Ensemble Modeling with Data Assimilation Models: A New Strategy for Space Weather Specifications and Forecasts

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, M. Butala, B. D. Wilson, and A. Komjathy

University of Southern California

C. Wang and G. Rosen

NASA-NSF Space Weather Modeling Collaboration
May 20-22, 2014
NASA Ames Research Center, CA

NASA/NSF Space Weather Modeling Collaboration

Science Focus

- **Elucidate the fundamental physical, chemical, and coupling processes that operate in the I-T-E system for a range of *actual, global-scale, space weather events*, including storms & substorms.**

- **Identify the spatial and temporal scales over which mass, momentum, and energy flow in the system.**

- **Determine the effect that *plasma and neutral gas structures (100-1000 km) have on global-scale flows.***

Model Construction

Construct a *Multimodel Ensemble Prediction System (MEPS)* for the Ionosphere-Thermosphere-Electrodynamics (I-T-E) system that will incorporate existing, first-principles-based, data assimilation models with different physics, numerics and initial conditions.

MEPS will allow ensemble modeling with different data assimilation models.

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

- **Global, Regional & Nested GRID Capabilities**
- **GAIM-GM & GAIM-BL are Operational Models**
- **Specifications & Forecasts**

MEPS Data Sources

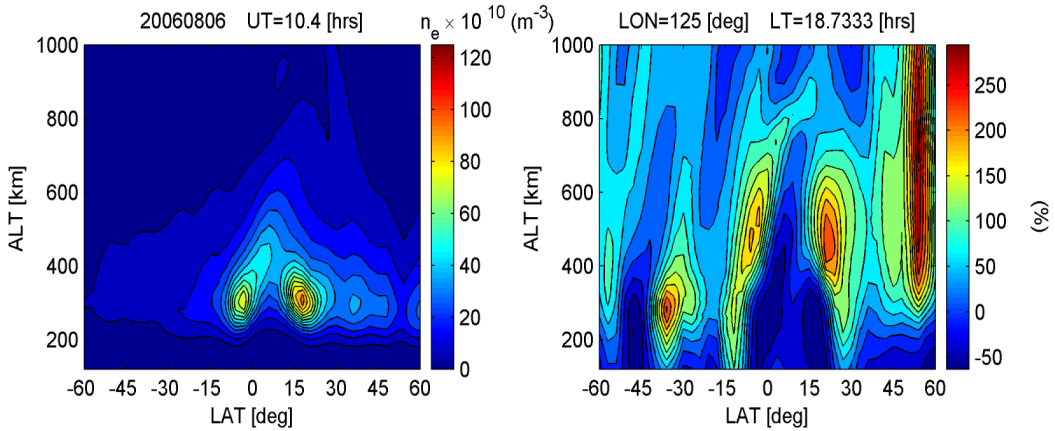
Table 1. Data Sources that our new Data Assimilation System will assimilate

Ionosphere	Electrodynamics	Thermosphere
Ground-Based GPS-TEC	Ground magnetometers	Satellite UV emissions
Satellite-Based GPS Occultation	DMSP cross-track velocities	In situ neutral densities and winds
Ionosonde and Digisonde	SuperDARN line-of-sight velocities	Satellite accelerometer and drag
In situ N_e	Iridium magnetometers	FPI winds
911Å, 1356Å, limb, disk (UV)	ACE IMF, Dst	ISR Neutral parameters
Solar UV, EUV	Solar UV, EUV	Solar UV, EUV

Black: Data sources already being assimilated; Red: New data sources to be assimilated

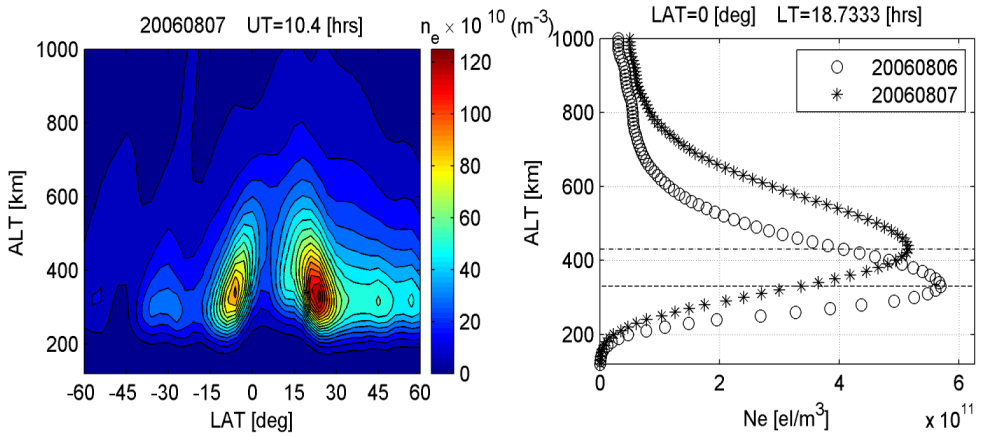
GAIM-BL Ionosphere Reconstructions

Ne Quiet



ΔNe

Ne Storm



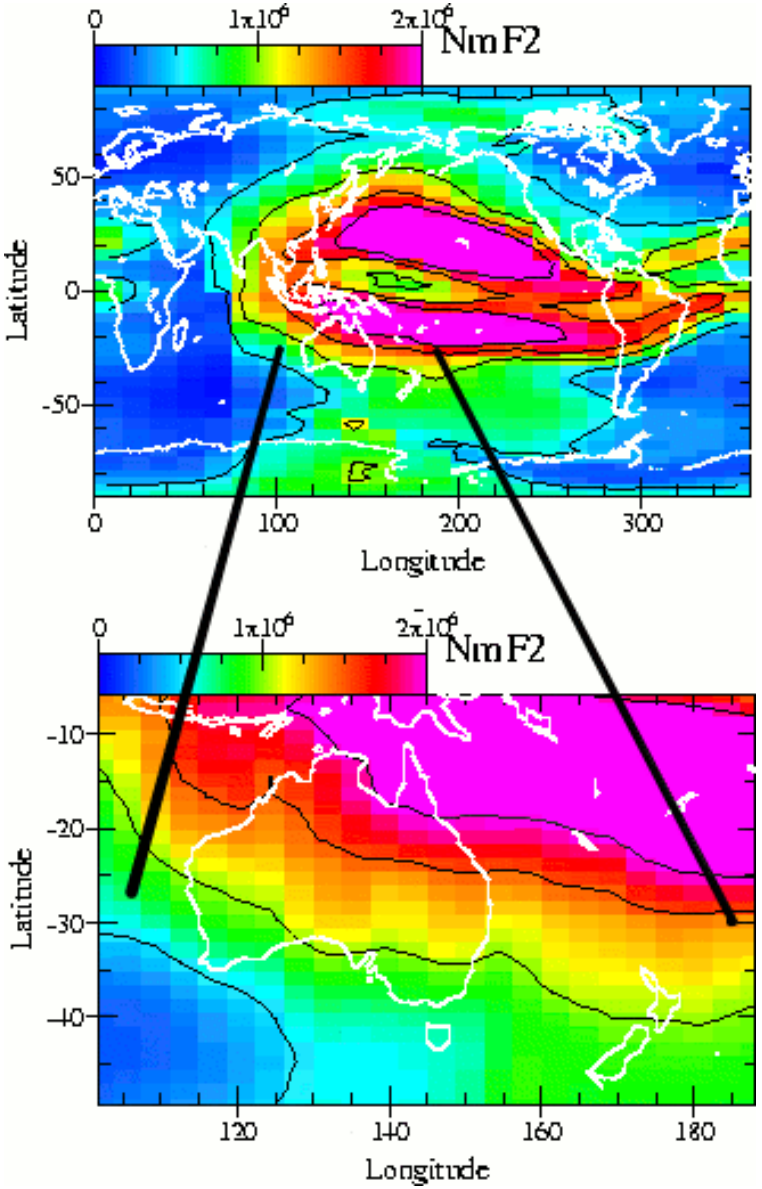
Ne Profiles

- **GAIM-BL assimilated ground-based and spaceborne (COSMIC) GPS data.**
- **August 7, 2006 storm**
- **Data assimilation reveals storm-time enhanced zonal E-field and equatorial anomaly.**

[Pi et al., 2009]

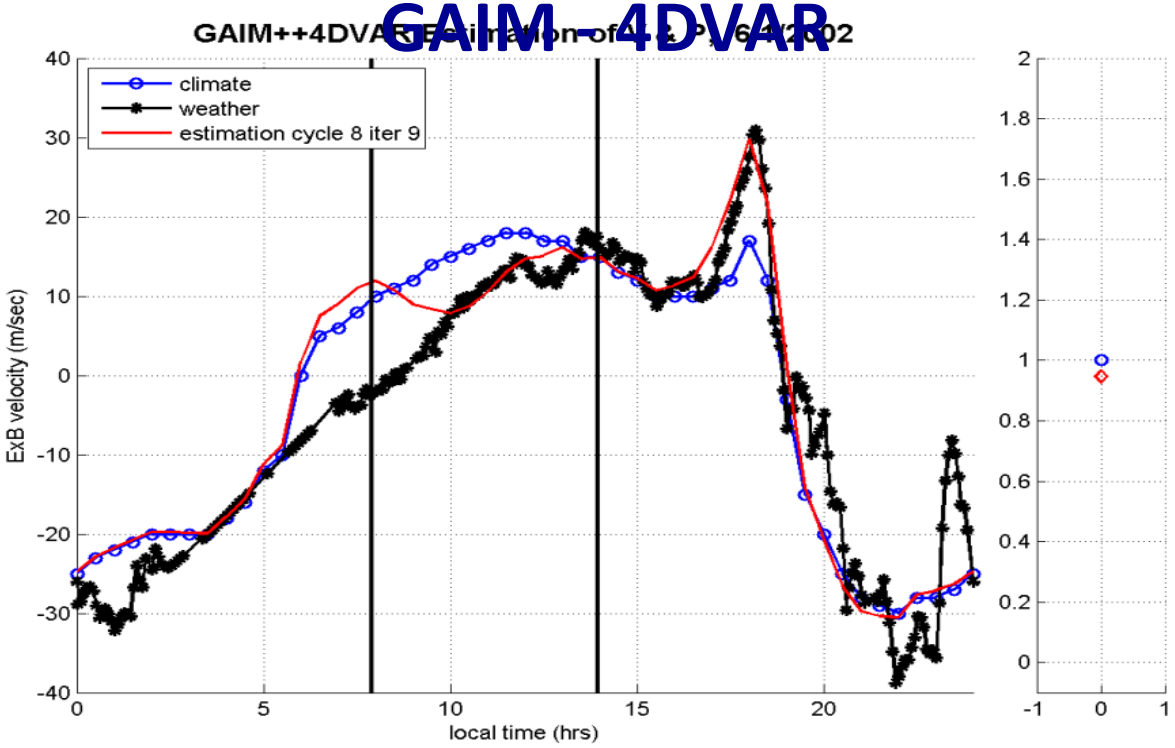
GAIM-GM Nested Grid Capability

- Improved Spatial Resolution
  - 1˚ Latitude (variable)
  - 3.75˚ Longitude (variable)
- Usefulness Depends on Data
- Capability Since 2004 in GAIM-GM Operational Model
- In 2004 Run - 11 ionosondes & 15 GPS in Nested Grid Region
- Captures Edge of Anomaly



Ionosphere Reconstructions With Self-Consistent Drivers

GAIM – 4DVAR



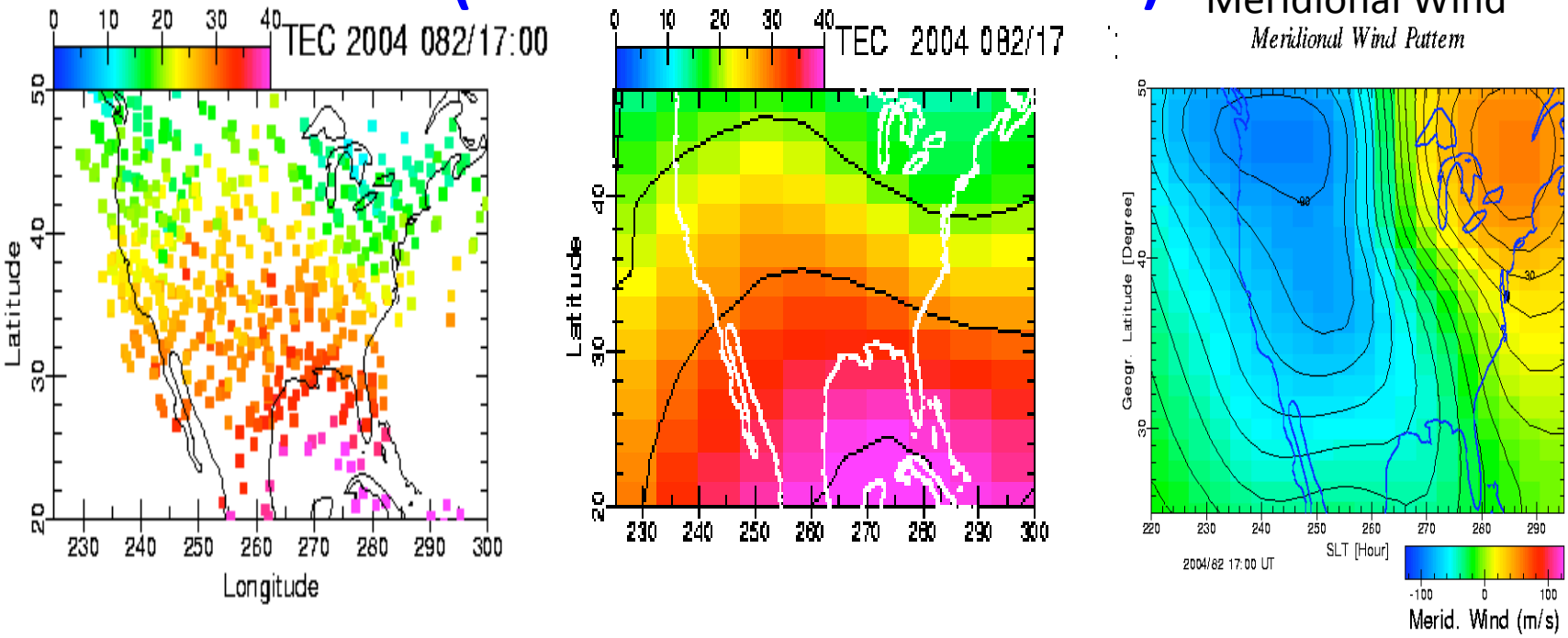
- Estimate equatorial electric field/plasma drift, ion production factor, and wind.
- Black circles indicate ISR measurements made at the Jicamarca Radio Observatory
- Blue curve is an empirical model result
- Red curve presents estimated vertical drift and a single-ion production factor
- Data assimilation helps GAIM catch the pre-reversal enhancement

  [Pi et al., 2008].

Ionosphere Reconstructions With Self-Consistent Drivers

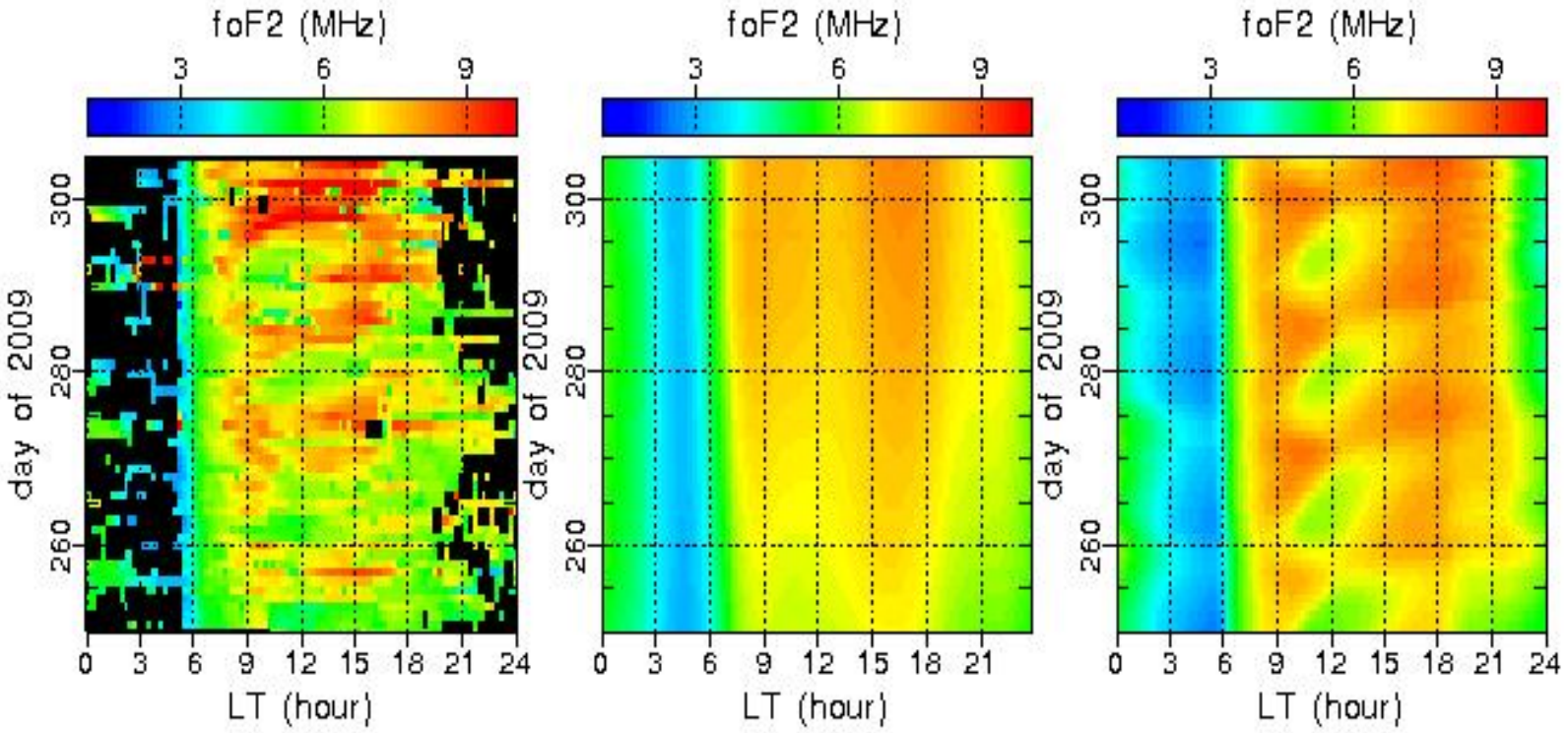
GAIM-FP ➔Regional Run

(Ensemble Kalman Filter)



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

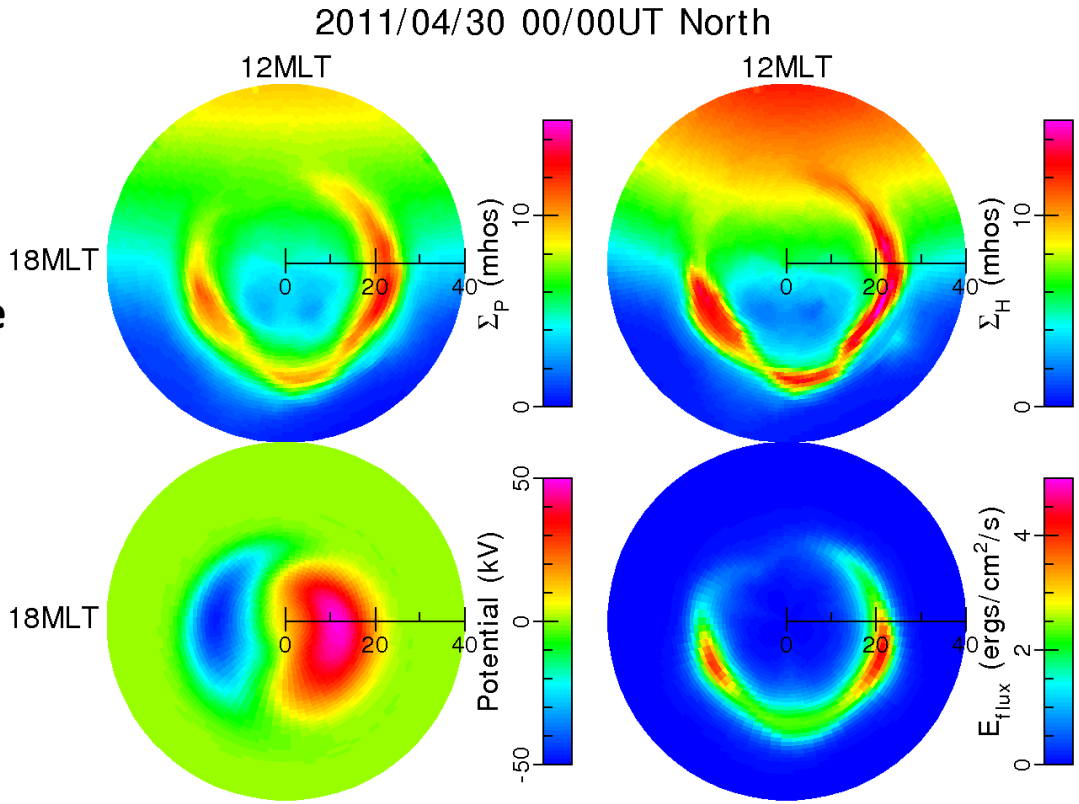
Ionosphere-Electrodynamics Reconstructions (Mid & Low Lat. Electrodynamics – DA)



- **Observed *foF$_2$* at Jicamarca (left)**
- **Modeled *foF$_2$* using Scherliess and Fejer plasma drifts (center)**
- **Derived *foF$_2$* using an ensemble data assimilation model (right)**
- **Captures lunar and solar tides**

(*Eccles et al., 2011*)

Ionosphere-Electrodynamics Reconstructions
IDED-DA



Height-integrated Pedersen conductance

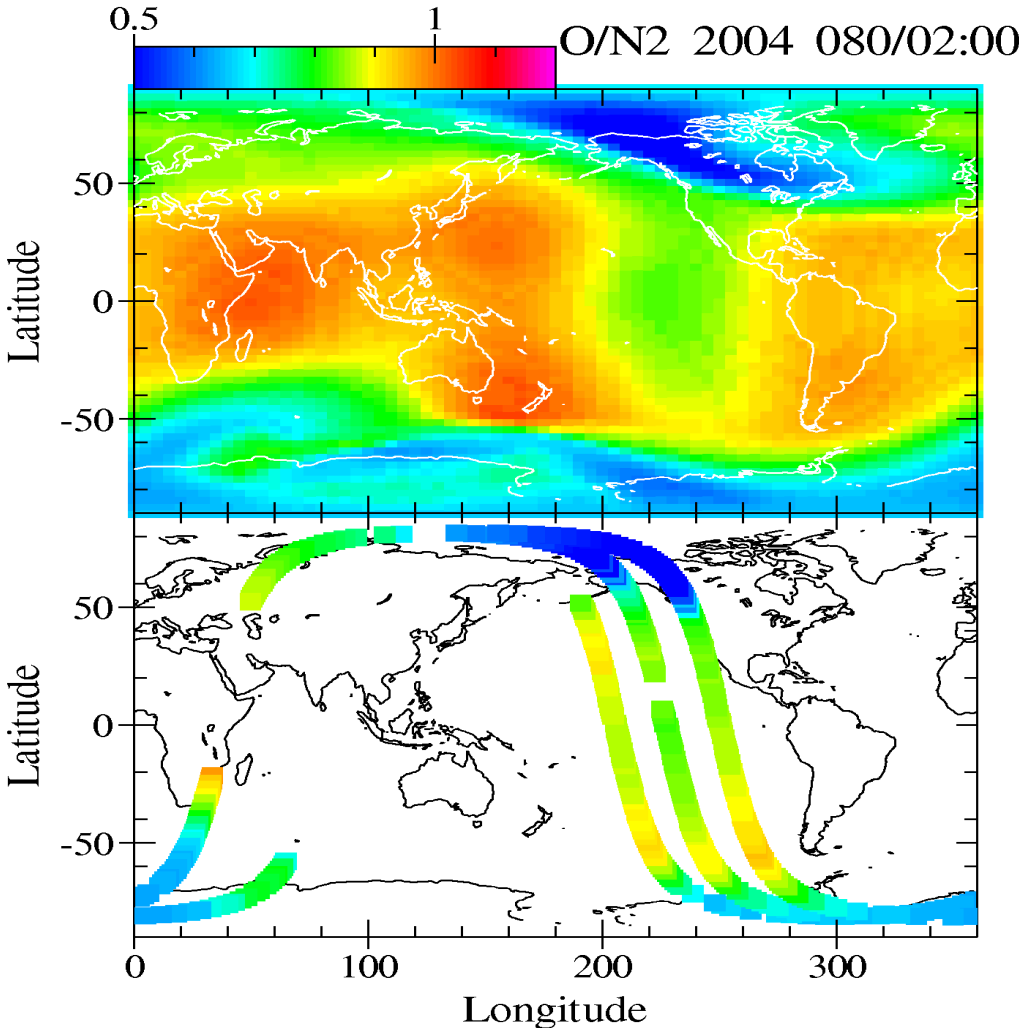
Height-integrated Hall conductance

Electric potential

Precipitating electron energy flux

- **Northern polar region**
- **Storm period 2011/119 23:55 UT**

Global Thermosphere Reconstructions
GTM-DA
(Ensemble Kalman Filter)



Global O/N_2 reconstruction from an ensemble Kalman Filter GTM-DA run

Synthetic SSUSI O/N_2 observations from 3 DMSP satellites were assimilated

MEPS Initial Simulation Plan

- **Run 4 data assimilation models independently for same case**
- **Run with TEC data from 530 ground GPS receivers**
- **Run with 530 ground GPS receivers & COSMIC occulation data**
- **Run with 530 ground GPS receivers, occultation data, & 80 digisondes**

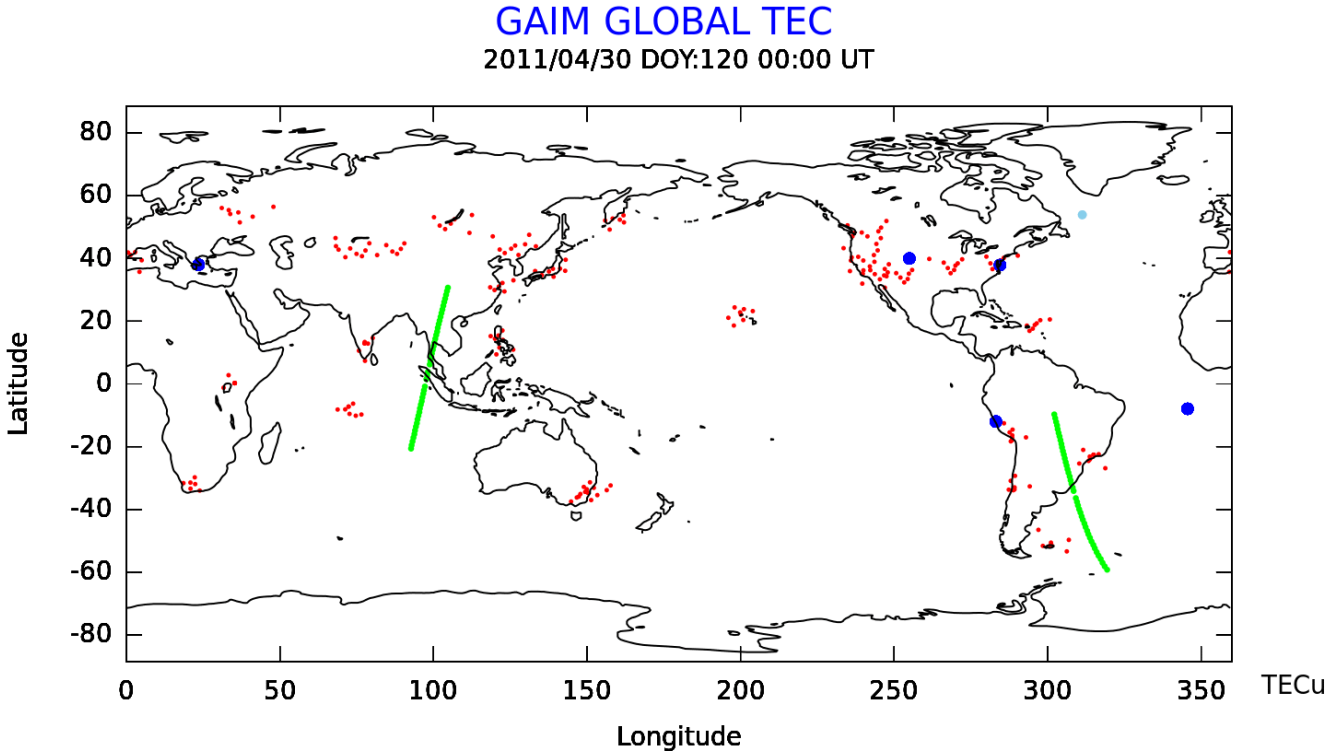
MEPS First Ionosphere Reconstructions

- **The first geophysical case we selected covers the period April 25 – May 1, 2011, which was initially magnetically quiet but later contained a magnetic storm.**

