GNSS Ionospheric Sounding for Space Weather

Dr. Thomas Berger,

Director

NOAA/NWS/NCEP Space Weather Prediction Center

Boulder CO

Space Weather Prediction Center

Operations – Space Weather Forecast Office

Putting out daily forecasts since 1965.

Specifications; Current conditions

Forecast; Conditions tomorrow

Watches; Conditions are favorable for storm

Warnings; Storm is imminent with high probability

Alerts; observed conditions meeting or exceeding storm thresholds

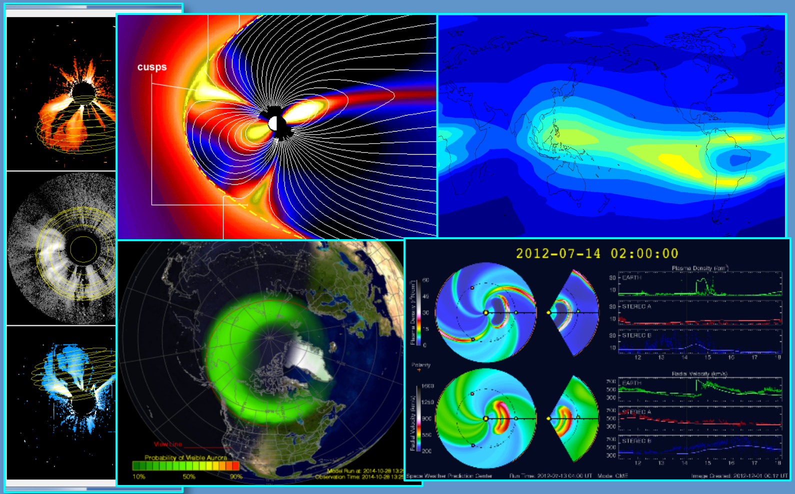
Research & Development– Space Weather Prediction Testbed

Research-to-Operations

- Applied Research
- Model Development
- Model Test/Evaluation
- Model Transition
- Operations Support

Operations-to-Research

- Customer Requirements
- Observation Requirements
- Research Requirements



Geomagnetic Storm Forecast – Sun to Earth Modeling

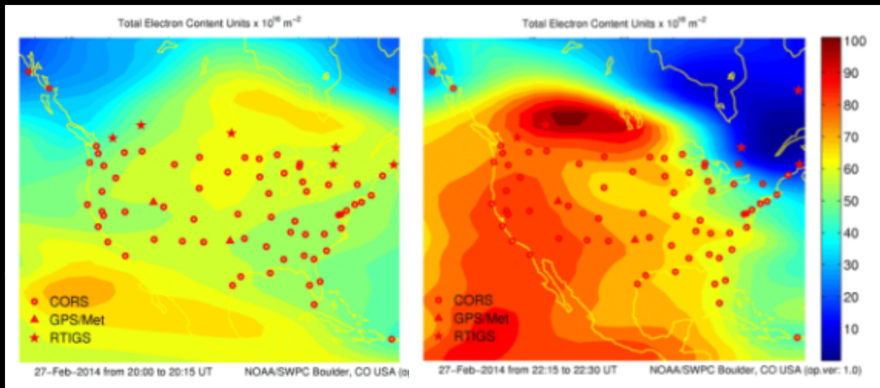
Partnerships with the Space Weather Research Community

This system will provide:

1-7 day forecasts of storms driven by solar wind and coronal holes

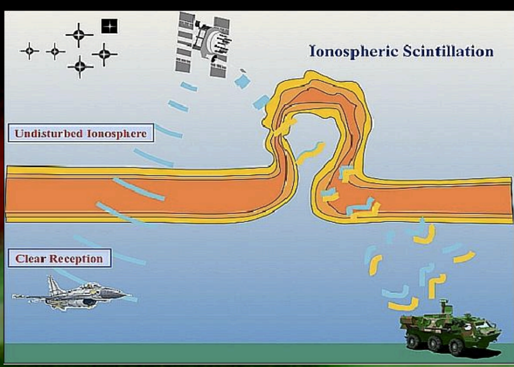
1-3 day forecast of major storms driven by CMEs

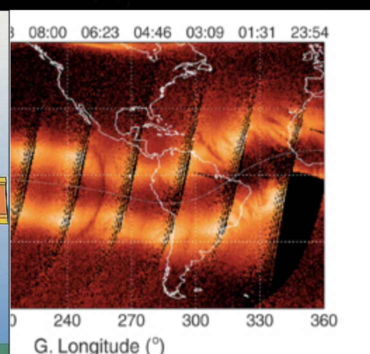
Space Weather Impacts to GNSS Operations



TEC Variation

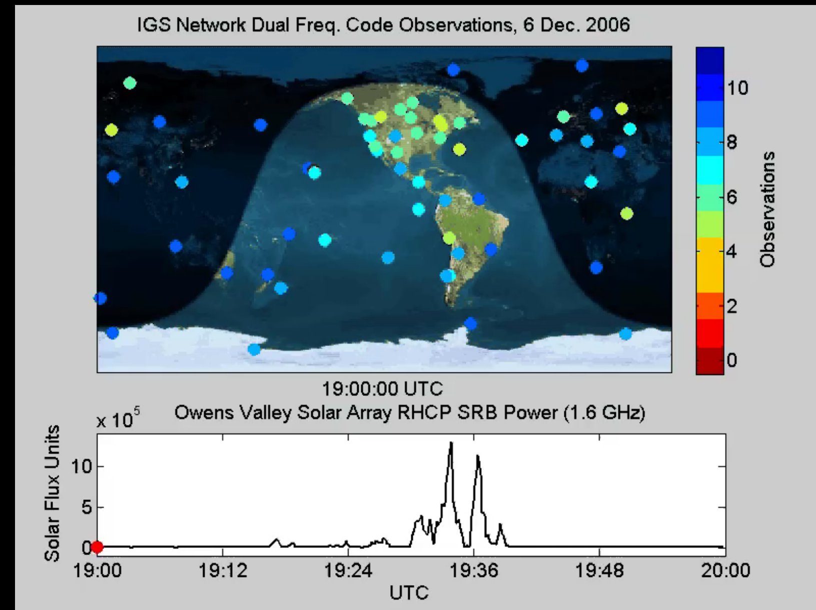
WAAS LPV lost





Scintillation

Ionospheric Storms



- Solar flare output in the L-band completely swamps day-side GNSS.
- Effect lasts for 10—20 minutes.

Solar Radio Noise (Flares)

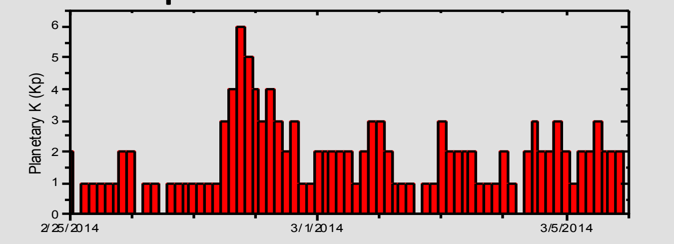
Impact of a Moderate Geomagnetic Storm on the FAA WAAS System

FAA Msg to SWPC

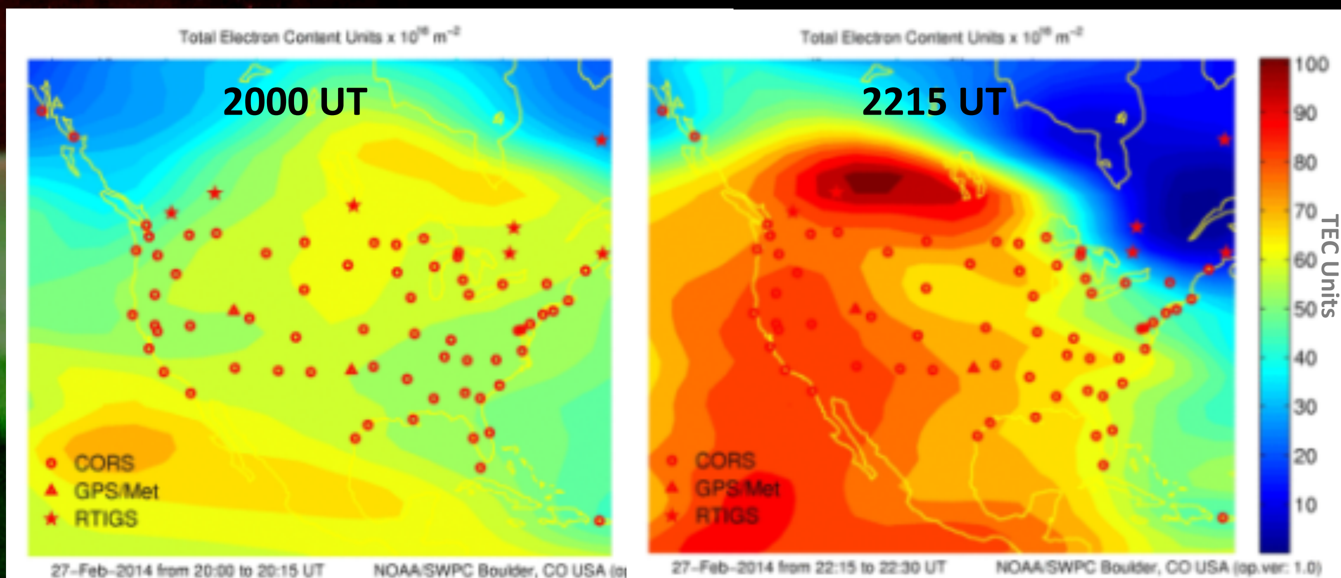
"An Ionospheric Storm began on 2/27/14. The Satellite Operations Specialists were alerted at the WAAS O&M by a Significant Event 757 at 2120 Zulu. So far, LPV and LPV200 service has not been available in Eastern Alaska and Northeastern CONUS. At times, North Central CONUS and all of Alaska have lost LPV and LPV200 Service."

Note: LPV is Localizer Performance with Vertical Guidance which takes the aircraft down to 250 ft altitude

Moderate Geomagnetic Storm:
Kp of 6 on a scale of 0-9



Effects last for hours

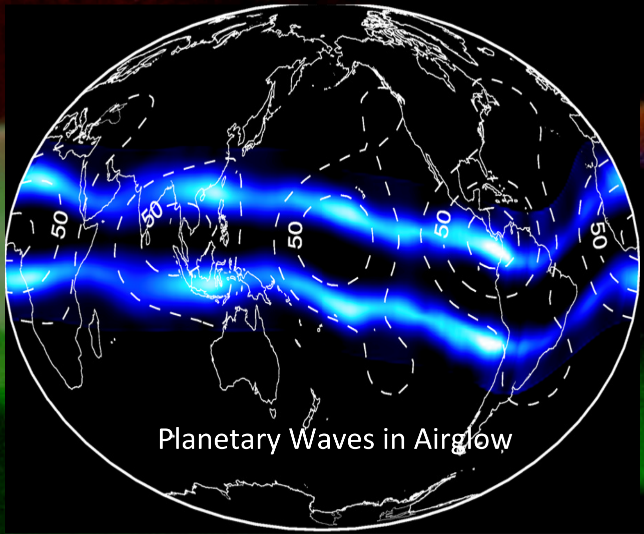


Requirement: One to Three Day Forecasts of the Ionosphere

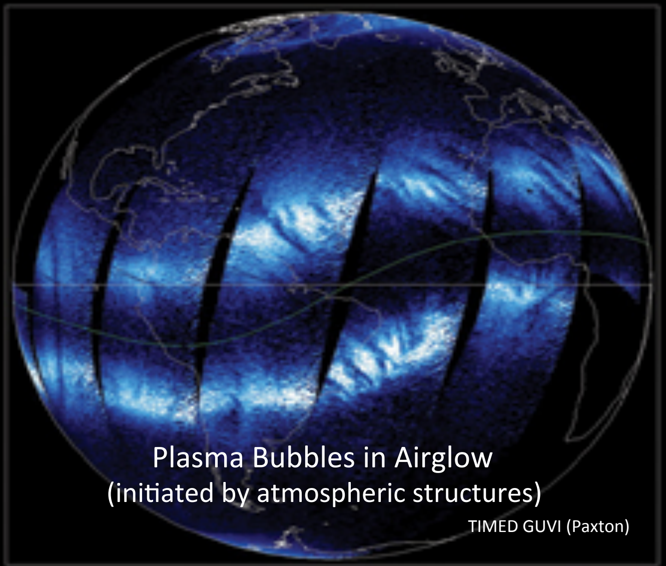
- Requires long-range forecasts of all three drivers
  - Solar EUV and X-ray irradiance
  - Geomagnetic Storms
  - Atmospheric structures from below (tides, waves, strat-warms)

Lower Atmospheric Structures Manifested in the Ionosphere

Gravity waves in Airglow



Planetary Waves in Airglow



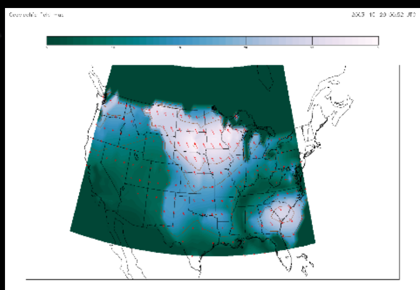
Plasma Bubbles in Airglow
(initiated by atmospheric structures)

TIMED GUVI (Paxton)

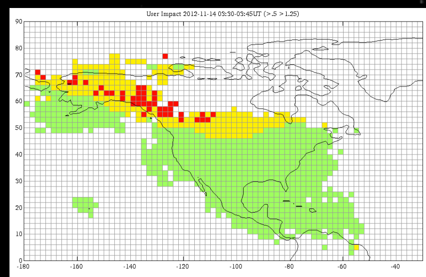
Ionospheric Models and Products

Development

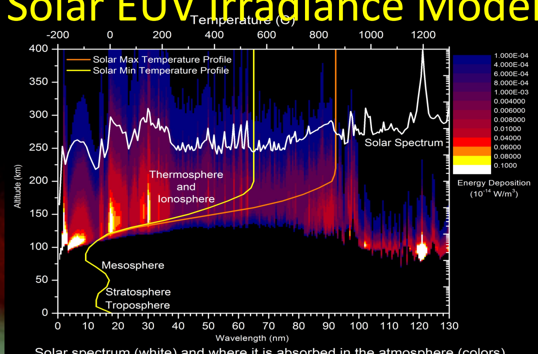
Electric Field Model



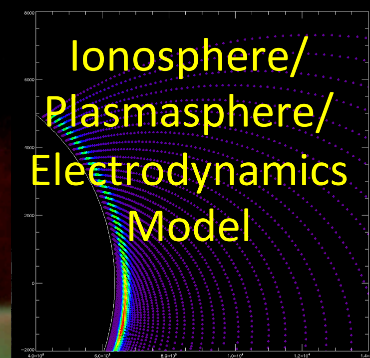
ROTI GPS Product



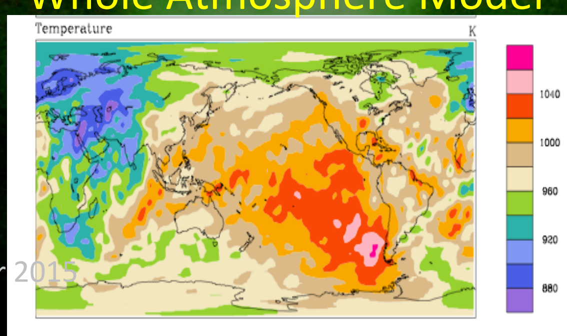
Solar EUV Irradiance Model



Ionosphere/ Plasmasphere/ Electrodynamics Model

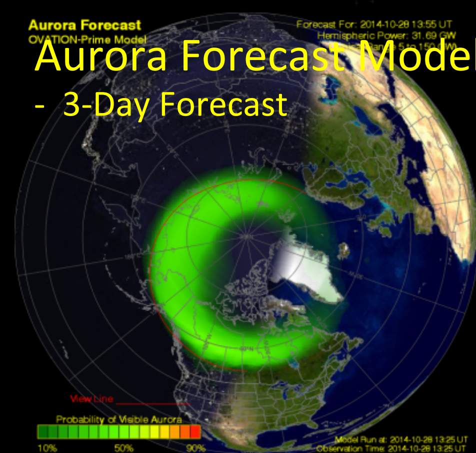


Whole Atmosphere Model

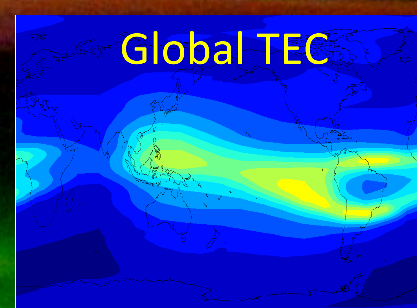


Prototype

Aurora Forecast Model
- 3-Day Forecast

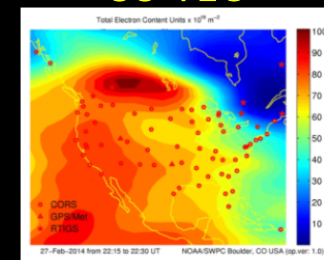


Global TEC

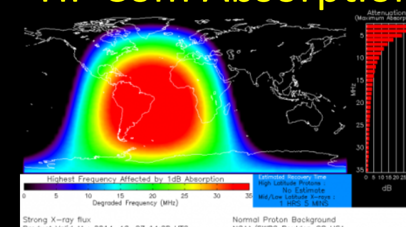


Operations

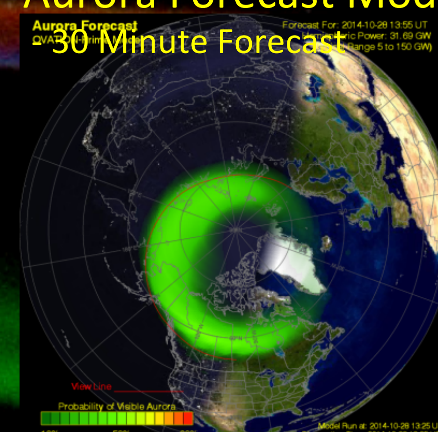
US-TEC



HF Com Absorption



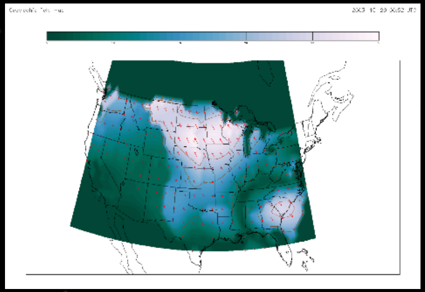
Aurora Forecast Model
30 Minute Forecast



