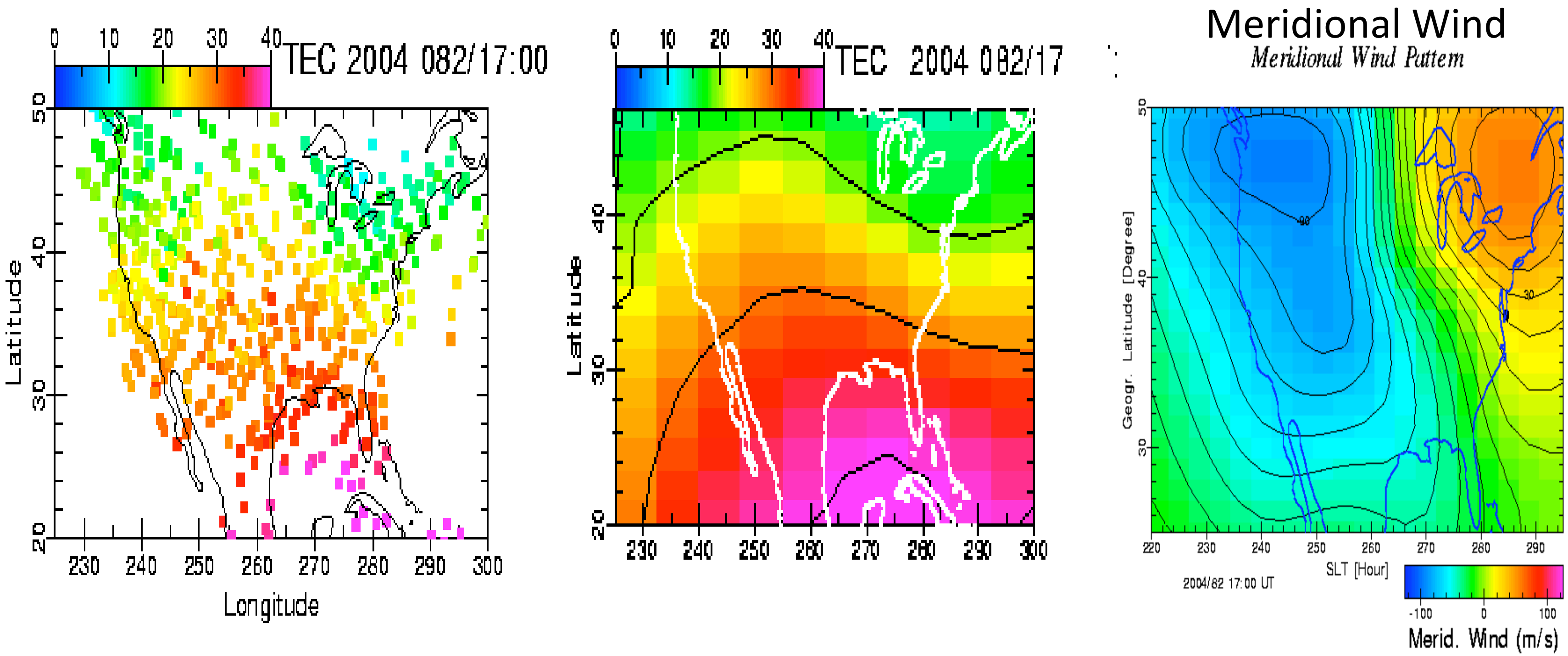
Reconstructions With Self-Consistent Drivers

GAIM-FP ➔Regional Run



- **Snapshots of TEC measurements (left)**
- **GAIM-FP reconstruction (middle)**
- **GAIM-FP neutral wind at 300 km (right)**
- **17:00 UT, day 82, 2004**

GAIM
"Bringing The Pieces Together"

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GAIM Data Assimilation Models have been or are currently running at:

- AFWA (557 Weather Wing)
- Northrup Grumman
- Air Force Research Laboratory (AFRL)
- Naval Research Laboratory (NRL)
- USU Space Weather Center (SWC)
- Community Coordinated Modeling Center (CCMC)

“Bringing The Pieces Together”

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Multimodel Ensemble Prediction System (MEPS): Ensemble Modeling with Data Assimilation Models

Utah State University

R. W. Schunk, L. Scherliess, V. Eccles, L. C. Gardner, J. J. Sojka and L. Zhu

Jet Propulsion Laboratory

X. Pi, A. J. Mannucci, and A. Komjathy

University of Southern California

C. Wang and G. Rosen

MEPS Data Assimilation Models

GAIM-BL ➔ Mid & Low Latitudes

GAIM-GM ➔ Mid & Low Latitudes

GAIM-4DVAR ➔ Mid & Low Latitudes, **with Drivers**

GAIM-FP ➔ Mid & Low Latitudes, **with Drivers**

Mid-Low Electro-DA ➔ Ionosphere **with Drivers**

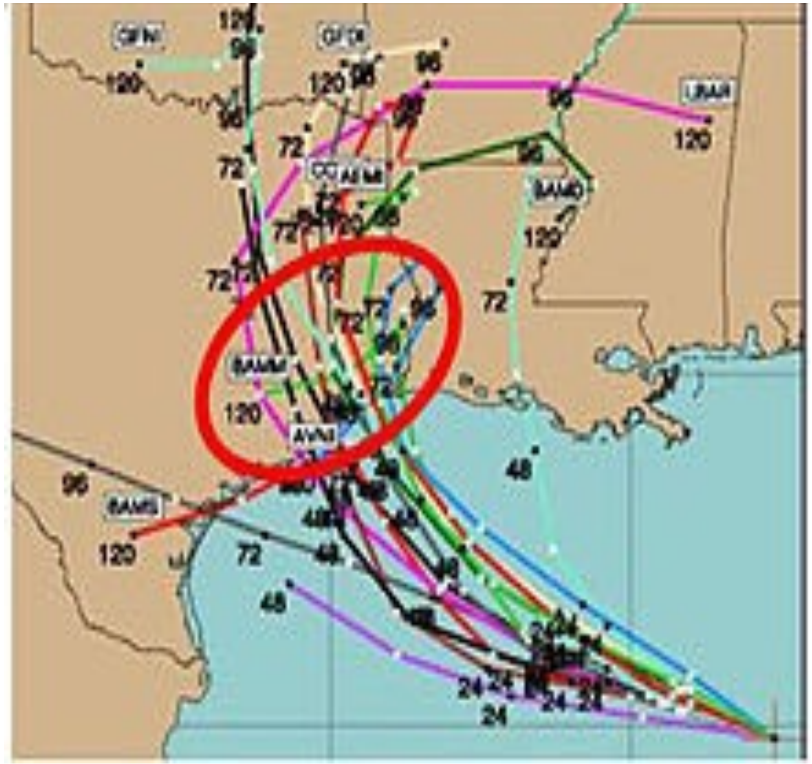
IDED-DA ➔ High Latitudes, **with Drivers**

GTM-DA ➔ Global Thermosphere

TWAM ➔ Thermospheric Wind Assimilation Model

- Global, Regional & Nested GRID Capabilities
- Science, Specifications & Forecasts