- **The different data assimilation models were run the way they are normally run, with different data amounts and data types.**

- **Clearly, the reconstructions will not be the same under these conditions, but this will establish the current 'state-of-the-art'.**

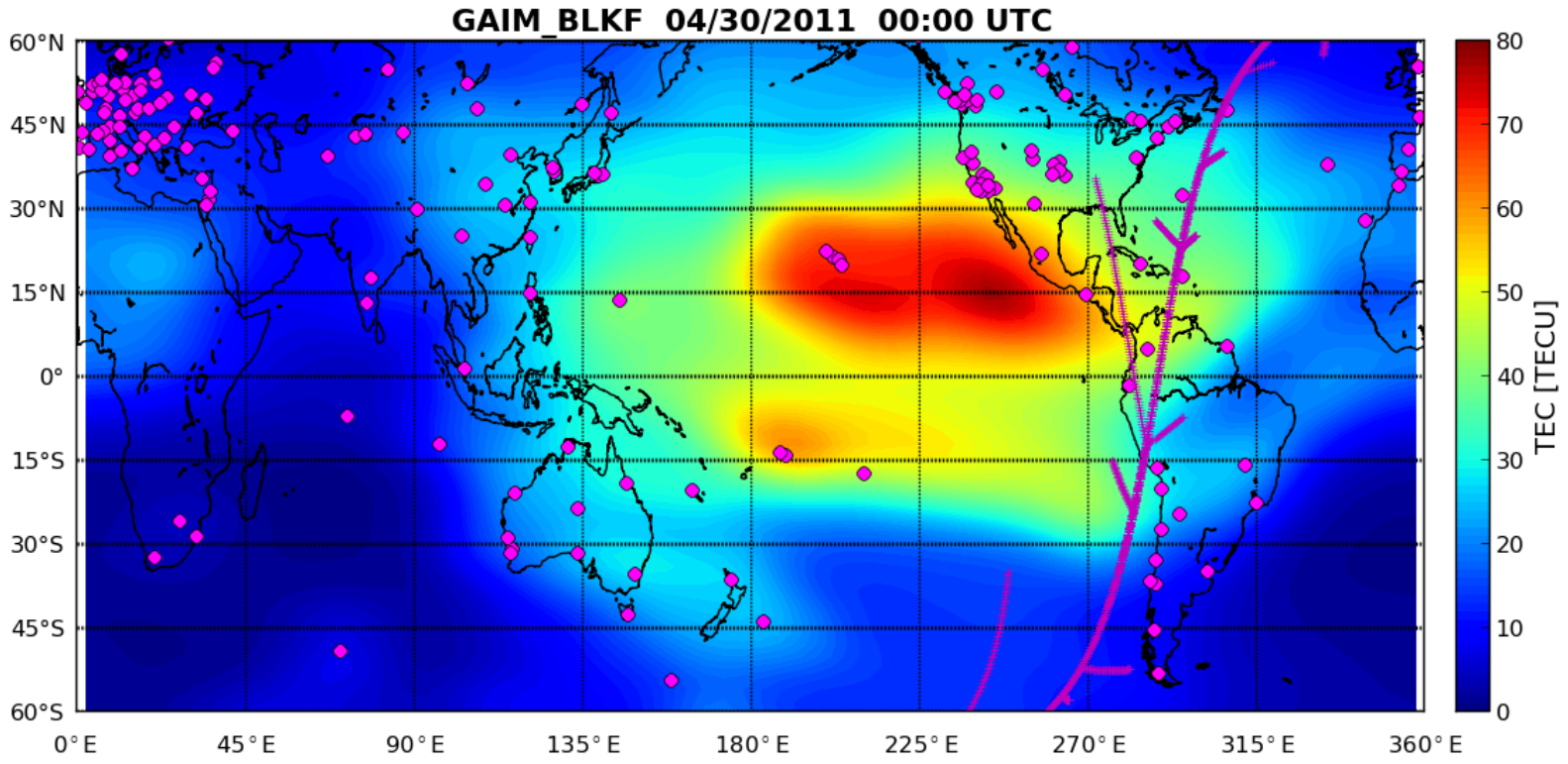
Data Available for GAIM-GM



- There were 64 GPS stations, with 200 slant TEC links per 15-minute step
- 15 DISS stations, with 120 densities per 15-minute step
- 100 DMSP in situ N_e per 15-minute step
- COSMIC - 20 densities and 250 occultations per 15-minute step

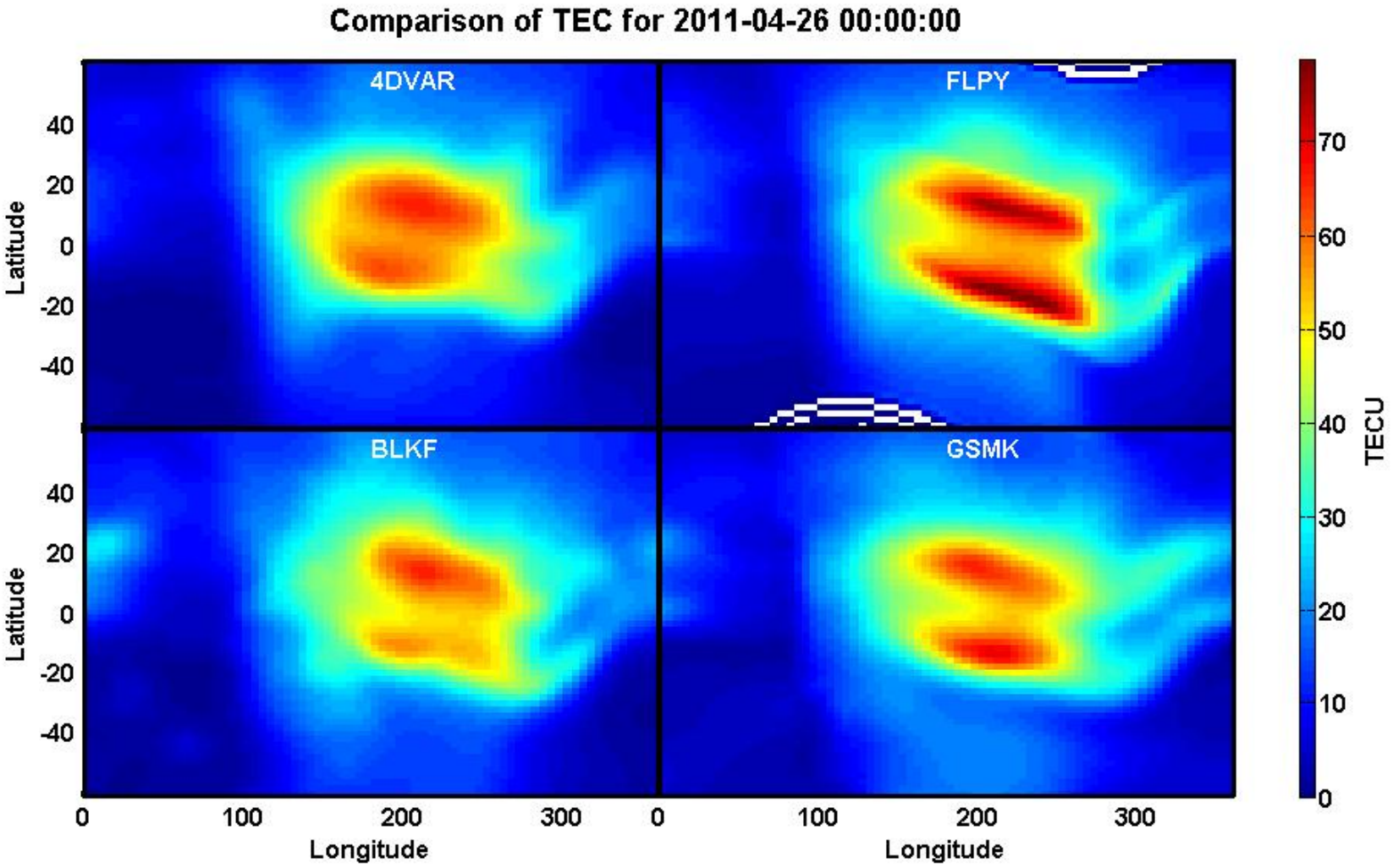
GAIM-FP model → Several Hundred Ground GPS Receivers

Data Available for GAIM-BL and GAIM-4DVAR



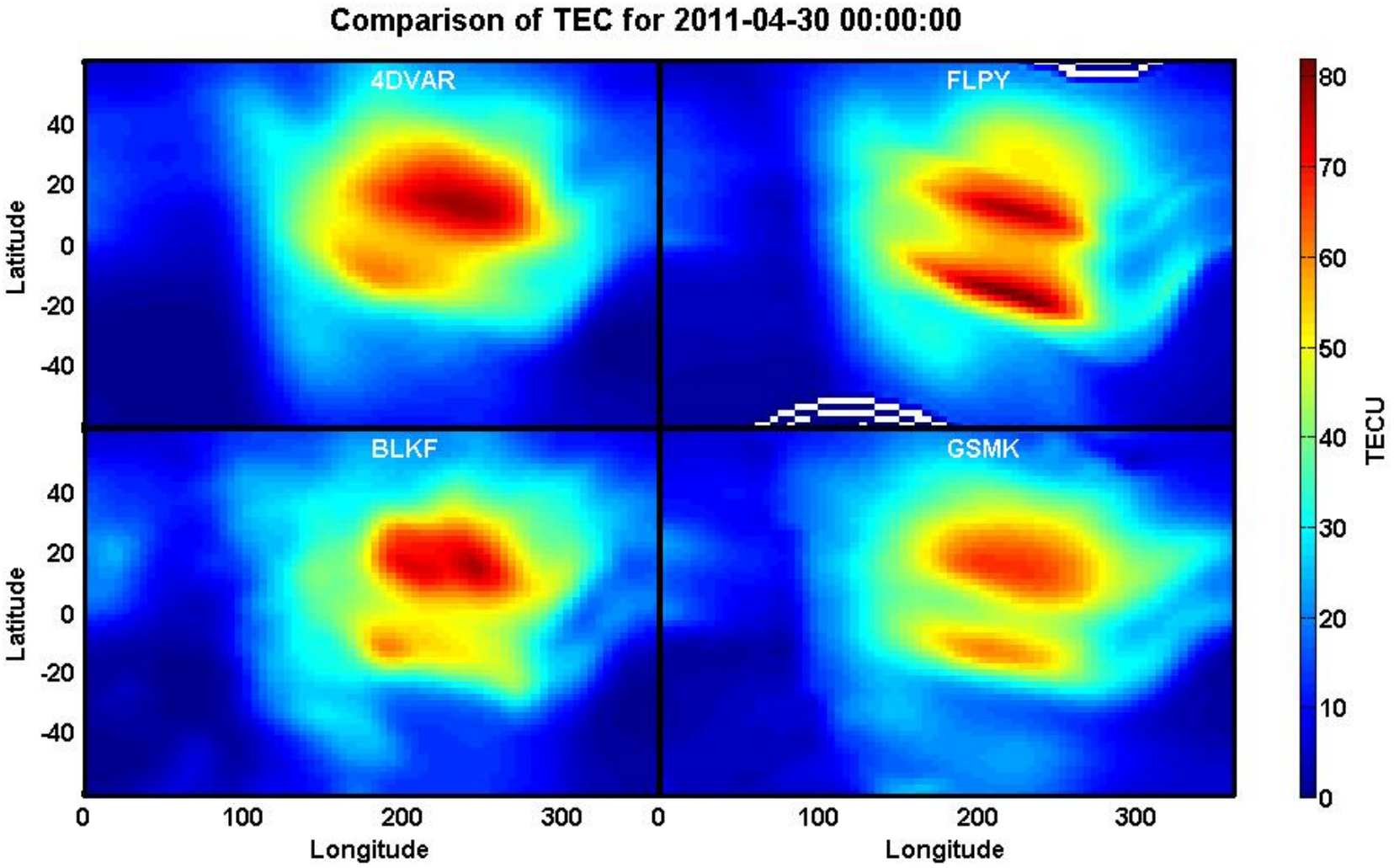
- GAIM-BL TEC on 4/30/2011 at 0 UT
- GPS TEC from 199 GPS stations
- COSMIC RO occultation data from three satellites

MEPS Initial Study



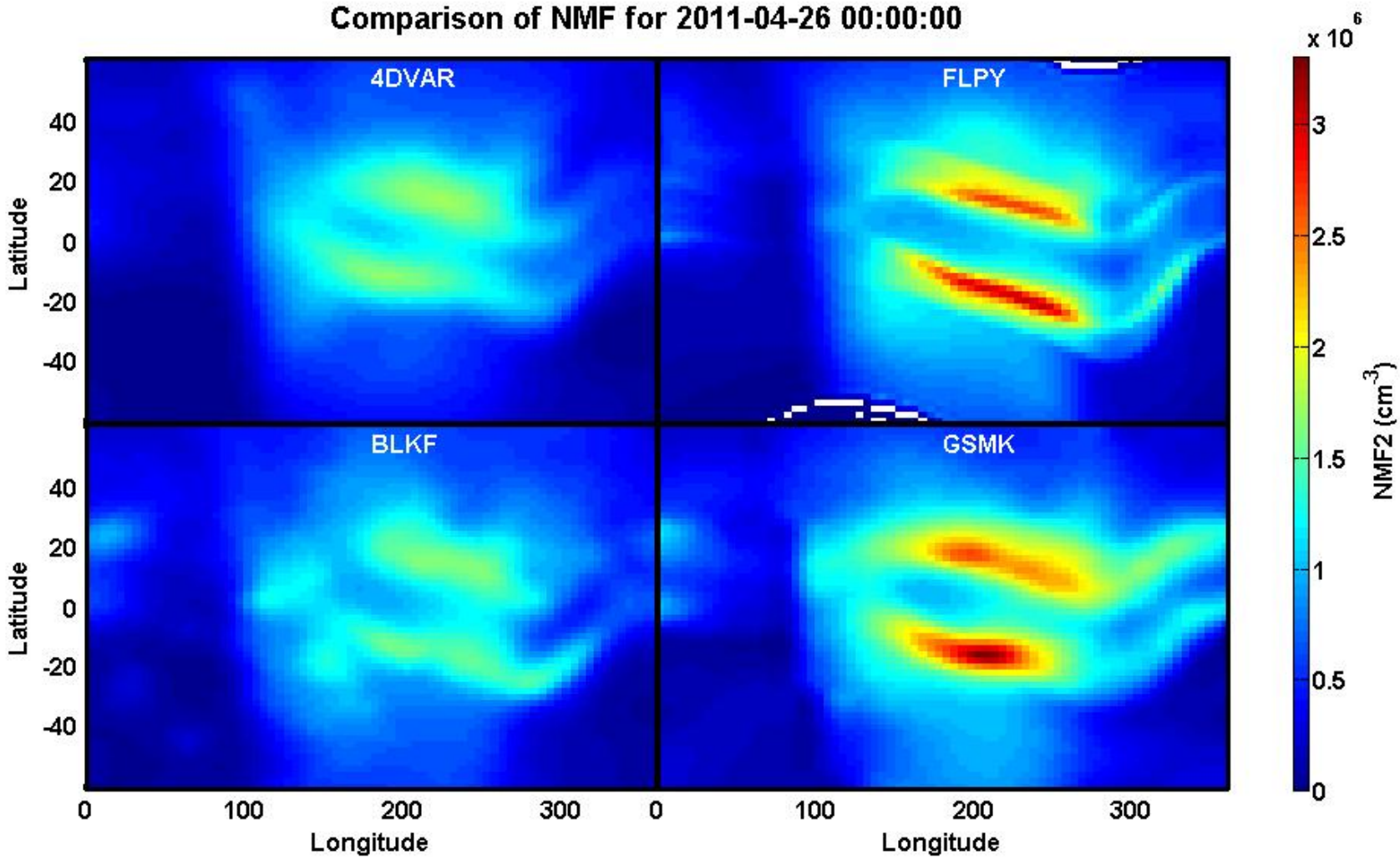
GAIM-4DVAR, GAIM-FP, GAIM-BL, GAIM-GM → Quiet

MEPS Initial Study



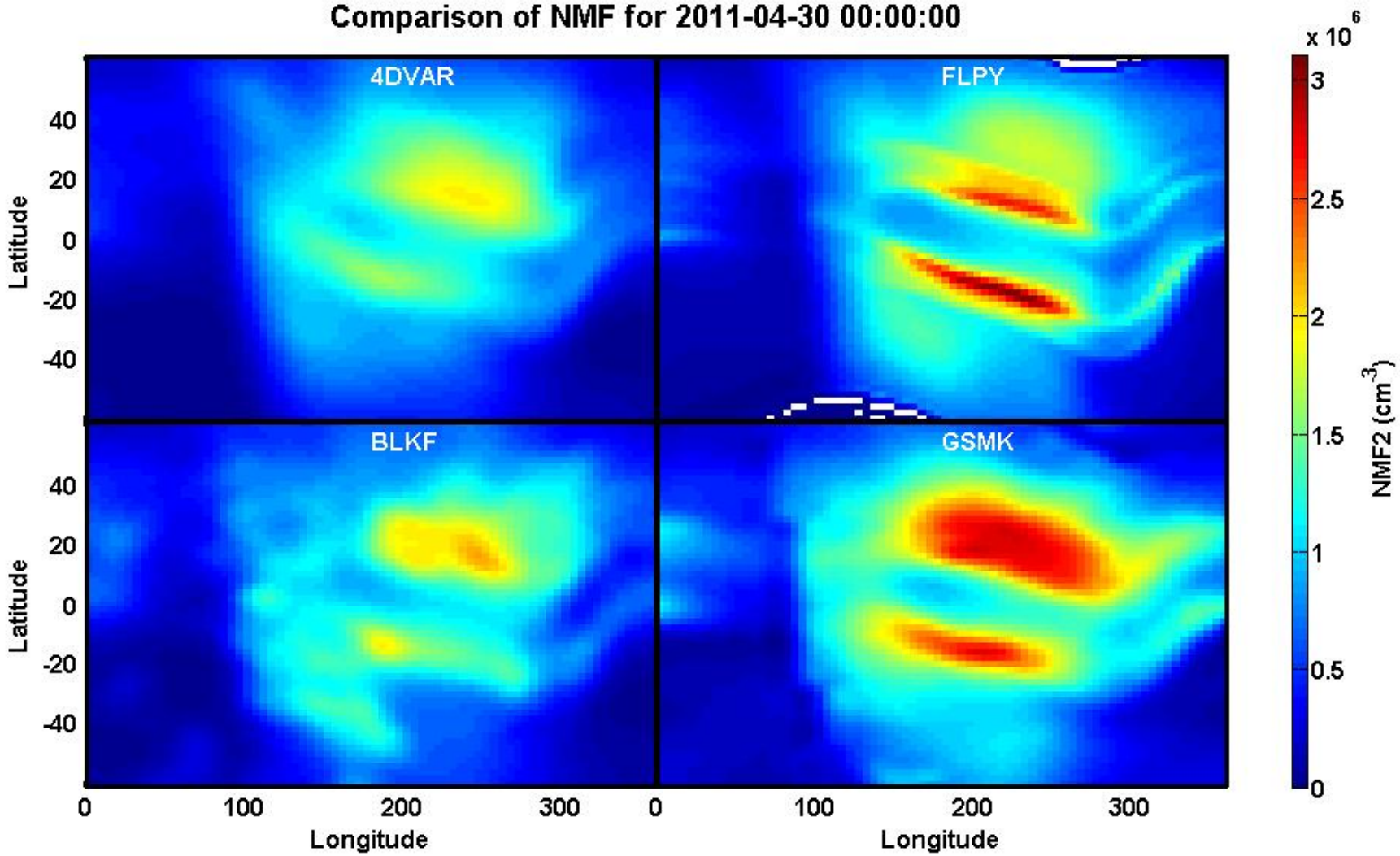
GAIM-4DVAR, GAIM-FP, GAIM-BL, GAIM-GM → Storm

MEPS Initial Study



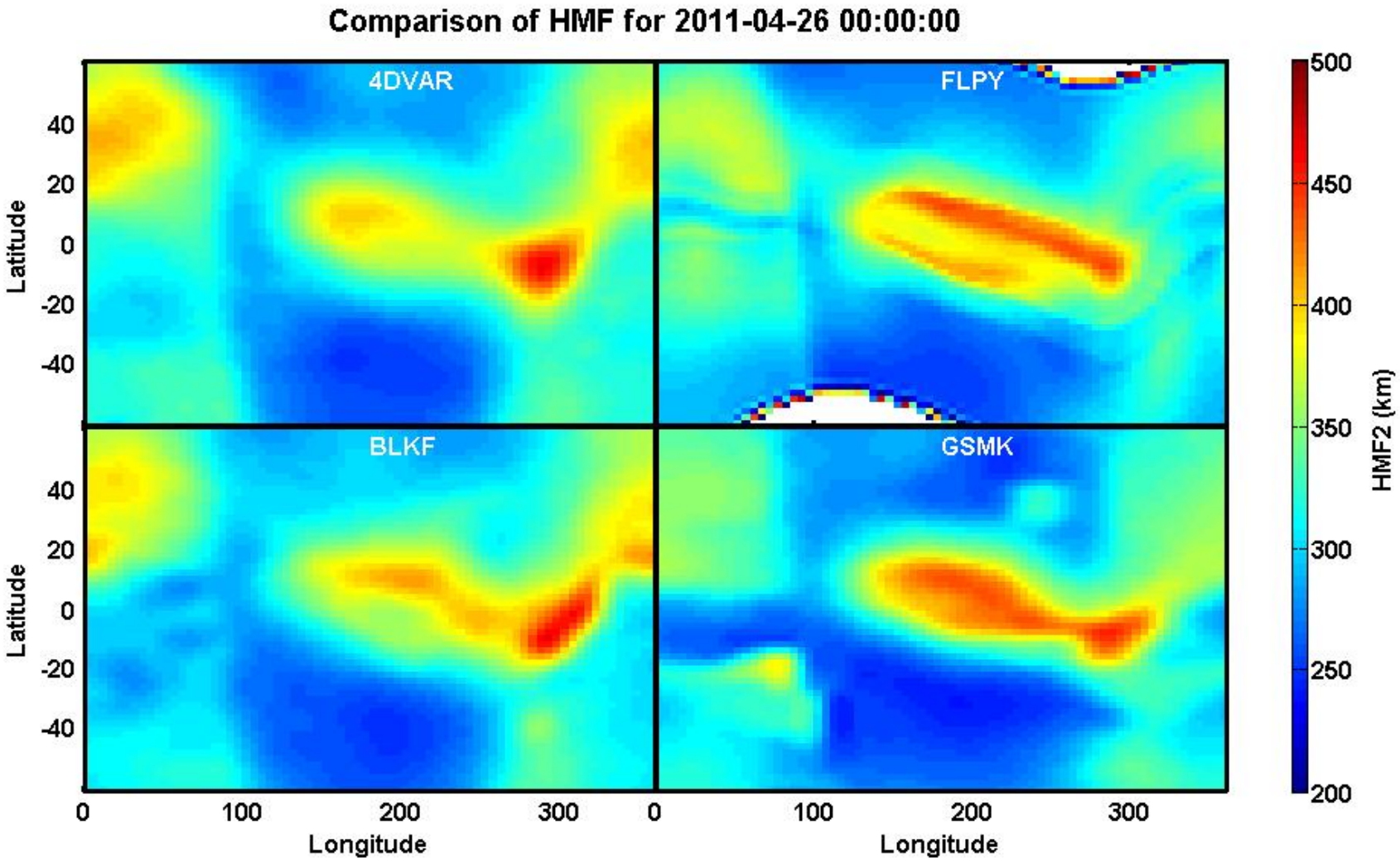
GAIM-4DVAR, GAIM-FP, GAIM-BL, GAIM-GM → Quiet

MEPS Initial Study



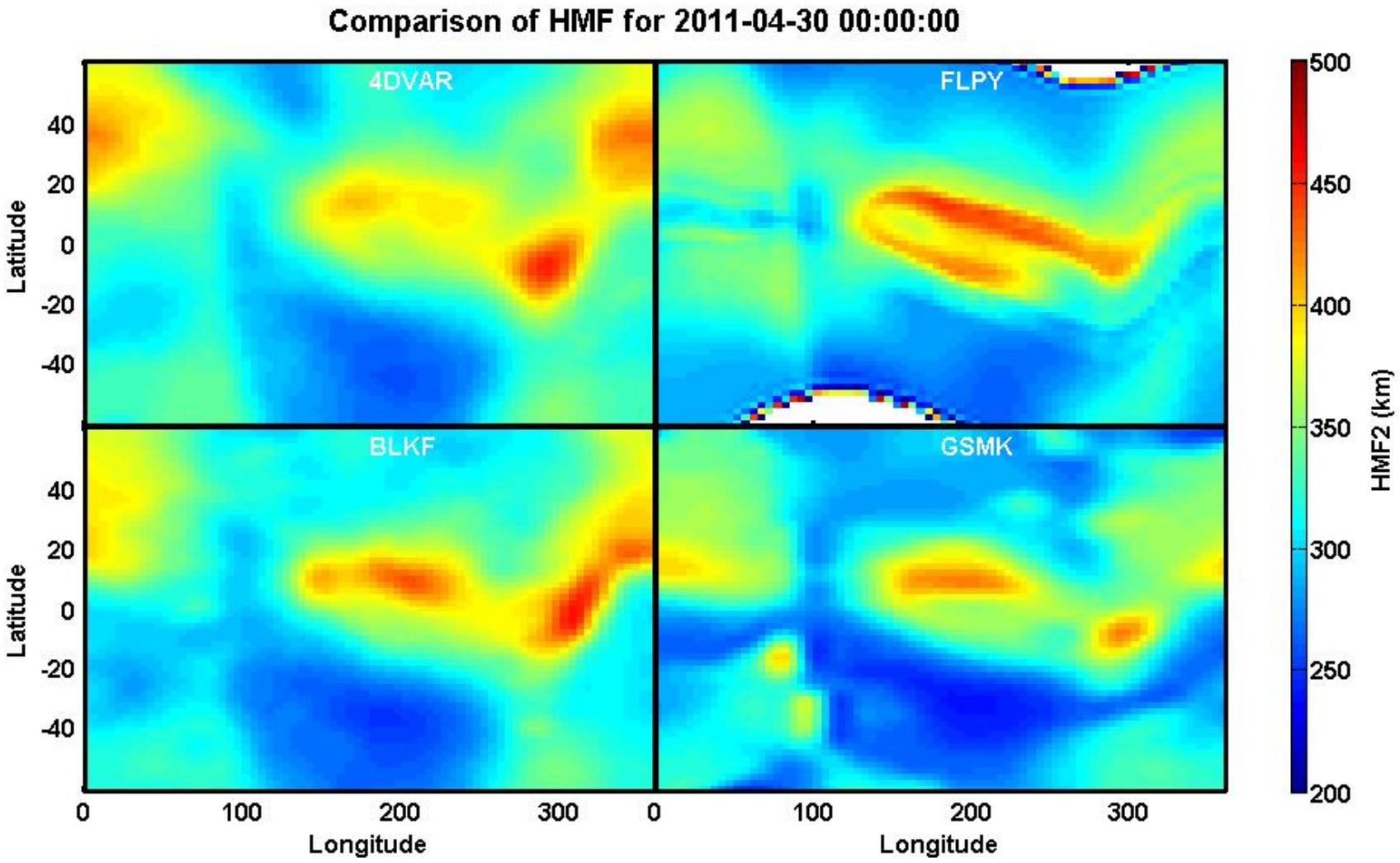
GAIM-4DVAR, GAIM-FP, GAIM-BL, GAIM-GM → Storm

MEPS Initial Study



GAIM-4DVAR, GAIM-FP, GAIM-BL, GAIM-GM → Quiet

MEPS Initial Study



GAIM-4DVAR, GAIM-FP, GAIM-BL, GAIM-GM → Storm

Models Display Both Qualitative and Quantitative Differences

- Different Background Physics-Based Models
- Different Data Amounts, Types and Locations
- 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

IDED-DA Physics-Based Models

Time-Dependent Ionosphere Model

- 3-D Density Distributions (NO^+,O_2^+,N_2^+,O^+,H^+,He^+)
- 3-D T_e and T_i Distributions
- Ion Drifts Parallel & Perpendicular to B
- Hall & Pedersen Conductances

M-I Electrodynamics Model

- MHD Transport Equations & Ohm's Law
- Alfven Wave Propagation
- Active Ionosphere
- 10 km & 5 sec Resolutions
- Potential, E-field, Currents, Joule Heating