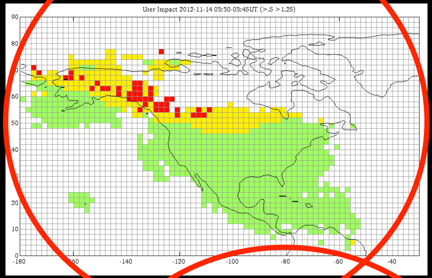
Ionospheric Models and Products

Development

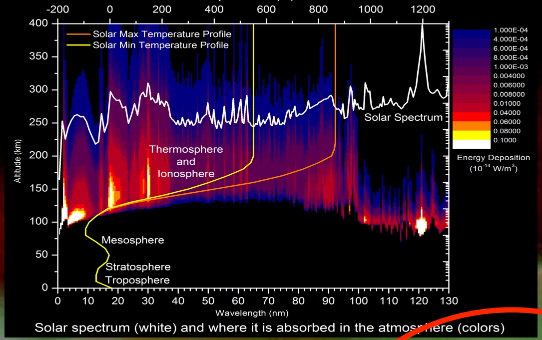
Electric Field Model



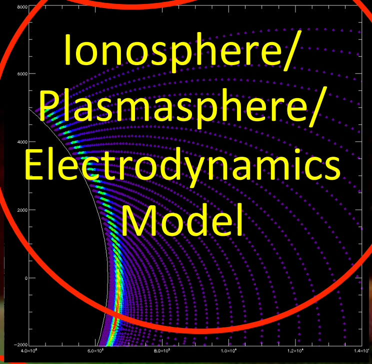
ROTI GPS Product



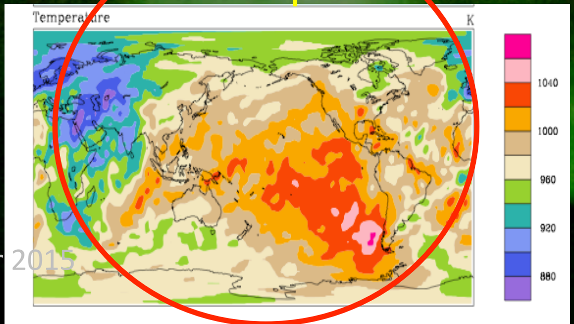
Solar EUV Irradiance Model



Ionosphere/ Plasmasphere/ Electrodynamics Model



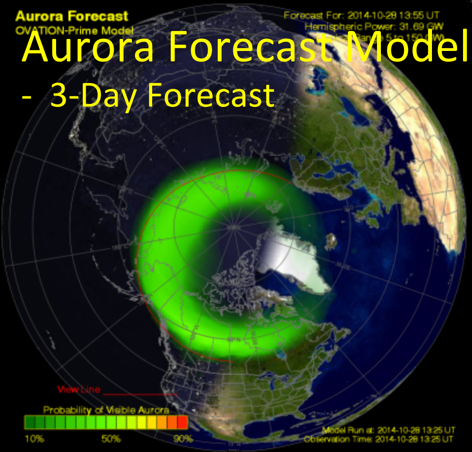
Whole Atmosphere Model



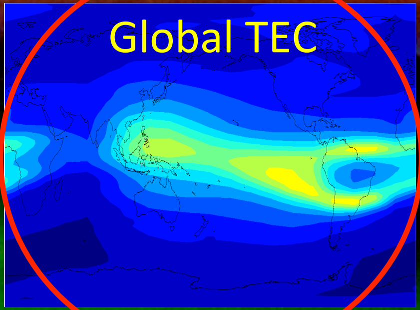
Prototype

Requires GNSS Data

Aurora Forecast Model
- 3-Day Forecast

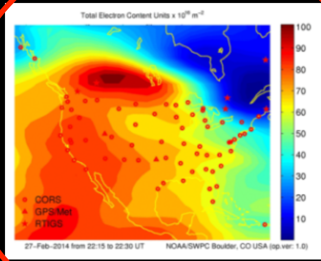


Global TEC

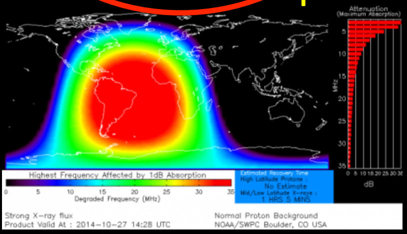


Operations

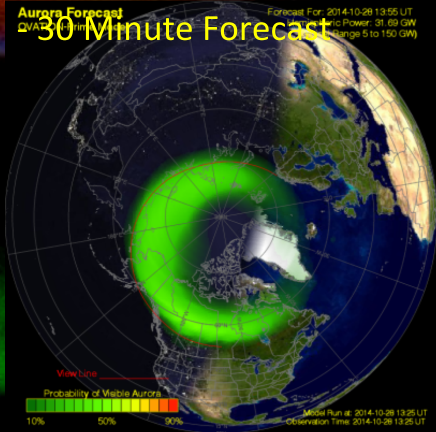
US-TEC



HF Com Absorption

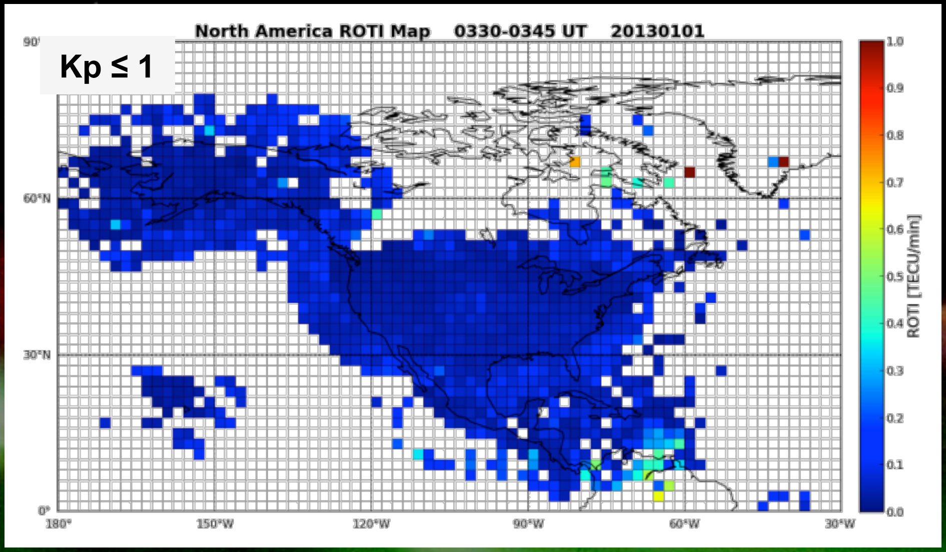


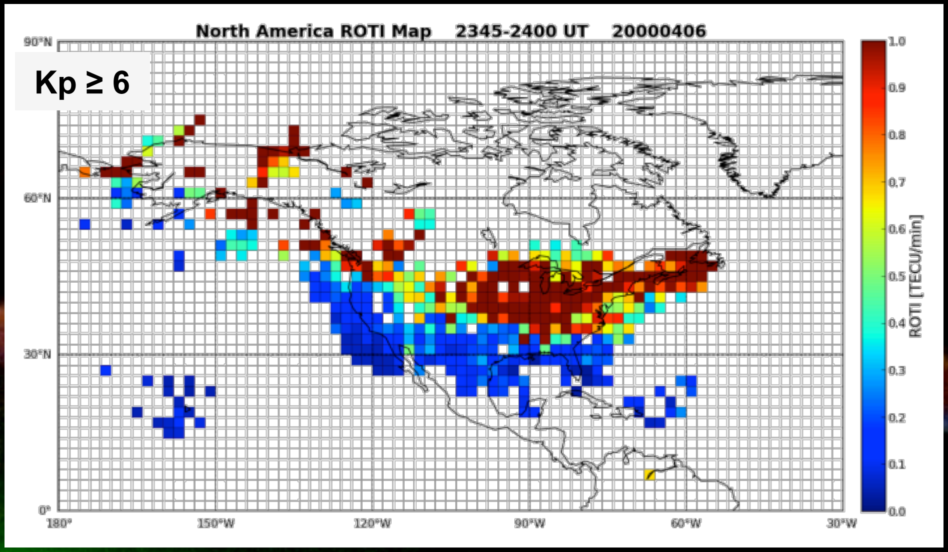
Aurora Forecast Model
- 30 Minute Forecast



New Product for Precision GPS/GNSS

- **Specification of conditions that lead to errors and outages in dual-frequency GPS/GNSS systems**
  - **Provides a real-time red-yellow-green index**
  - **Based on Rate Of TEC Index (ROTI) and satellite signal stability.**
  - **Provides dual-frequency GPS users with estimates of scintillation**
  - **Test Product in 2016**



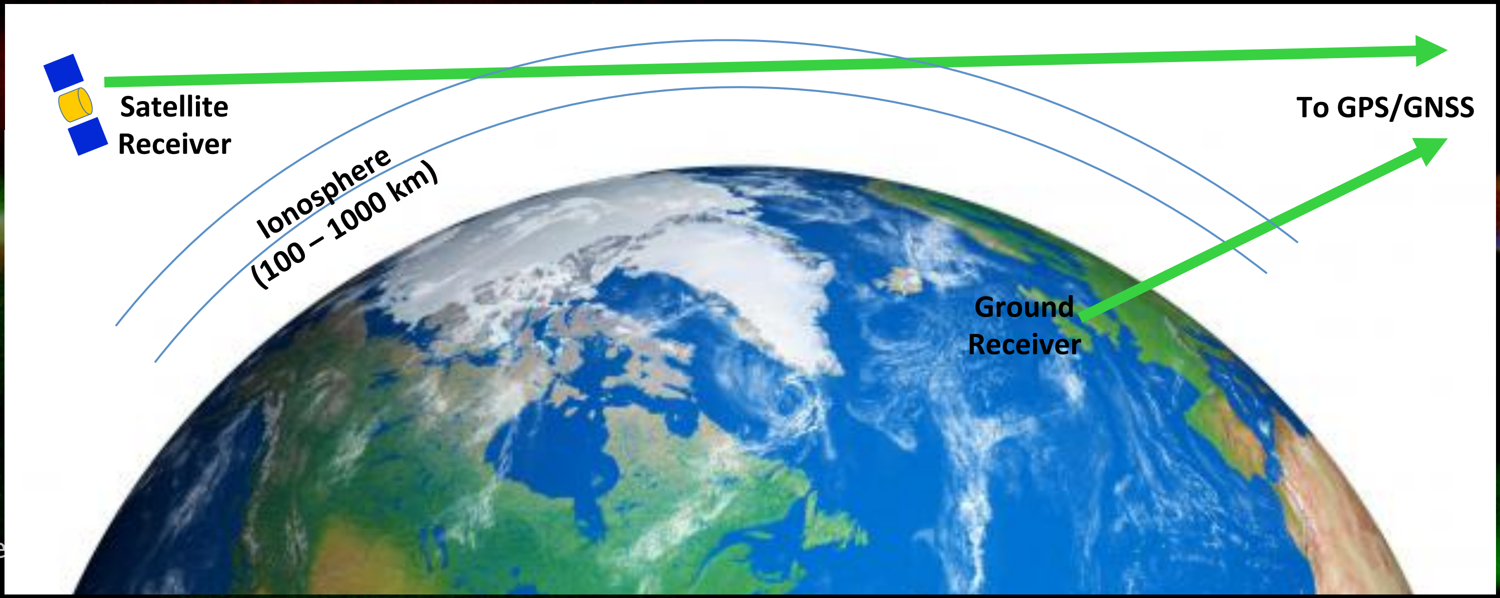


ROTI Maps of North America

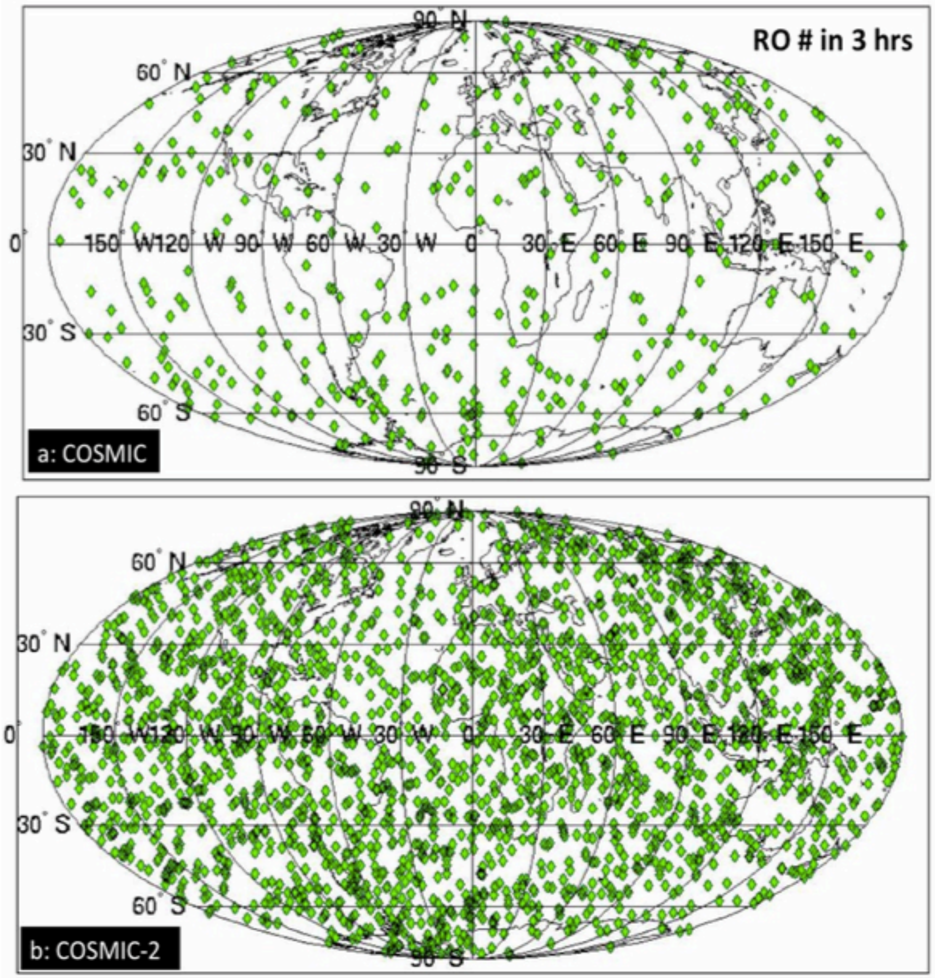
Developed for NOAA by Propagation Research Associates and NASA/JPL under an SBIR contract

GPS/GNSS Ionospheric Sounding

- GPS observations provide information of the ionospheric conditions along the line of site.
  - The difference between signal arrival times at different frequencies is a measure of the ionospheric delay which is a function of the electron density integrated along the line of site
- Ground-based observations provide a measure of the horizontal structure in the ionosphere
- Space-base observations provide a measure of the vertical structure in the ionosphere



COSMIC vs. COSMIC-2



RO Payload	Satellite	Space Weather Payload
IGOR GPS ~2,000 per day Latency: 2 hr	6 LEO satellites ~72° inclination ~800 km altitude ~61 kg >0.68 for 2 years launched 2006	TIP TBB
TriG GPS+ GLONASS >8,000 tropo per day >12,000 iono per day Latency: 38 min	First Launch 6 LEO satellites ~24° inclination ~520 km altitude ~215 kg >0.66 for 5 years ~launch 2016	IVM RF Beacon
	Second Launch 6 LEO satellites ~72° inclination ~720 km altitude ~215 kg >0.66 for 5 years ~launch 2019	TBD