Why Ensemble Modeling

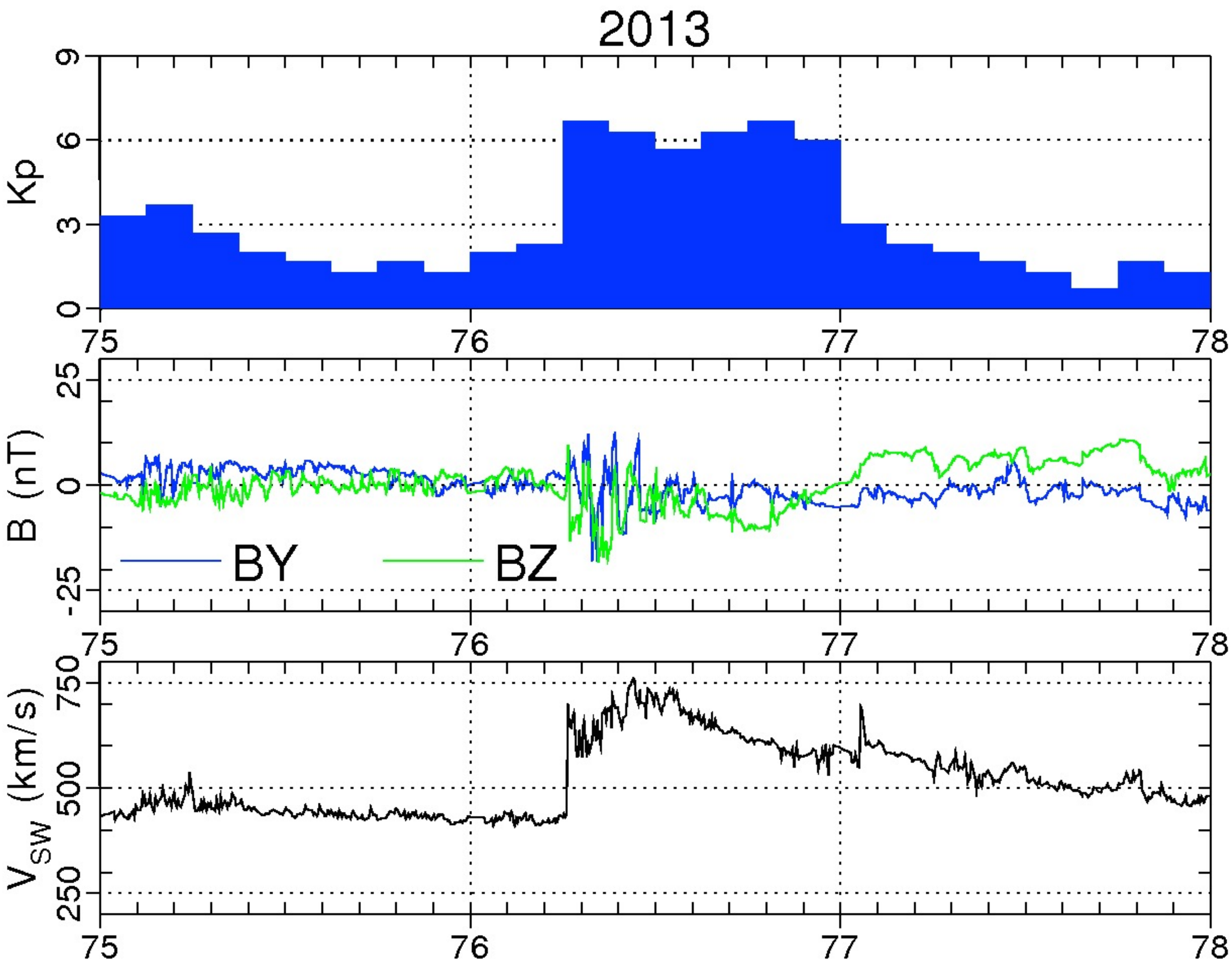


National Hurricane Center multi-model ensemble forecast for hurricane Rita.

MEPS Initial Tasks

- Select a Storm Period
- Select MEPS Models and Data
- Conduct MEPS Ensemble Model Runs
- Study the Effect of Different Data Types
- Compare MEPS Reconstructions
- Study the Usefulness of Ensemble Averaging

Magnetic Storm Period



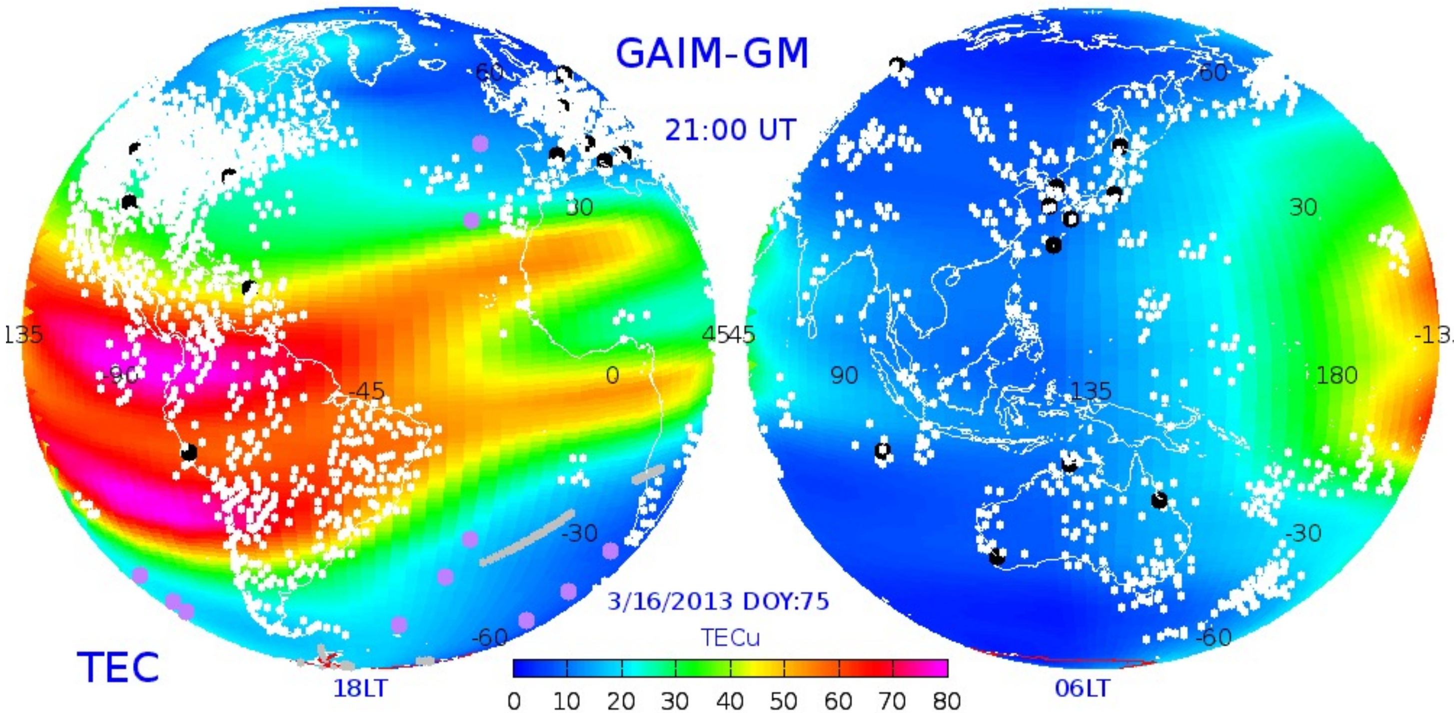
Selected MEPS Models and Data

GAIM-BL → Mid & Low Latitudes
GAIM-GM → Mid & Low Latitudes
GAIM-4DVAR → Mid & Low Latitudes, with Drivers
GAIM-FP → Mid & Low Latitudes, with Drivers

BL – Band Limited
GM – Gauss Markov
4DVAR – 4D Adjoint Method
FP – Full Physics

- Ground-Based GPS-TEC
- Satellite to Satellite Occultation
  Yields N_e at 800 km
- Ionosonde-Digisonde N_e (sao)
- 911A, 1356A; limb, disk (UV)

Global Data Distribution



White Dots – Locations of 530 ground GPS receivers
Black Dots – Locations of 80 ionosondes/digisondes (sao)
Purple Dots – COSMIC derived electron densities at 800 km
Background – GAIM-GM reconstruction for the quiet day at 21 UT

Gardner et al., 2014

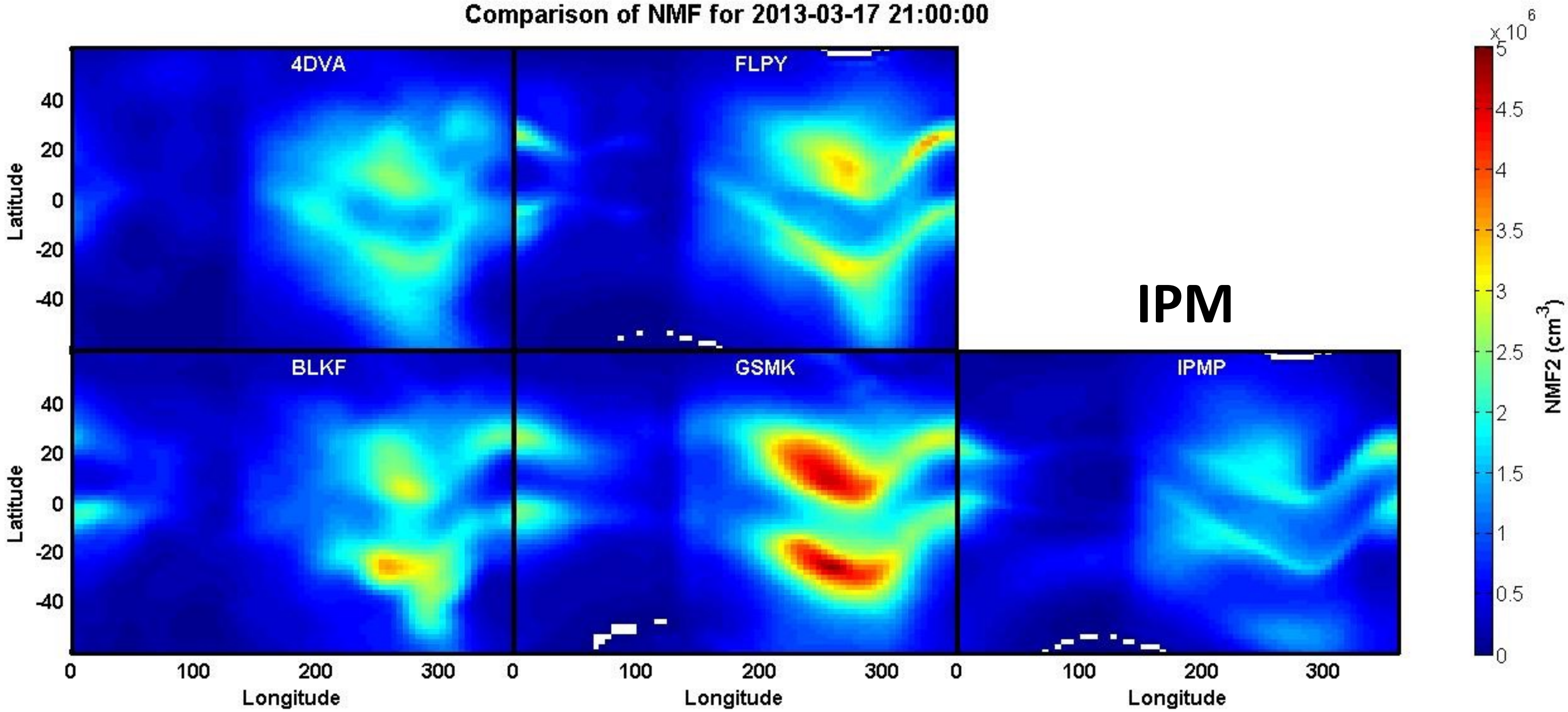
MEPS – Effect of Different Data Types

- Run with TEC data from 530 ground GPS receivers
- Run with 530 ground GPS receivers & COSMIC occultation data
- Run with 530 ground GPS receivers, occultation data, & 80 digisondes (sao)