Magnetic Induction Model

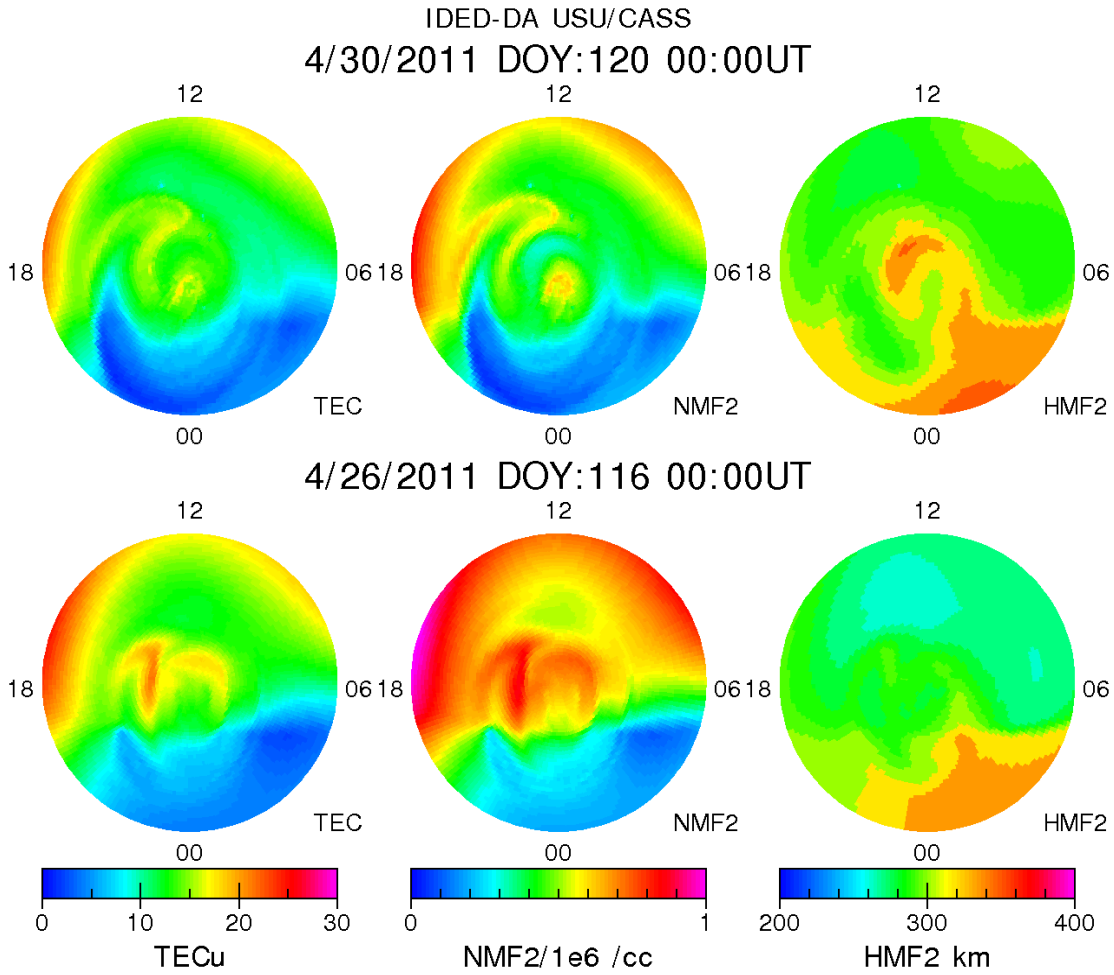
- Calculates B Perturbations in Space & on Ground
- Includes Earth's Induction Effect

Data Assimilated in IDED-DA

- Ground Magnetic Data from 100 Sites
- Cross-Track Velocities from 4 DMSP Satellites
- Line-of-Sight Velocities from 9 SuperDARN Radars
- In-situ Magnetic Perturbations from the 66 IRIDIUM Satellites

Output of the IDED-DA Model

- Electric Potential
- Convection Electric Field
- Energy Flux and Average Energy of Precipitation
- Field-Aligned and Horizontal Currents
- Hall and Pedersen Conductances
- Joule Heating Rates
- 3-D Electron and Ion Densities
- 3-D Electron and Ion Temperatures
- TEC
- Ground and Space Magnetic Disturbances



IDED-DA model → 60 Ground Magnetometers

Snapshots of TEC (left), N_mF_2 (middle), and h_mF_2 (right) at 0 UT

Storm day 120 (top row) at 0 UT in 2011

Quiet day 116 (bottom row) at 0 UT 2011

Table 2. Delivery Schedule for Data Assimilation Models

	2013		2014		2015		2016		2017	
GAIM-GM				x						
GAIM-BL				x						
GAIM-FP						x				
GAIM-4DVAR							x			
IDED-DA								x		
GTM-DA									x	
Low-Mid Electrodynamics						x				
MEPS										x

Delivery Includes:

- Data Assimilation Model
- Associated Physics-Based Model
- User's Manuel
- Sample Test Cases (Input Data/Output)
- MEPS Team Support

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

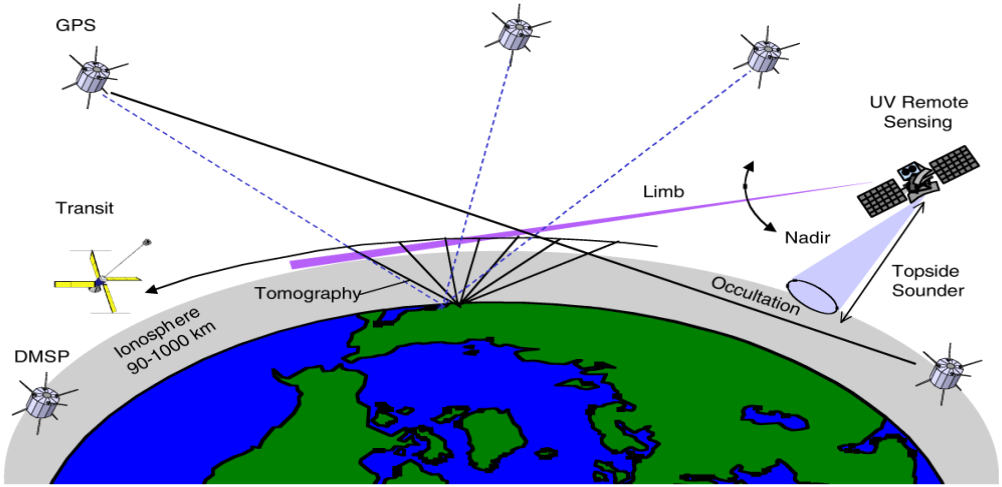
GTM-DA ➔ Global Thermosphere

- **Global, Regional & Nested GRID Capabilities**
- **GAIM-GM & GAIM-BL are Operational Models**
- **Specifications & Forecasts**

USU-GAIM Data Assimilation Models for the Ionosphere

- **GAIM-GM:** Gauss-Markov Kalman Filter Model of the Ionosphere
- **GAIM-FP:** Full Physics Ensemble Kalman Filter Model of the Ionosphere/Plasmasphere

GAIM Ionosphere Models Assimilate Multiple Data Sources



Additional Features:

- Quality Control Algorithms
- Data Latency (up to 3 hours)
- Hot Start Capability
- 24-Hour Forecast Algorithm
- User's Manual

- Data Assimilated Exactly as They Are Measured
  - Bottomside N_e Profiles from Digisondes (~100)
  - Slant TEC from more than 1000 Ground GPS Receivers
  - N_e Along Satellite Tracks (several DMSP satellites)
  - Integrated UV Emissions (LORAAS, SSULI, SSUSI)
  - Occultation Data (CHAMP, IOX, SAC-C, COSMIC)

Gauss-Markov Kalman Filter Model

GAIM-GM uses a simplified Kalman Filter

- **Ionospheric Physics is contained in background model IFM**
  - **Global physics-based model**
  - **Provides 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 deviation from background field**
- **Kalman filter is based on a statistical process**
- **Static database of 1107 global time-dependent IFM runs is used to construct error covariances**
- **GAIM-GM does not provide information about driving forces**

Can easily be run on 1-2 CPUs

GAIM-FP Basic Approach

Full Physics-Based Model

Full Physics GAIM uses an **Ensemble Kalman Filter Technique**

Multi CPU/Cores are needed (24-48)

Allows to **incorporate ionospheric physics** in data assimilation

--> GAIM-FP uses physics-based ionosphere-plasmasphere model

Provides both specifications for the ionospheric plasma densities and **unobserved drivers**:

- Electric Field
- Neutral Wind
- Neutral Composition

GAIM-Full Physics Data Assimilation Model

Uses the full physics that is included in the physics-based model (IPM) in the data assimilation scheme

Ionosphere-Plasmasphere Model (IPM)

- 3-D Time-Dependent Parameters
  - NO^+, O_2^+, N_2^+, O^+, H^+, He^+
  - T_e, T_i
  - $u_{||}$, $u_\perp$
- Auxiliary Parameters
  - N_mF_2
  - h_mF_2
  - N_mE
  - h_mE
  - TEC
- Grid System
  - Global
  - Regional
  - Localized
  - 90-30,000 km
  - Realistic Magnetic Field (IGRF)
- Spatial Resolution Along **B**
  - 0.9 km in E-Region
  - 1.3 km in F-Region
  - 3.8 km in Topside
  - 240 km at 17,000 km

GAIM-GM and GAIM-FP can assimilate the same data but differ in their data assimilation technique

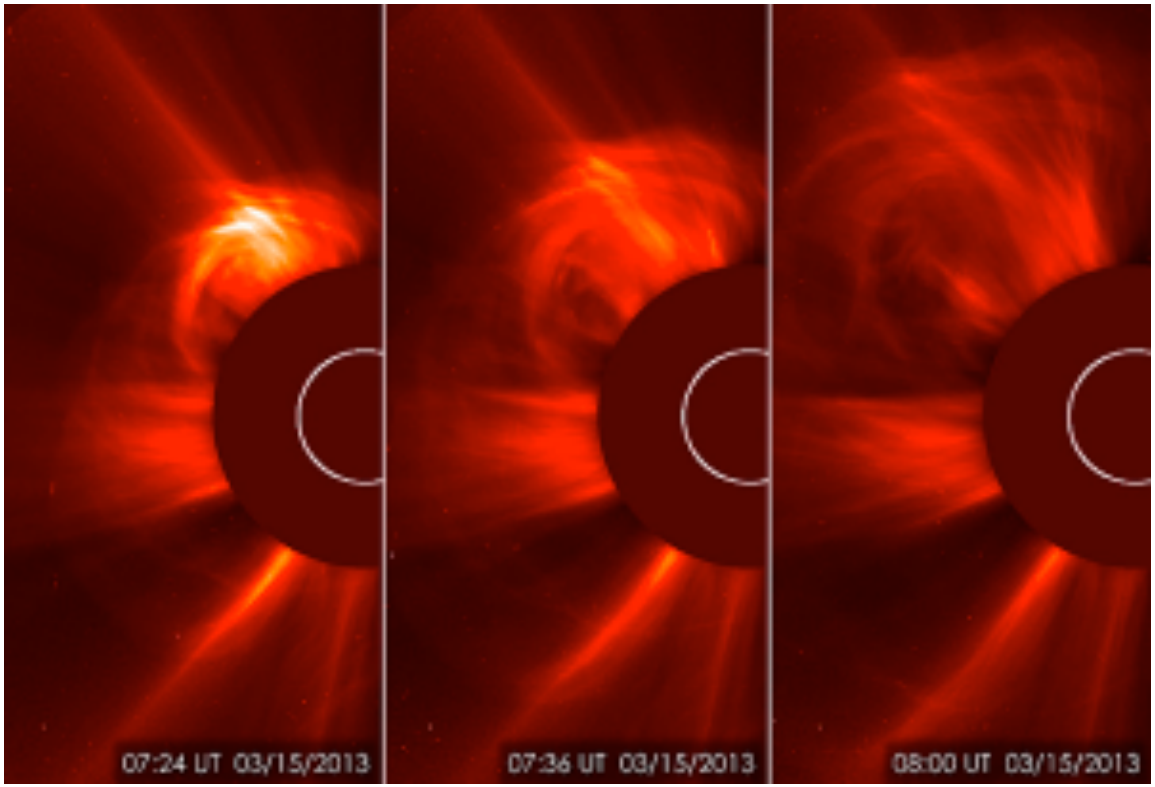
Differences exist in the Underlying Physics-Based Models

IFM versus IPM

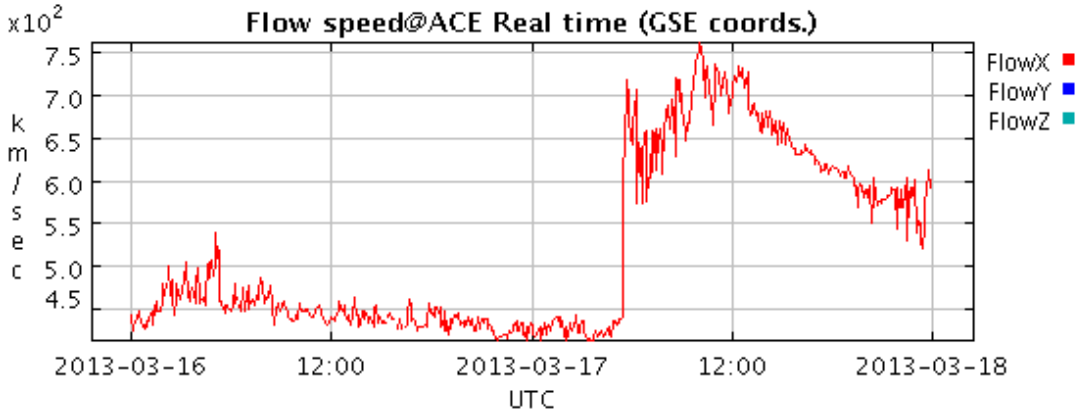
IFM	IPM
Simple B-Field	IGRF **B**-field
Simple H^+	Rigorous H^+
No He^+	Rigorous He^+
Coarse Spatial Grid	Better Spatial Grid
1500 km Top Boundary	30,000 km Top Boundary
No Interhemisphere Flow	Interhemisphere Flow

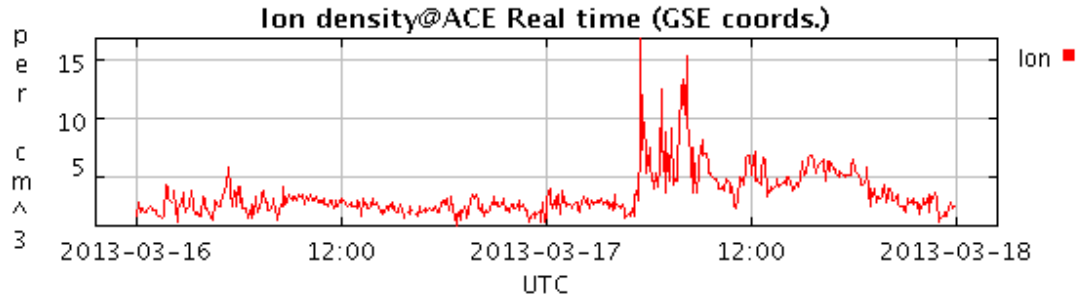
March 16-17 2013 Case Study

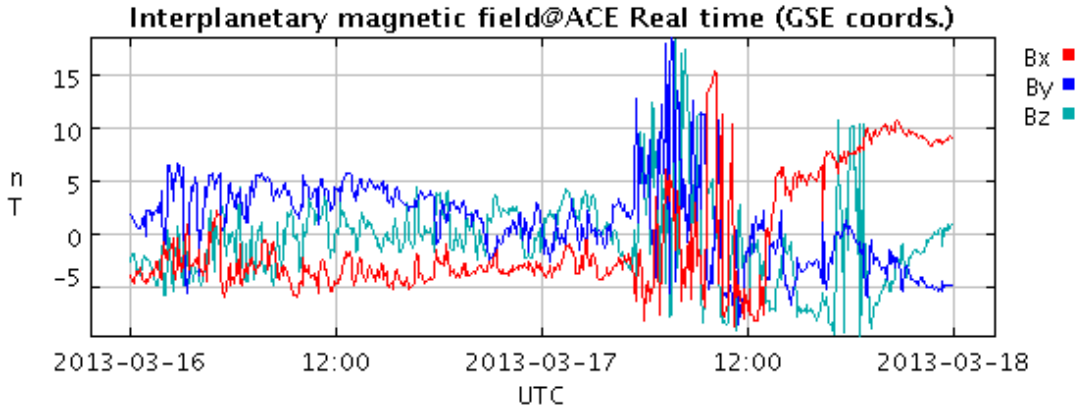
On March 17, 2013, at about 5:00 UT, the coronal mass ejection (CME) from March 15 passed by NASA's Advanced Composition Explorer (ACE) as it approached Earth.



March 16-17 2013 Case Study







Kp reached a maximum value of 6

March 16-17 2013 Case Study

GPS/TEC from about 530 ground receivers are assimilated every 15 minutes.

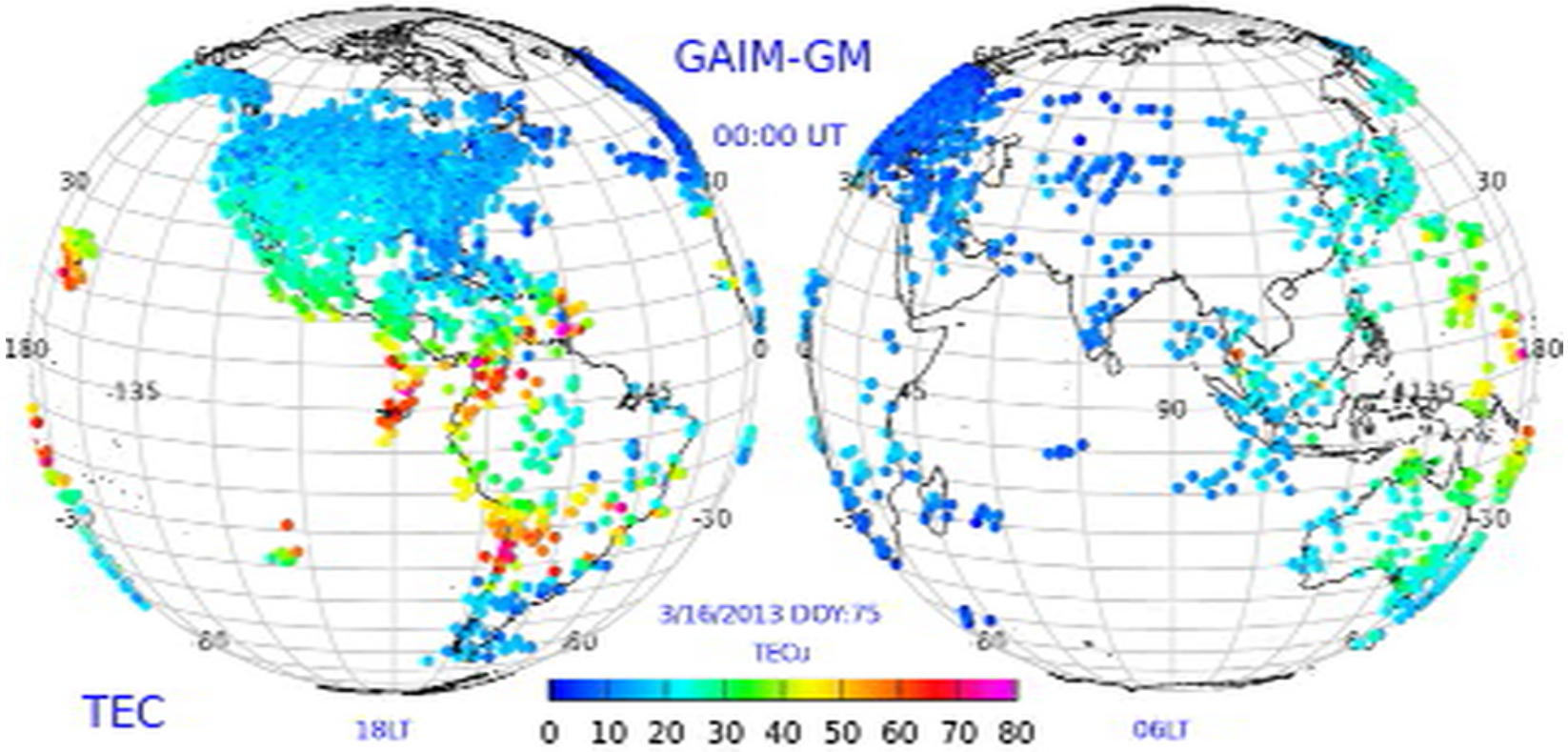


Illustration of Locations of GPS/TEC Data. Slant TEC Values have been mapped to the Vertical Direction

March 16-17 2013 Case Study

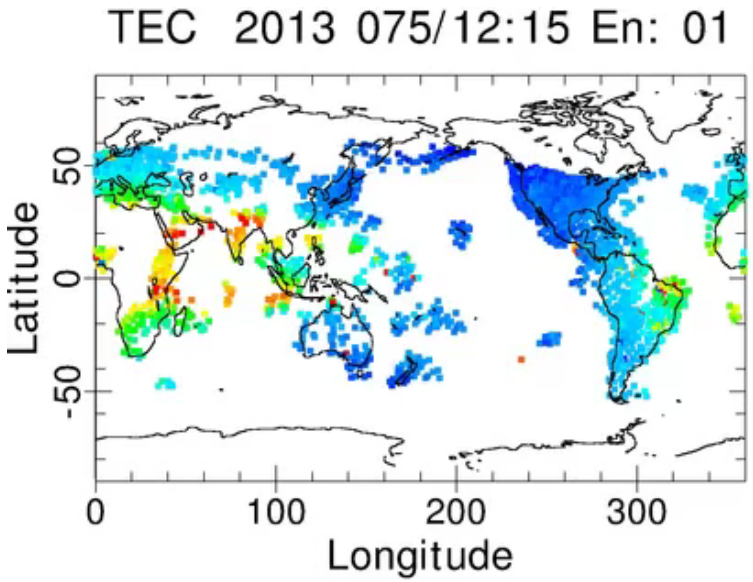
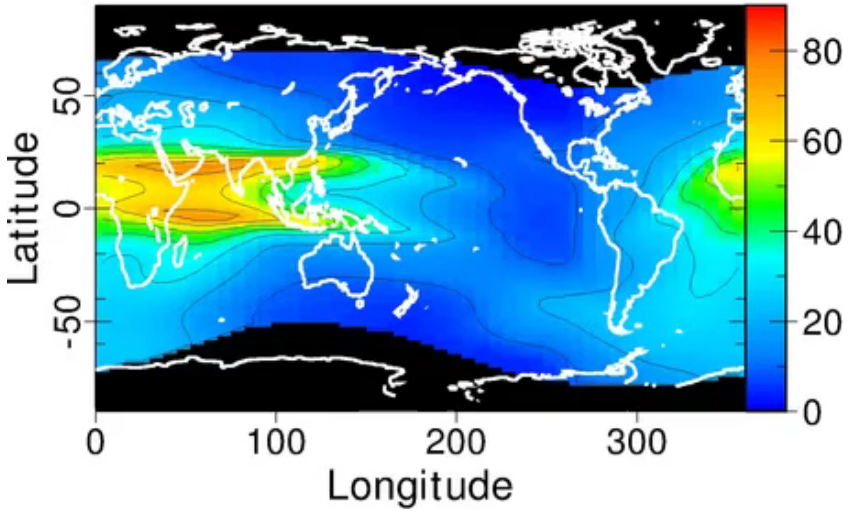


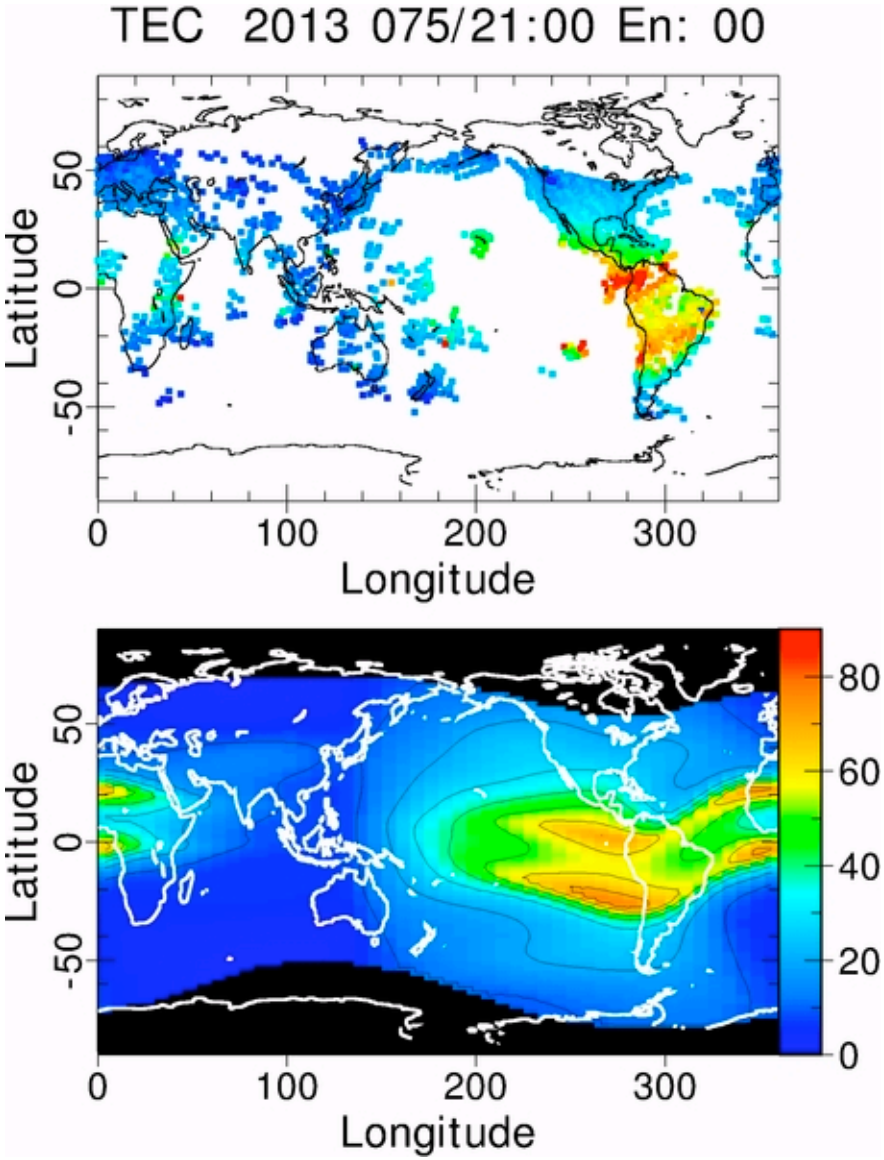
Illustration of Locations of GPS/TEC Data. Slant TEC Values have been mapped to the Vertical Direction



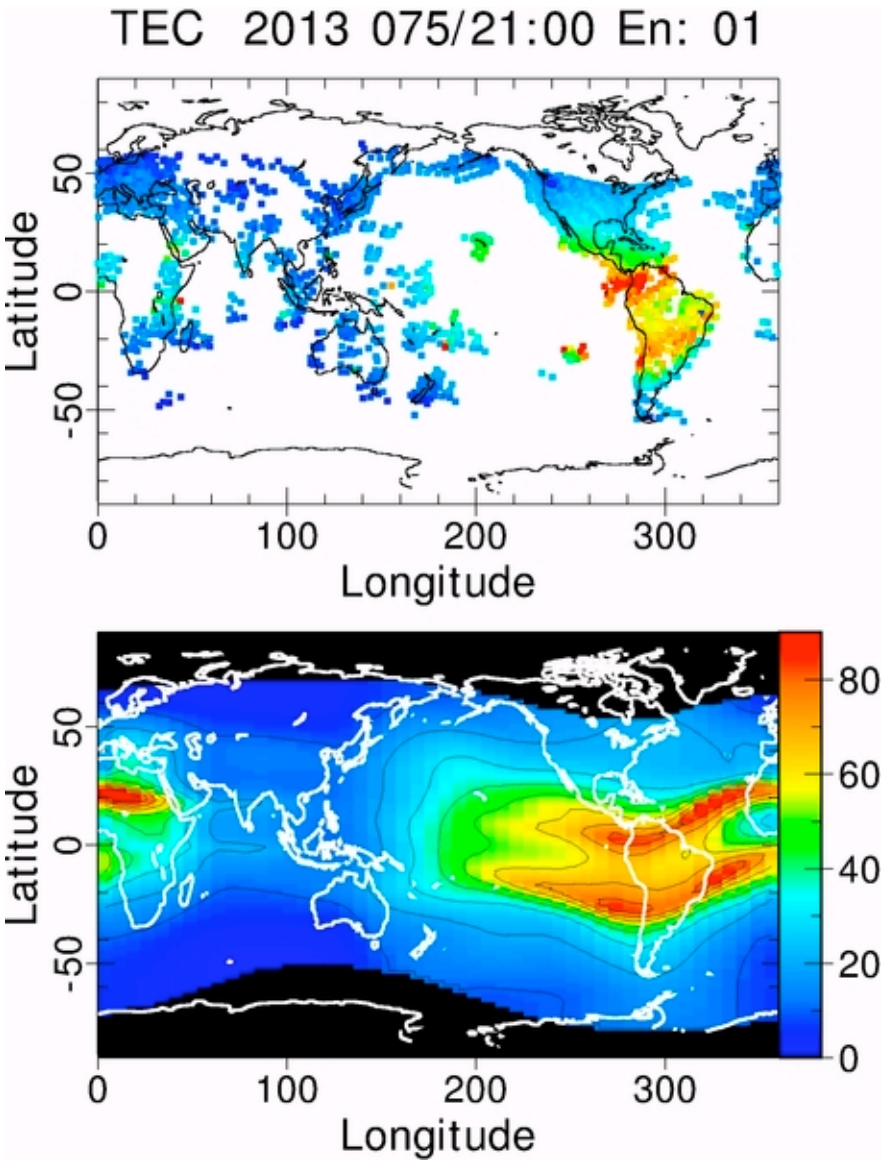
GAIM-FP Specification of Global TEC Distribution