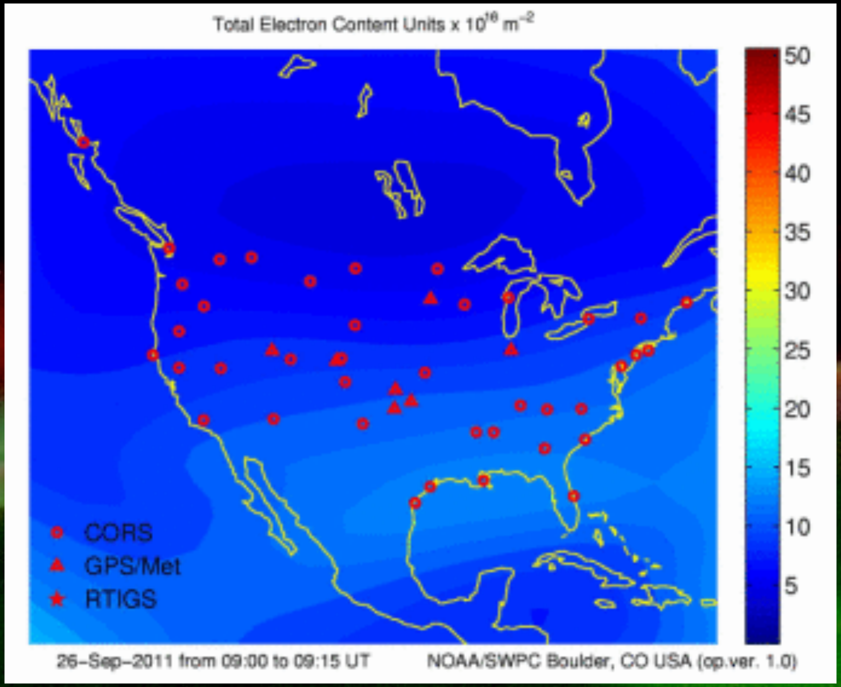
Courtesy Xinan Yue, UCAR

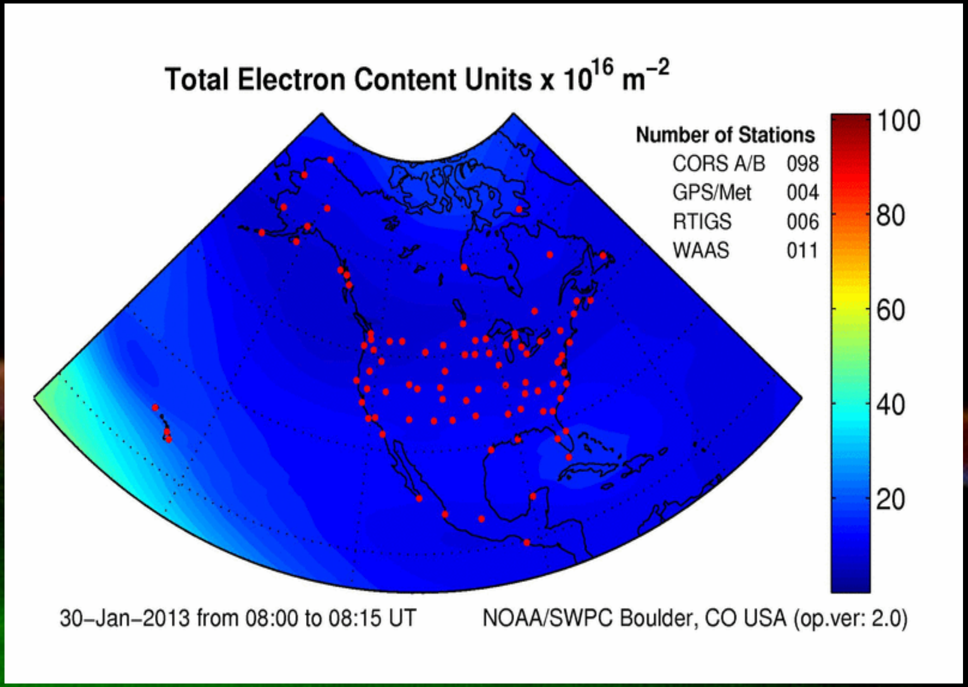
Real-time data assimilation model ready to receive COSMIC-2 data by 2018.

Current Products: Regional Specification

Current:
US-TEC: Provides real-time specification of Total Electron Content over the US

Upgrade:
North America-TEC: Provide real-time specification of Total Electron Content over the North America (Operational in 2016)





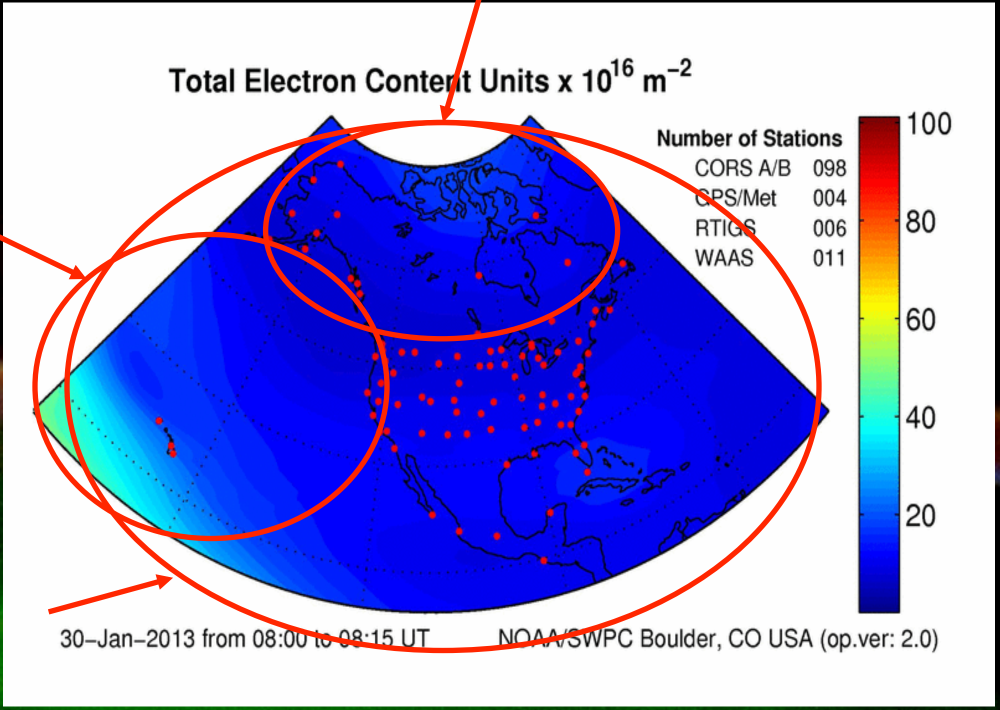
Expanding Products with More Data

- **Current products limited by lack of global data coverage**
  - Need more data in the arctic
  - Need data over oceans

Working to get more real-time GPS data from arctic regions
- Use of N-Trip to access more data
- Plate Boundary Observatory data
- Partnering with JRC to deploy additional receivers

Air Force SBIR: Partner with ASTRA to develop a ground GPS receiver and data processing system that will work on ocean buoys
- NOAA Data Buoy Center will assist with design and deploy test models on the TAO Buoys in the mid Pacific

Developing data assimilation techniques to use COSMIC-2 data

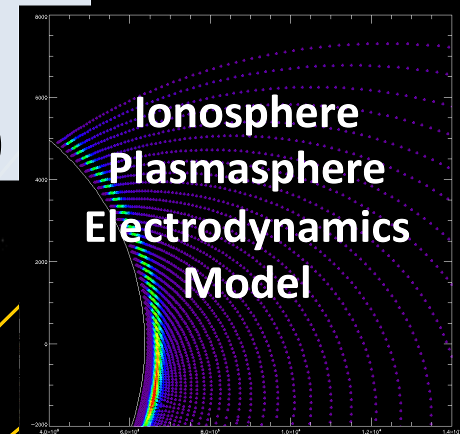


Forecasting Ionospheric "Weather"

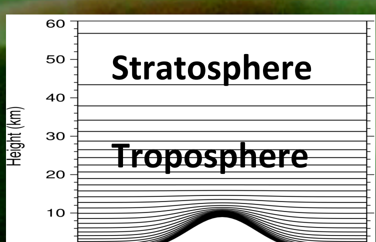
Integrated Dynamics in Earth's Atmosphere (IDEA)

Whole Atmosphere Model (WAM = Extended GFS)
Ionosphere Plasmasphere Electrodynamics (IPE)
Integrated Dynamics in Earth's Atmosphere (IDEA = WAM +IPE)

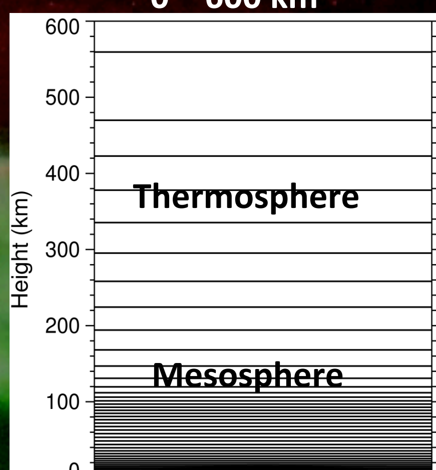
- FY15: Real-time WAM
- FY17: Real-time WAM driving IPE
- FY19: Fully Coupled WAM-IPE with data assimilation

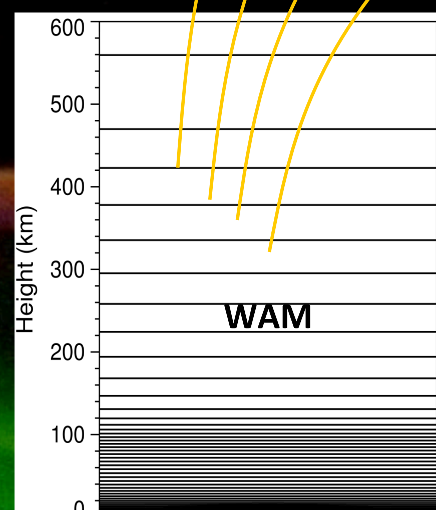


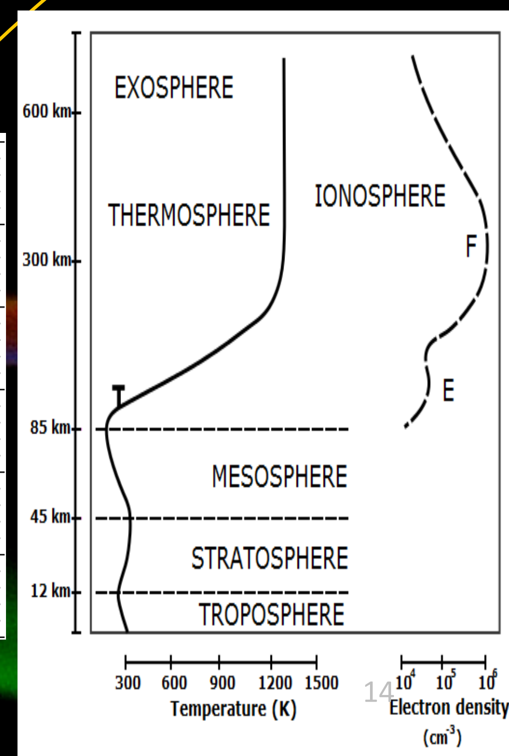
GFS
0 – 60 km



WAM
Neutral Atmosphere
0 – 600 km



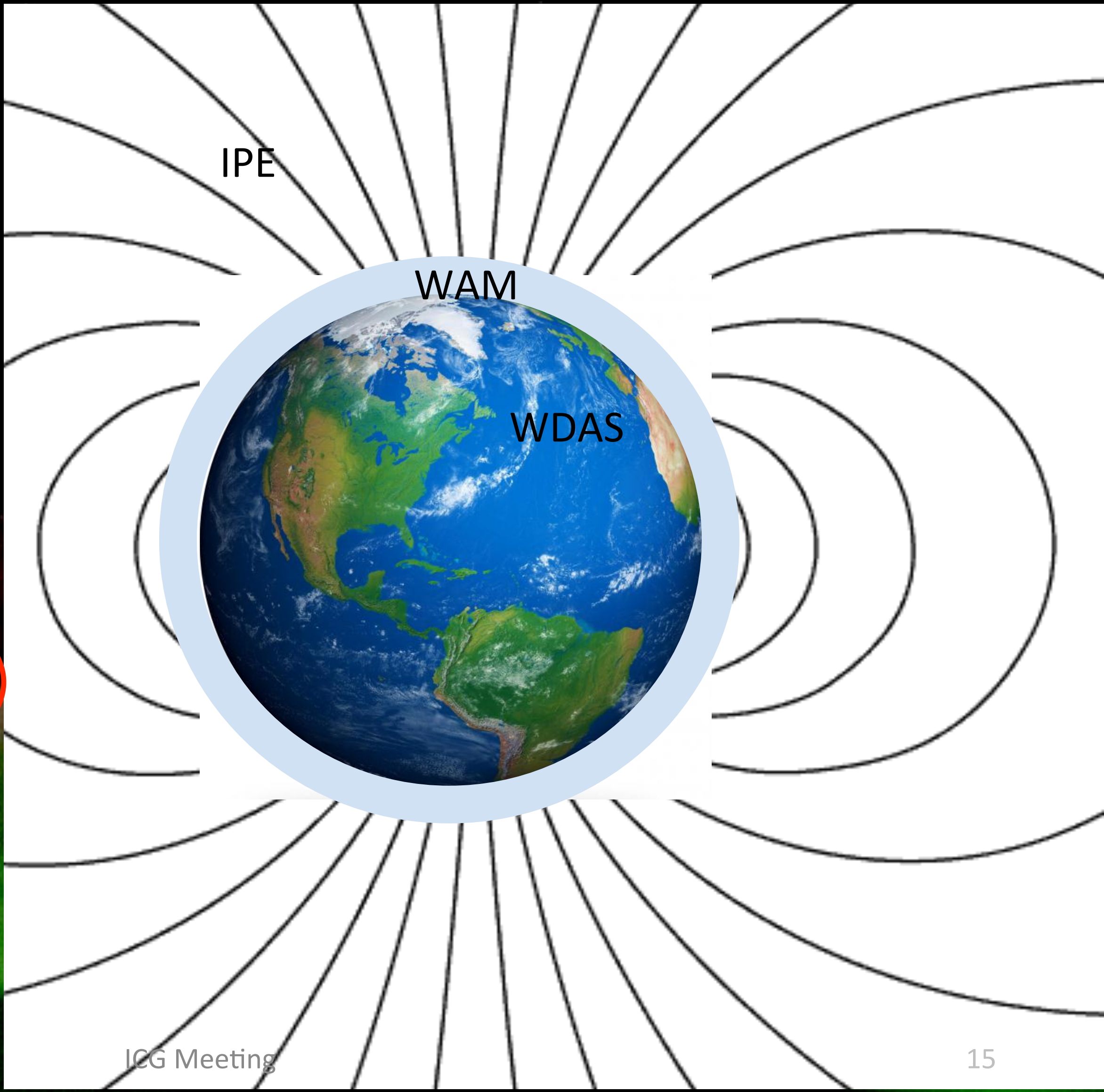




What's the big IDEA?

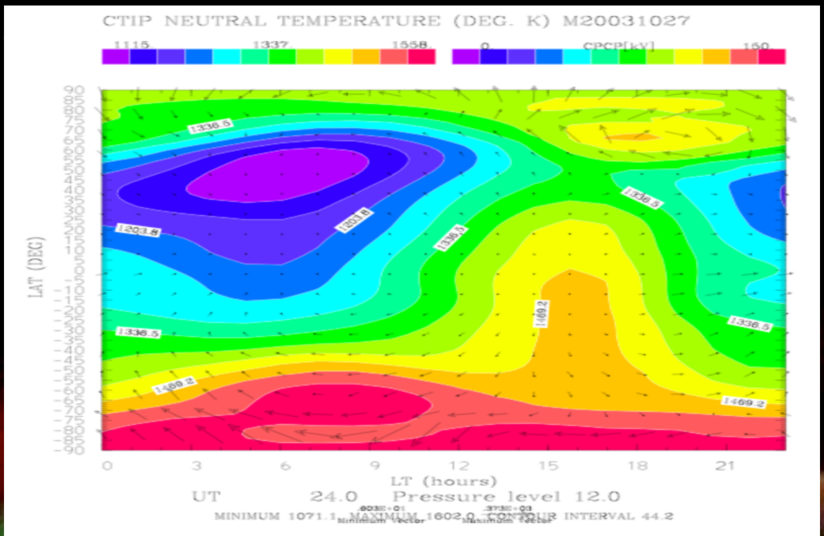
Integrated Dynamics in Earth's Atmosphere

- WAM = Whole Atmosphere Model (0 – 600 km)
- IPE = Ionosphere Plasmasphere Electrodynamics Model (100 – 10000 km)
- WDAS = WAM-IPE Data assimilation System (0 – 100 km)
- ITDAS = Ionosphere/ thermosphere data assimilation system
- IDEA = WAM + IPE + WDAS + ITDAS A coupled modeling system spanning from the 0 to 10,000 km

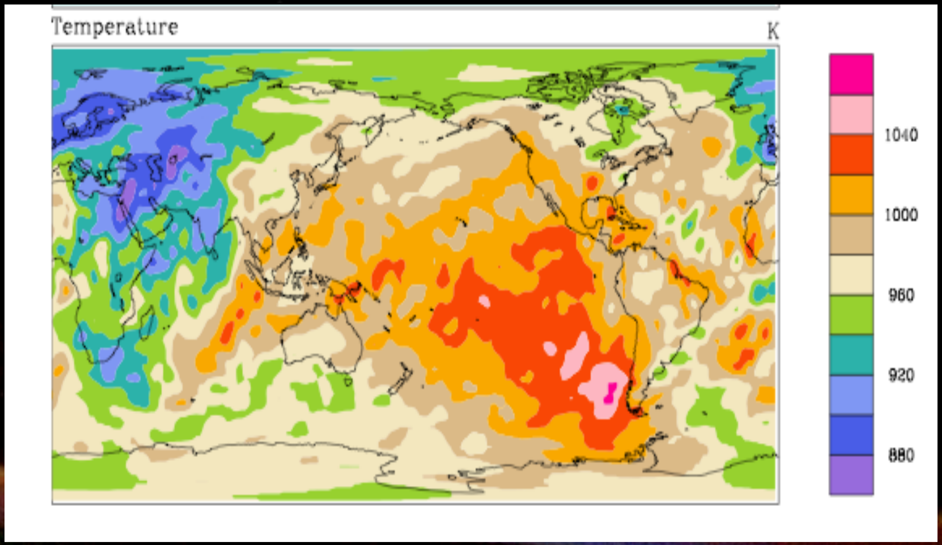


With and Without WAM: Adding the Lower Atmosphere

Typical ionosphere-thermosphere model: Global maps show little fine structure



Ionosphere-thermosphere model coupled to the lower atmosphere: Global maps show structure relevant to GPS accuracy and available



The temperature structure from a stand-alone thermosphere ionosphere plasmasphere model (e.g., CTIPe) is similar to the MSIS empirical model. The Whole Atmosphere Model (WAM) drives variability from the chaotic lower atmosphere which introduces a whole spectrum of variability.