Goal is to see the differences in the model results and to see how the different models handle the same data type

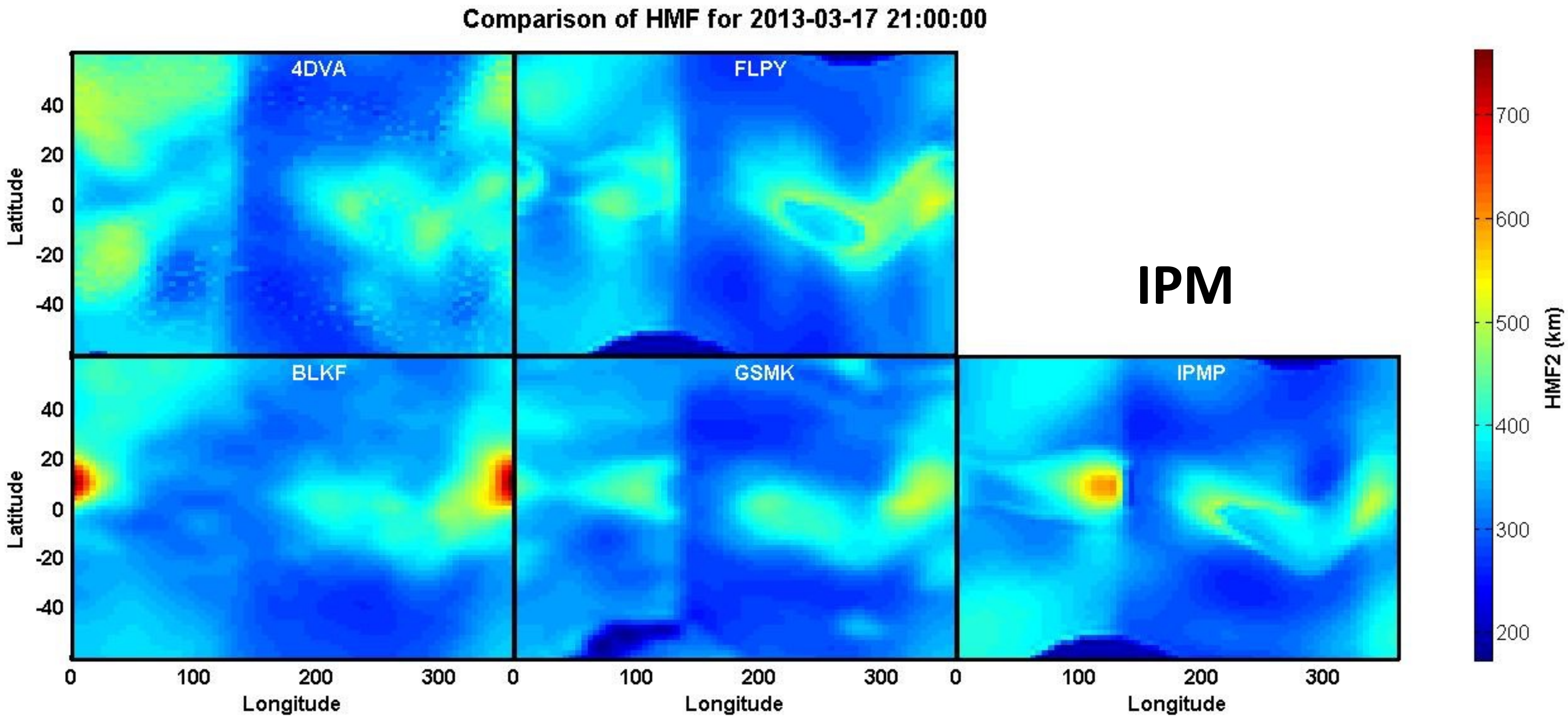
Run the Four Data Assimilation Models with TEC data from 530 ground GPS receivers

NmF2 Comparison for the Storm Day



- Differences in magnitude of the equatorial anomaly.
- Some differences in longitude and width of equatorial anomaly
- Four models show enhanced NmF2 in the southern hemisphere beyond 30° latitude
- IPM is background physics-based model for GAIM-FP

HmF2 Comparison for the Storm Day



Differences in

- the equatorial region near 0° and 120° longitude
- middle latitudes in the southern hemisphere
- IPM is background physics-based model for GAIM-FP

Run the Four Data Assimilation Models with TEC data from 530 ground GPS receivers and Satellite to Satellite Occultation data (N_e at 800 km)

GAIM 2013 Day 76 21:00 UT – GPS + Ne_{COSMIC}(800 km)

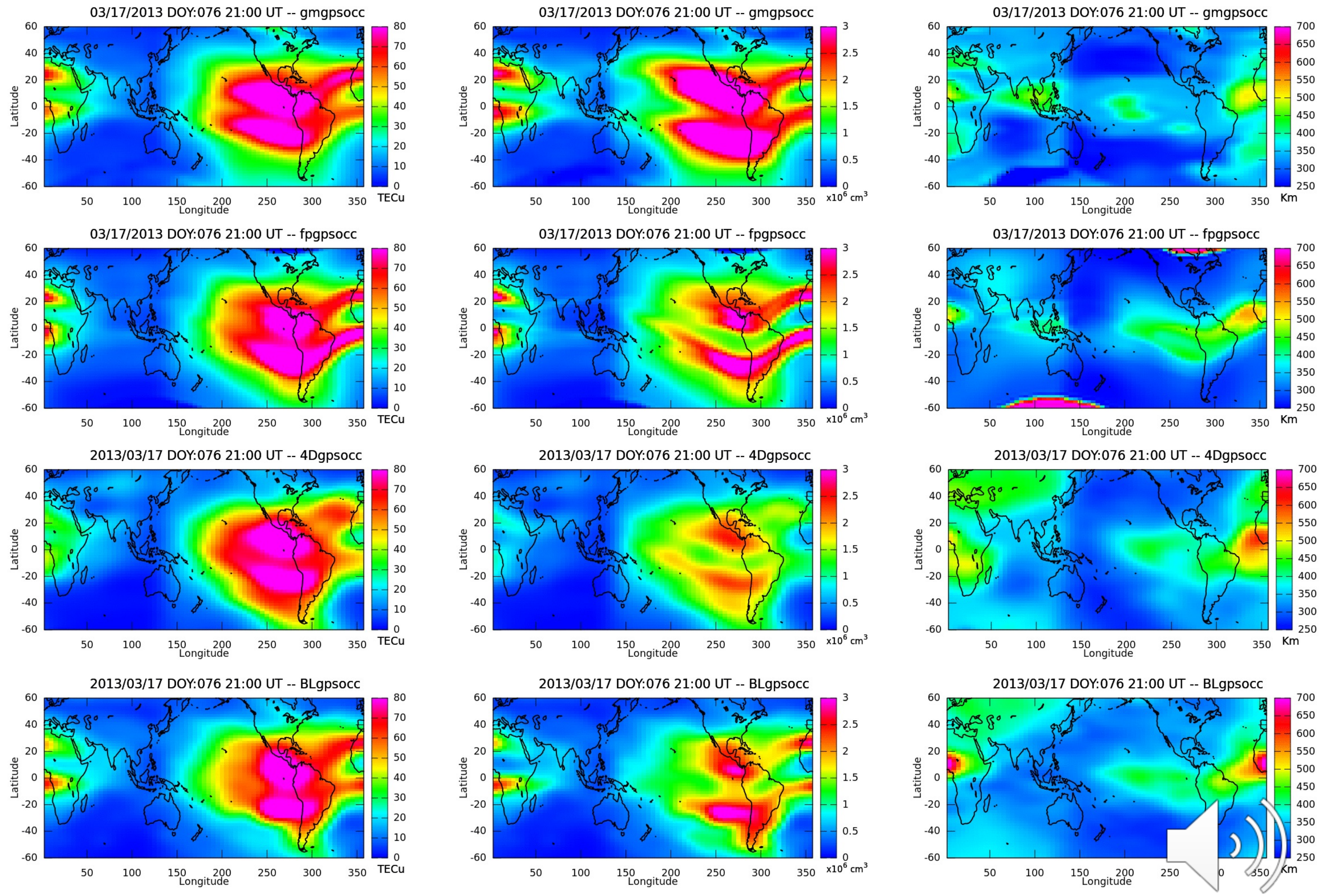
TEC | NmF2 | hmF2

GAIM-GM

GAIM-FP

GAIM-4D

GAIM-BL



Run the Four Data Assimilation Models with TEC, Occultation, and Digisonde (sao) data