Total Electron Content: **Quiet Conditions**

IPM

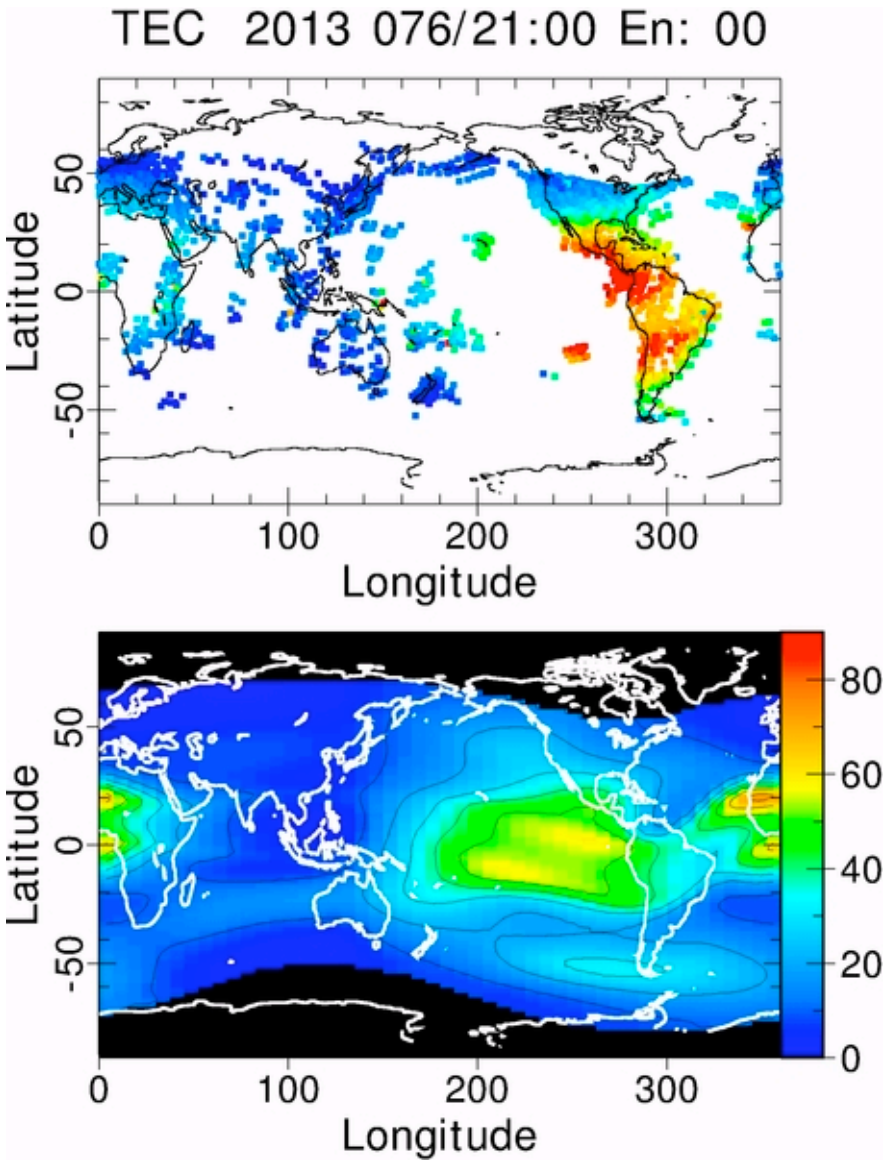


GAIM-FP

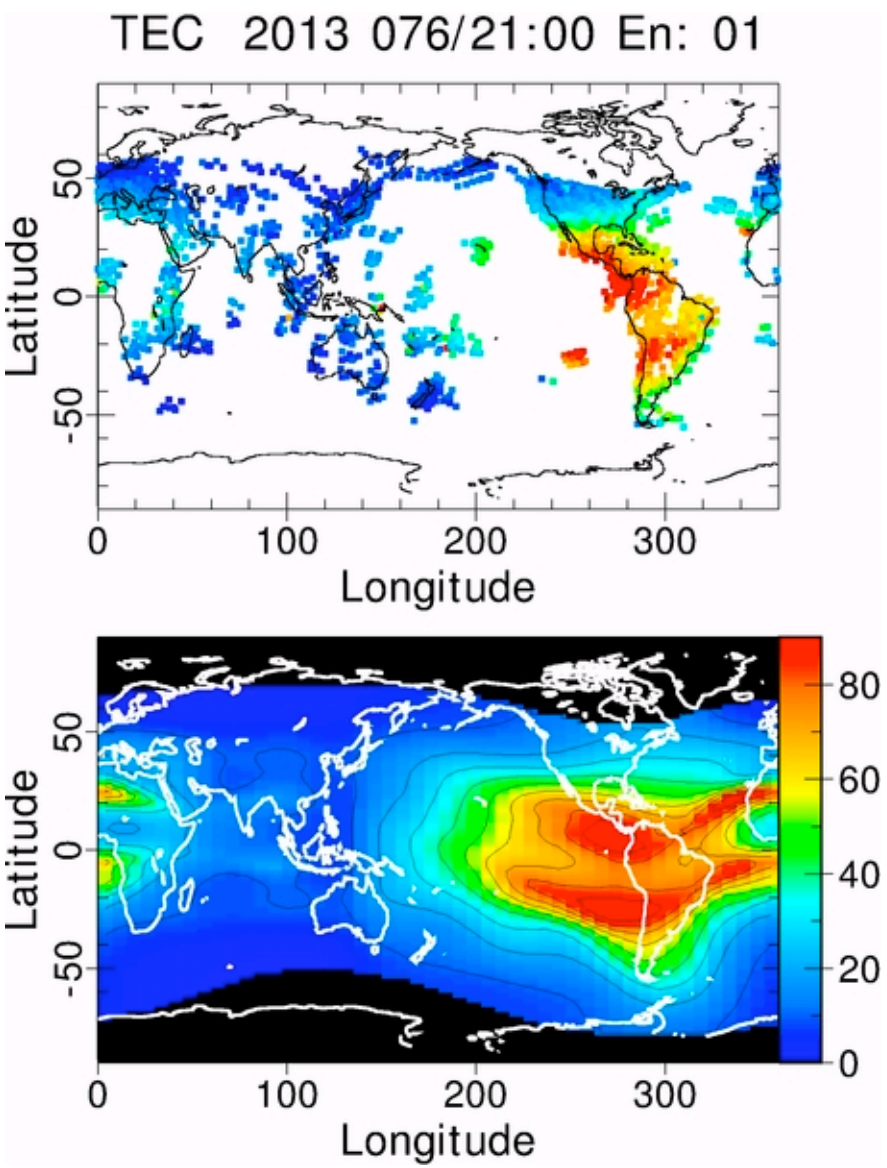


Total Electron Content: **Storm Conditions**

IPM

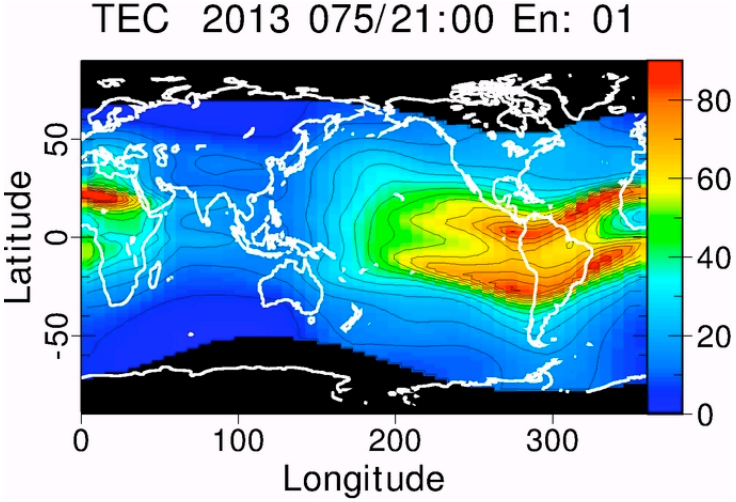


GAIM-FP

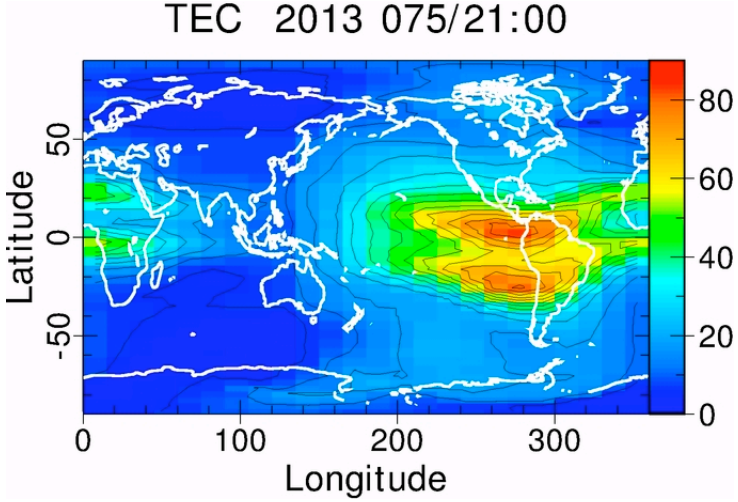


Comparison of GAIM-FP with GAIM-GM: **TEC**

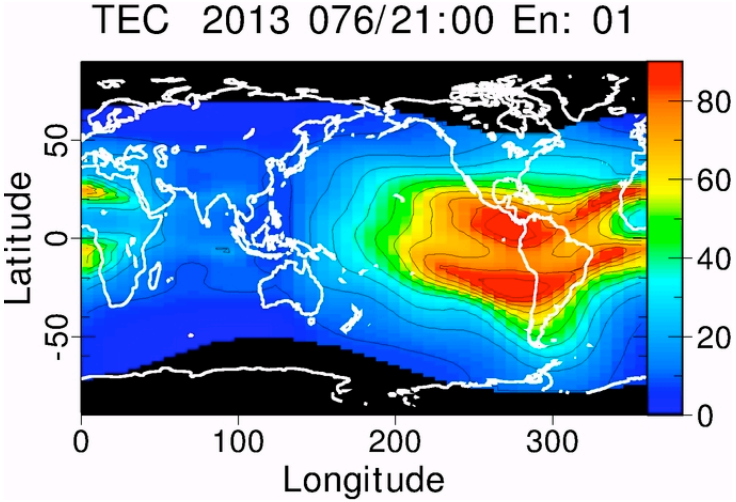
GAIM-FP

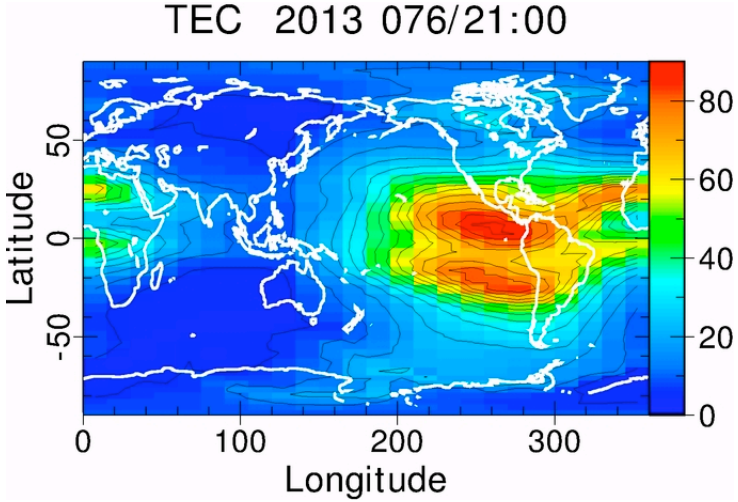


GAIM-GM



Quiet

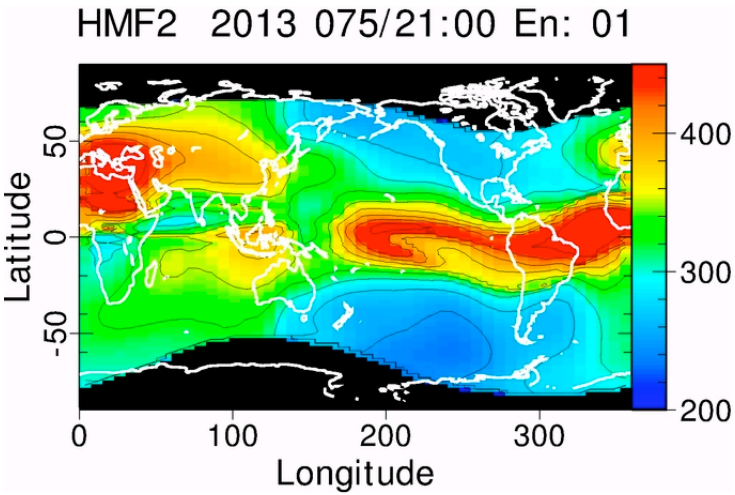




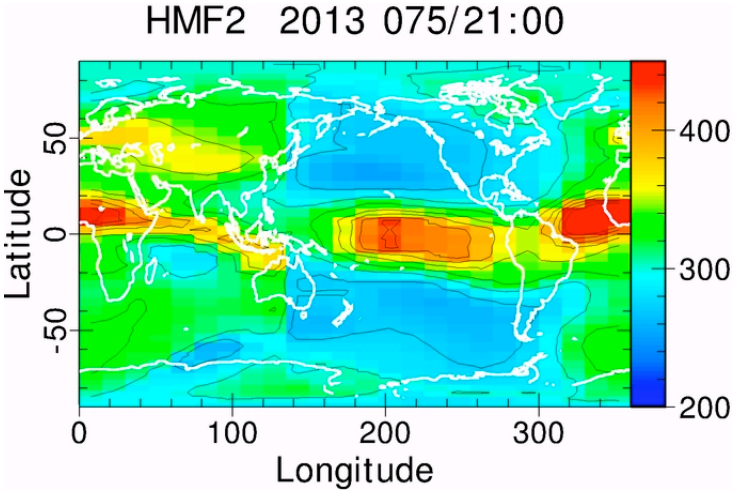
Storm

Comparison of GAIM-FP with GAIM-GM: **hmF2**

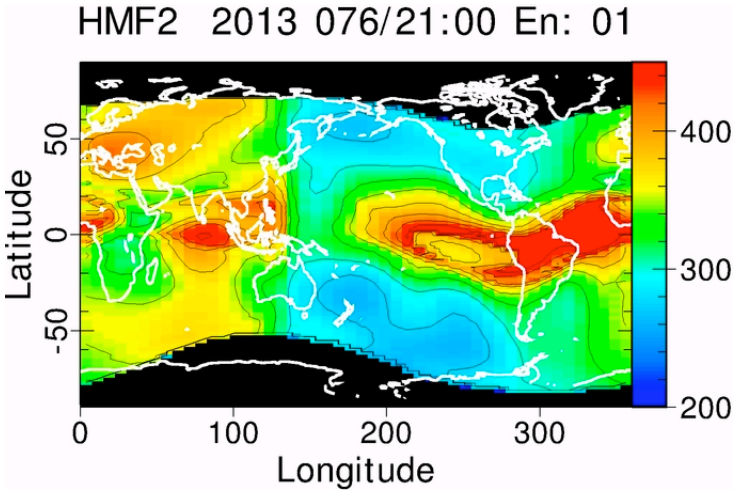
GAIM-FP

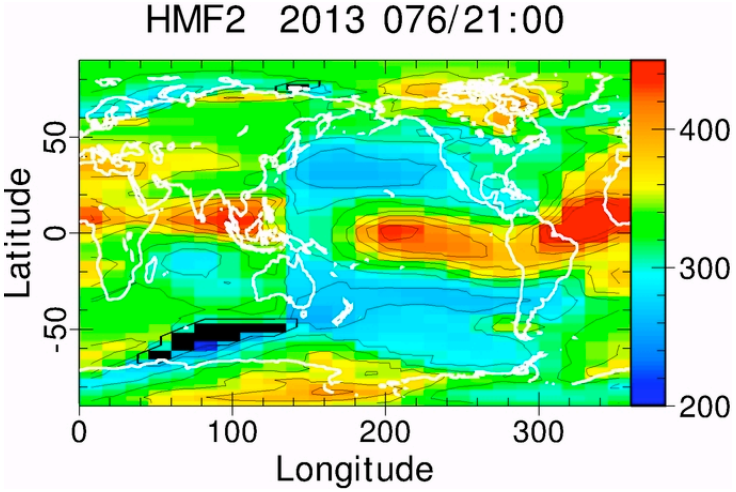


GAIM-GM



Quiet

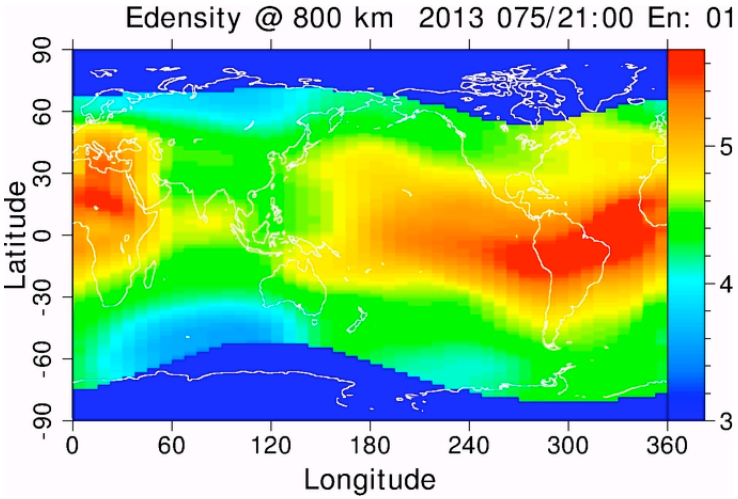


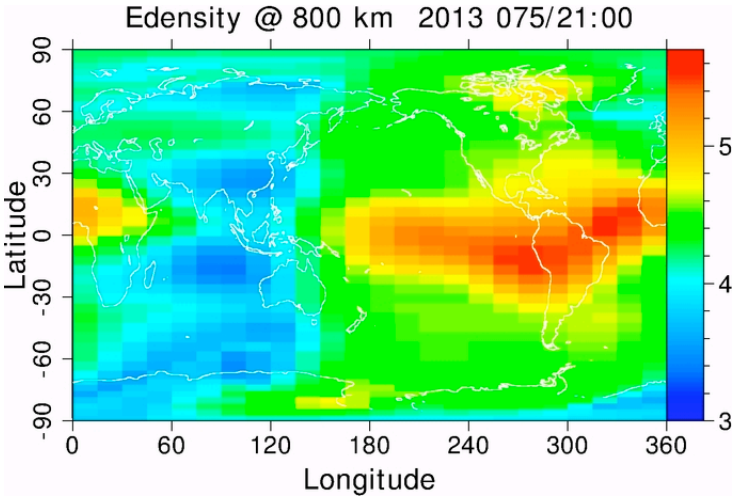


Storm

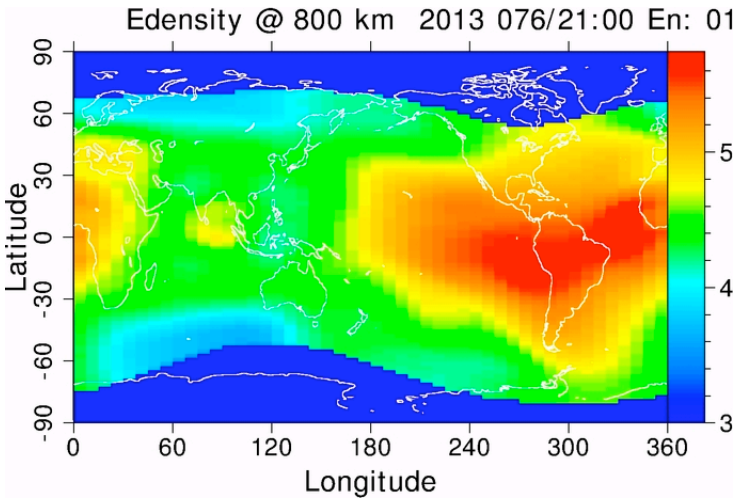
Comparison of GAIM-FP with GAIM-GM: N_e @ 800 km

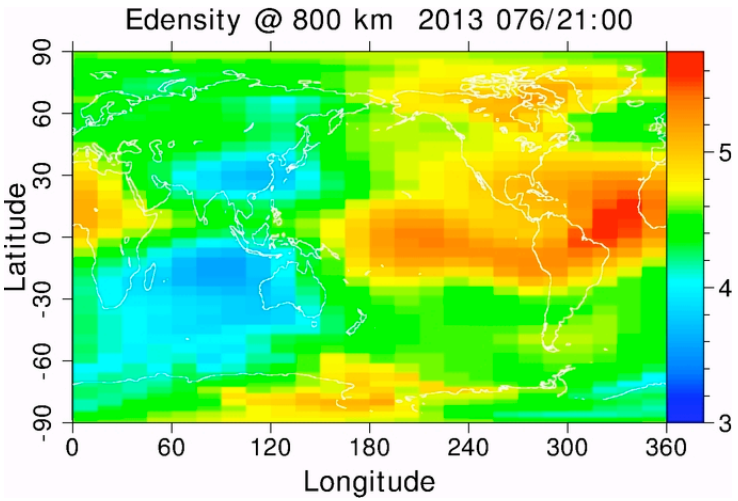
GAIM-FP | **GAIM-GM**





Quiet

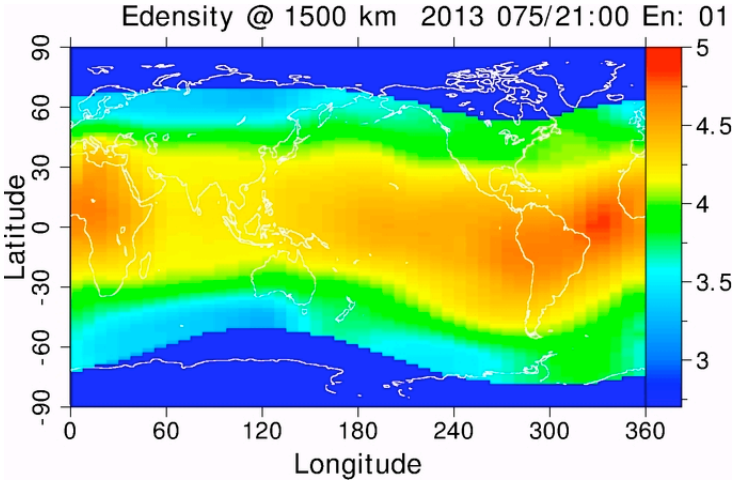


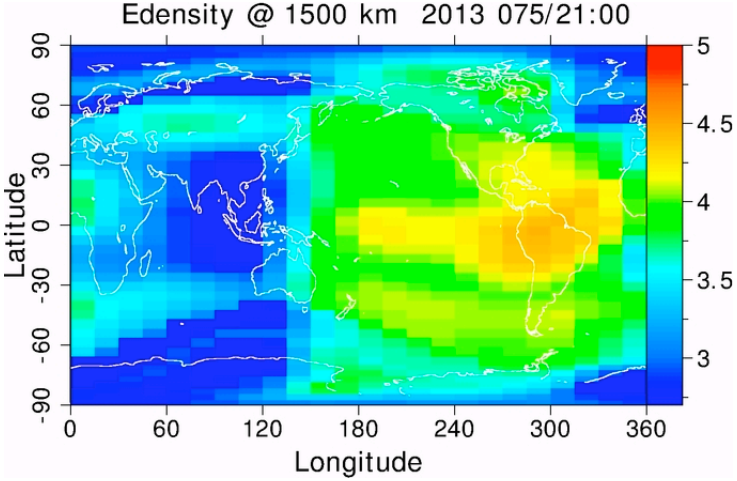


Storm

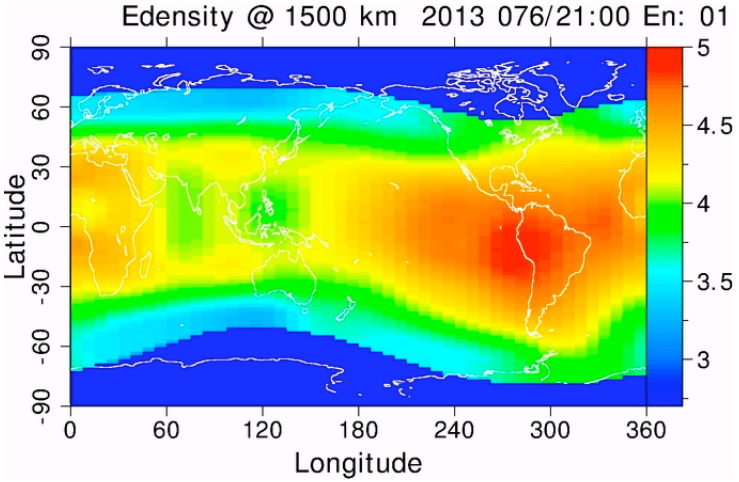
Comparison of GAIM-FP with GAIM-GM: N_e @ 1500 km