What Will IDEA Provide?

- The coupled WAM-IPE model system will provide global maps of the ionospheric parameters (specification and forecasts) relevant to customer requirements.
  - Total Electron Content (TEC = height integrated electron density)
  - Rates of change of TEC (spatial and temporal)
  - Single frequency GPS error
  - Scintillation probability for dual frequency (precision) GPS
- Customers
  - Single frequency GPS (airlines, agriculture, shipping, navigation, FEMA, etc…)
  - Dual frequency GPS (mineral/oil exploration, agriculture, navigation, surveying/mapping, DOD, etc…)
  - Satellite communication (satellite operators, NASA, DOD, etc…)

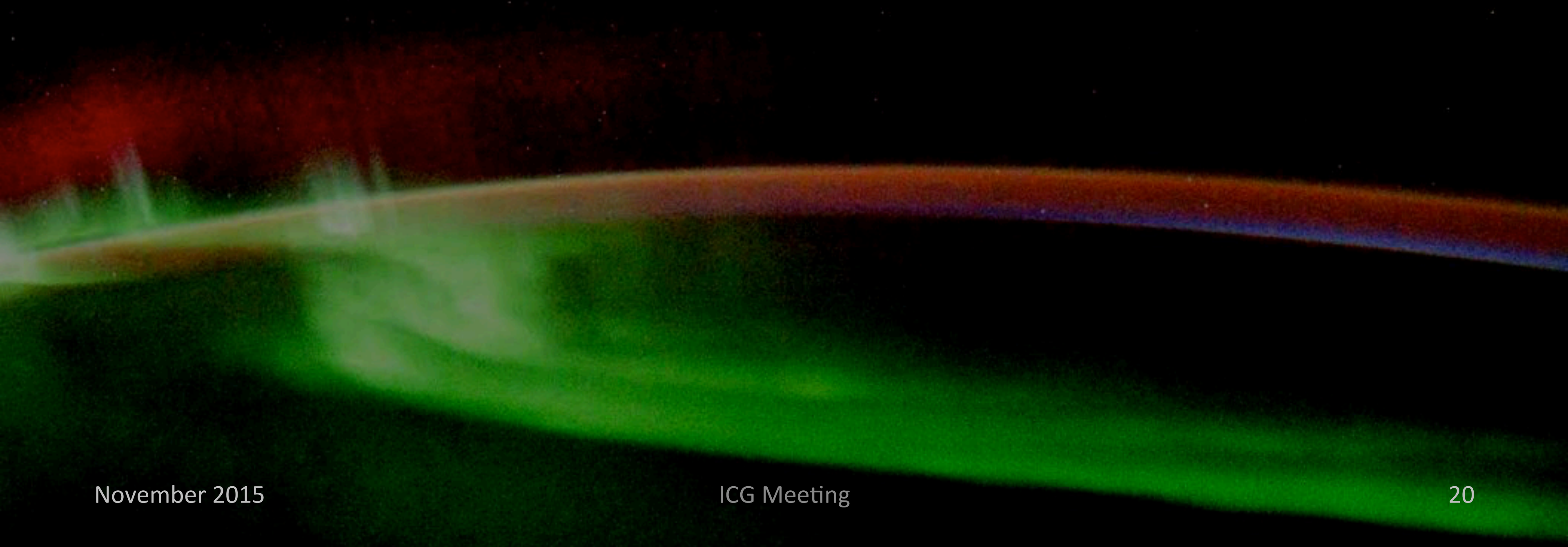
- Physics-based operational forecast of thermospheric density for satellite and debris orbit prediction.

Summary

- GNSS data is needed to produce a number of products
  - Ground-based GNSS sensor data
  - Space-based GNSS radio-occultation data
- Products for GNSS users
  - Maps of TEC for all GNSS users
  - Scintillation maps for precision GPS users (under development)
- Products that require GNSS data
  - HF radio propagation
  - Satellite communication
  - Coupled thermosphere-ionosphere forecast models

Thank You!

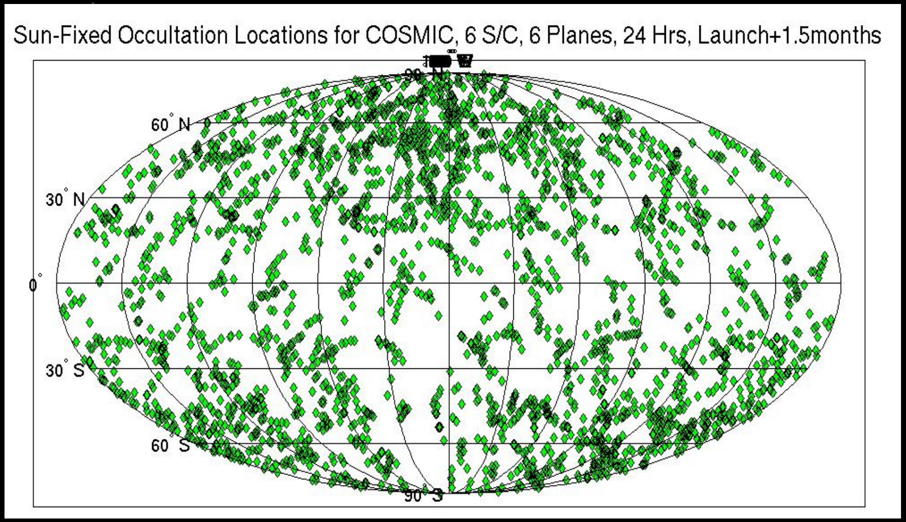
Backup Slides



COSMIC vs. COSMIC II

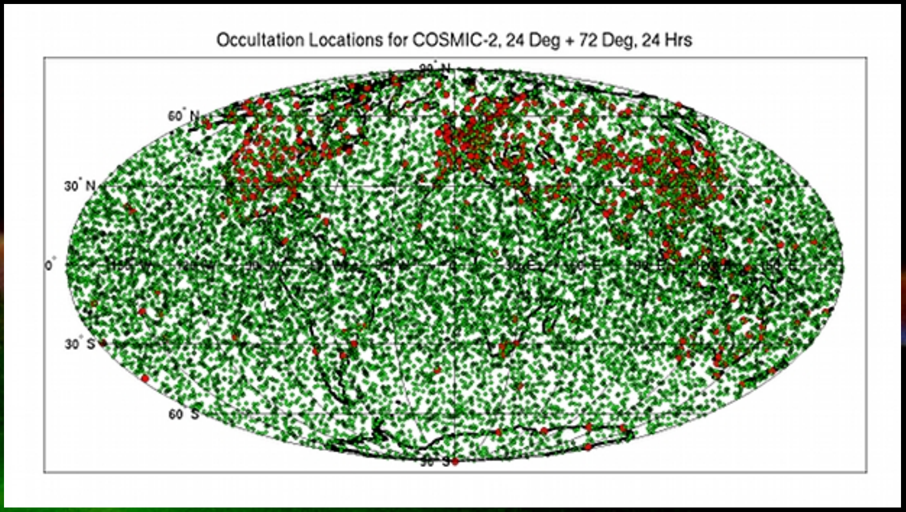
COSMIC I:

- Sparse coverage
- 2 hour latency (not real time)
- Good for developing assimilative models



COSMIC II:

- Better coverage
- 38 minute latency (limited ground stations).
- Initial launch in 2016.



Real-time data assimilation model ready to receive COSMIC II data by 2018.

GNSS Applications

- Standard (1-Hz) observations provide electron density information along the line of site.
  - Relevant to GPS/GNSS users
  - Input to ionosphere/thermosphere models
- Higher frequency observations (~50 Hz) provide ionospheric scintillation information.
  - Relevant to precision GPS/GNSS users

GPS Customers

- Airlines
  - WAAS and NextGen
- Shipping and Transportation
- Precision Agriculture/Construction/Surveys
- Precision Navigation
  - Autonomous vehicles and UAVs
  - Zero visibility driving
- Precision Timing
- Exploration
  - Oil
  - Minerals
- Government Agencies:
  - DOD, FAA, FEMA, DHS, Coast Guard, etc…

New Customers at High Latitudes

- Navigation:
  - Shipping through the NW passage saves 6000km off of a 22000km trip from New York to Hong Kong (28%)
    - Avoiding ice and navigating in the arctic requires precise GPS positioning information
  - Oil and mineral exploration in arctic regions
    - Drilling and surveying require precision GPS
  - Airlines use polar routes extensively (13000/year)
- Oil Exploration
  - Oil drilling in the arctic ocean is under consideration.
- Space Weather Impacts at High Latitudes
  - Stronger geomagnetic storms
  - Poorer GPS Satellite Viewing

"When Aurora is Strong, GPS is wrong"

Arctic Shipping Lanes Require New GPS Services

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The First-Ever Bulk Freighter To Pass Through The Arctic Was Carrying Coal

BY ARI PHILLIPS POSTED ON SEPTEMBER 26, 2013 AT 1:44 PM UPDATED: SEPTEMBER 30, 2013 AT 9:26 AM

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Sometime earlier this week a cargo ship passed through the Northwest Passage into Baffin Bay, along Greenland's southwestern coast, making it the first bulk carrier ever to make the voyage. This journey was completed by the Nordic Orion, a 225-meter, ice-strengthened vessel loaded with coal in Vancouver, British Columbia and headed for Finland.

The Nordic Orion along the Northern Sea Route.

CREDIT: NAVAL MATTERS

Long eyed as a commercial route, the

TRANSPORTATION

More: AFP China

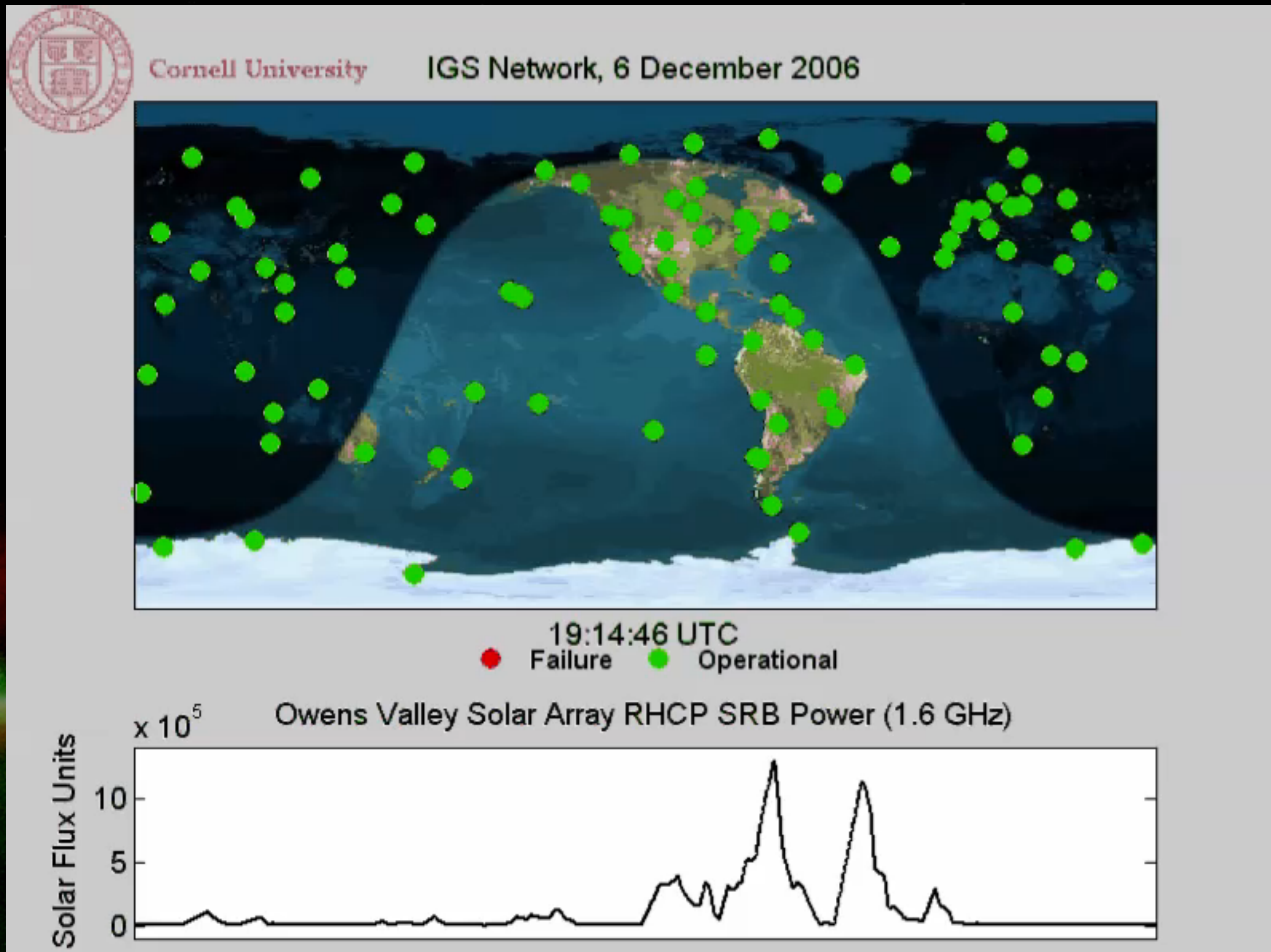
China Begins Using Arctic Shipping Route That Could 'Change The Face Of World Trade'

BILL SAVADOVE, AGENCY FRANCE-PRESSE

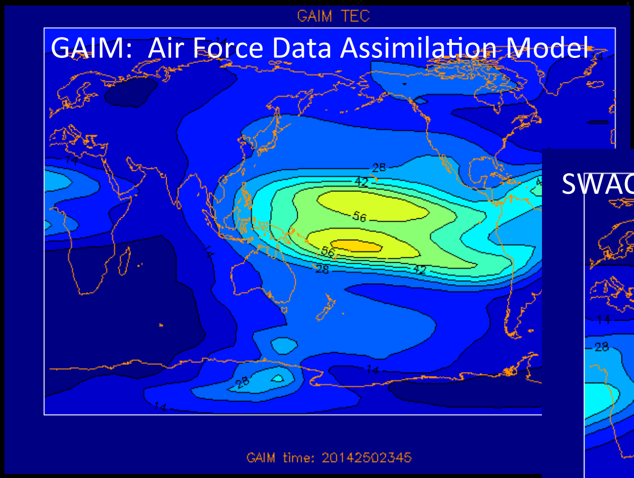
AUG. 16, 2013, 6:27 AM 30,948 78

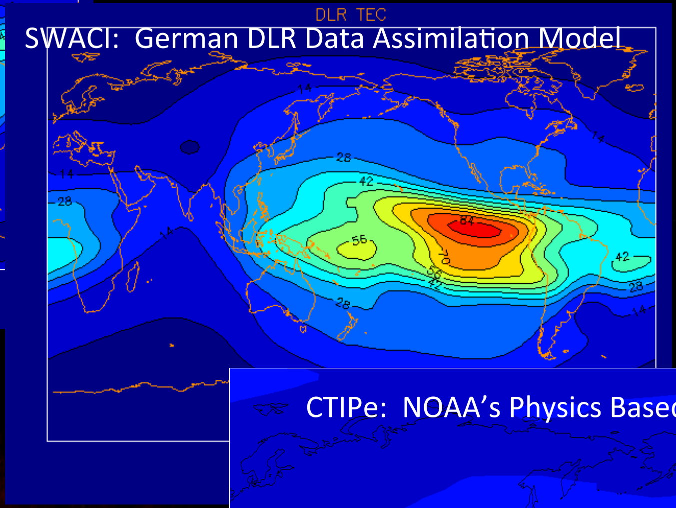
Impact of Solar Flare

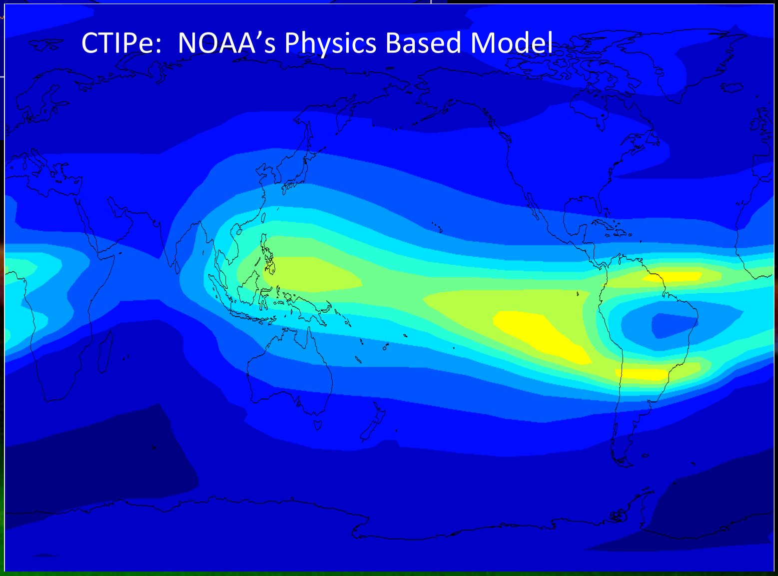
Solar Radio Burst at GPS/GNSS Frequencies