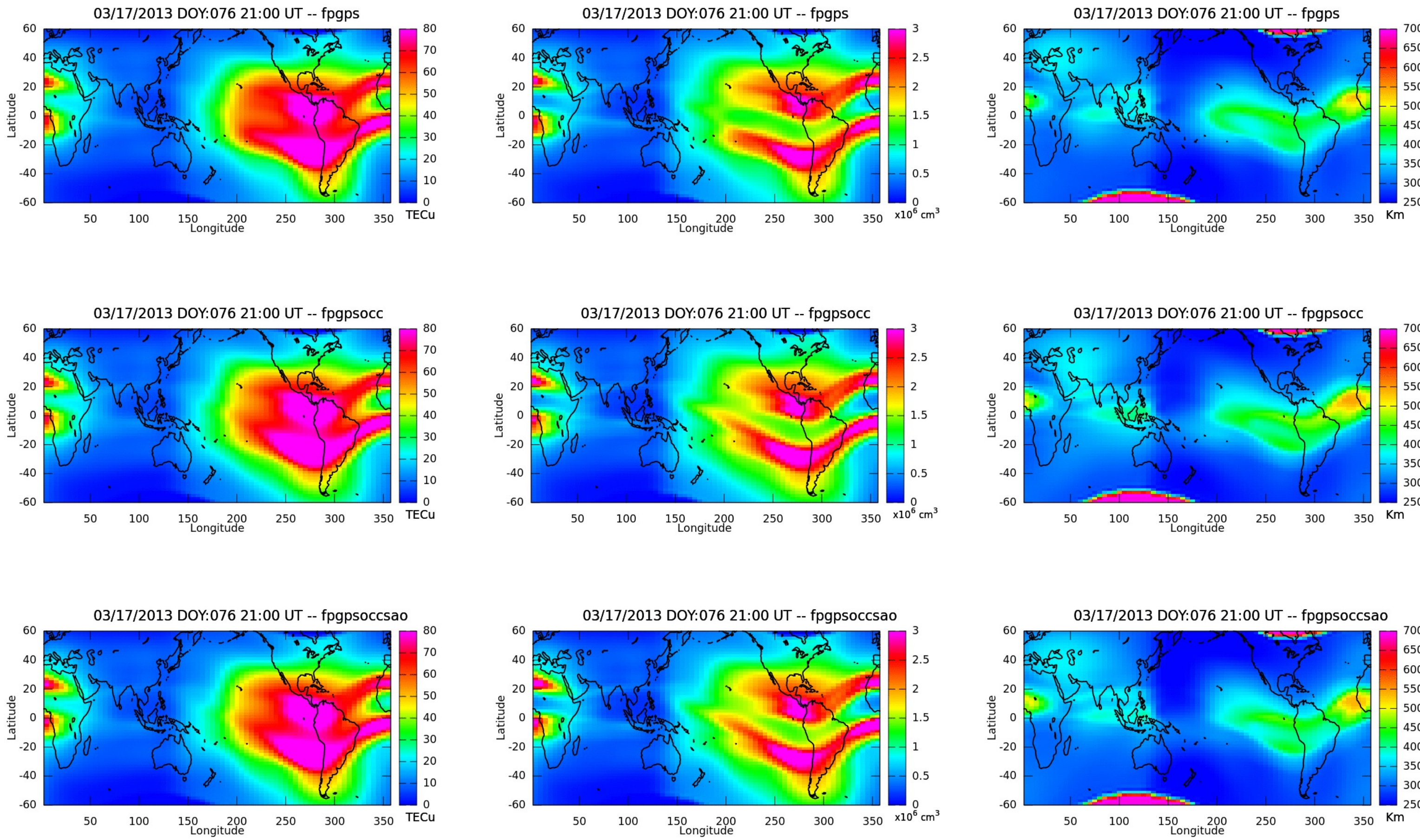
GAIM-FP 2013 Day 76 21:00 UT

TEC | NmF2 | hmF2

GPS

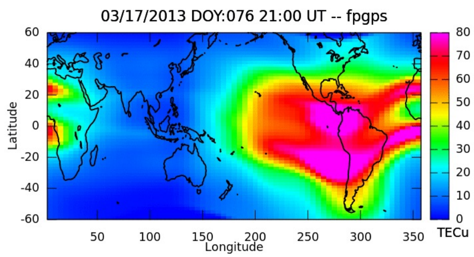
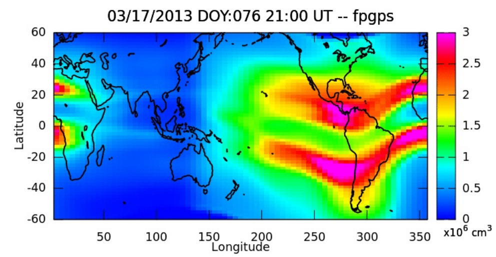
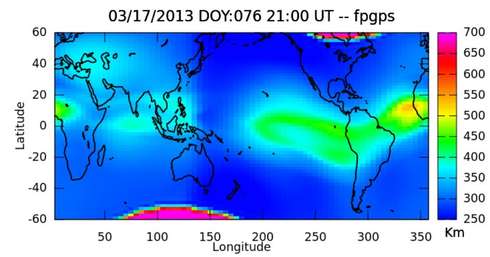
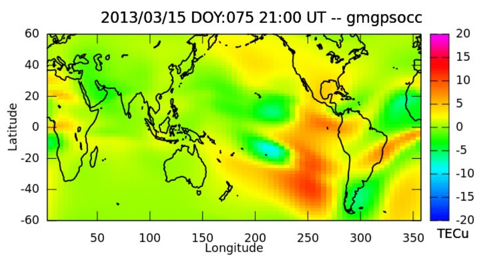
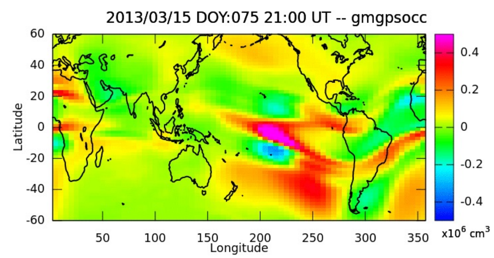
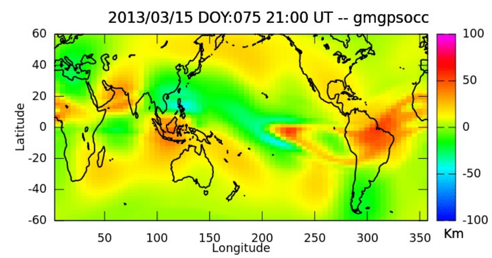
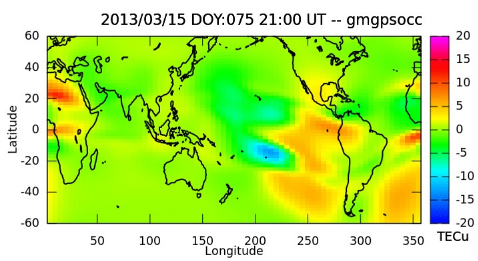
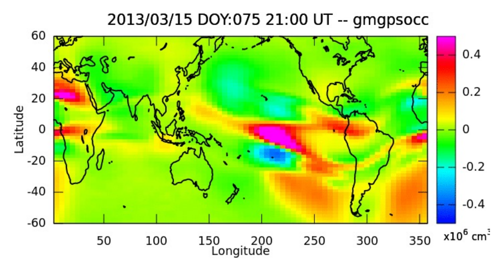
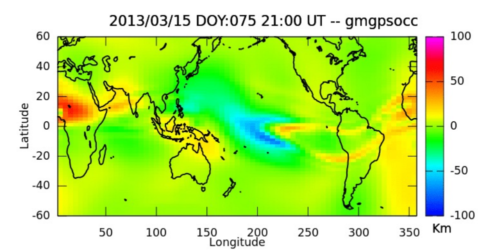
GPS + Ne(800 km)

GPS + Ne(800 km) + sao



Storm Day

GAIM-FP 2013 Day 76 21:00 UT Diff

	TEC	NmF2	hmF2
GPS			
GPS + Ne(800 km)			
GPS + Ne(800 km) + sao			

Storm Day

Models Reconstructions are Very Similar but there are Differences which are due to:

- Different Background Physics-Based Models
- Different Assimilation Techniques
- Different Spatial and Temporal Resolutions
- Different Deduced Electrodynamics Drifts
- Different Deduced Neutral Winds and O/N_2 Ratios

Goal is a Systematic Study to Elucidate Causes of Differences

Ensemble Model Averaging Example

<u>March 12-19, 2013</u>

- 5 Data Assimilation & 1 Physics Model
- Mid and Low Latitudes
- GPS and Occultation Data
- Solar Medium, Equinox, Storm
- Simple Average of Model Outputs
  - Sum models, divide by number of models
- Weighted Average of Model Outputs
  - Sum models weighted by fit to GPS data, divide by number of models

Ensemble Average (6 Models)

GAIM-BL → Mid & Low Latitudes

GAIM-GM → Mid & Low Latitudes

GAIM-4DVAR → Mid & Low Latitudes, with Drivers

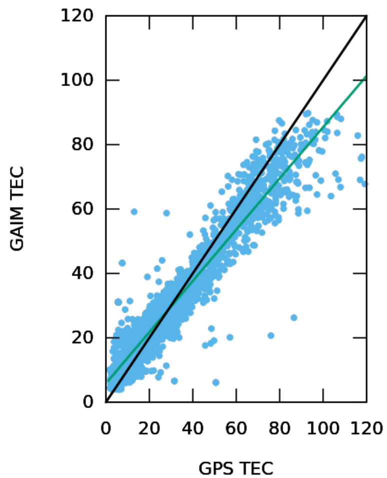
GAIM-FP → Mid & Low Latitudes, with Drivers