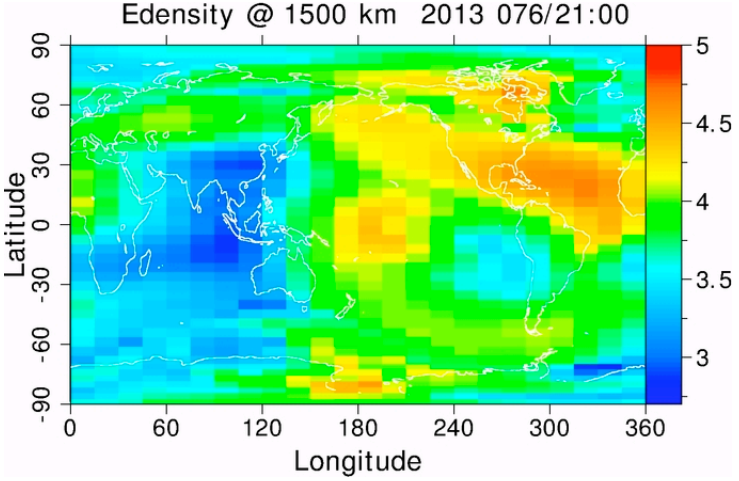
GAIM-FP | **GAIM-GM**





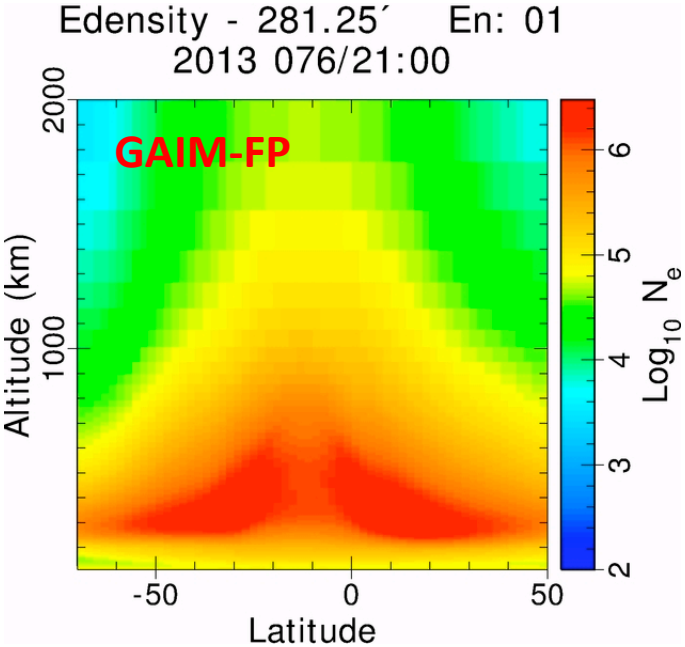
Quiet

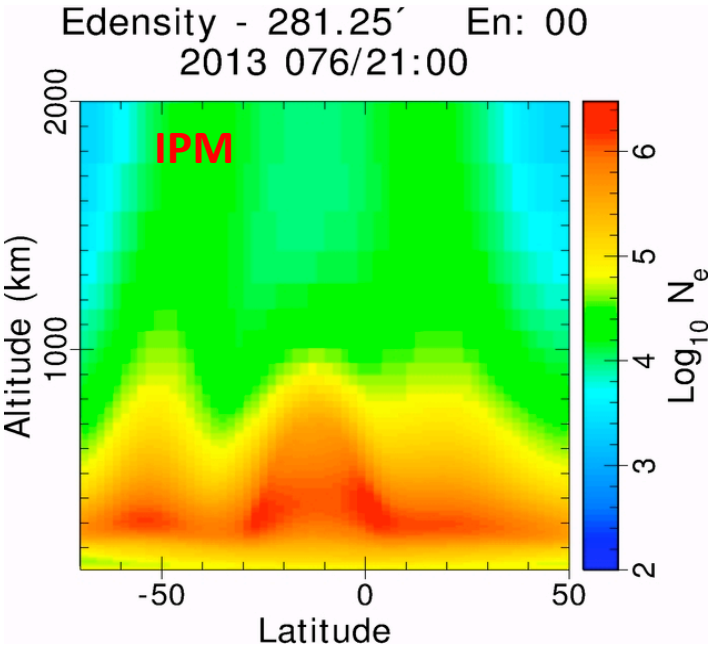


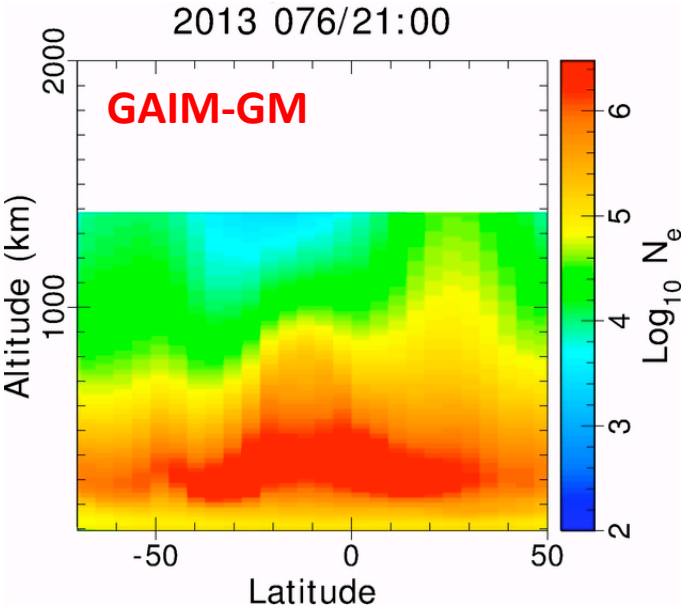


Storm

Altitude/Latitude Cuts in American Sector



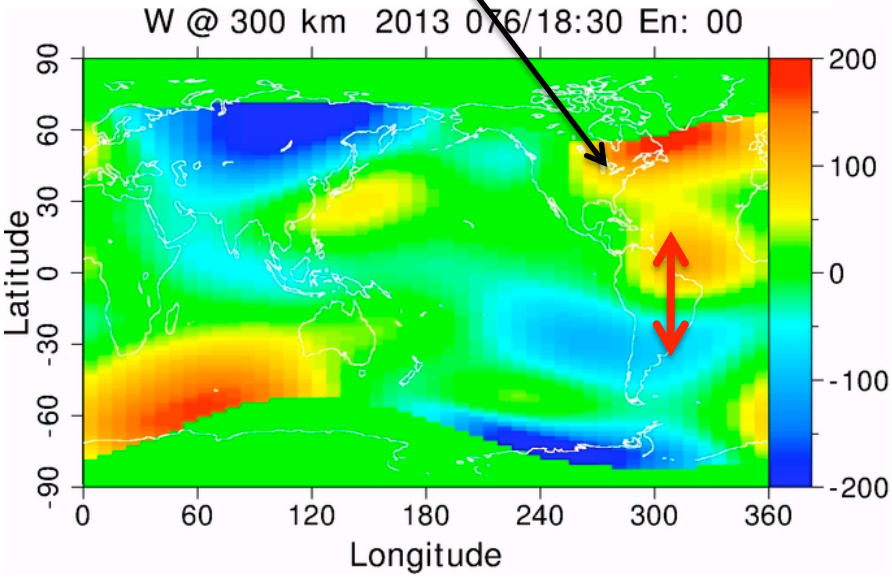


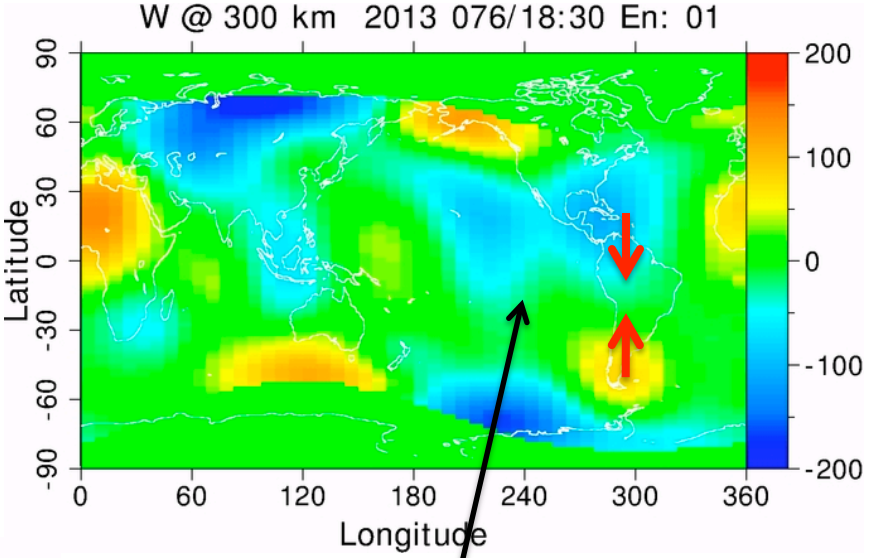


- **GAIM-FP shows large density enhancement in the topside ionosphere due to changes in the wind and electric field forcing.**
- **IPM lacks the topside enhancement.**
- **GAIM-GM is strongly influenced by background model and consequently also lacks the topside density increase.**

Thermospheric Neutral Wind During Storm Period

IPM (HWM-93) Winds blow Poleward in American Sector

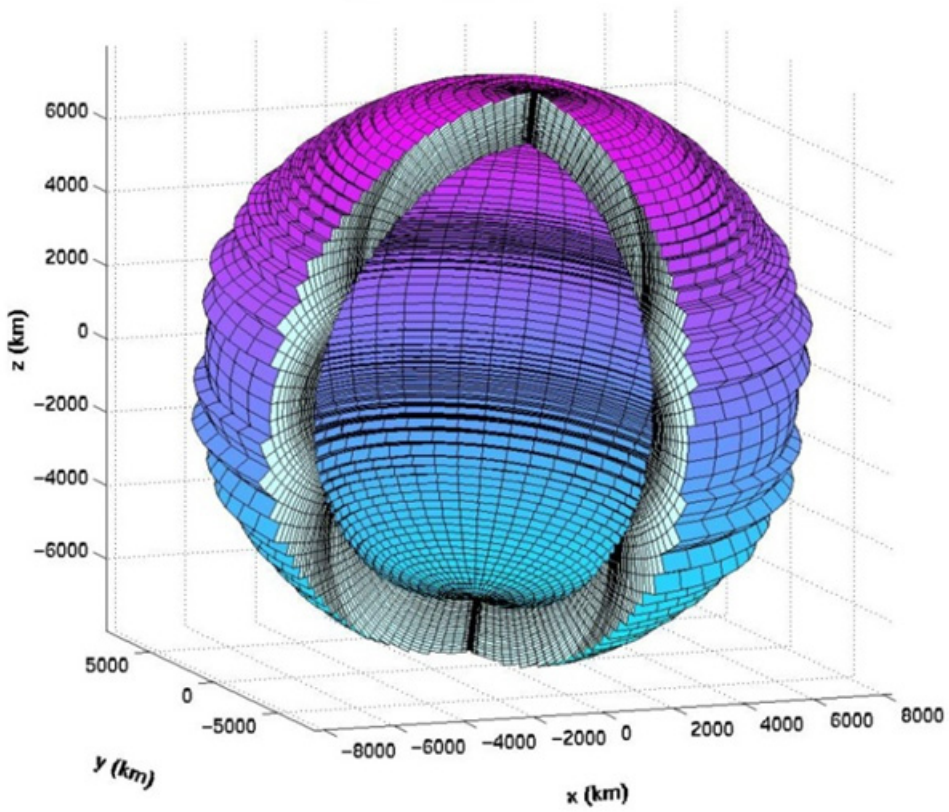




GAIM-FP Winds blow Equatorward in American Sector

JPL-USC Global Assimilative Ionospheric Models – 1. GAIM 4D Physics Model

- Finite volumes on a fixed Eulerian grid
- Global 3D grid based on an IGRF-like geomagnetic field model
- Nested grid
- User specified temporal and spatial resolutions as well as regions
- Variable altitude range
  - ➢ Full or partial fluxtubes
  - ➢ 90 to 20,000 km
  - ➢ 90 to 2000 km
- C++ code



JPL-USC Global Assimilative Ionospheric Models – 1. GAIM 4D Physics Model

Empirical models to specify ionospheric drivers

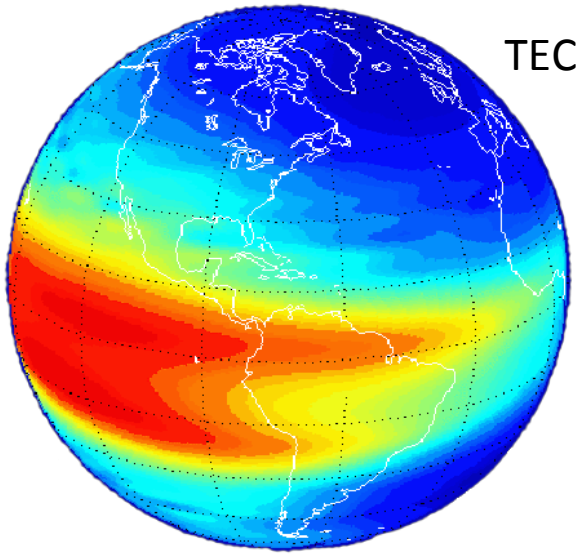
- Solar EUV irradiance models
- MSIS thermosphere
- Horizontal wind models (HWM)
- Global plasma drift (electric field) derived from various empirical models
- Energy and energy flux of precipitating charged particles at high latitudes

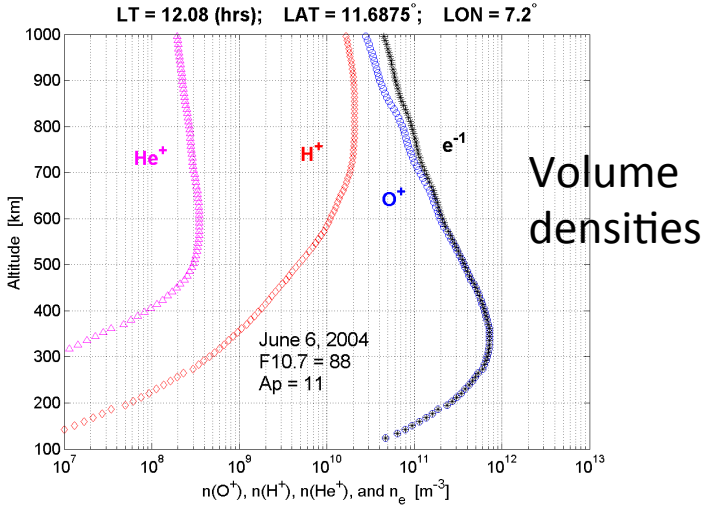
Multiple ions

- O^+, H^+, He^+, NO^+, O_2+, and N_2^+

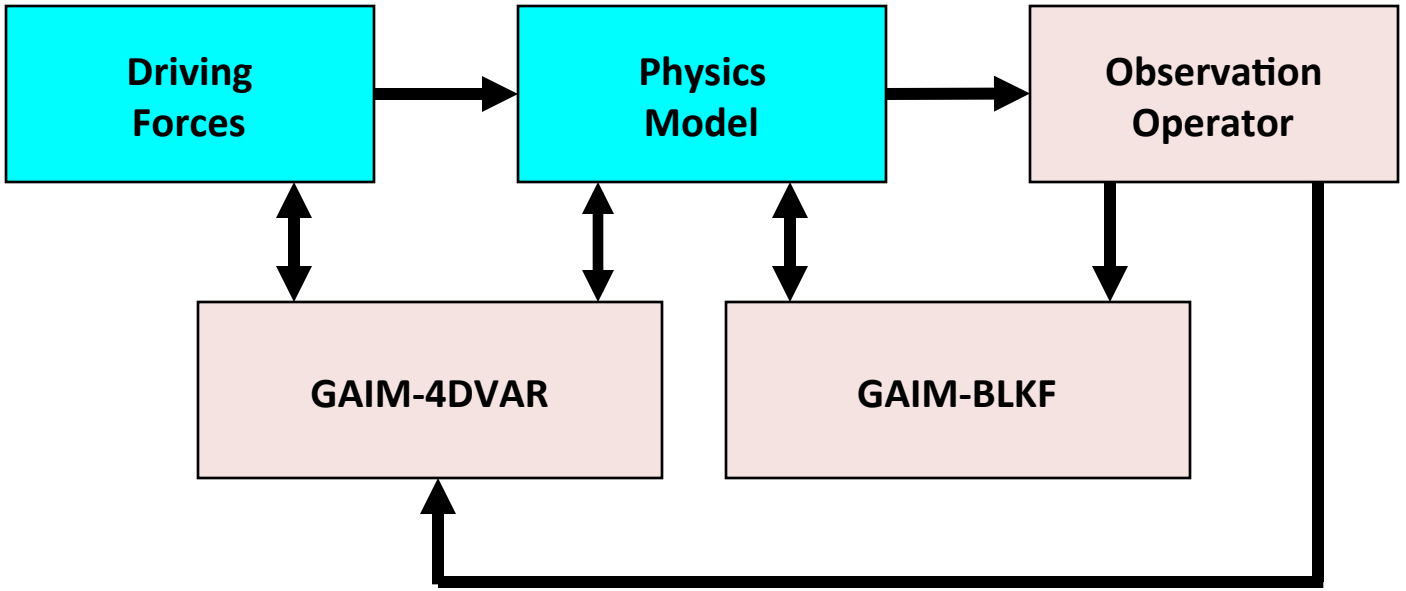
Real-time GAIM: GAIM-RT

- Tested with a real-time global GPS network





GAIM-BLKF and GAIM-4DVAR



GAIM-BLKF

- Band-limited Kalman filter to estimate state (Ne) and its error covariance matrix
- Computation of error covariance matrix limited to the correlation length
- Ionospheric rivers not estimated

GAIM-4DVAR

- Non-linear least-squares minimization to estimate drivers (EUV irradiance, wind, drift, etc.)
- Adjoint method to compute the gradient of the cost function
- Driver parameterization to reduce the number of parameters to be estimated

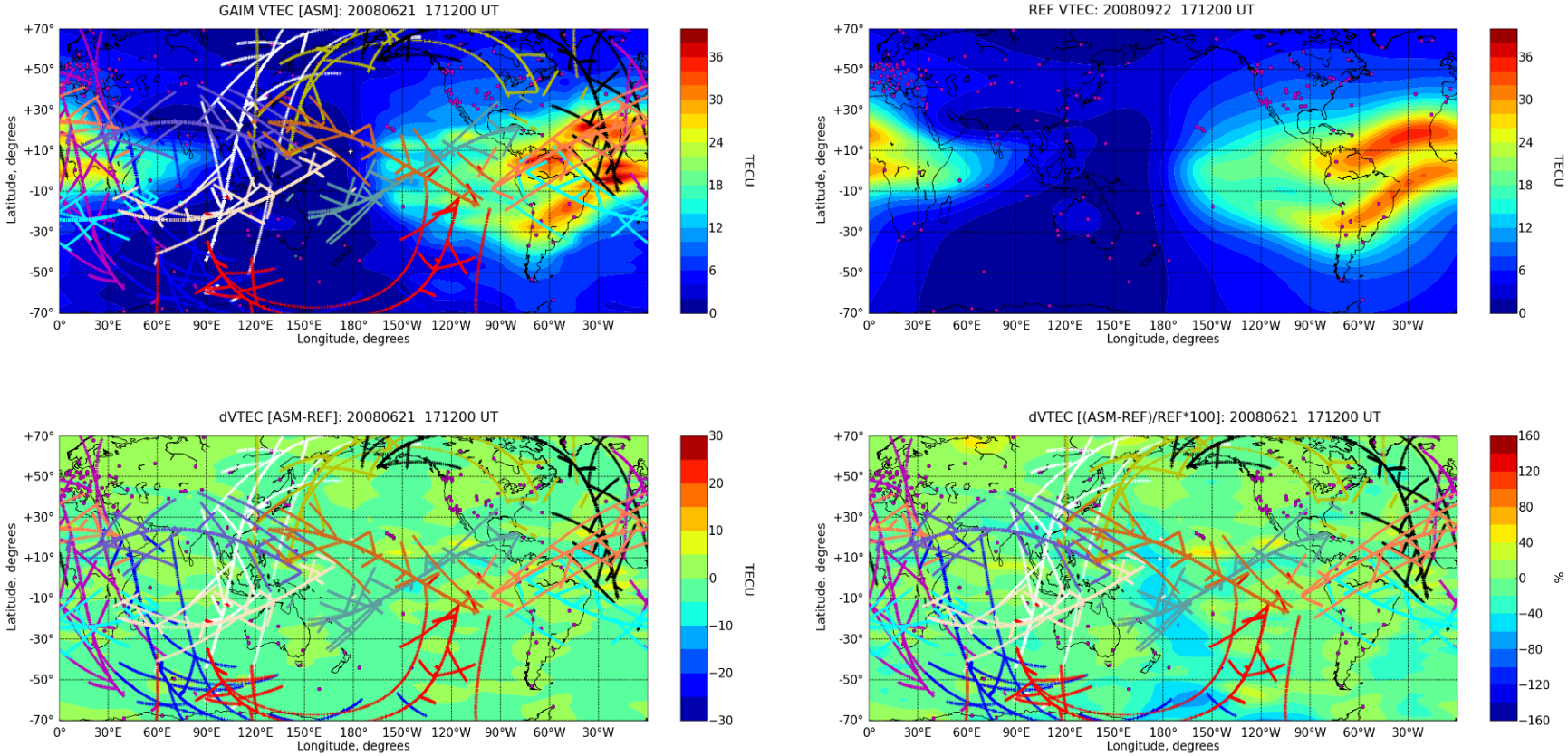
Assimilation of Various Data Types

Line-of-sight integrated vs. in-situ observations
Radio vs. optical observations
State vs. driver observations

Ionosphere	Electrodynamics	Thermosphere
Ground-Based GPS-TEC	Ground magnetometers	Satellite UV emissions
Satellite-Based GPS Occultation	DMSP cross-track velocities	In situ neutral densities and winds
Ionosonde and Digisonde	SuperDARN LOS velocities	Satellite accelerometer and drag
In situ N_e	Iridium magnetometers	FPI winds
911Å, 1356Å, limb, disk (UV)	ACE IMF, Dst	ISR Neutral parameters
Solar UV, EUV	Solar UV, EUV	Solar UV, EUV

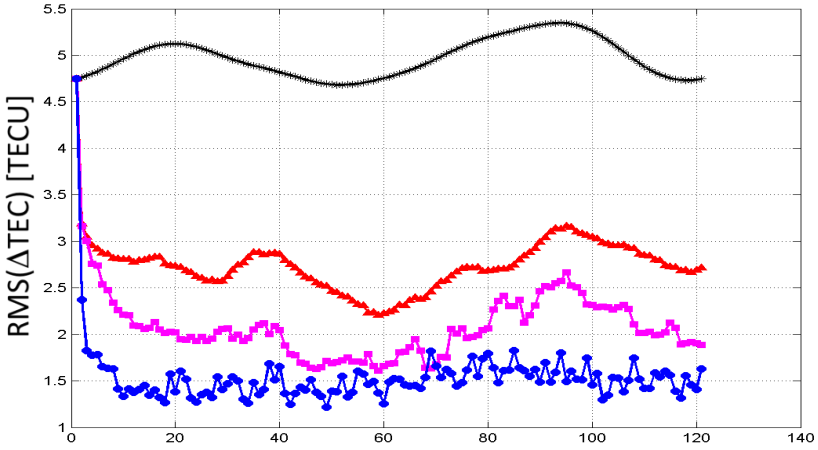
Using GAIM to Support Mission Studies
Observation System Simulation Experiments (OSSEs)

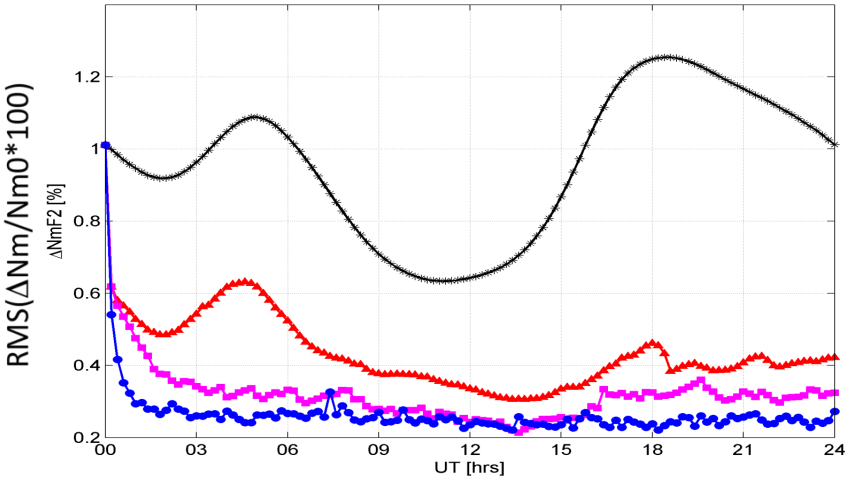
- Goal is to estimate quantitatively how **COSMIC-2** helps ionospheric specifications
- The constellation (12 satellites) will provide GPS radio occultation observations data
- The OSSE uses a different model (e.g. IRI) to simulate ionospheric observations

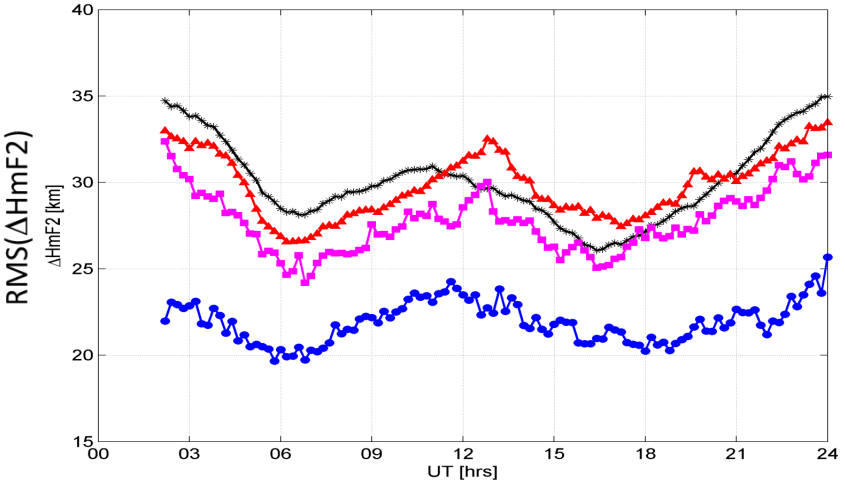


COSMIC-2 radio links marked by ground tracks of RO tangent points

COSMIC2 OSSE Results







Simulated data using IRI with real GPS orbits and ground networks as well as simulated COSMIC2 observations

Twisted climatological modeling

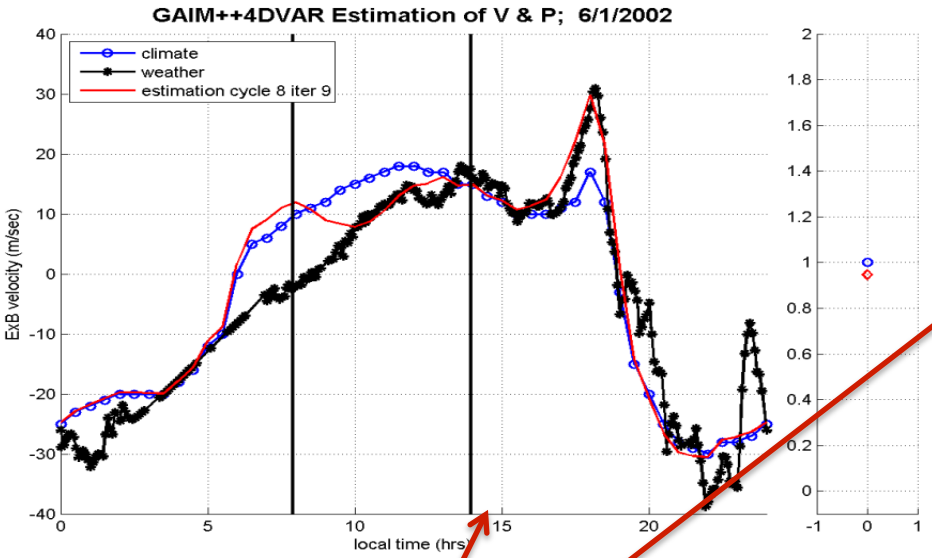
GAIM-BLKF results

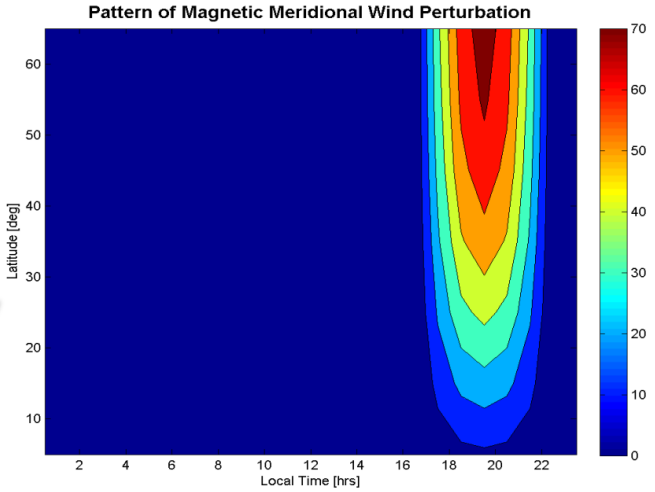
-- with ground GPS data

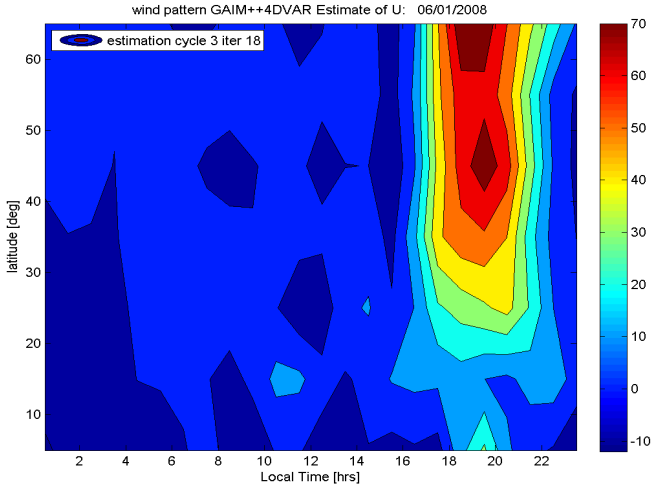
-- with ground + COSMIC1 data

-- with ground + COSMIC2 data

GAIM-4DVAR Experiments







GAIM-4DVAR experiment with ground GPS data

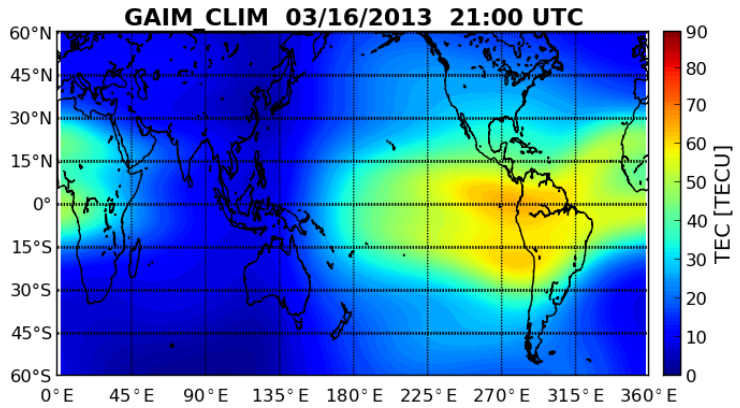
OSSE

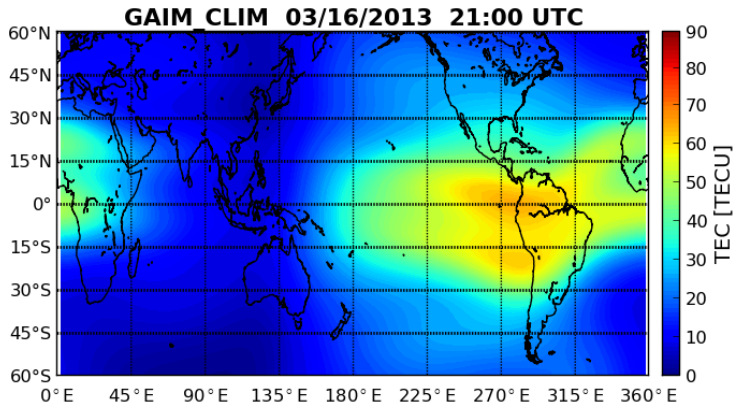
- Simulated wind perturbation
- Estimated wind perturbation with assimilation of ground GPS data