Developing Global Specification Product

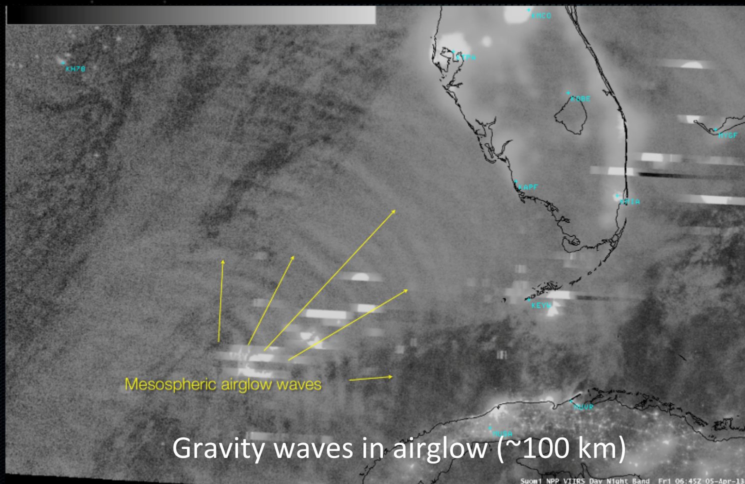






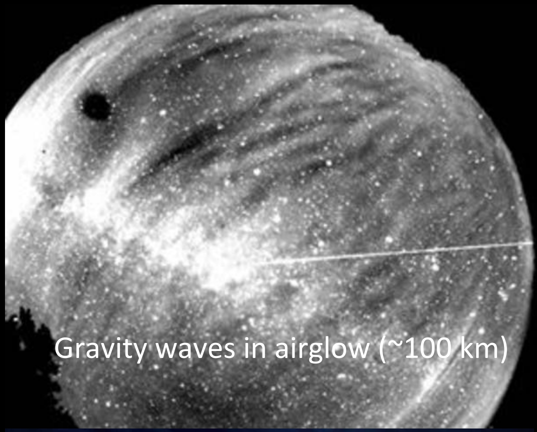
- **Testing global TEC models:**
  - **Air Force GAIM**
  - **DLR SWACI**
  - **NOAA CTIPe**
- **Significant differences remain**
  - **A prototype product will be available in 2016**

Why Couple to the Lower Atmosphere?
1. Gravity Waves

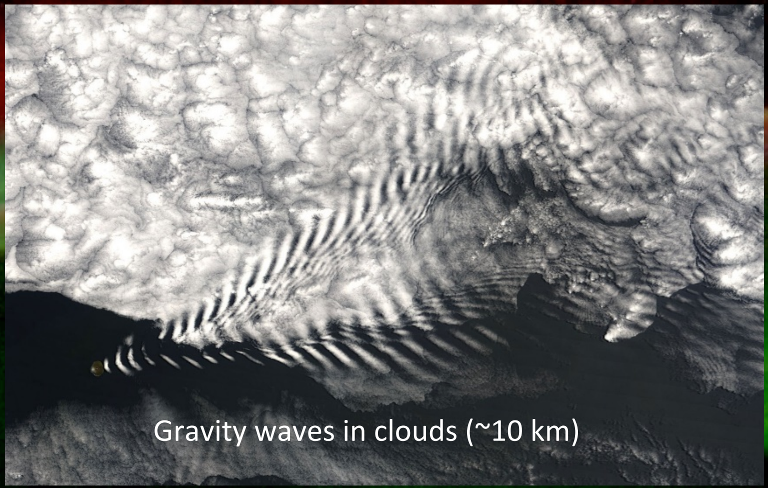


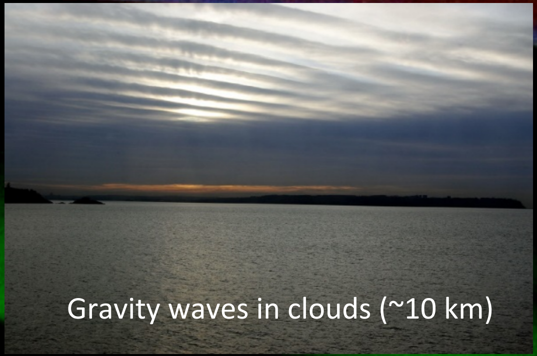
Gravity waves in airglow (~100 km)

Gravity waves
- Propagate upward
- Grow in amplitude as they go up.
- Often break at some altitude
- When the break, they deposit energy (both thermal and momentum)


Gravity waves in airglow (~100 km)

Gravity waves in clouds (~80 km)

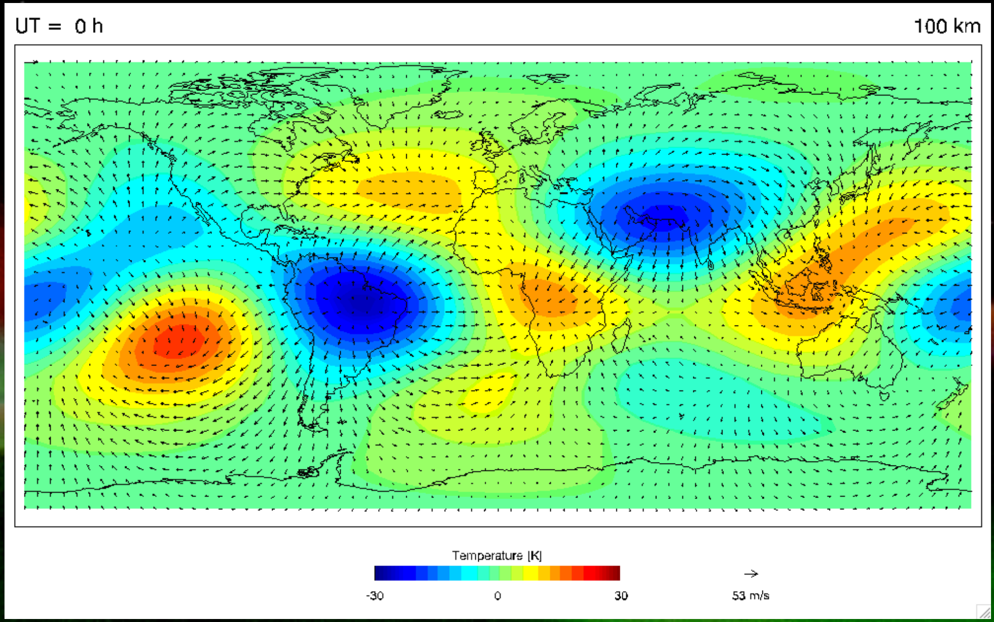

Gravity waves in clouds (~10 km)


Gravity waves in clouds (~10 km)

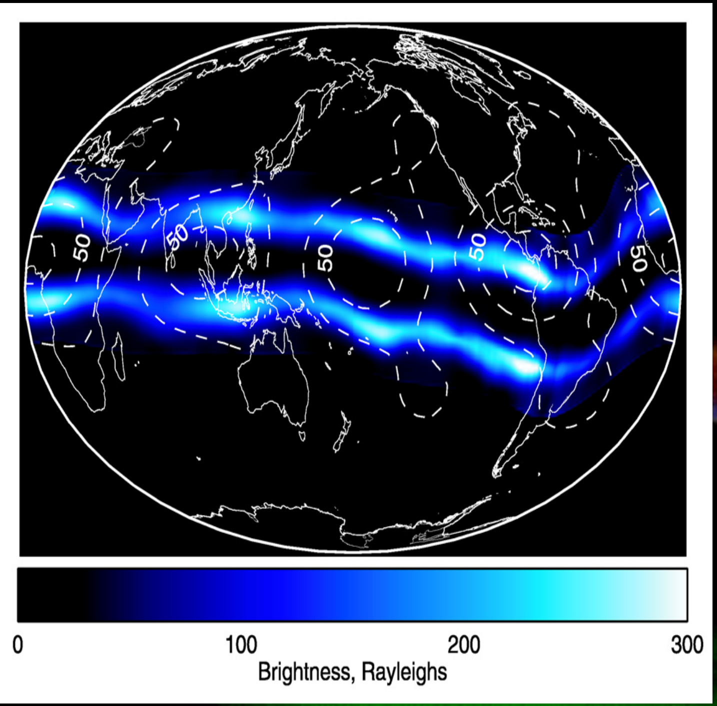
Why Couple to the Lower Atmosphere?
2. Atmospheric Tides

The four peaks in diurnal temperature amplitude result from superposition of the migrating (to the west) tide (DW1) and nonmigrating eastward mode with zonal wavenumber 3 (DE3).
Tides induce variability in the Ionosphere/Thermosphere System

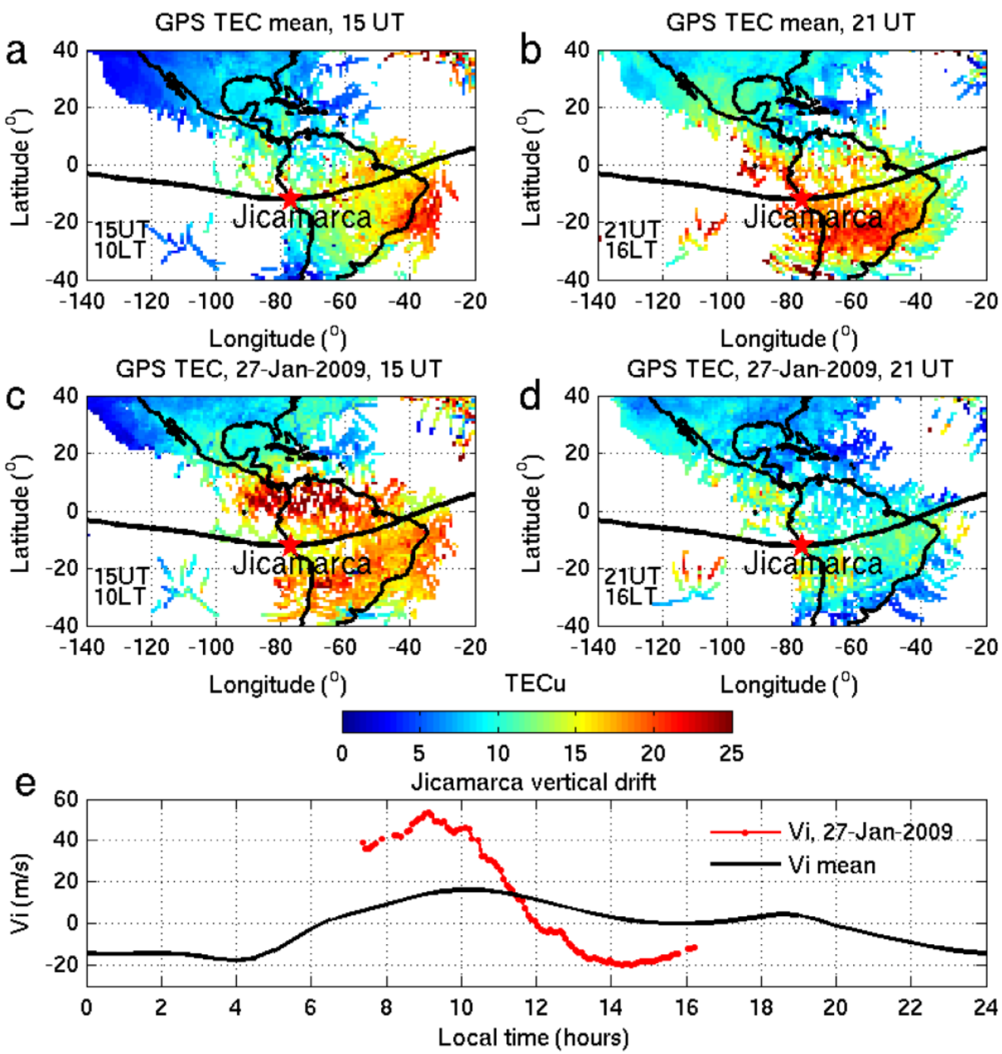
NASA TIMED SABER and TIDI



NASA IMAGE (Immil et al)



2009 Strat-warm Impact on Ionosphere and Space Weather



Goncharenko et al. (2010):

Climatological TEC @ 10 and 16 LT from ground GPS observations.

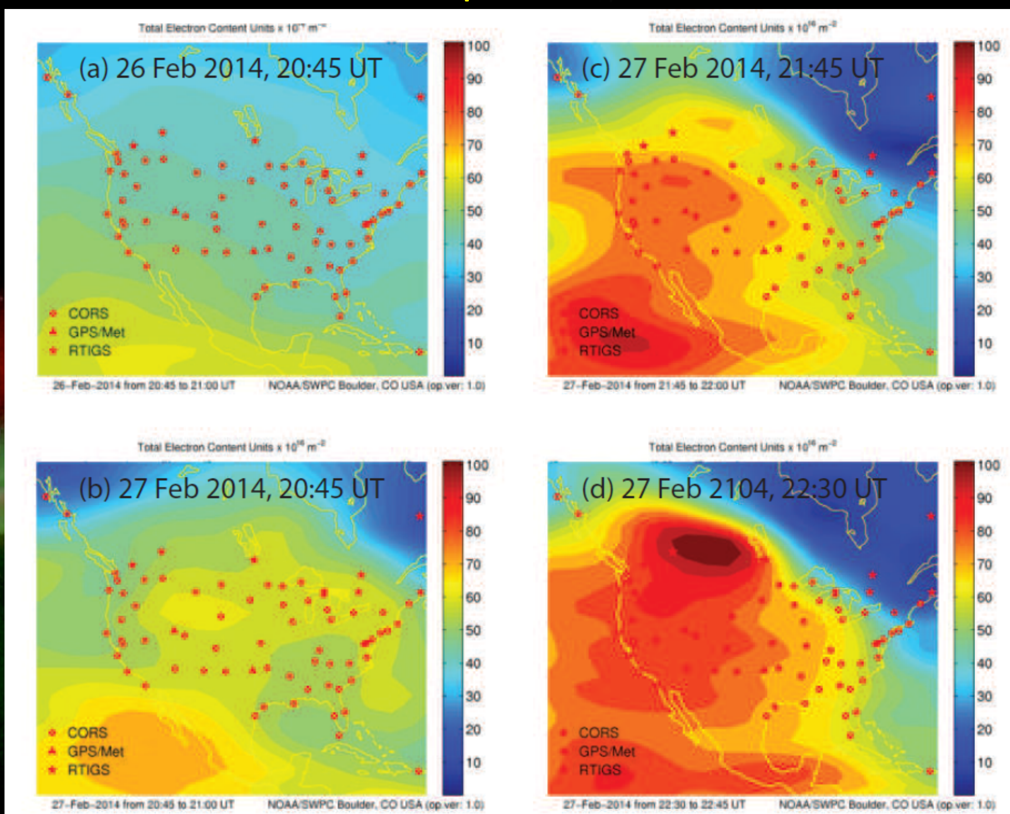
Same on January 27, after the peak of the warming.

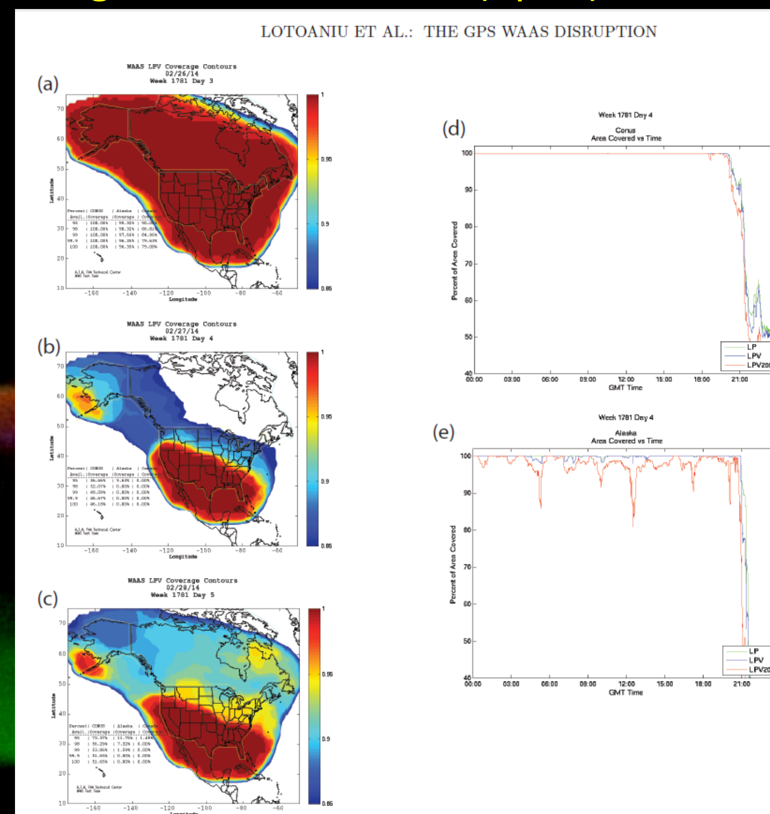
Comparison of plasma drift climatology with observations on Jan. 27.