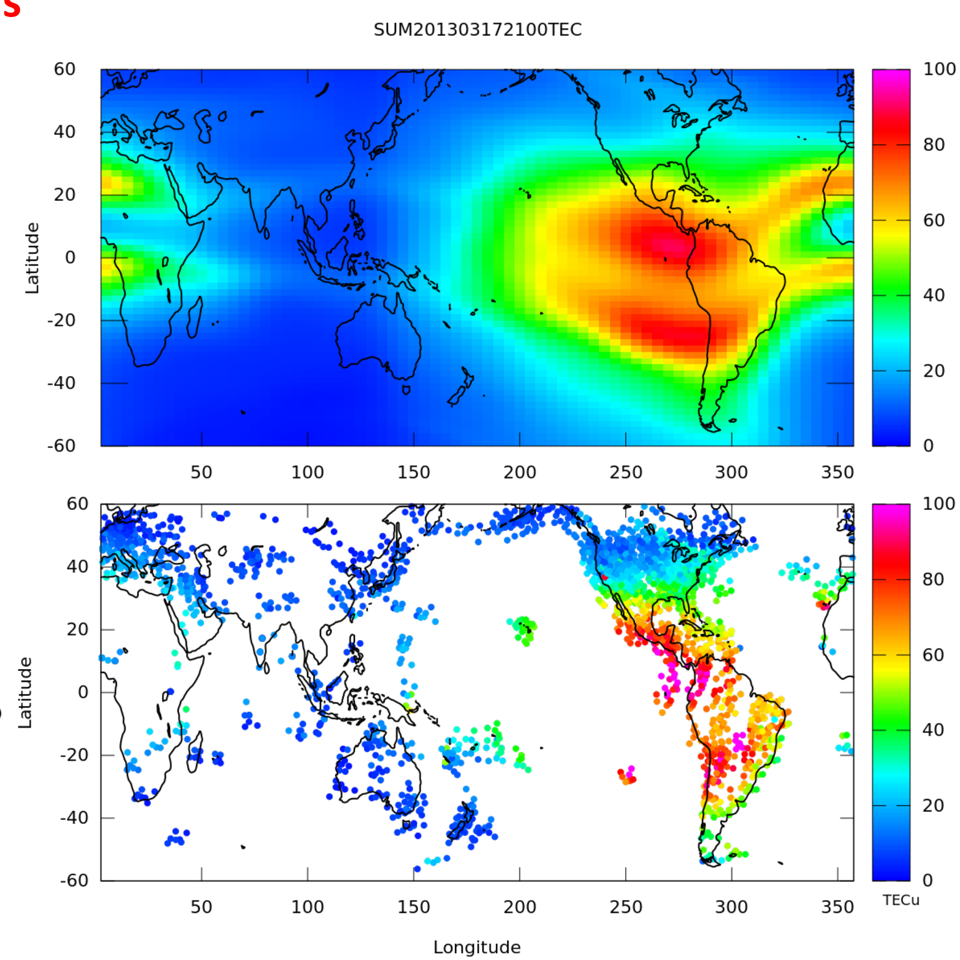
Mid-Low Electro-DA → Ionosphere with Drivers

IFM Physics-Based Model → No DA

Ensemble Average - Simple

Ensemble Mean Vertical TEC Versus TEC Data



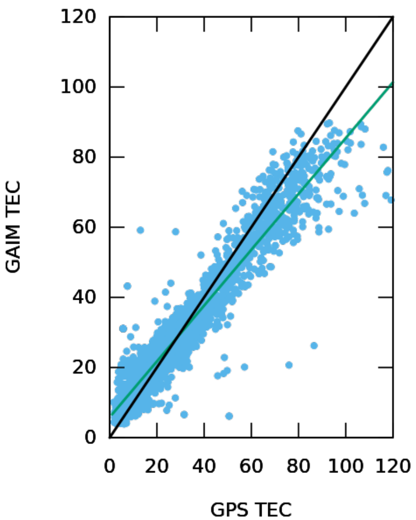


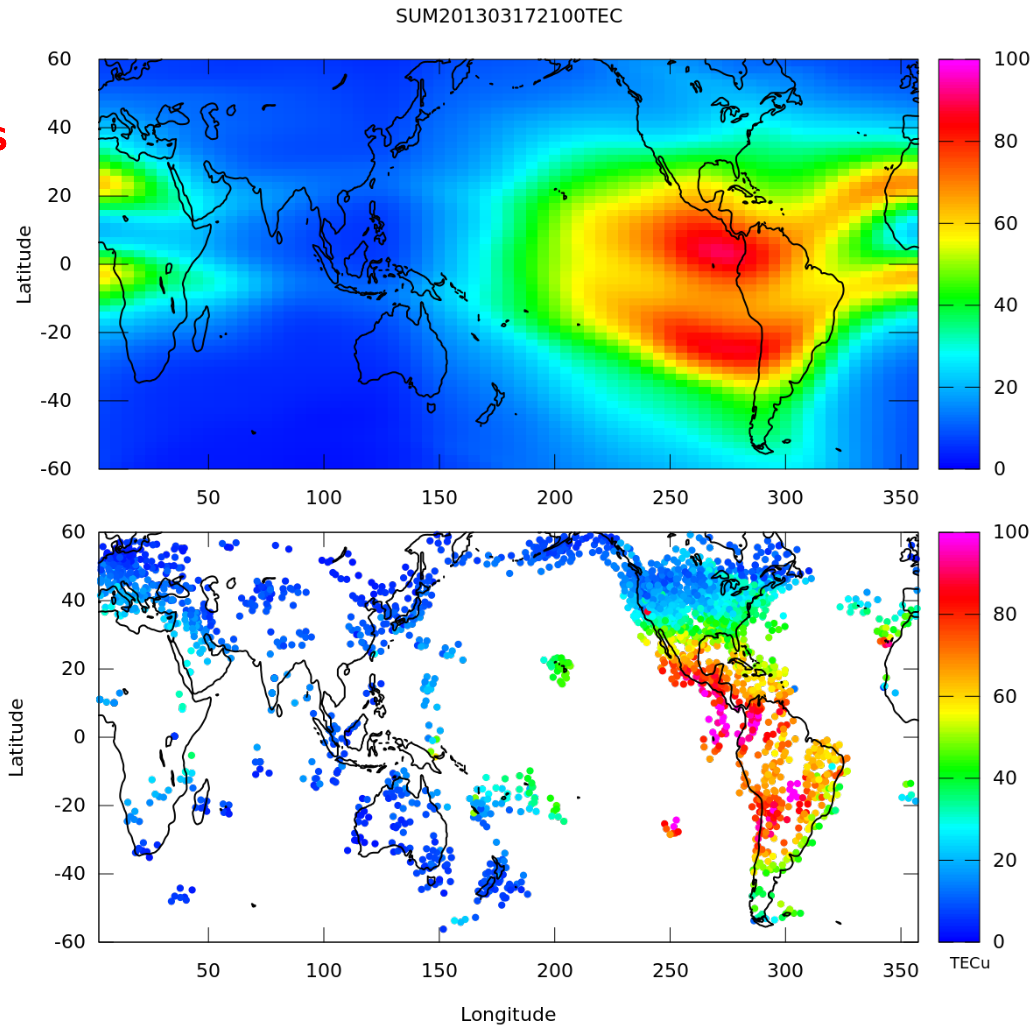
Ensemble Mean Vertical TEC From GPS & Occultation Run

Vertical TEC Data

Ensemble Average - Simple

Ensemble Mean Vertical TEC Versus TEC Data





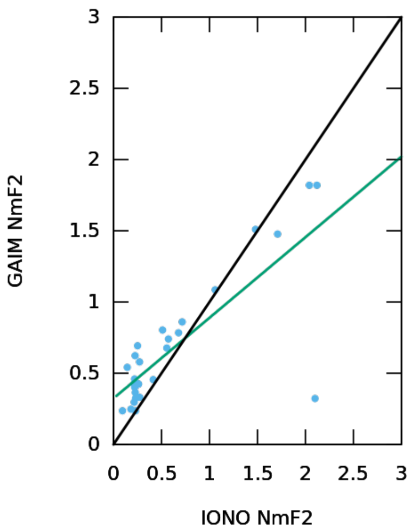
Ensemble Mean Vertical TEC From GPS & Occultation Run