The Latest Storm Study

Comparison between Climatological and Assimilative Modeling

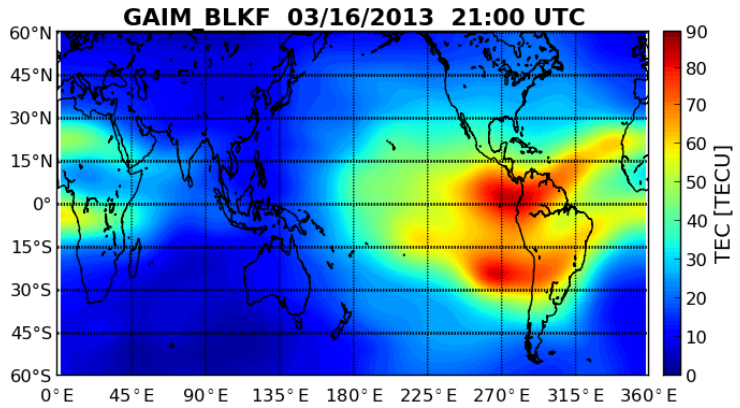
CLIM

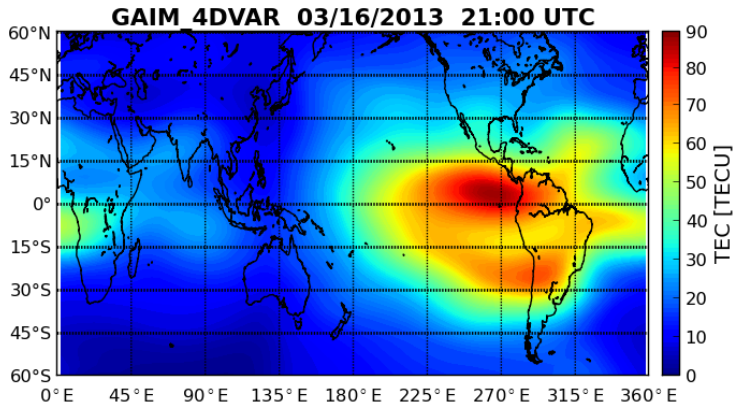




CLIM

BLKF



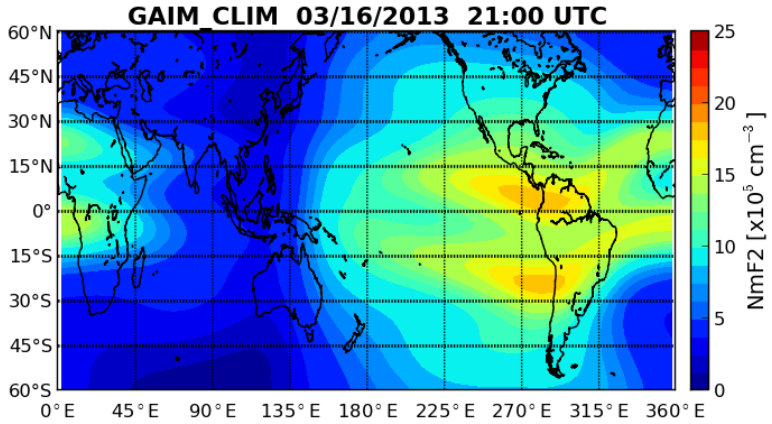


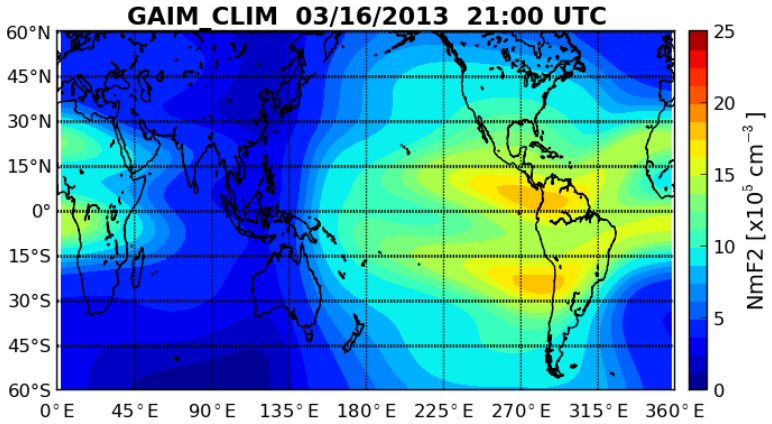
4DVAR

- **TEC** under **quiet** conditions
- Enhanced TEC in “weather” is shown in data assimilation results from different techniques

Comparison between Climatological and Assimilative Modeling

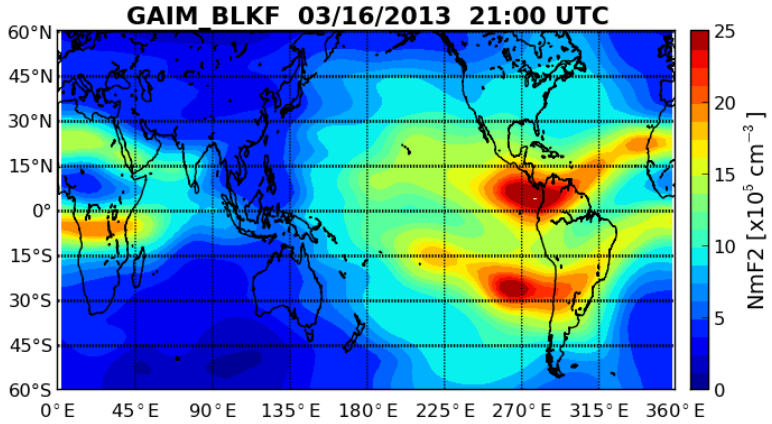
CLIM

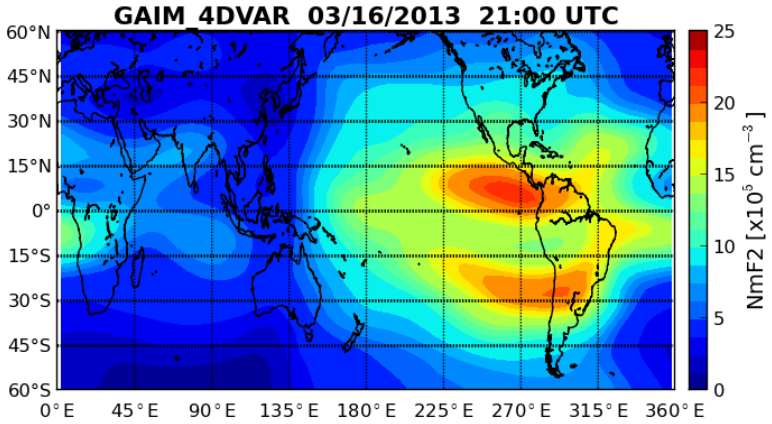




CLIM

BLKF



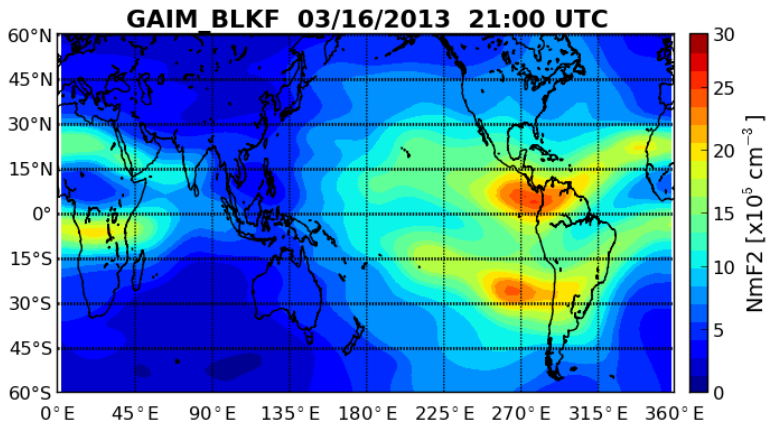


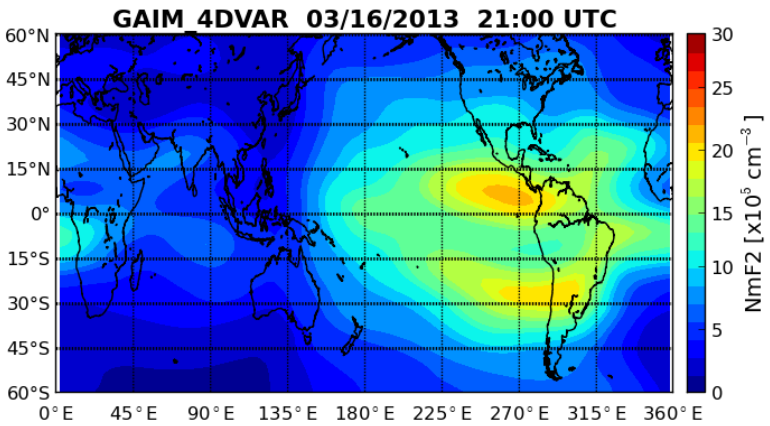
4DVAR

- **NmF2** under **quiet** conditions
- Enhanced peak density in “weather” is shown in data assimilation results

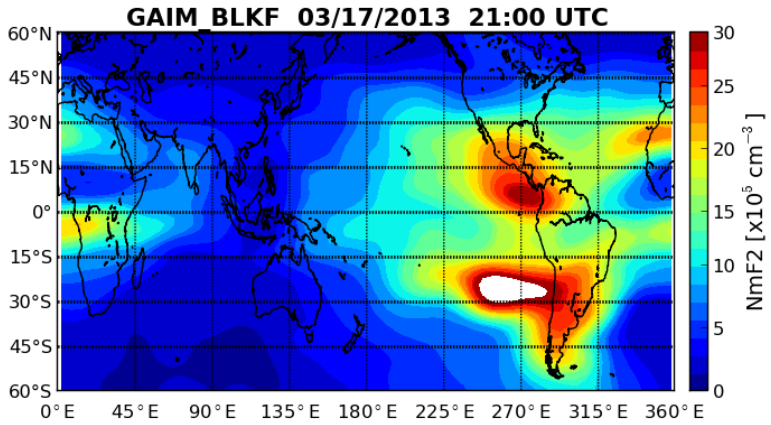
Comparison between Different Assimilative Models

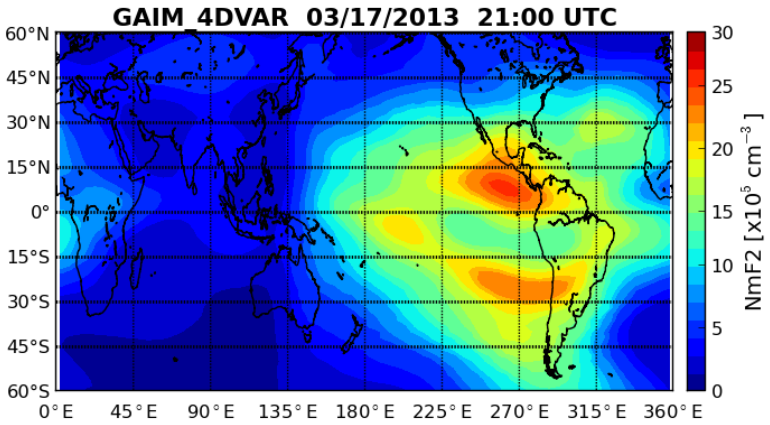
BLKF





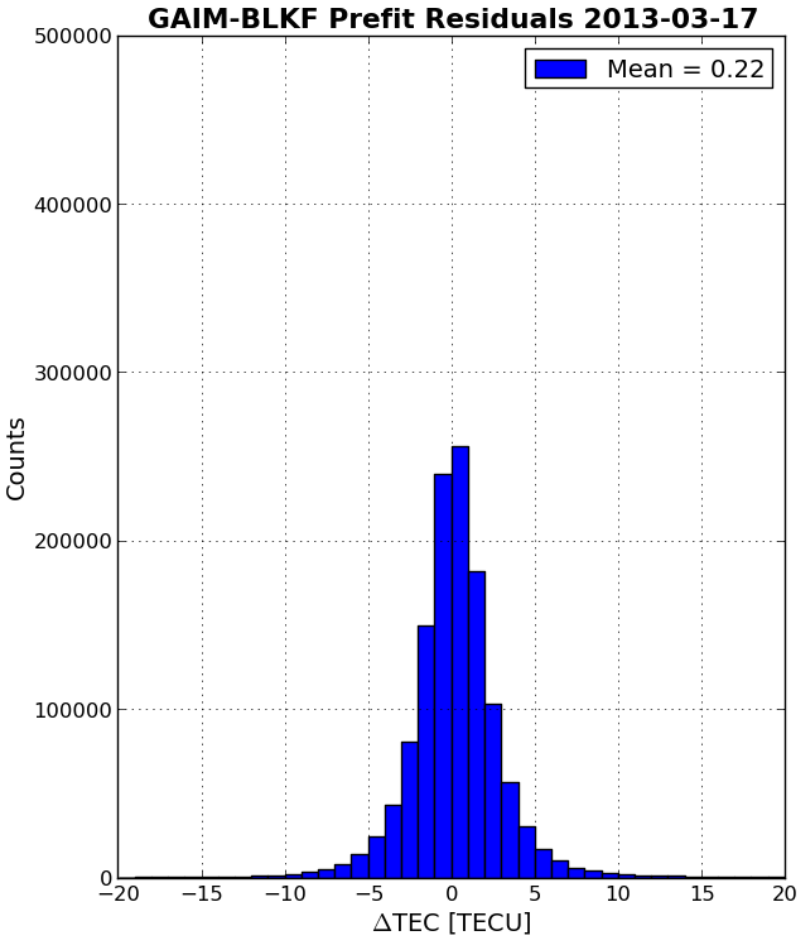
4DVAR



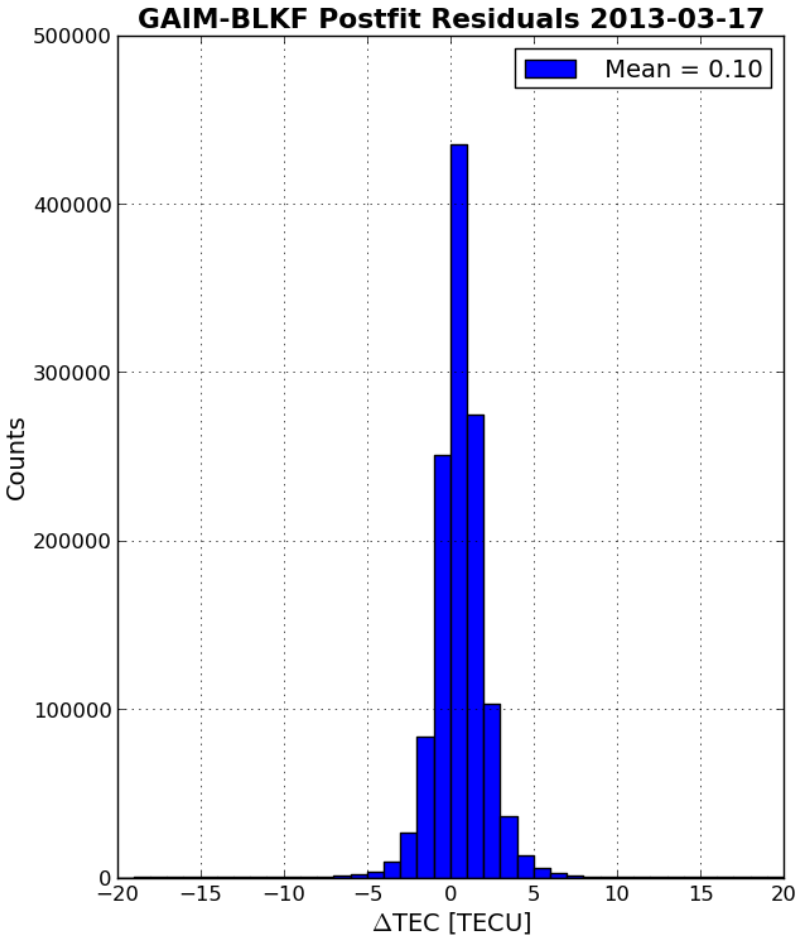


- **NmF2** under both **quiet** and **storm** conditions
- Enhanced peak density during the storm is shown in data assimilation results

Accuracy Assessment of Modeling Storm Conditions

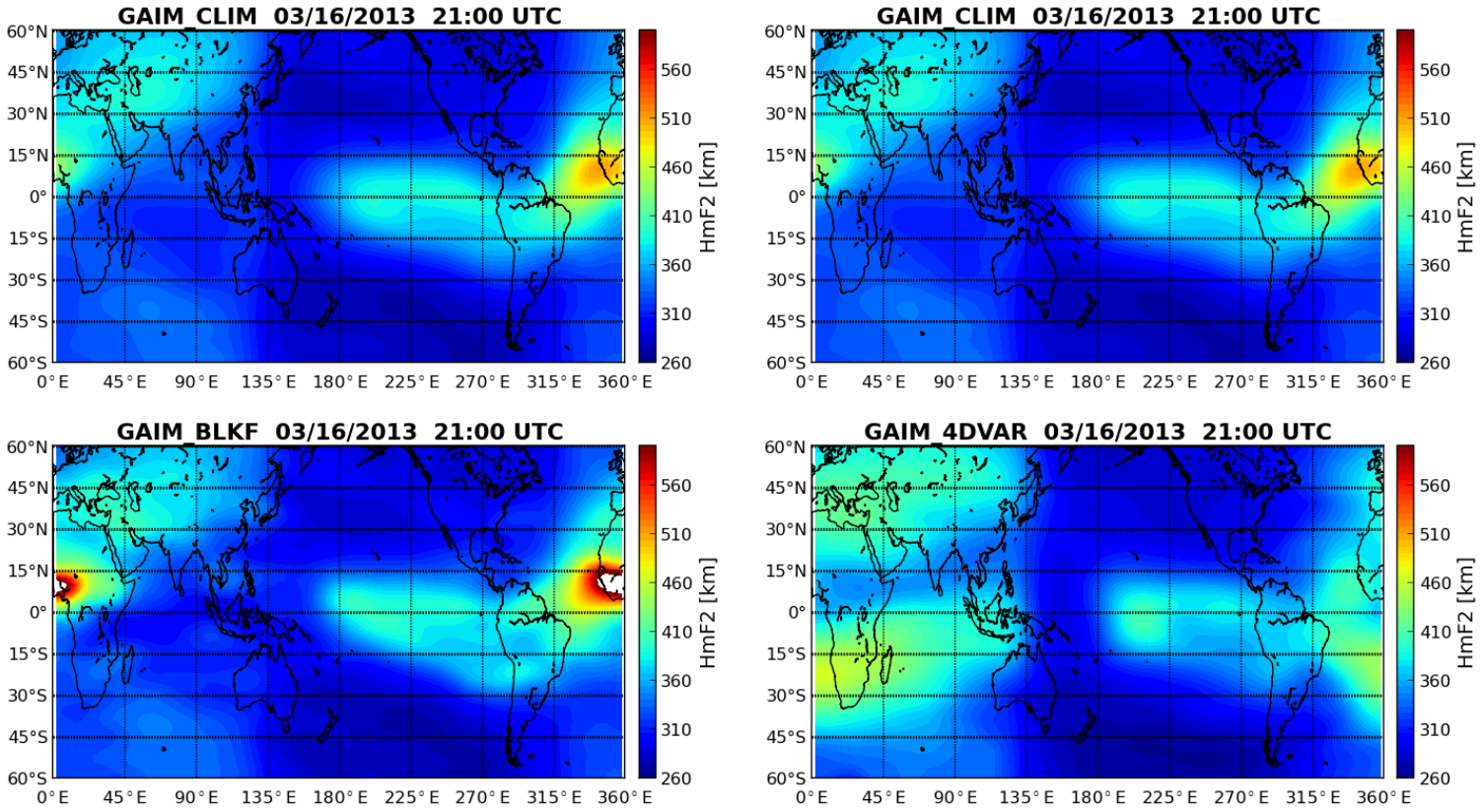


Prefit



Postfit

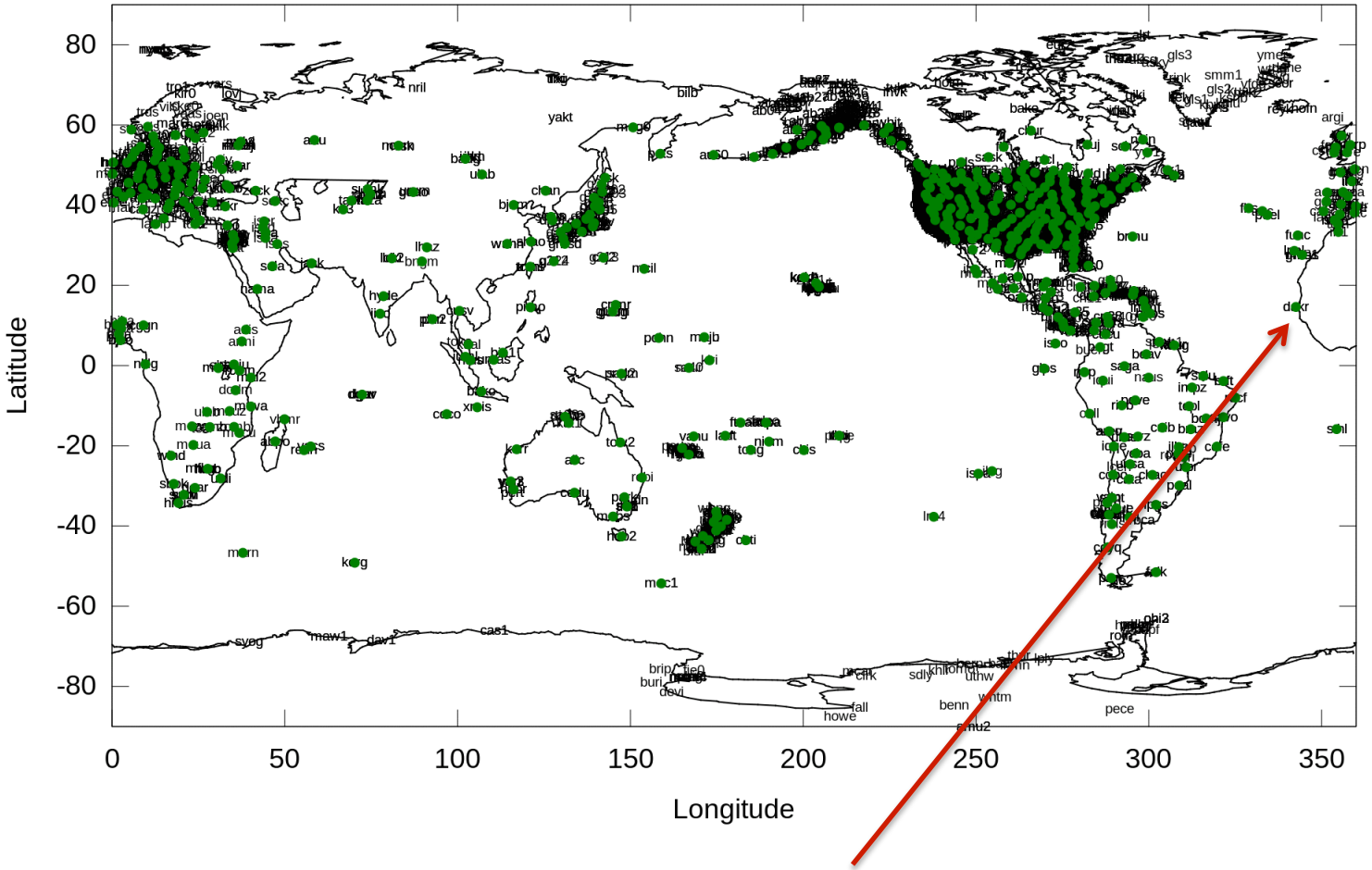
Comparison between Climatological and Assimilative Modeling



- **HmF2** under **quiet** conditions
- Enhanced HmF2 near the equator at ~0° longitude sector
- Difference in HmF2 between the two GAIMs

GPS Station Distribution

(~ 530 Stations)



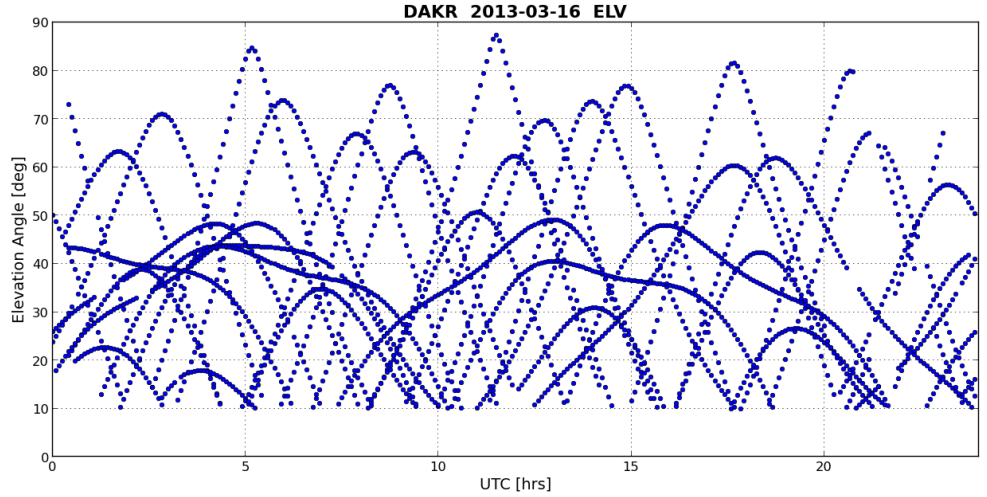
The region where the HmF2 results are under investigation.

Investigation of Data Quality

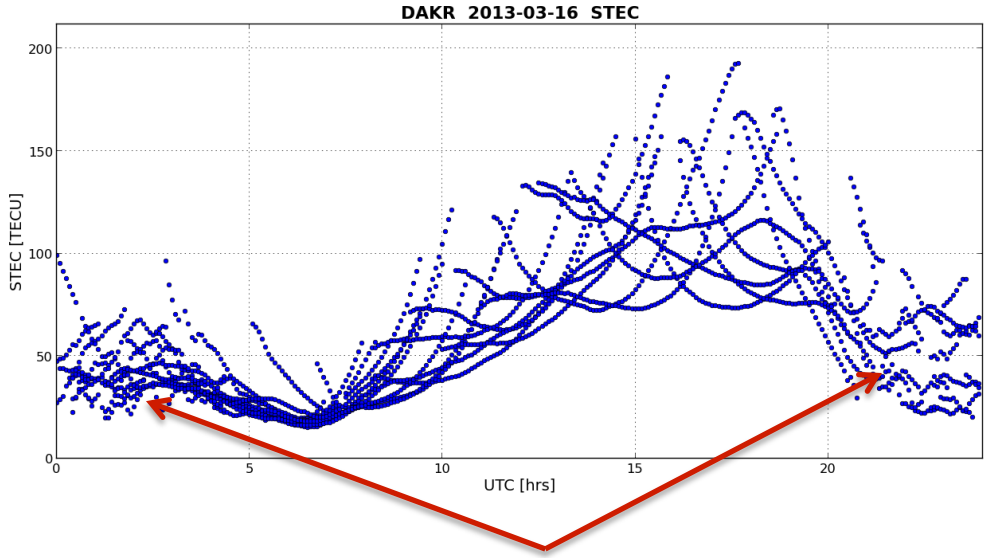
Data are from a large number of GPS receivers. Data quality must be under control.