USTEC and the FAA Wide Area Augmentation System (WAAS)

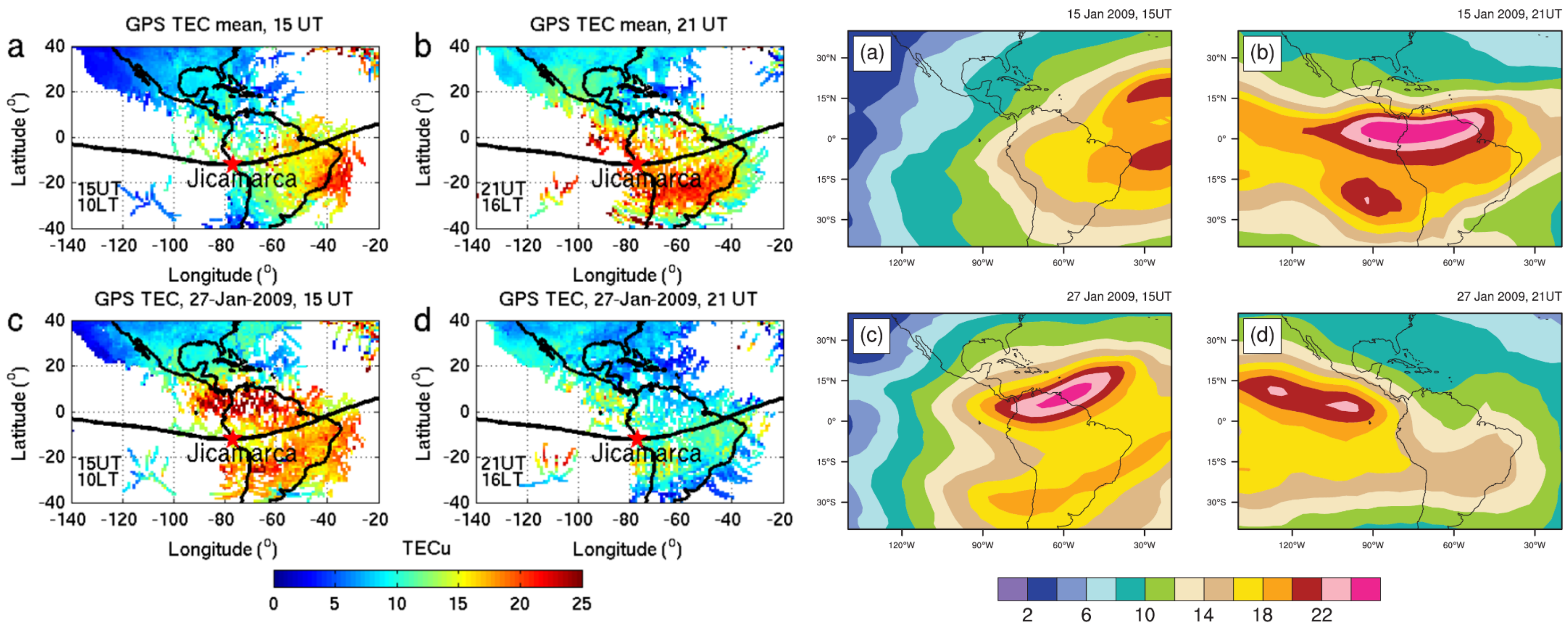
- US Total Electron Content (US-TEC)
- Critical for GPS/GNSS Users (Airlines, FAA, Transportation, etc…)
- Inputs: Ground GPS Receivers
- Future Inputs: COSMIC II Radio Occultation

USTEC captures the TEC enhancement during a moderate storm(Kp<6)





Does the WAM-IPE Concept Work?
2009 SSW: IDEA TEC forecast



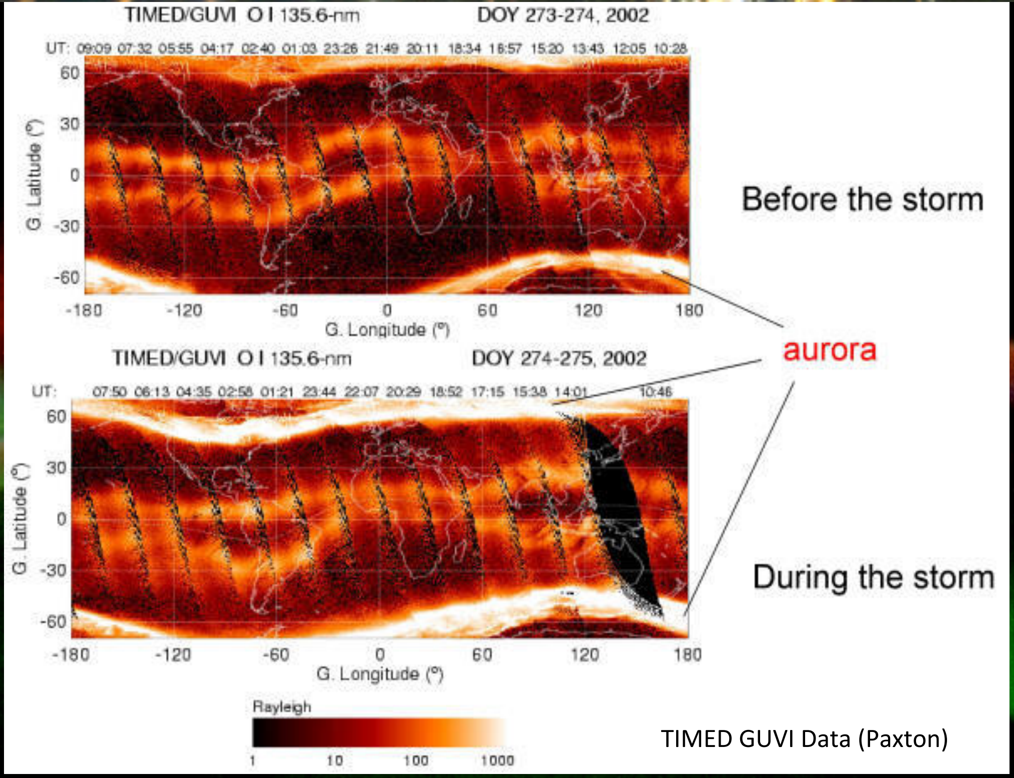
IDEA 14-day forecast (from Jan 13, 2009) of TEC in the American sector (Wang et al., 2014) vs. observations (Goncharenko et al., 2010).

Customer Wish List

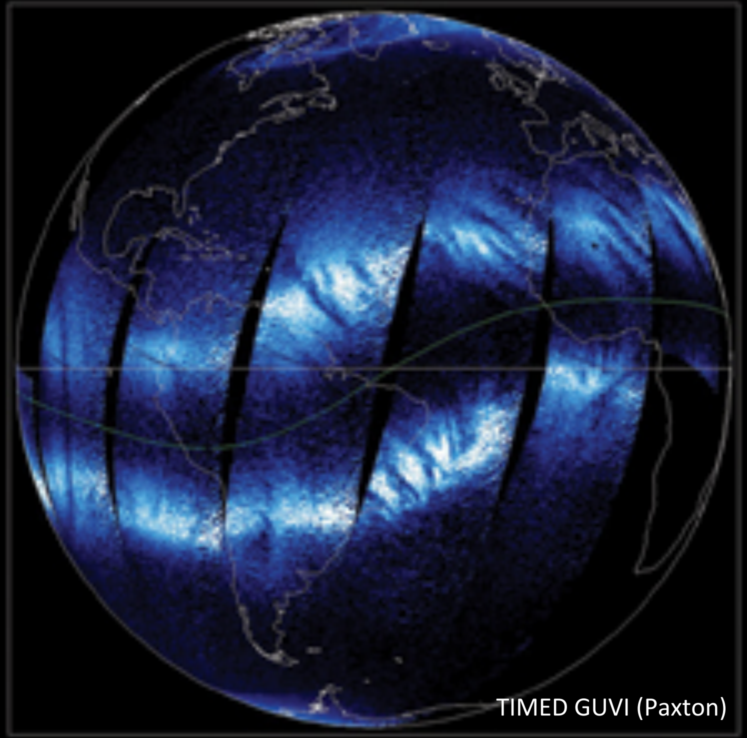
- 24 hour lead time forecast of regional amplitude scintillation, in units of S4 (dimensionless) with S4 = .5 a critical threshold
- 24 hour lead time forecast of regional phase scintillation, in units of sigma phi (radians), with sigma phi = .7 a critical threshold
- 24 hour lead time forecast of bulk TEC change from current conditions, with a change of 50% (up or down) a critical threshold
- Nowcast of regional amplitude scintillation (similar to #1)
- Nowcast of regional phase scintillation (similar to #2)
- NOAA Ionosphere (I) Scale, starting with a meridional chain of software receivers through N. America broadcasting data to SWPC
- More ground-based stations taking data for USTEC to capture small scale irregularities causing scintillation
- Alerts of L-band solar radio bursts with right-hand circular polarization of a magnitude affecting codeless/semi-codeless/radio occultation GPS
- With USTEC as the basis, find gradients and generate warnings of regions with heightened probability of scintillation activity
- Link the daily geomagnetic activity forecasts as a flag in the display of USTEC, alerting users of the higher probability of abnormal conditions

Dynamic Equatorial Plasma

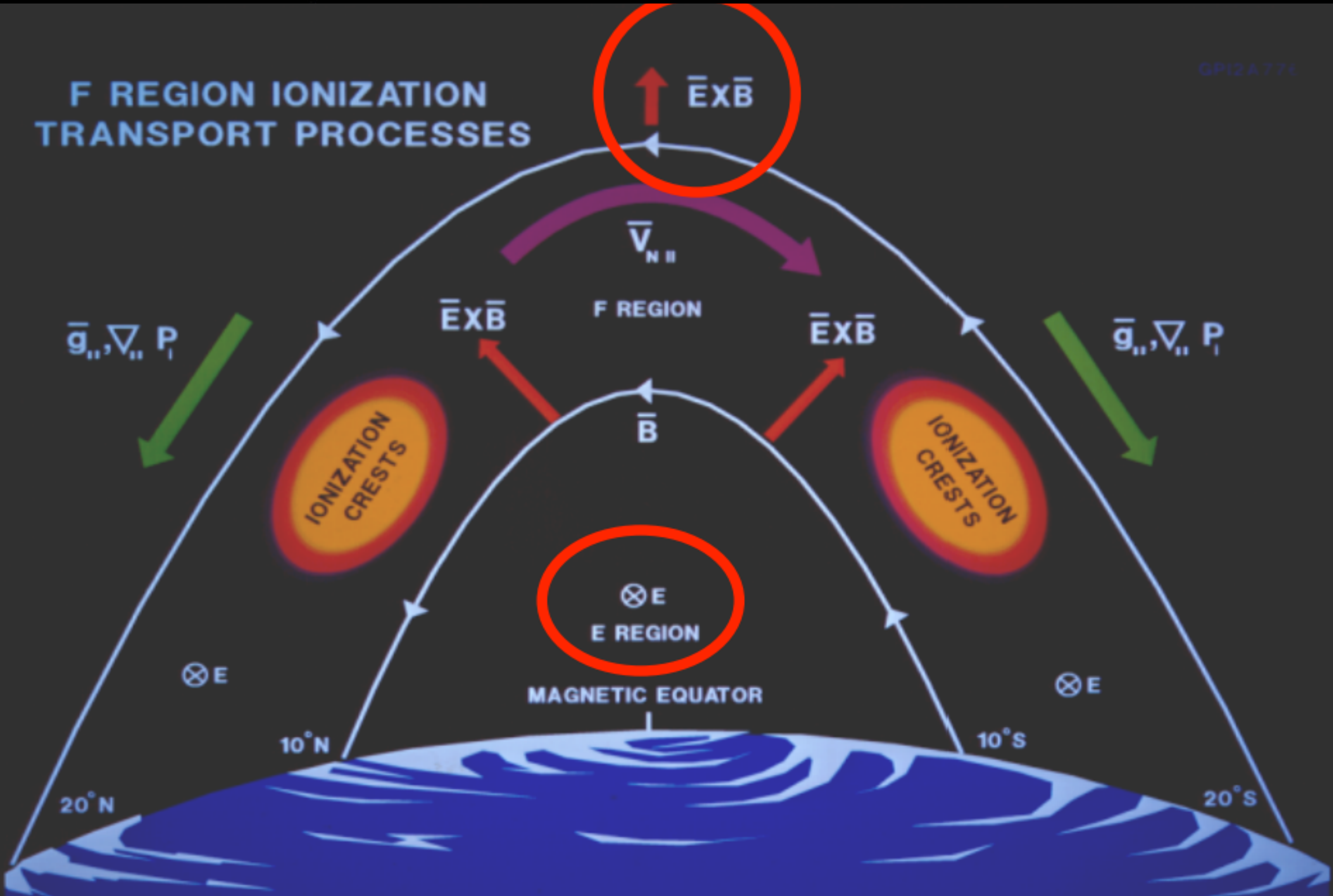
Equatorial Plasma Structures from the Space Station (NASA)



TIMED GUVI Data (Paxton)

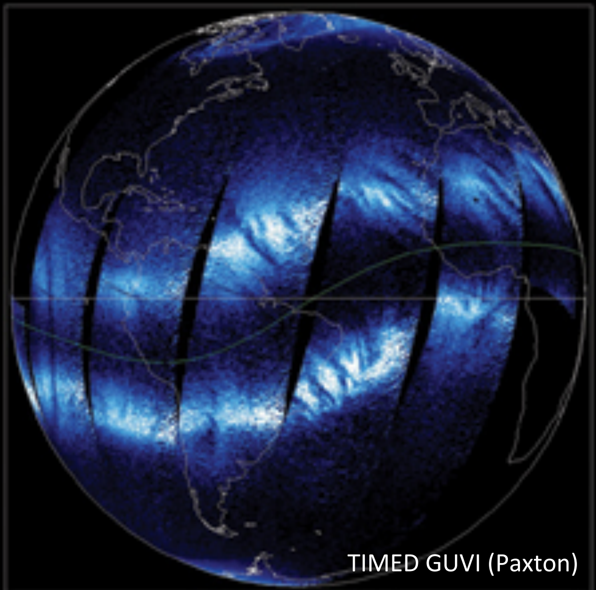


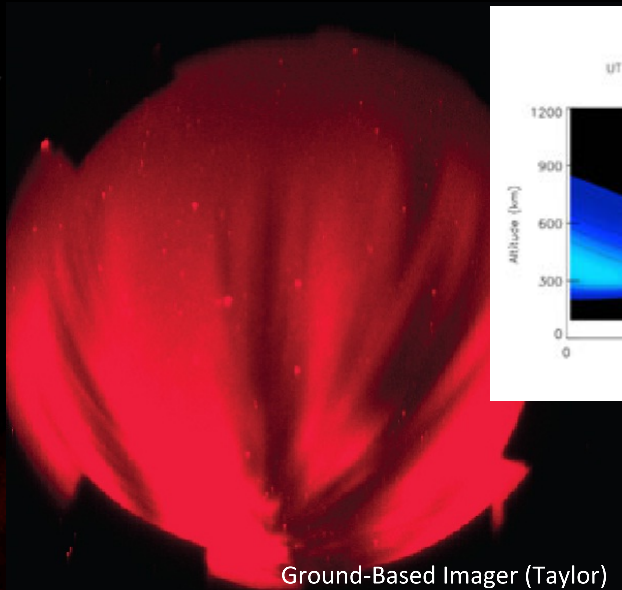
TIMED GUVI (Paxton)

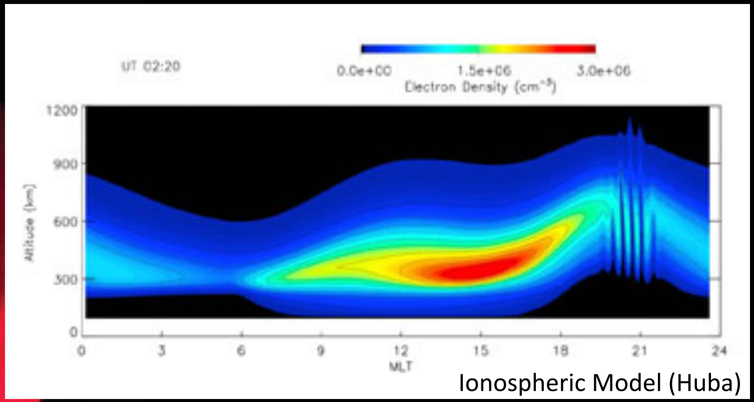


F REGION IONIZATION
TRANSPORT PROCESSES
ĒXB̄
V̄N II
F REGION
ĒXB̄
ĒXB̄
g̅II,∇II Pi
g̅II,∇II Pi
IONIZATION CRESTS
IONIZATION CRESTS
B̄
⊗E
E REGION
⊗E
⊗E
MAGNETIC EQUATOR
10°N
10°S
20°N
20°S

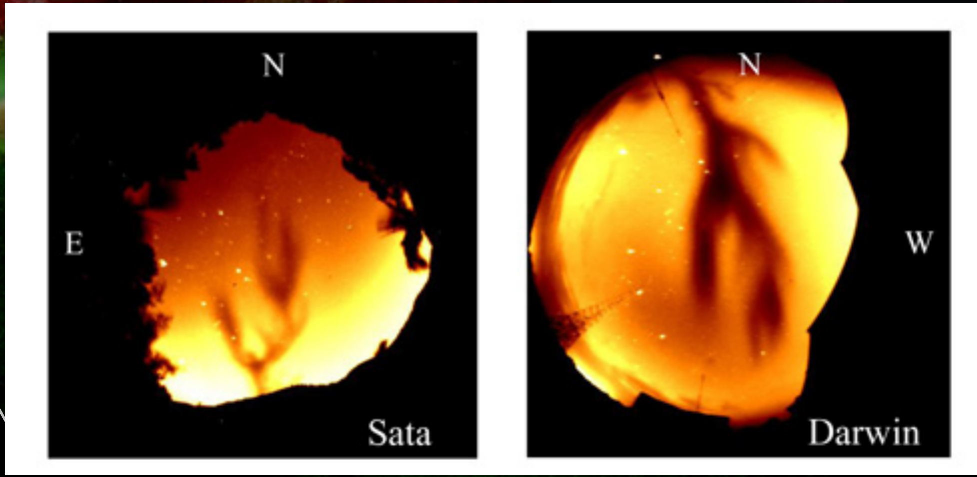
ExB Drift Leads to Plasma Bubbles
Plasma Bubbles Lead to Dropped GPS Signals