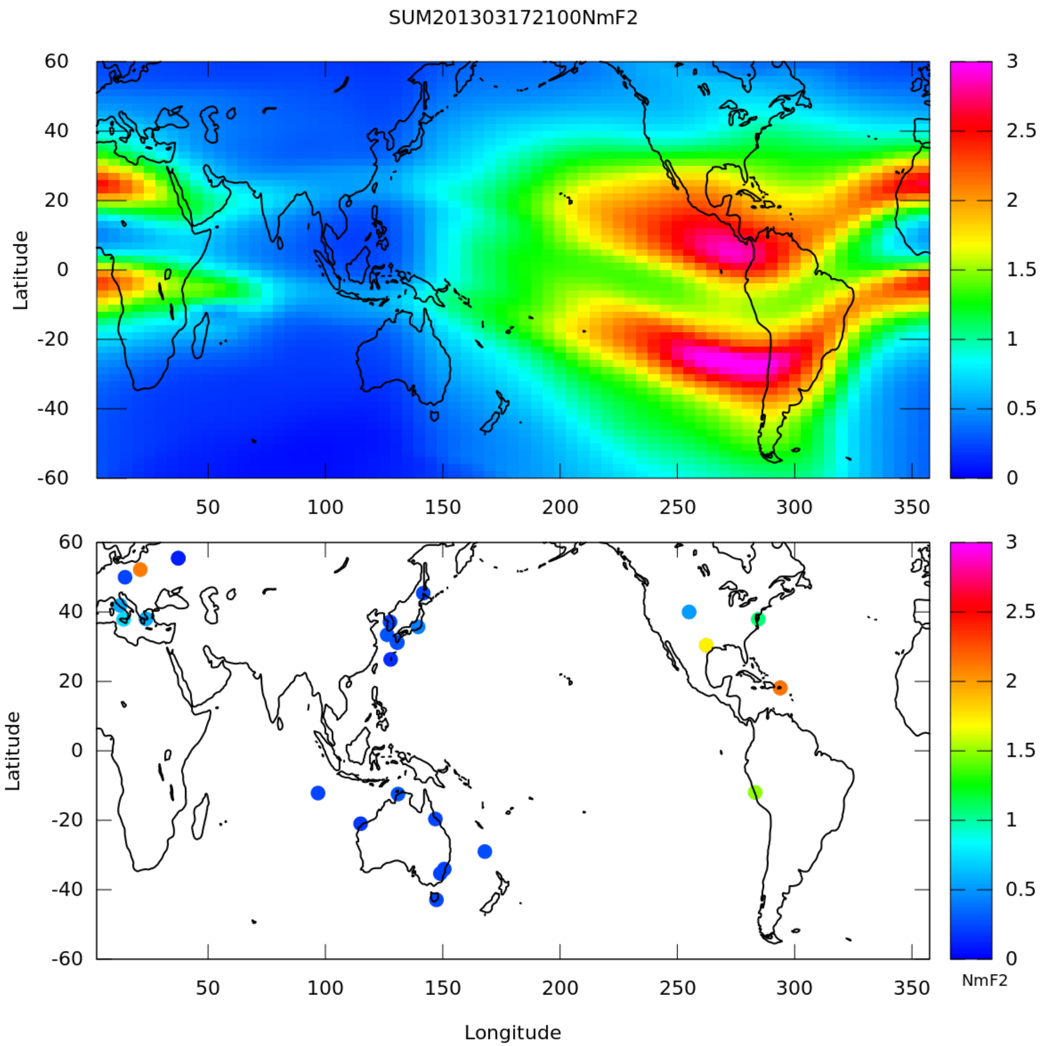
Vertical TEC Data

The Ensemble Mean at all times throughout the 7-day period was better than the Individual Data Assimilation Models

Ensemble Average - Simple

Ensemble Mean
N_mF_2 Versus
N_mF_2 Data



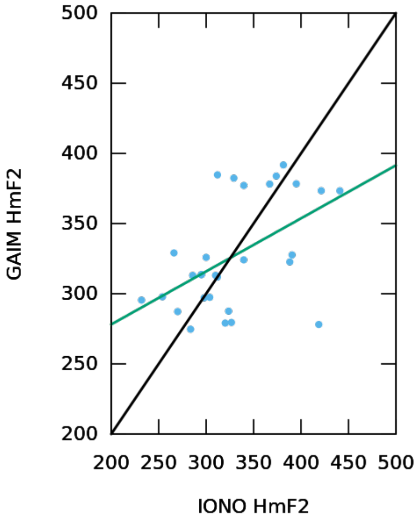


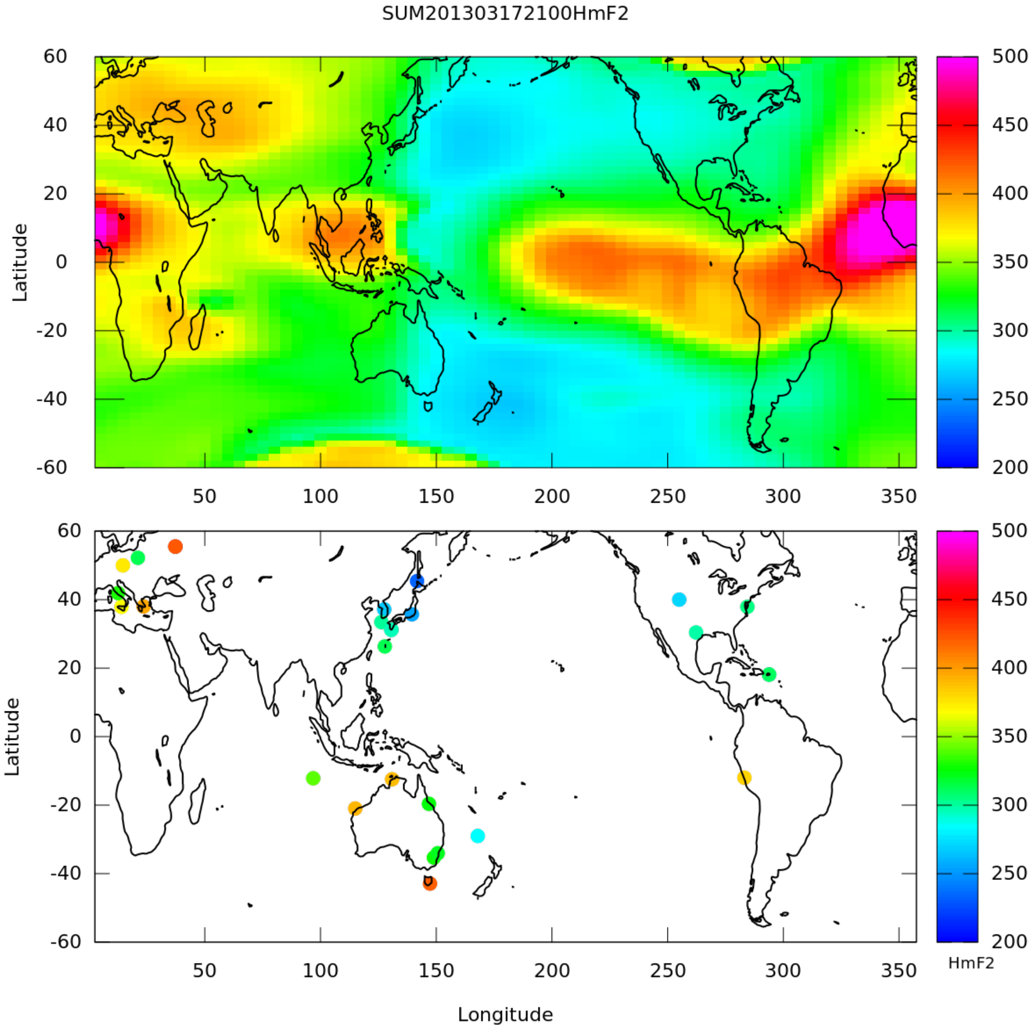
Ensemble Mean
N_mF_2
From GPS &
Occultation Run

N_mF_2 from
Ionosondes

Ensemble Average - Simple

Ensemble Mean h_mF_2 Versus h_mF_2 Data



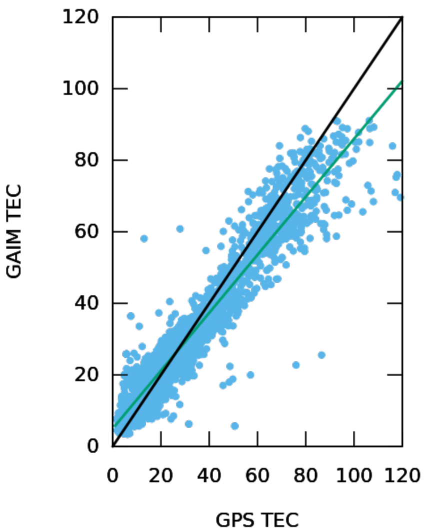


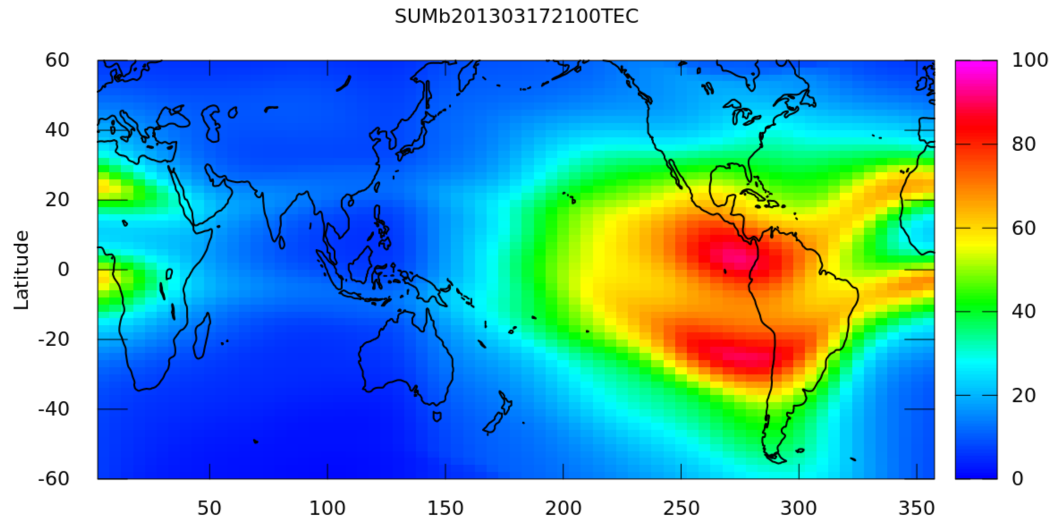
Ensemble Mean h_mF_2 From GPS & Occultation Run