Example

- Frequent phase breaks can occur under scintillation conditions, which affect the GPS data quality
- The quality can be receiver dependent



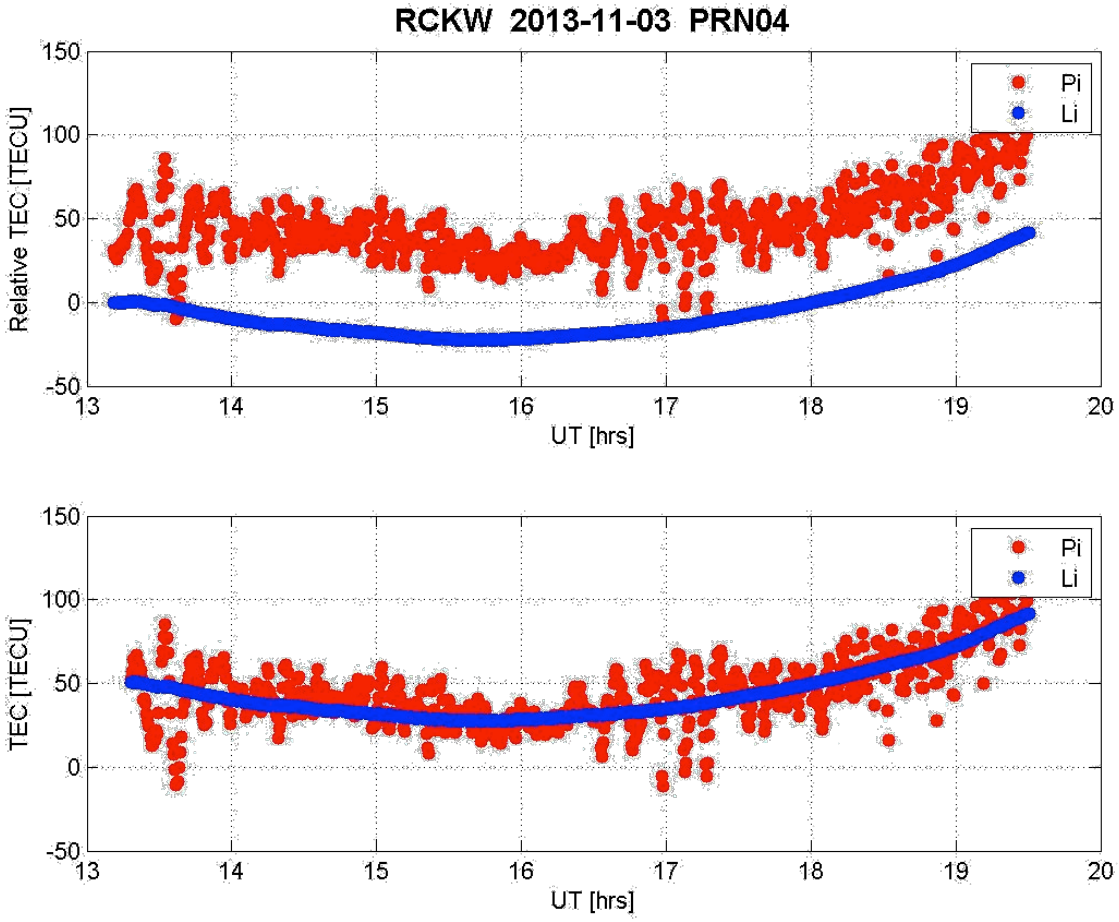
ELV



$STEC_o$

Noisy or Irregular Data Arcs

Basics of GPS TEC Data



Slant TEC measurements

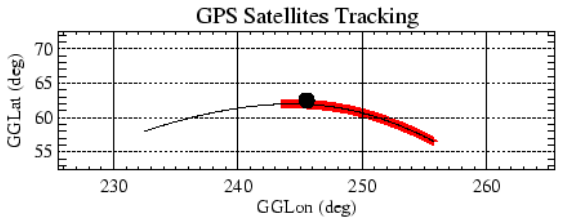
- From pseudorange – Pi, noisy and biased
- From carrier phase – Li, high precision but arbitrary offset

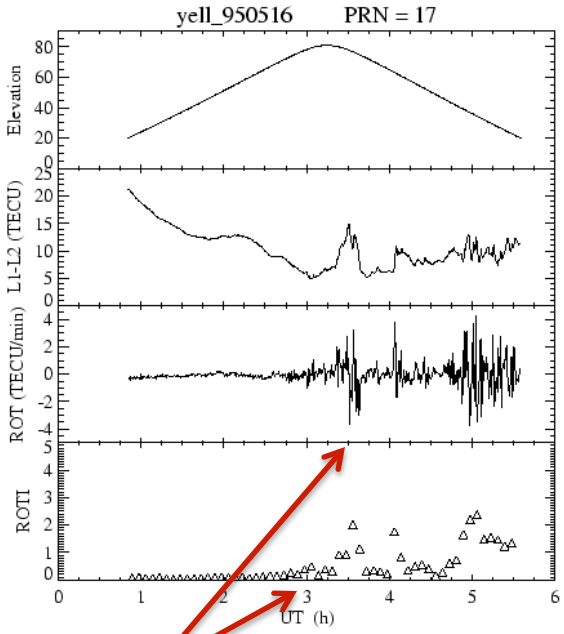
Data processing to use phase data

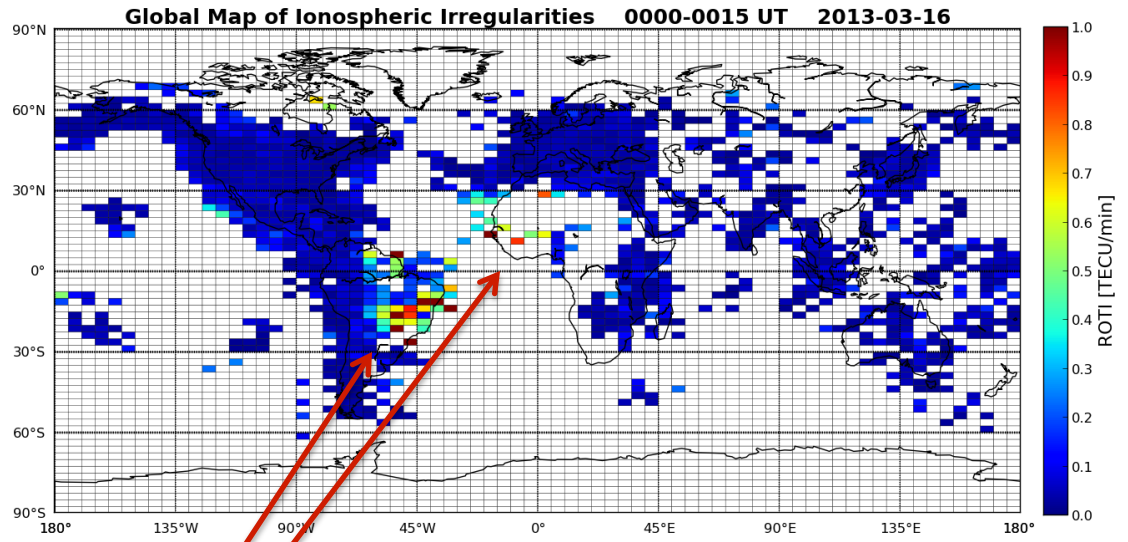
Scenarios of noisy TEC data

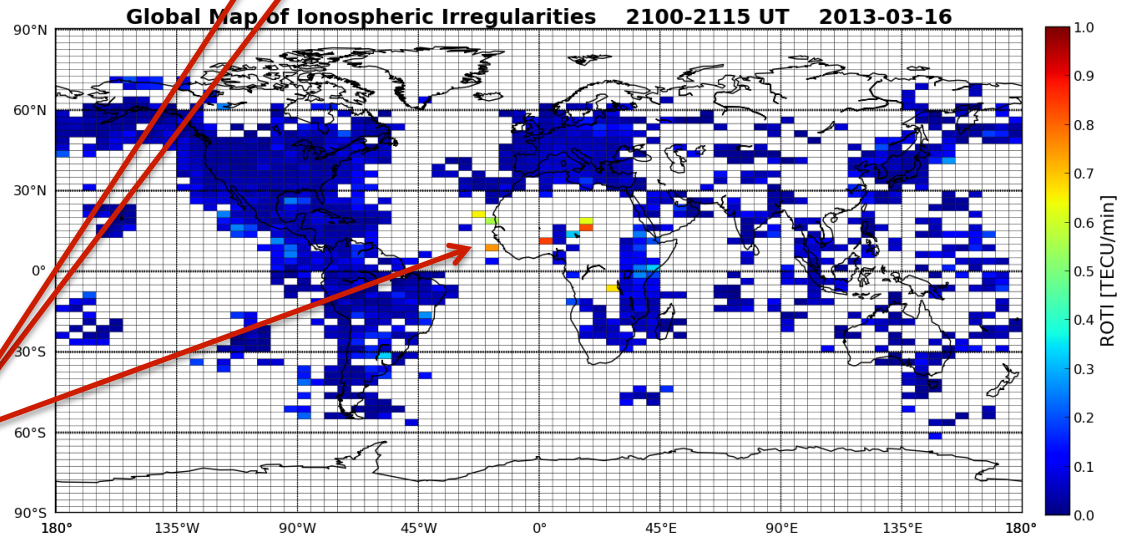
- Phase breaks result in short Li data arcs
- Short Li arcs can cause errors in leveling Li to bias-removed Pi since Pi is very noisy

Ionospheric Irregularities & Scintillation







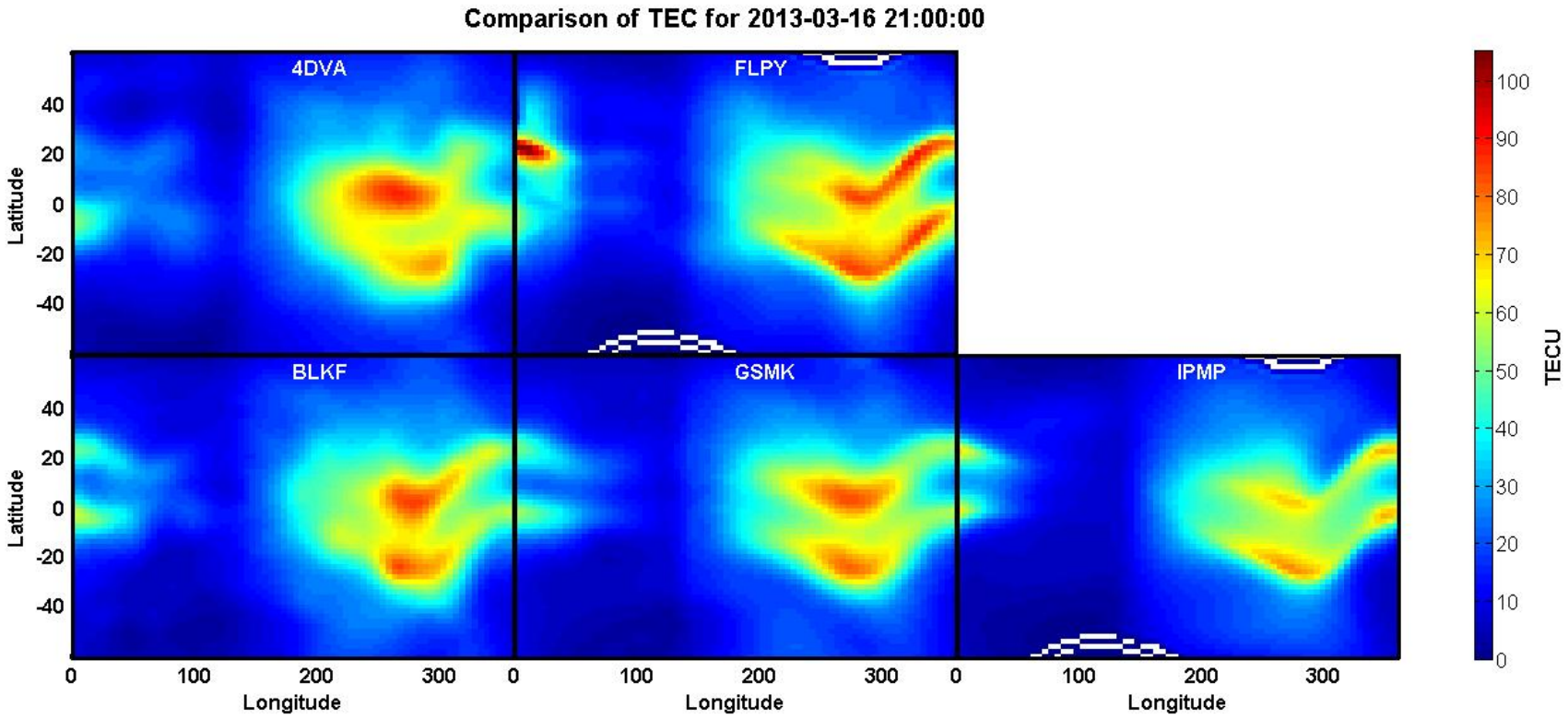


- Fundamentals of ROTI
- GMIISs show conditions of irregularities and scintillation in places where noisy data are seen

GAIM Comparisons for MEPS Development

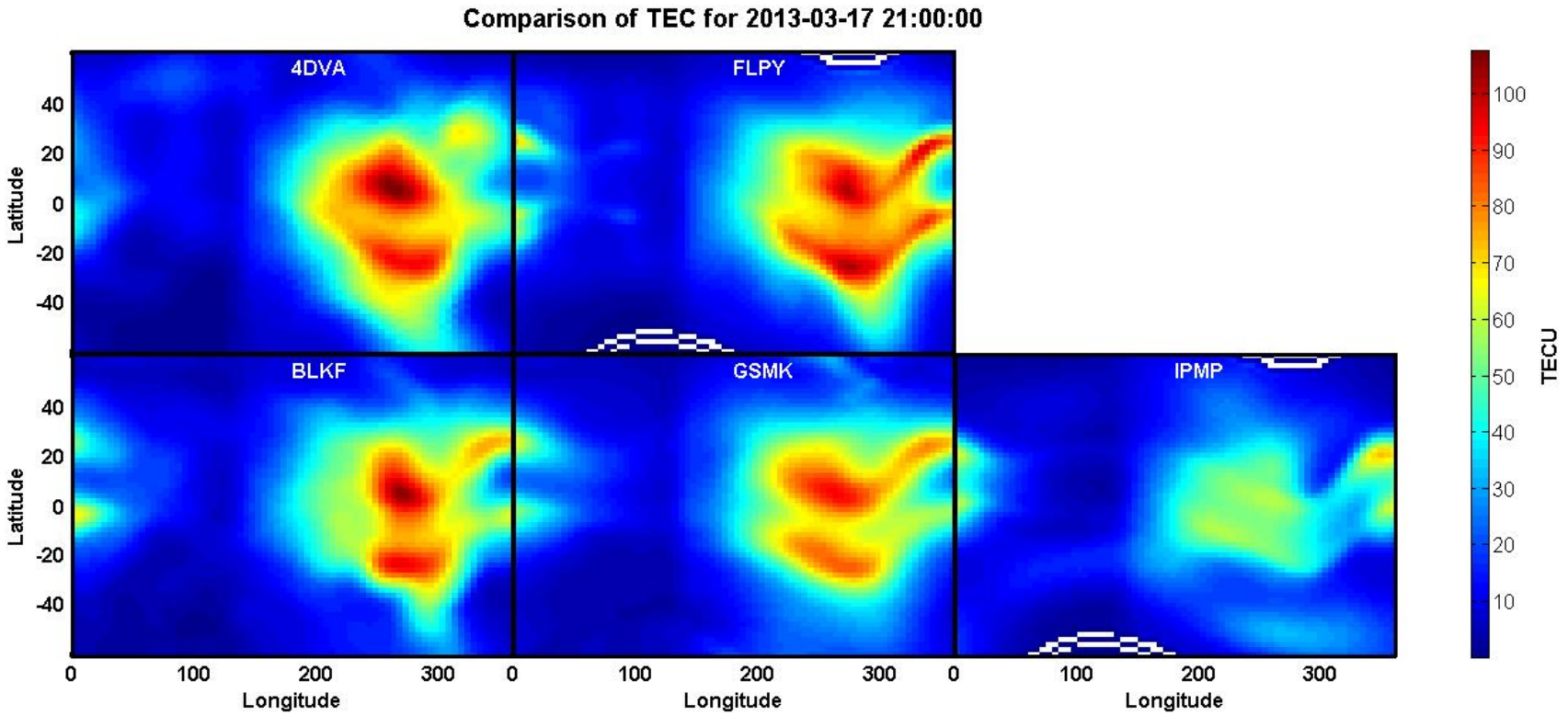
530 GPS Stations

TEC Comparison for the Quiet Day



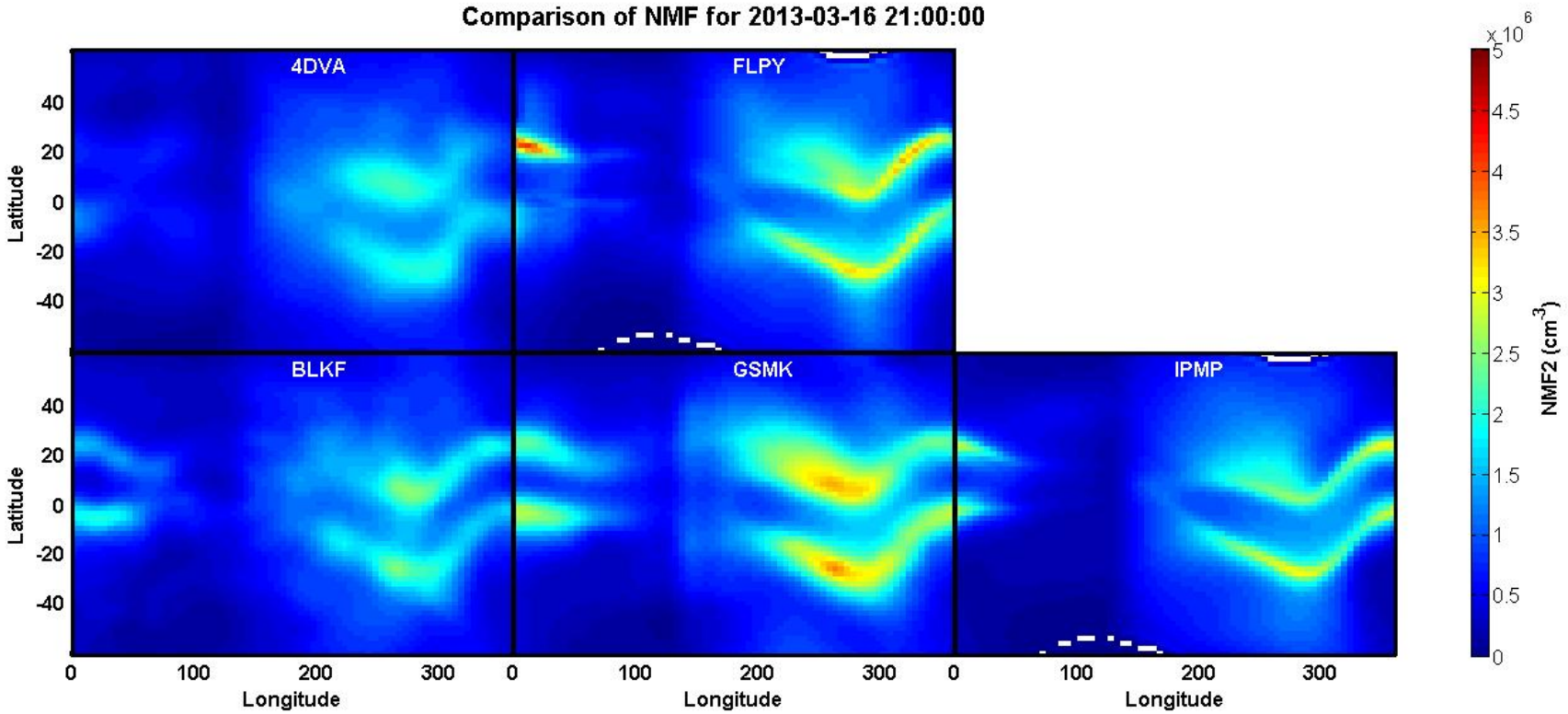
- Magnitude of the equatorial anomaly is generally in agreement (one is weaker)
- Some differences in the width and asymmetry of the equatorial anomaly

TEC Comparison for the Storm Day



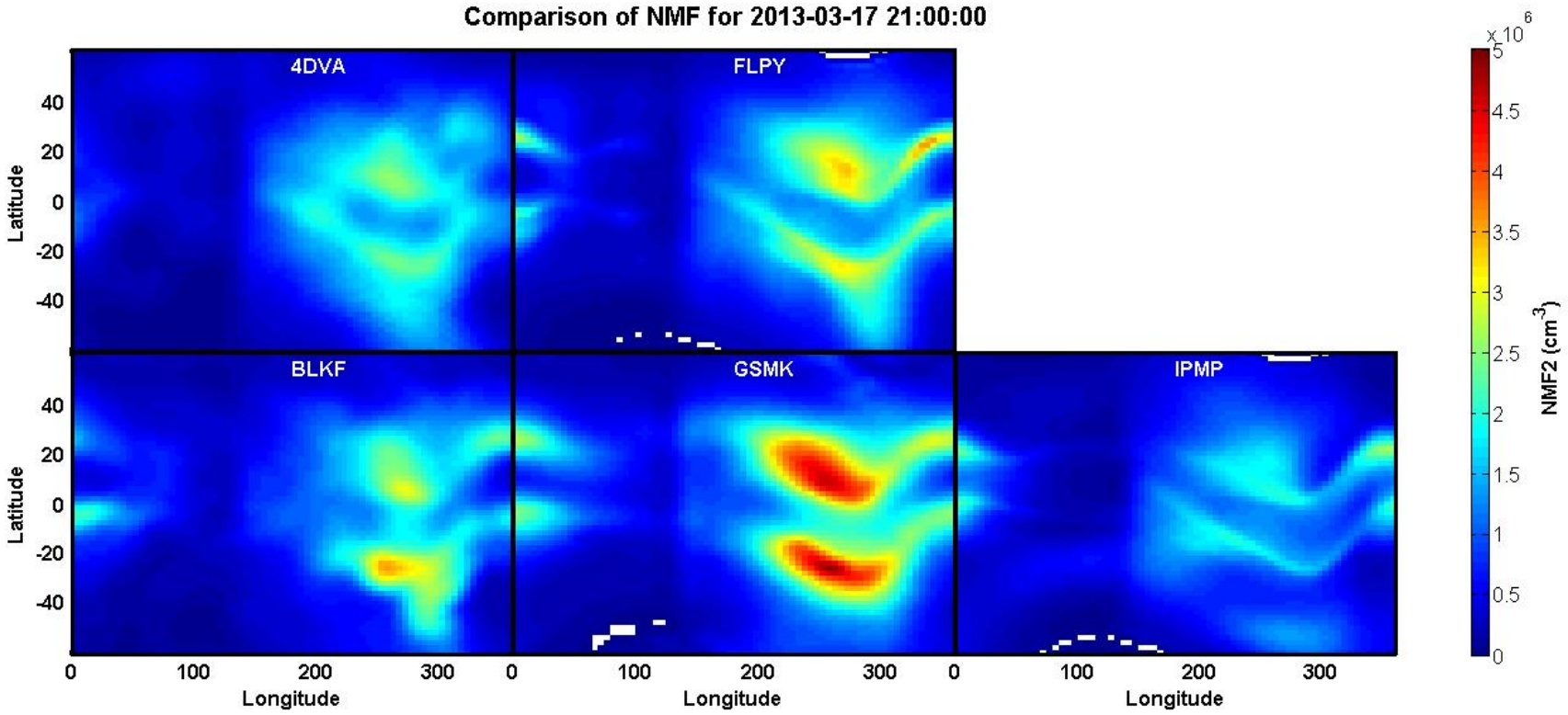
- Agreement in TEC enhancement (magnitude) except one model
- Some differences in the extension and width of equatorial anomaly
  - Four models show enhanced TEC in the southern hemisphere beyond 30° lat
  - Extent of the enhancement

NmF2 Comparison for the Quiet Day



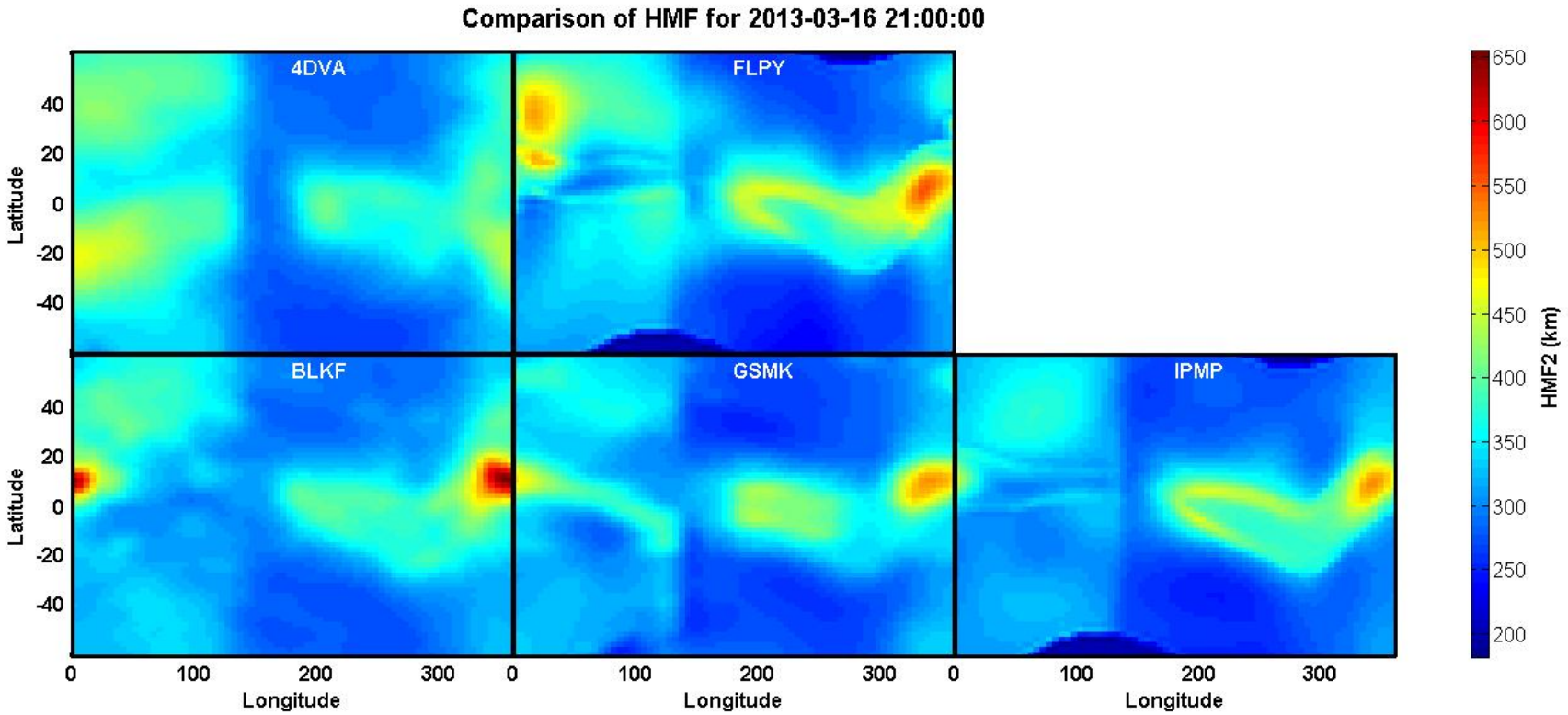
- Good agreement in most of regions.
- Differences in magnitude and longitude of the equatorial anomaly.