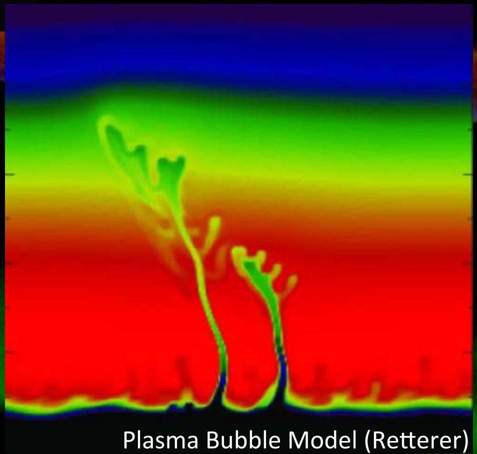

TIMED GUVI (Paxton)


Ground-Based Imager (Taylor)



Ionospheric Model (Huba)

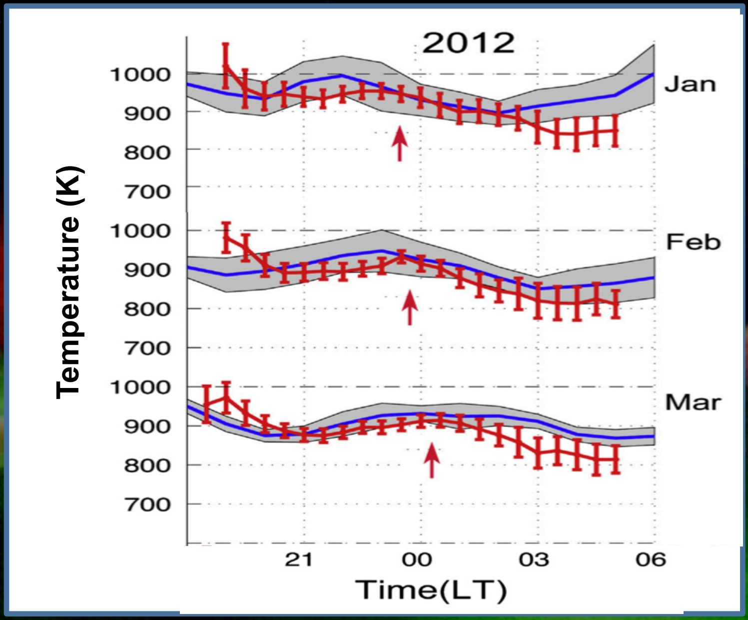



Plasma Bubble Model (Retterer)

Midnight Temperature Maximum (MTM)

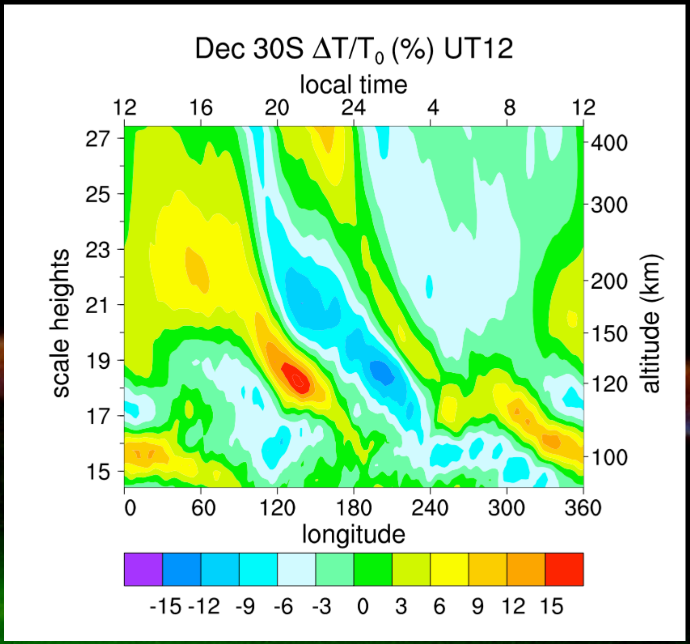
Fang et al 2014

- **WAM can produce the MTM**
- WAM appears to be the first comprehensive model to internally generate an MTM of a realistic magnitude in the thermosphere. Simulation results from the WAM have shown the robust feature of MTM and the associated midnight density maximum (MDM).
- **MTM is the Result of Tides in the Lower Atmosphere:**
- Model results indicate that the feature may be traced down to the lower thermosphere, where it is manifested primarily in the form of an upward propagating terdiurnal tidal wave. Thermospheric tides with higher-order zonal wavenumbers and frequencies can also contribute to the feature.



Meriwether et al. (2013)

Comparisons of WAM MTM (blue) with FPI measurements at Brazil (red) from Sep 2009 to Aug 2012.

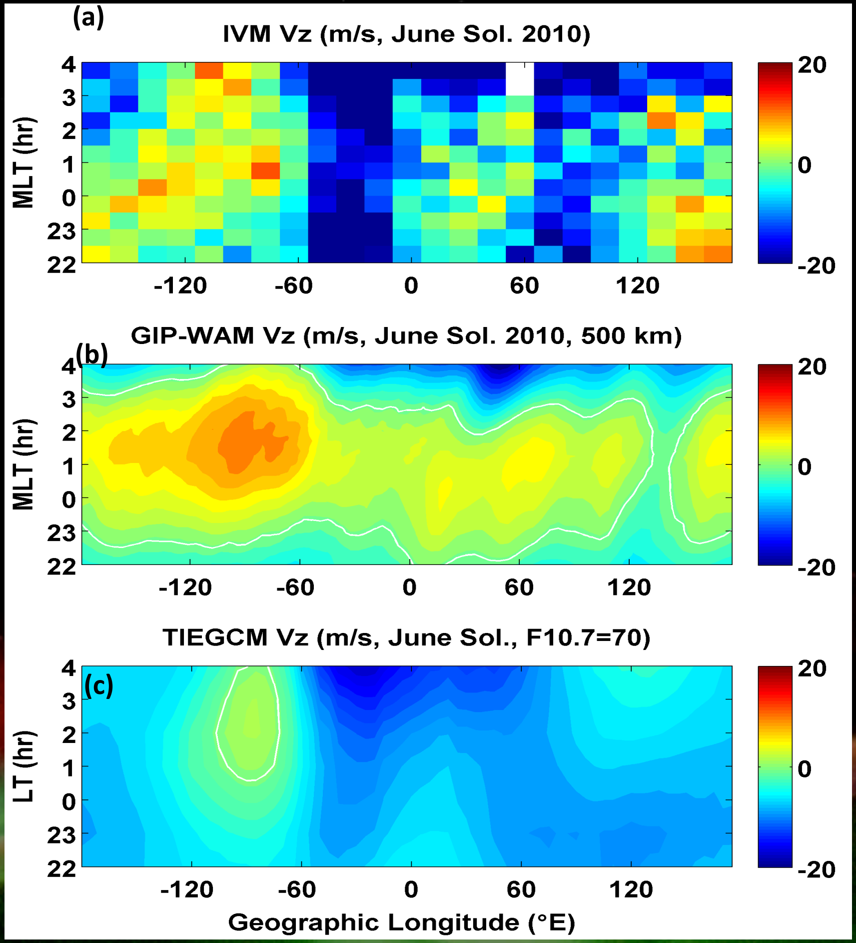


Akmaev et al. (2009)

WAM simulation of relative temperature deviation as a function of height and longitude (local time)

Vertical Ion Drifts from Models and Observation

Fang et al 2014



MTM Produces ExB Drift

The nighttime upward drift is more pronounced in June-July season from the GIP/WAM simulation. For the season, WAM reproduces the magnitude and longitudinal distribution of nighttime upward drift observed by C/NOFS IVM. In contrast, the vertical drift produced by the NCAR TIEGCM shows downward in most longitude except in the American longitude sector.

(a) C/NOFS IVM climatology in 2010 June solstice

(b) WAM-GIP climatology of June and July 2010

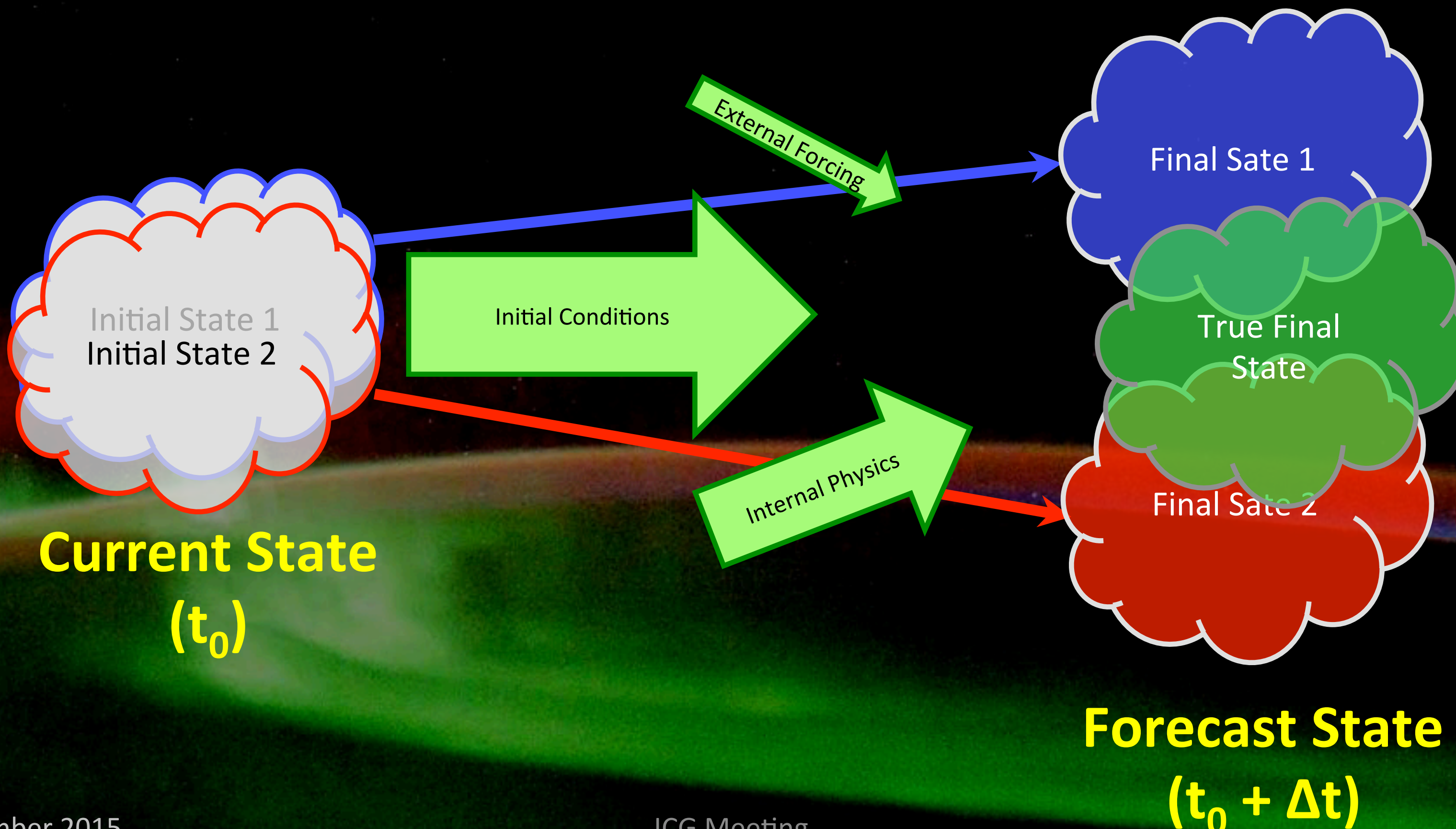
(c) NCAR-TIEGCM results on June solstice (F10.7=70)

WAM + GIP produces the conditions necessary for post sunset plasma bubbles to form

Data Assimilation

Chaotic System (Weather)

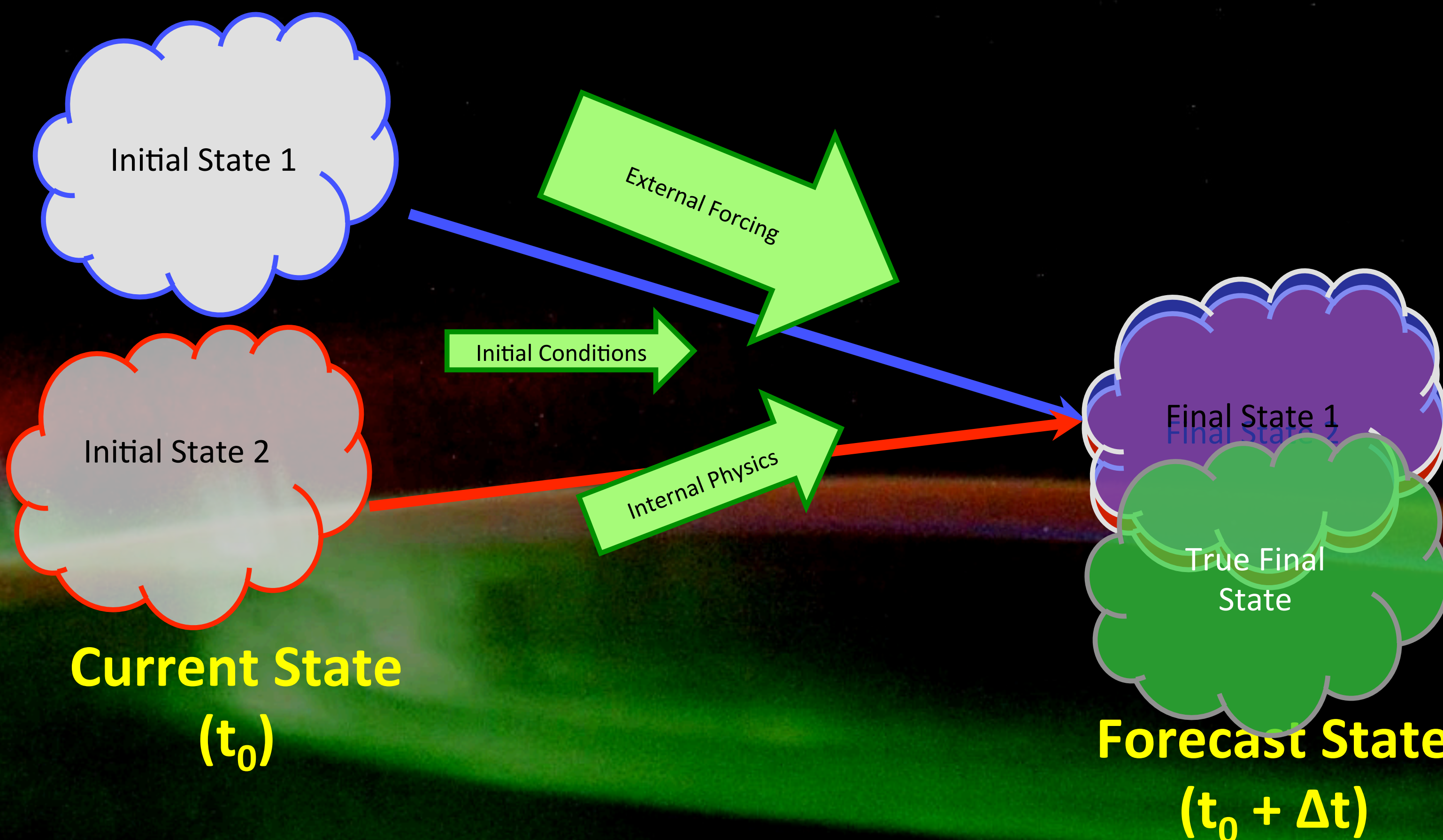
- Errors in the initial state have a big impact on the final state
- Fine tuning the input with data assimilation is important



Space Weather Data Assimilation

Driven System (Space Weather)

- Initial state loses importance quickly over time
- Changes in the external forcing dominate