h_mF_2 from Ionosondes

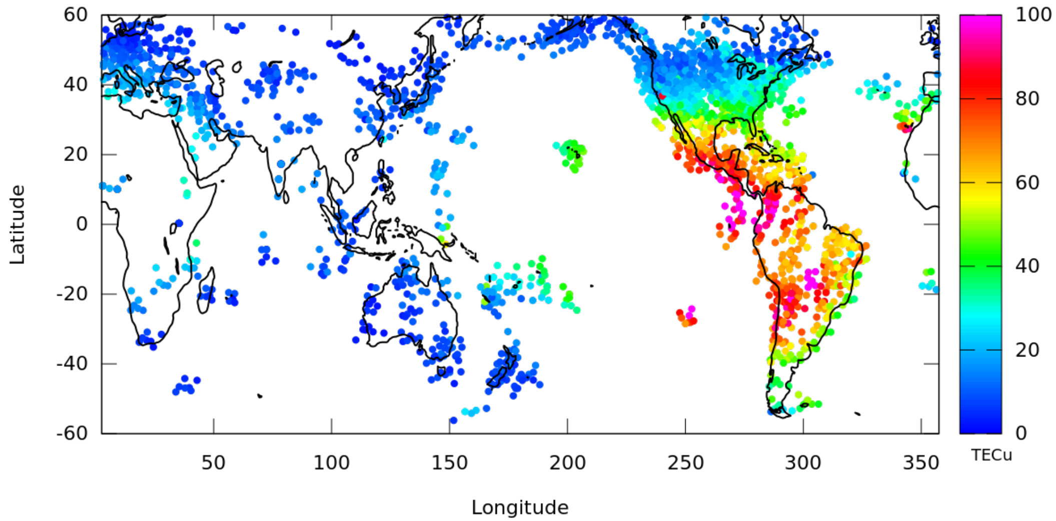
Ensemble Average - Weighted

Ensemble Mean
Vertical TEC
Versus
TEC Data





Ensemble Mean
Vertical TEC
From GPS &
Occultation Run



Vertical TEC
Data

The Weighted Average of the Ensemble of Models Is slightly better than the Simple Average.

Schunk et al., 2021

Forecasting

- **We provide a 24-hour Ionosphere Forecast with our GAIM Operational Models based on Persistence of the I-T Drivers**
- **In general, this Forecast is more reliable during slowly varying magnetic activity**
- **However, the Forecast is reasonable at mid-latitudes, somewhat reasonable at low latitudes, and unreliable at high latitudes.**
- **A reliable 24-hour Ionosphere/Thermosphere Forecast requires reasonable Forecasts of the I-T Drivers**
  - **Convection E-Fields, Auroral Precipitation, Field-Aligned and Horizontal Currents**
  - **Equatorial E-Fields**
  - **Upward Propagating Waves from the Lower Atmosphere**
- **A Significant Challenge for the Next Decade**

Summary

- MEPS → ensemble modeling with different data assimilation models
- Data assimilation on multiple spatial & temporal scales
- Wide range of ground and space data
- An important tool for studying basic physics
- Can combine different data sets into a coherent picture
- Fills in regions where there are no data
- New approach for specifying and forecasting space weather

Selected Physics-Based I-T Model Publications

Time-Dependent Ionosphere Model (TDIM)

Schunk, R. W., Sojka, J. J., and Bowline, M. D. (1986), Theoretical study of the electron temperature in the high-latitude ionosphere for solar maximum and winter conditions. *Journal of Geophysical Research* 91, 12041.

Schunk, R. W., (1988), A mathematical model of middle and high-latitude ionosphere. *Pure and Applied Geophysics (PAGEOPH),* l27, 255-303.

Sojka, J. J., (1989), Global scale, physical models of the F region ionosphere. *Reviews of Geophysics* 27, 371-403.

Ionosphere Forecast Model (IFM)

Schunk, R. W., Sojka, J. J., and Eccles, J. V. (1997), Expanded capabilities for the ionospheric forecast model, Report AFRL-VS-HA-TR-98-0001, Air Force Research Lab., Space Vehicles Directorate, Hanscom AFB, Mass.

Zhu L., et al., (2006), Validation study of the Ionosphere Forecast Model (IFM) using the TOPEX total electron content measurements, *Radio Sci., 41, RS5S11, doi:10.1029/2005RS003336.*

Ionosphere-Plasmasphere Model (IPM)

Schunk, R. W., et al. (2003), Assimilation Ionosphere Model (AIM), *Final Report*, Space Environment Corporation, Logan, UT.

Schunk, R. W., et al. (2004), Global Assimilation of Ionospheric Measurements (GAIM). *Radio Science,* 39, RS1S02, doi:10.1029/2002RS002794.

IPM-Global

Schunk R. W., et al., (2021), Challenges in Specifying and Predicting Space Weather**,** *Space Weather,* 19, https://doi.org/10.1029/2019SW002404.

Physics-Based I-T Model Publications Continued

<u>Global Thermosphere Model (GTM-Ionosphere)</u>

Demars, H. G., and Schunk, R. W., (2008), Modeling and consequences of supersonic winds in the thermosphere, *Proceedings of the 2008 Ionospheric Effects Symposium,* JMG Associates, National Technical Information Services, Springfield, VA.

Gardner, L. C., and Schunk, R. W., (2010), Generation of traveling atmospheric disturbances during pulsating geomagnetic storms, *J. Geophys. Res., 115,* A08314, doi:10.1029/2009JA015129.

Gardner, L. C., and Schunk, R. W., (2011a), Large-scale gravity wave characteristics simulated with a high-resolution global thermosphere-ionosphere model, *J. Geophys. Res., 116,* A06303, doi:10.1029/2010JA015629.

Gardner, L. C., and Schunk, R. W., (2011b), Thermosphere wave interactions in a global thermosphere/ionosphere model, *Proceedings of the 2011 Ionospheric Effects Symposium*, JMG Associates.

Gardner, L., J. J. Sojka, R. W. Schunk, and R. Heelis (2012), Changes in thermospheric temperature induced by high-speed solar wind streams, J. Geophys. Res., 117, A12303, doi:10.1029/2012JA017892

Ma, T.-Z., and Schunk, R.W., (1995), Effect of polar cap patches on the polar thermosphere, *Journal of Geophysical Research 100, 19*,701-19,713.

Ma, T.-Z., and Schunk, R.W., (2001), The effects of multiple propagating plasma patches on the polar thermosphere, *Journal of Atmospheric and Solar-Terrestrial Physics 63*, 355-366.

Schunk, R.W., and Demars, H.G., (2003), Effect of equatorial plasma bubbles on the thermosphere, *Journal of Geophysical Research 108*, No. A6, 1245.

Schunk, R. W., et al., (2008), Effect of lower atmospheric waves on the ionosphere and thermosphere, *Proceedings of the 2008 Ionospheric Effects Symposium,* JMG Associates, National Technical Information Services, Springfield, VA.

Selected USU GAIM and MEPS Publications

Eccles J. V. (2004), Assimilation of global-scale and mesoscale electric fields from low-latitude satellites, *Radio Science, 39*, RS1S09, https//doi.org/10.1029/2002RS002810.

Eccles, J. V., R. D. Hunsucker, D. Rice, and J. J. Sojka (2005), Space weather effects on mid-latitude HF propagation paths: observations and a data-driven D-region model, *Space Weather, 3,* S01002, doi:10.1029/2004SW000094.

Gardner, L. C., R. W. Schunk, L. Scherliess, L. Zhu, and J. J. Sojka (2014a), Ionospheric reconstruction for various solar, seasonal, and geomagnetic conditions obtained from the Global Assimilation of Ionospheric Measurements – Gauss Markov (GAIM-GM) model, *Proceedings of the 2014 Institute of Navigation International Technical Meeting*, San Diego, CA.

Gardner, L. C., R. W. Schunk, L. Scherliess, J. J. Sojka and L. Zhu (2014b), Global Assimilation of Ionospheric Measurements (GAIM) - Gauss Markov (GM) Model: Improved Specifications with Multiple Data Types, *Space Weather*, *12*, 675-688, doi:10.1002/2014SW001104.

Gardner, L. C., Schunk, R. W., Scherliess, L., Eccles, V., Basu, S., & Valladeres, C. (2018). Modeling the mid-latitude ionosphere storm-enhanced density distribution with a data assimilation model. *Space Weather*, 16, 1539–1548. https://doi.org/10.1029/2018SW001882

Lomidze, L., and L. Scherliess, (2015), Estimation of thermospheric zonal and meridional winds using a Kalman filter technique, *Space Weather*, 13, 747–760, doi:10.1002/2015SW001250, 2015.