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

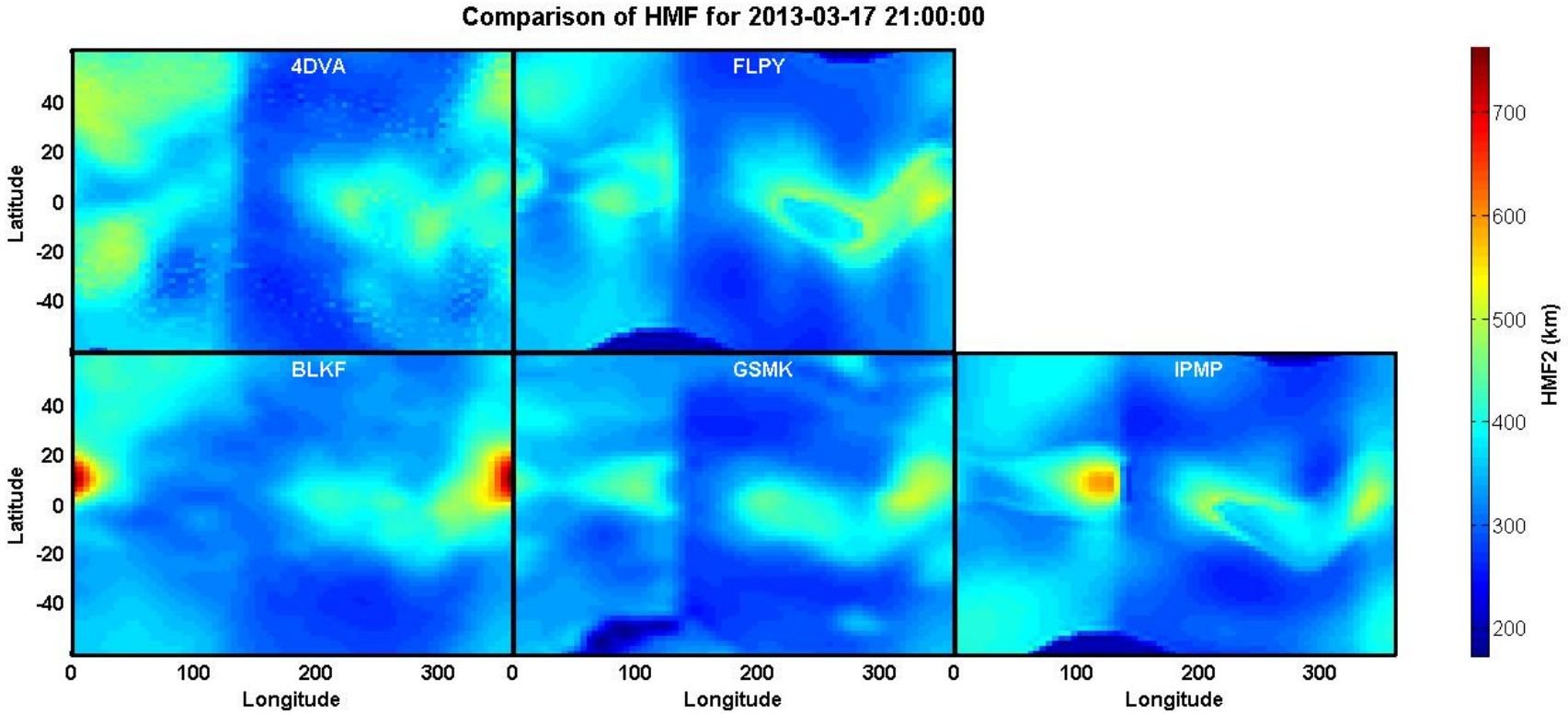
HmF2 Comparison for the Quiet Day



Differences in

- the equatorial region near 0° longitude
- middle latitudes in the southern hemisphere

HmF2 Comparison for the Storm Day



Differences in

- the equatorial region near 0° and 120° longitude
- middle latitudes in the southern hemisphere

Brief Summary of the Latest MEPS Study

At 21 UT

Weather vs. Climatology

- Enhanced TEC and densities, particularly in the equatorial anomaly regions

Storm Features Identified

- Enhanced equatorial anomaly
- Latitudinal widening of the anomaly peak
- Enhanced TEC and Ne in the southern hemisphere middle latitudes in the American longitude sector

Data quality investigation

- GPS TEC data quality under scintillation conditions

GAIM Comparisons

TEC

- Agreement in most of regions
- Some differences in the width of the equatorial anomaly

NmF2

- Agreement in most of regions
- Differences in magnitude and longitude (above ocean) of the equatorial anomaly

HmF2

- Differences in the equatorial region
- Differences in the southern hemisphere

MEPS Initial Simulation Plan

- Run 4 data assimilation models independently for same case
- Run with TEC data from 530 ground GPS receivers
- Run with 530 ground GPS receivers & COSMIC occulation data
- Run with 530 ground GPS receivers, occultation data, & 80 digisondes

Improved coverage over oceans and information on altitude structure

To build MEPS we need to understand the effects of …

- Different Background Physics-Based Models
- Different Data Amounts, Types and Locations
- 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

Typically the GAIM Data Assimilation models are used to determine ionospheric weather

The GAIM Models can also be used to deduce Climate Variations

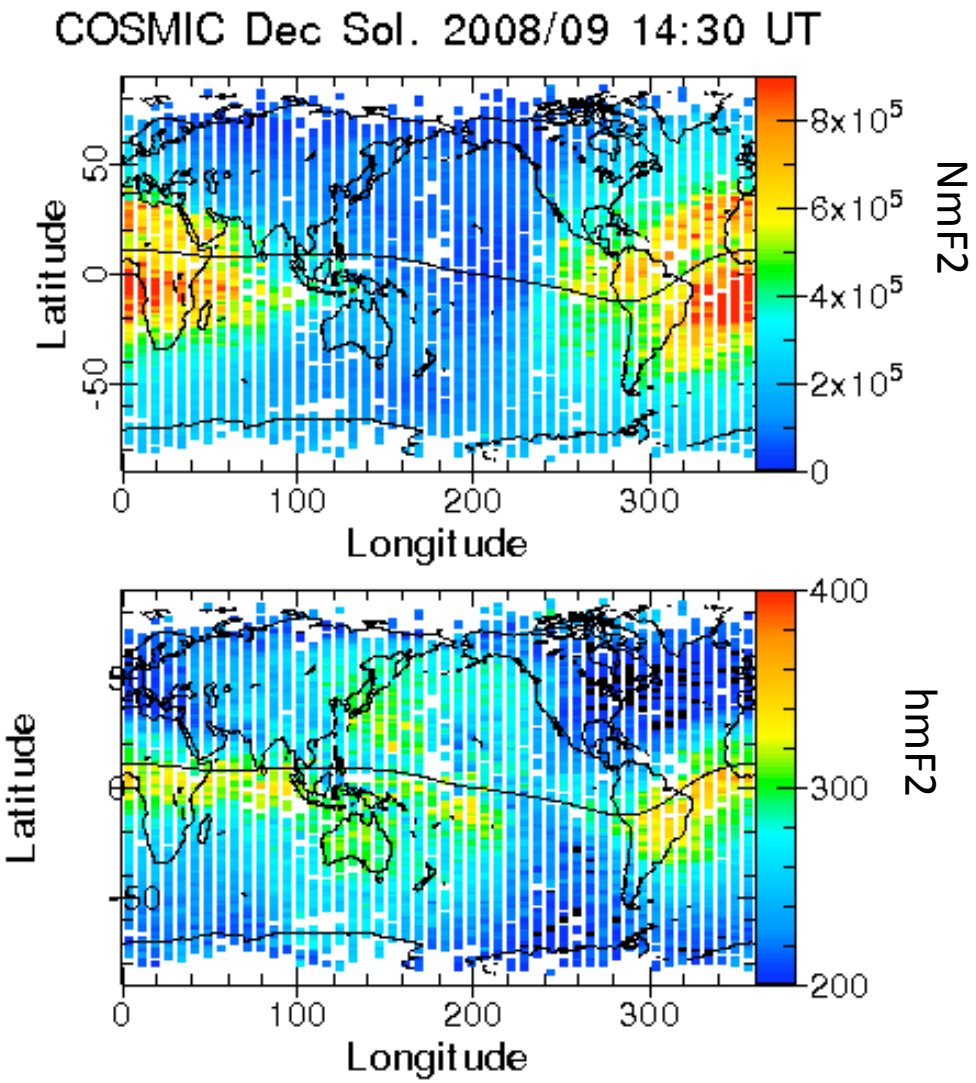
For the first time, we use a Data Assimilation Model (GAIM-FP) with COSMIC Data to derive climate variations:

- **the seasonal climatology of the ionosphere and**
- **the thermospheric and electrodynamic drivers**

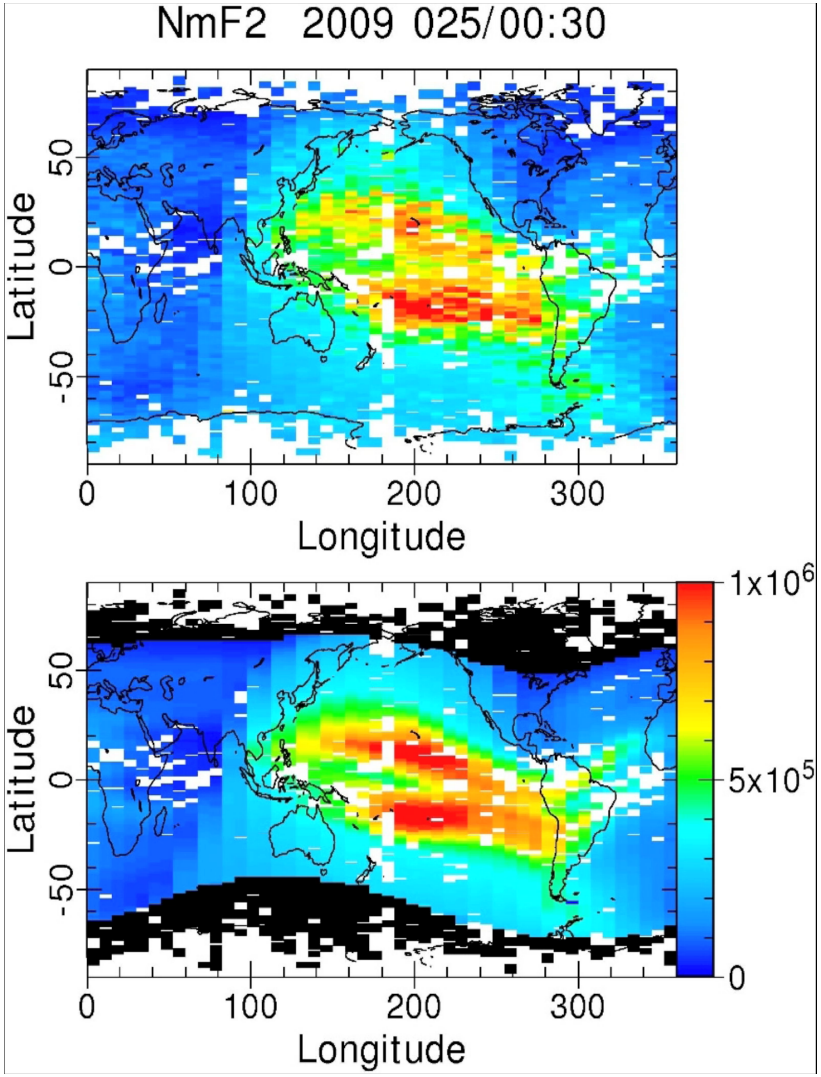
Assimilate Empirical Maps (NmF2, hmF2)

- ~190,000 COSMIC electron density profiles
- Half-hourly maps of peak density (NmF2) and peak height (hmF2)
- Grid size: 1.25^0 X 7.5^0 (Latitude x Longitude)
- Period: Nov, 2008 – Feb, 2009

Assimilate Empirical Maps (NmF2, hmF2) from COSMIC



Mean NmF2 for December Solstice 2008/09

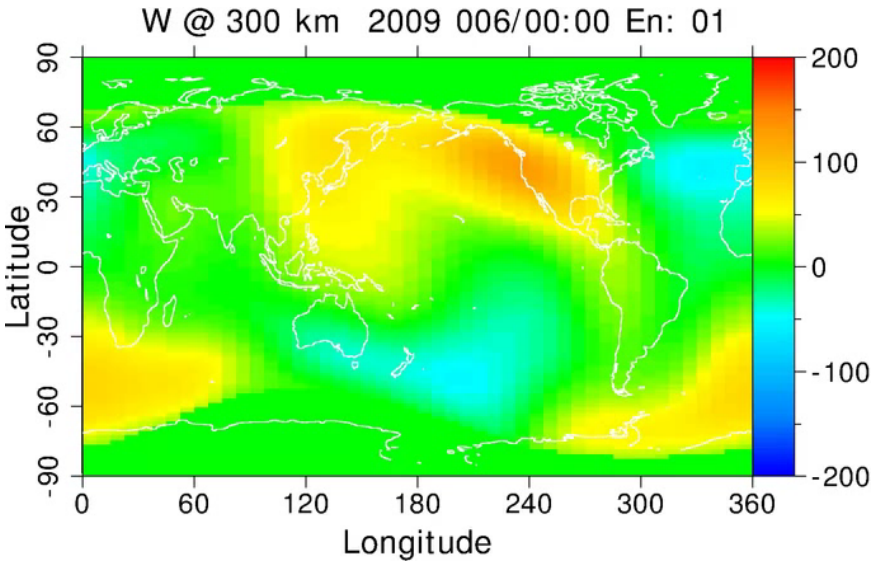


COSMIC

GAIM-FP

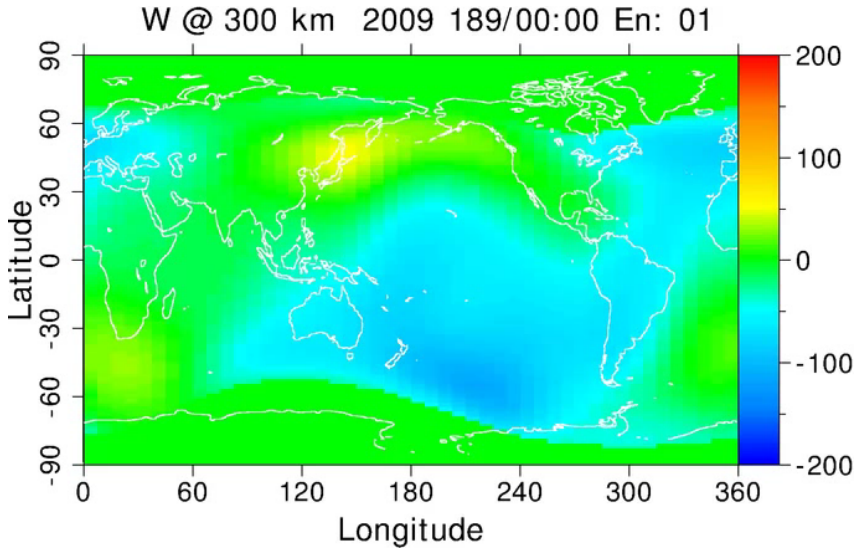
GAIM-FP results are shown below 60 magnetic latitude

Magnetic Meridional Neutral Wind Derived from GAIM Seasonal Averages



December Solstice

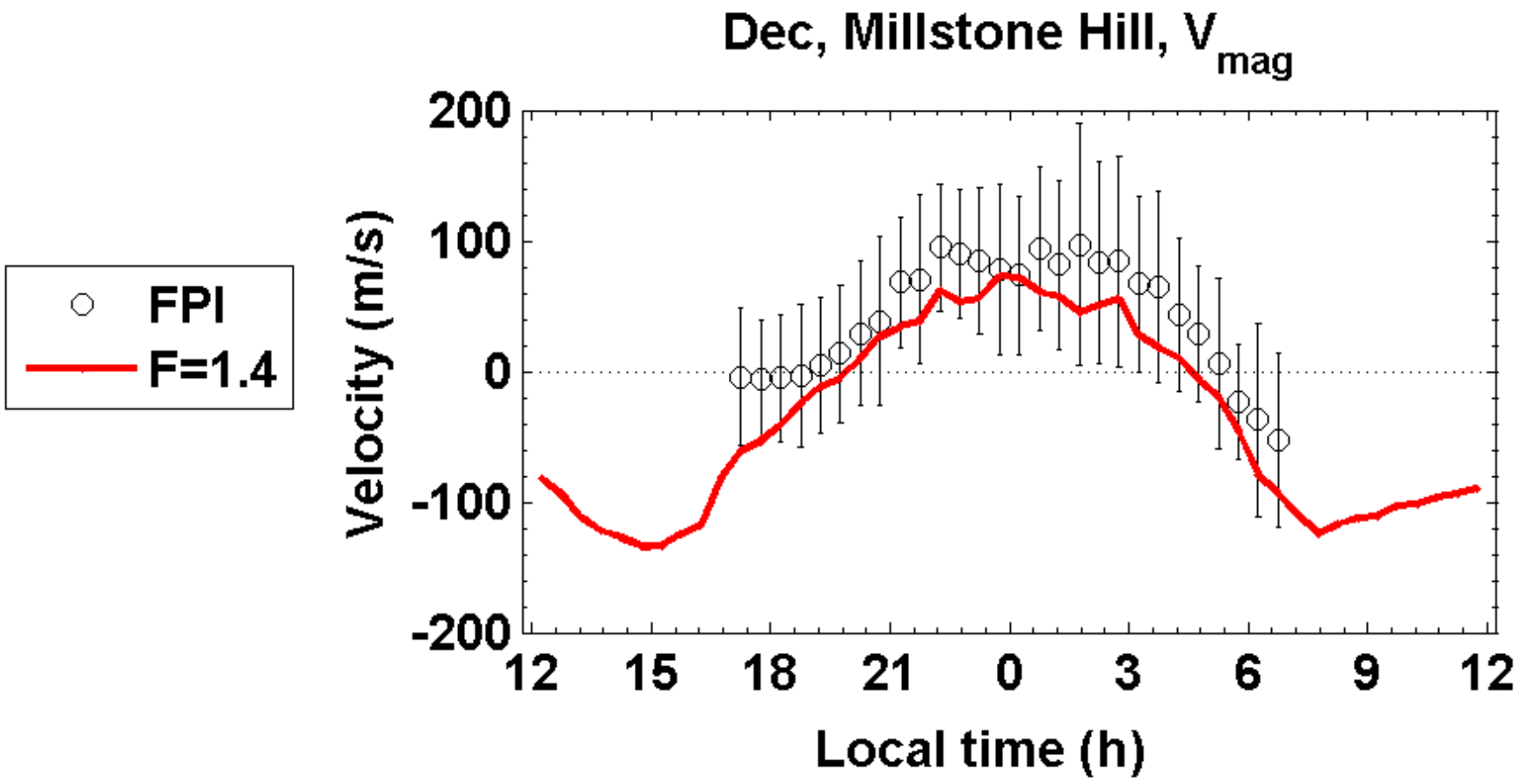
Wind blows mostly northward



June Solstice

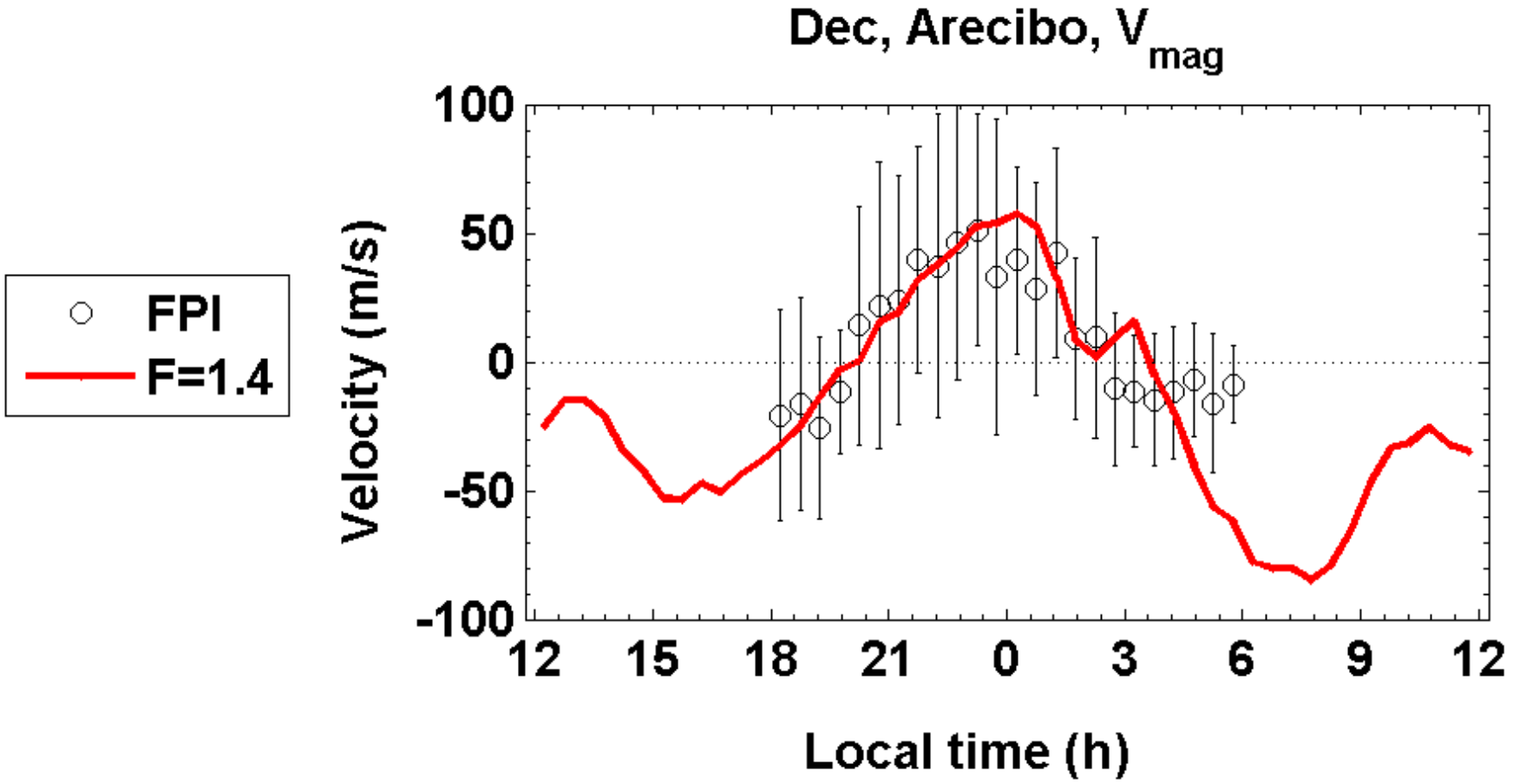
Wind blows mostly southward

Derived Thermospheric Neutral Wind over Millstone Hill



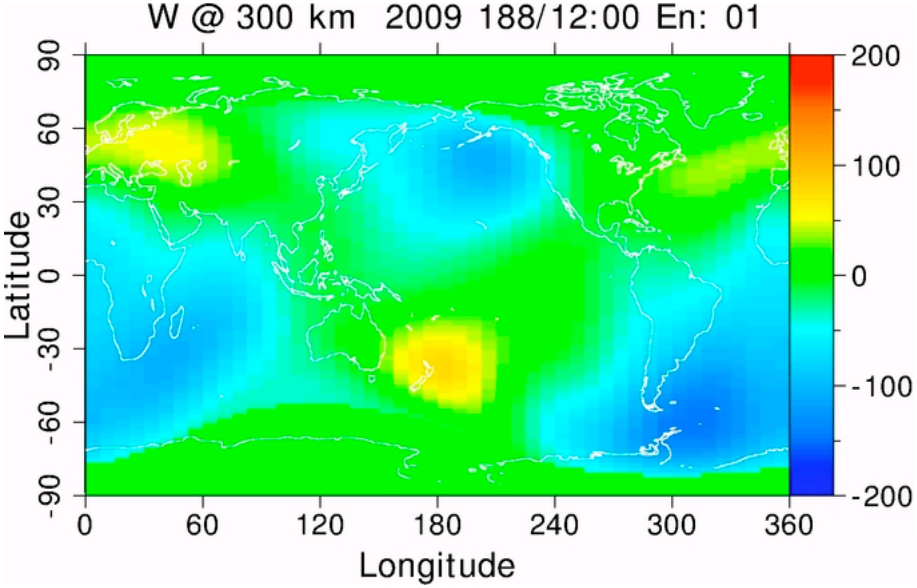
GAIM-FP derived neutral wind agrees well with FPI observations

Derived Thermospheric Neutral Wind over Arecibo



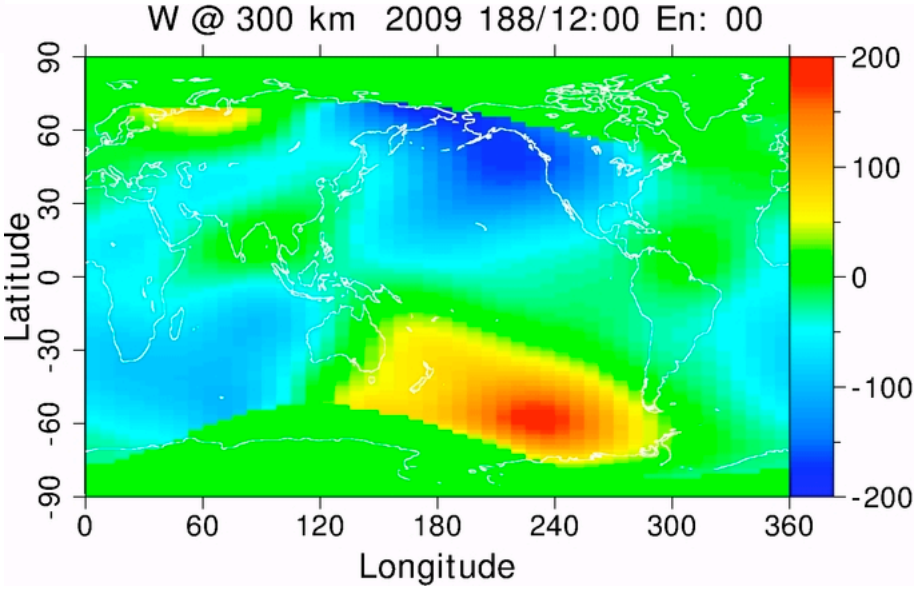
GAIM-FP derived neutral wind agrees well with FPI observations

Comparison of GAIM-Derived Thermospheric Neutral Wind Climatology with HWM-93 climatology: June Solstice 2009

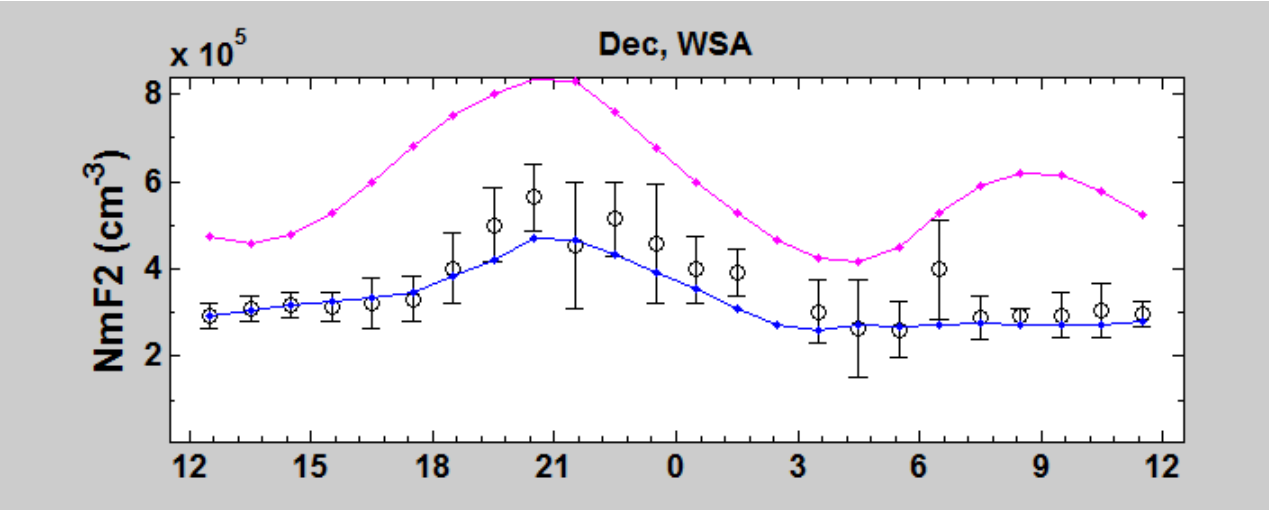


GAIM-FP derived

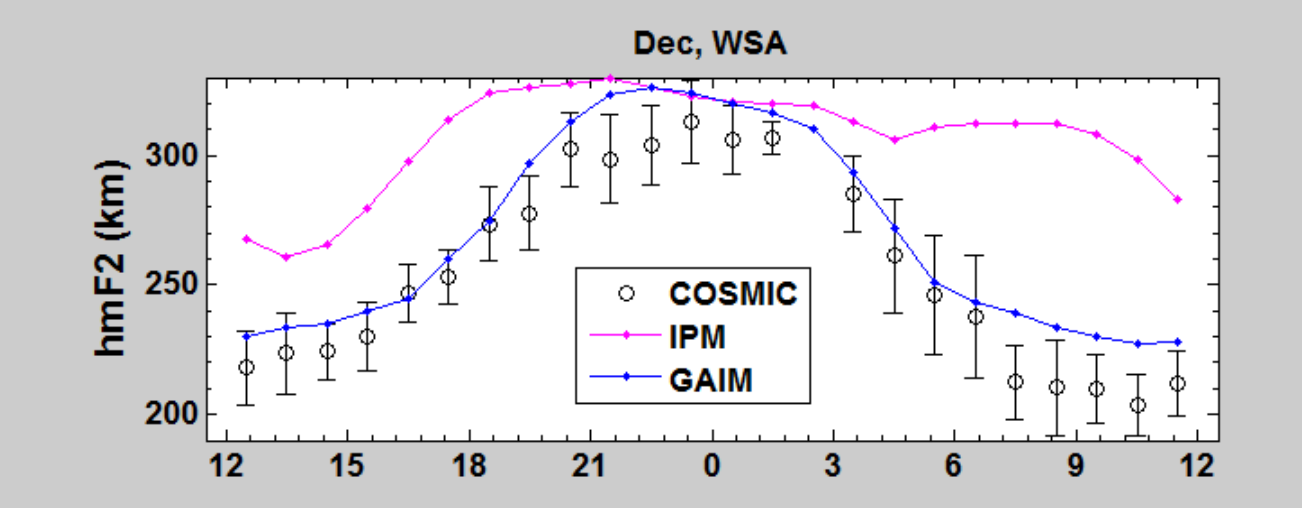
Empirical Wind Model (HWM-93) used in IPM



COSMIC, GAIM-FP and IPM NmF2 and hmF2 over Weddell Sea



NmF2



hmF2