Scherliess, L., R. W. Schunk, J. J. Sojka, and D. Thompson (2004), Development of a physics-based reduced state Kalman filter for the ionosphere, *Radio Sci., 39 (RS1S04),* doi:10.1029/2002RS002797.

Scherliess, L., R. W. Schunk, J. J. Sojka, D. C. Thompson, and L. Zhu (2006), Utah State University Global Assimilation of Ionospheric Measurements Gauss-Markov Kalman filter model of the ionosphere: Model description and validation, *J. Geophys. Res., 111 (A11315)*, doi:10.1029/2006JA011712.

Scherliess, L., Thompson, D. C., & Schunk, R. W. (2009), Ionospheric dynamics and drivers obtained from a physics-based data assimilation model, *Radio Science*, 44 (RS0A32), https//doi.org/10.1029/2008RS004068.

Scherliess, L., D. C. Thompson, and R. W. Schunk (2011), Data assimilation models: A new tool for ionospheric science and applications, in The Dynamic Magnetosphere, *IAGA Special Sopron Book Series, vol. 3,* edited by W. Liu and M. Fujimoto, pp. 329–339, Springer, Berlin.

Scherliess, L., R. W. Schunk, L. C. Gardner, L. Zhu, J. V. Eccles, and J. J. Sojka (2015), The USU-GAIM data assimilation models for ionospheric specifications and forecasts, *Proceedings of the 2015 Ionospheric Effects Symposium*.

Schunk, R.W., L. Scherliess, J.J. Sojka, and D. Thompson (2004a), Global Assimilation of Ionospheric Measurements (GAIM), *Radio Sci*, *39*, RS1S02, doi:10.1029/2002RS002794.

Schunk, R. W., L. Scherliess, J. J. Sojka, and D. C. Thompson (2004b), USU global iono- spheric data assimilation models, *Proc. SPIE*, 5548, 327–333 doi:10.1117/12.562448.

Schunk, R. W., L. Scherliess, J. J. Sojka, D. C. Thompson, and L. Zhu (2005a), An operational data assimilation model of the global ionosphere, *Proc. Ionospheric Effects Symposium*, edited by J. M. Goodman, 512-518 pp., JMG Assoc., Alexandria, Va.

USU GAIM and MEPS Publications Continued

Schunk, R. W., L. Scherliess, J. J. Sojka, D. C. Thompson, and L. Zhu (2005b), Ionospheric weather forecasting on the horizon, *Space Weather, 3*, S08007, doi:10.1029/2004SW000138.

Schunk, R. W., L. Gardner, L. Scherliess, and L. Zhu (2012), Problems associated with uncertain parameters and missing physics for long-term ionosphere-thermosphere forecasting, *Radio Science, 47,* RS0L23, doi:10.1029/2011RS004911.

Schunk, R. W., L. Scherliess, V. Eccles, L. C. Gardner, J. J. Sojka, L. Zhu, X. Pi, A. J. Mannucci, Mark Butala, B. D. Wilson, A. Komjathy, C. Wang and G. Rosen, (2014a), Multimodel ensemble prediction system for space weather applications, *Proceedings of the 2014 Institute of Navigation International Technical Meeting*, San Diego, CA.

Schunk, R. W., NASA/NSF Space Weather Modeling Collaboration: Advancing Space Weather Modeling for Improved Specification, Forecasting and Mitigation, (2014b), *Space Weather,* doi:10.1002/2014SW001049.

Schunk, R. W., L. Scherliess, V. Eccles, L. C. Gardner, J. J. Sojka, L. Zhu, X. Pi, A. J. Mannucci, B. D. Wilson, A. Komjathy, C. Wang and G. Rosen (2014c), Ensemble Modeling with Data Assimilation Models: A New Strategy for Space Weather Specifications, Forecasts and Science, *Space Weather* 12, 123-126, doi:10.1002/2014SW001050.

Schunk, R. W., L. Scherliess, J. V. Eccles, L. C. Gardner, J. J. Sojka, L. Zhu, X. Pi, A. J. Mannucci, M. Butala, B. D. Wilson, A. Komjathy, C. Wang, and G. Rosen, (2016), Space weather forecasting with a Multimodel Ensemble Prediction System (MEPS). *Radio Science*. 51, DOI: doi:10.1002/ 2015RS005888.

Schunk, R. W., et al., (2021), Challenges in Specifying and Predicting Space Weather, *Space Weather, 19*, Issue 2, https://doi.org/10.1029/2019SW002404.

Sojka, J. J., D. C. Thompson, R. W. Schunk, T. W. Bullett, and J. J. Makela, (2001), Assimilation Ionosphere Model: Development and testing with combined ionospheric campaign Caribbean measurements, *Radio Sci., 36*, 247-259.

Sojka, J. J., D. C. Thompson, L. Scherliess, and R. W. Schunk (2007), Assessing models for ionospheric weather specification over Australia during the 2004 CAWSES campaign, *J. Geophys. Res.,* 112, A09306, doi:10.1029/2006JA012048.

Thompson, D. C., L. Scherliess, J. J. Sojka and R. W. Schunk, (2006), The Utah State University Gauss-Markov Kalman filter in the ionosphere: The effect of slant TEC and electron density profile data on model fidelity, *J. Atmos. Solar-Terr. Phys*., 68, 947-958.

Thompson, D. C., L. Scherliess, J. J. Sojka and R. W. Schunk, (2009), Plasmasphere and upper ionosphere contributions and corrections during the assimilation of GPS slant TEC, *Radio Sci., 44*, RS0A02, doi:10.1029/2008RS004016.

Zhu, L., R. W. Schunk, L. Scherliess, and J. V. Eccles (2012), Importance of the assimilation technique in define the model drivers for the space weather specification of the high-latitude ionosphere, *Radio Sci., 47*, RS0L24, doi:10.1029/2011RS004936.

Zhu, L., R. W. Schunk, V. Eccles, L. Scherliess, J. J. Sojka, and L. Gardner (2014), Terminator field-aligned currents: A new finding from the Ionospheric Dynamics and Electrodynamics Data Assimilation Model, *J. Geophys. Res., 119,* 4752-4757, doi:10.1002/2013JA019518.

Selected JPL/USC MEPS Publications

Hajj, A. G., Lee, L. C., Pi, X., Romans, L. J., Schreiner, W. S., Straus, P. R., & Wang, C. (2000), COSMIC GPS ionospheric sensing and space weather, *Terrestrial Atmospheric and Oceanic Sciences., 11*, 235.

Hajj, G. A, Wilson, B. D., Wang, C., Pi, X., & Rosen, I. G. (2004), Data assimilation of ground GPS total electron content into a physics-based ionospheric model by use of the Kalman filter, *Radio Science, 39(2)*, RS1S05, https//doi.org/10.1029/2002RS002859.

Komjathy, A., Wilson, B., Pi, X., Akopian, V., Dumett, M., Iijima, B., et al. (2010), JPL/USC GAIM: On the impact of using COSMIC and ground-based GPS measurements to estimate ionospheric parameters, *Journal Geophysical Research*, *115*, A02307, https//doi.org/10.1029/2009JA014420.

Pi, X., Wang, C., Hajj, G. A., Rosen, I. G., Wilson, B. D., & Bailey, G. (2003), Estimation of E×B drift using a global assimilative ionospheric model: An observation system simulation experiment, *Journal of Geophysical Research, 108*(A2), 1075-1087, doi:10.1029/2001JA009235.

Pi, X., Wang, C., Hajj, G. A., Rosen, G., Wilson, B. D., & Mannucci, A. J. (2004), Assimilative modeling of low-latitude ionosphere, *Proceedings IEEE PLANS*, 543-550.

Pi, X., Akopian, V., Mannucci, A. J., Wilson, B. D., Komjathy, A., Iijima, B. A., et al. (2008), Modeling low-latitude ionosphere using GAIM assimilating GPS data, paper presented at *12th International Symposium on Equatorial Aeronomy* (ISEA-12), Crete, Greece.

Pi, X., Mannucci, A. J., Iijima, B. A., Wilson, B. D., Komjathy, A., Runge, T. F., & Akopian, V. (2009), Assimilative modeling of ionospheric disturbances with FORMOSAT-3/COSMIC and ground-based GPS measurements, *Terrestrial Atmospheric Oceanic Science*, *20*(1), 273-285.

Rosen, I. G., Wang, C., Hajj, G., Pi, X., & Wilson, B. (2001), An adjoint method based approach to data assimilation for a distributed parameter model for the ionosphere, paper presented at *40th Conference on Decision and Control*, Inst. of Electr. and Electron. Eng., Orlando, Fla.

Wang, C., Hajj, G. A., Pi, X., Rosen, I. G., & Wilson, B. D. (2004), Development of the global assimilative ionospheric model, *Radio Science, 39*(2), https//doi.org/10.1029/2002RS002854

Other Publications

Eddy, J. A. (1976), The Maunder minimum, *Science*, 192, 1189.

Frank, L. A. (1986), The Theta aurora, *J. Geophys. Res.,* 91, 3177.

Fukui, K., Buchau, J., and Valladares, C. E. (1994), Convection of polar cap patches at Qaanaaq, Greenland during the winter of 1989-1990, *Radio Science, 29. 231.*

Hysell, D. L., and Burcham, J. D. (1998), JULIA radar studies of equatorial spread F, *J. Geophys. Res.,* 103, 29155.