Data Assimilation in the Ionsphere

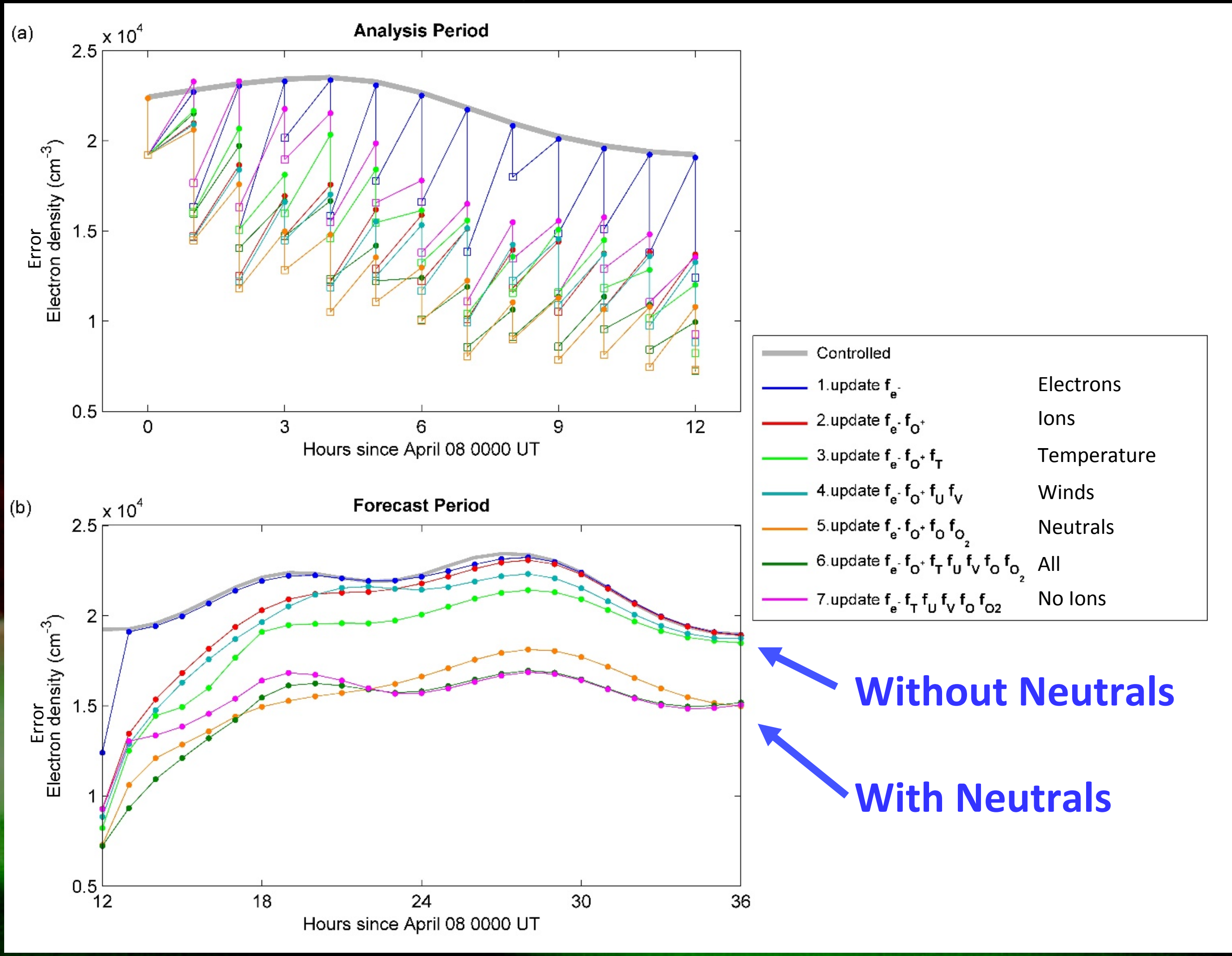
(Hsu, Matsuo, Wang, Liu, 2014)

Question:

- Does Data Assimilation Work in the ionosphere?

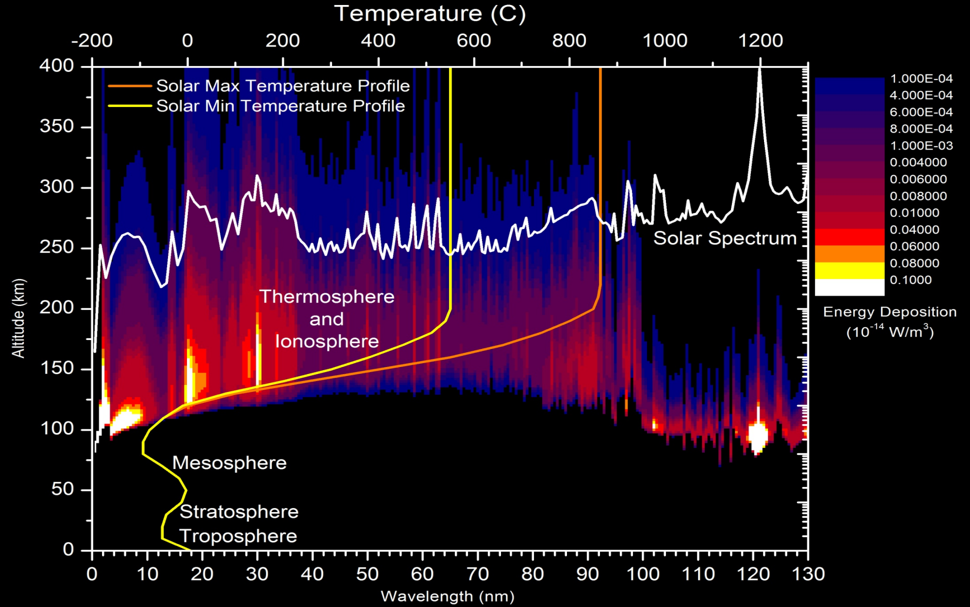
Answers:

- Assimilating only electron and ion data does not work very well
- Assimilating winds and temperatures helps a little
- Assimilating neutral composition is really required for improving forecasts



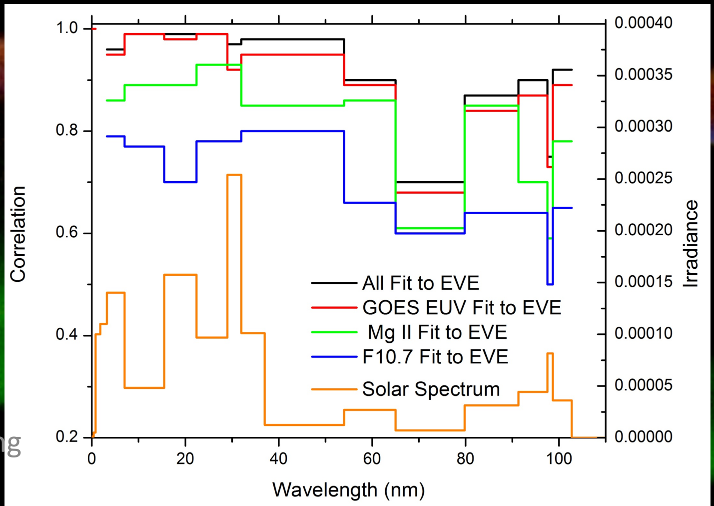
Model Development:
Solar EUV Irradiance Specification and Forecast

- Real-time Proxy model of solar EUV spectrum
  - Based on the "Stan-bands"
  - Driven by GOES broadband EUV observations
- 3-Day Forecast model of solar EUV irradiance
  - Driven by forecasts of F10.7 flux.
- 7-Day forecasts
  - Driven by the AFRL ADAPT model (Arge, Hock, Henney)



Solar spectrum (white) and where it is absorbed in the atmosphere (colors)

Broadband Parameterization by Solomon and Qian (2005)



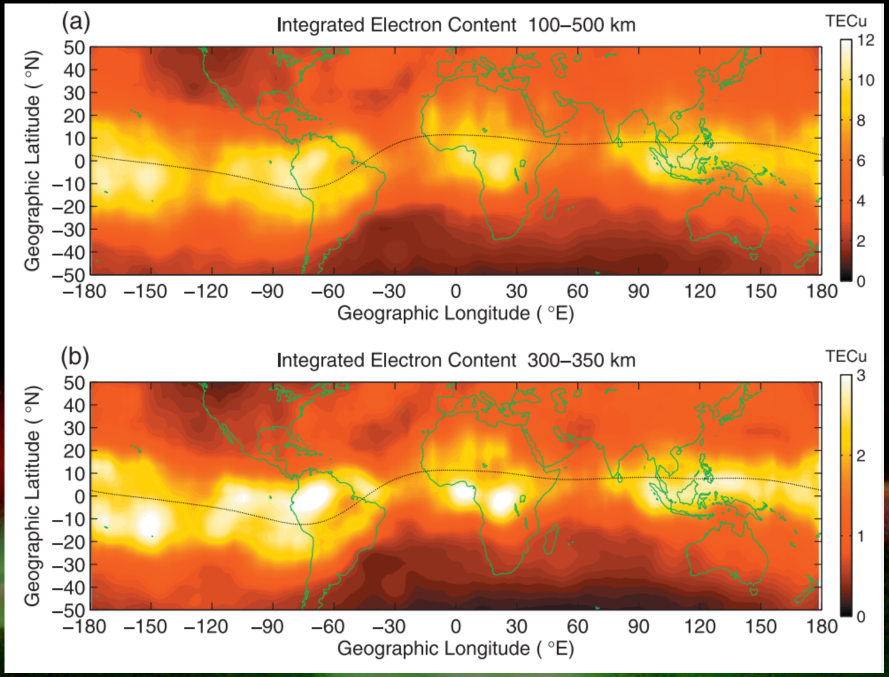
Improving Forecasts for Space Weather

- Initial or current state is not as important for space weather as it is for terrestrial weather
- Estimating errors in the drivers is more important for bounding the final solution (forecasting)
- Estimating errors in the physics by running multiple models would be more effective than running a single model from multiple initial states.
- Assimilating neutral density and composition data would be more effective than assimilating electron or ion data.

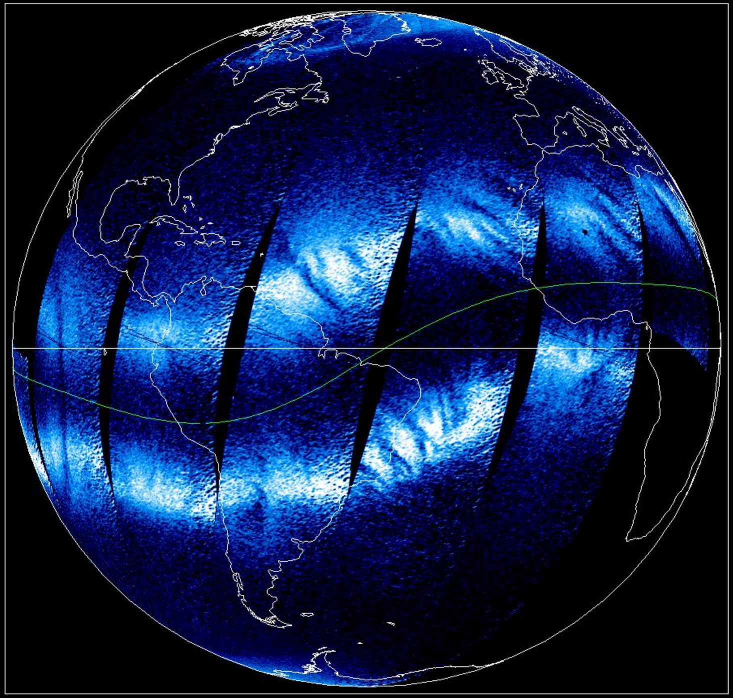
Capturing Global Phenomena

Ionospheric Total Electron Content Observation

FORMOSAT-3/COSMIC:
Accumulation of a months worth of data taken between 20:00 and 22:00 local time



TIMED GUVI (similar to DMSP SSUSI):
6 orbits of data

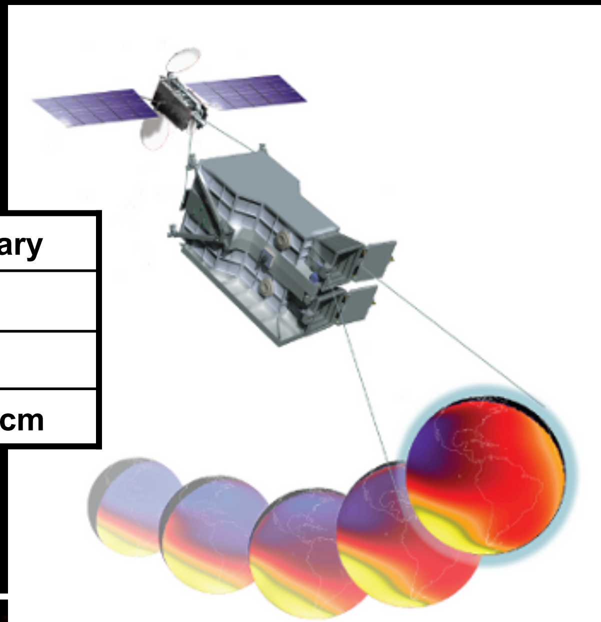


Capturing the spatial and temporal variations in the ionosphere is very difficult from LEO orbit.

Global-scale Observations of the Limb and Disk (GOLD)

NASA Instrument of Opportunity

Instrument Summary	
Mass	34 kg
Power	61 W
Size	42×42×70 cm



Observations:

- Hemispheric maps of…
  - Neutral temperature
  - O/N_2 ratio (composition)
  - Electron density
- Limb scans of temperature

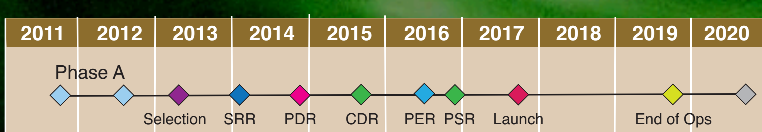
Imaging Spectrograph:

Two independent, identical channels

Wavelength range: 132 – 160 nm

Target Launch: October 2017

Hosted Payload on geostationary commercial satellite



Florida Space Institute (FSI) University of Central Florida

PI: Richard Eastes

Project Coordinator: Andrey Krywonos

Laboratory for Atmospheric and Space Physics (LASP)
University of Colorado

Deputy PI: William McClintock

Project Manager: Mark Lankton

NOAA SWPC

Collaborator: Mihail Codrescu

Why is IDEA a Good Idea?
Multi-Day Ionospheric Forecasts

- IDEA is driven by customer requirements for better forecasting of space weather impacts on systems.
  - GPS/GNSS systems are affected by small and medium scale structures in the ionosphere that are not captured in current ionosphere models.
  - HF Communication is affected by large, medium, and small scale structures in the lower ionosphere that are not captured in current ionosphere models
  - Satellite Communication (Ground to space) is affected by small and medium scale structures
  - Satellite drag is affected by medium scale structures and winds in the thermosphere (neutral atmosphere) that are not currently modeled.

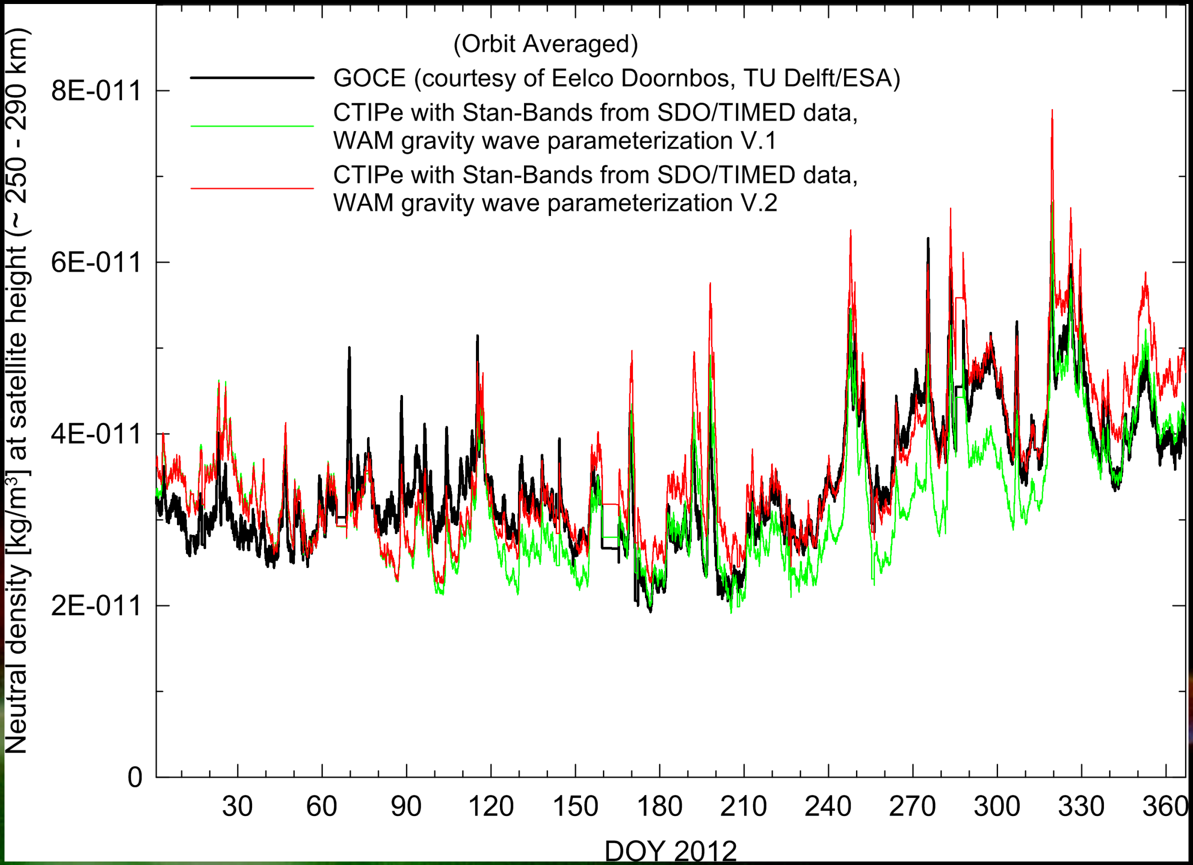
How will IDEA meet the Customer Requirements?

- The Ionosphere/Thermosphere (I/T) systems is a strongly driven system.
  - Most of the variability is the result of external forcing
- There are three primary external forces or drivers.
  1. Solar x-ray and EUV irradiance
     - Induces global variability of factors of 0.2 to 10 on times scales of minutes to years
  2. Geomagnetic storms
     - Induces regional variability of factors of 0.1 to 10 on time scales of minutes to hours
  3. Tropospheric variability
     - Induces local variability of 0.1 to 3 on time scales of minutes to hours.
- Nearly all I/T models capture the first two drivers but not the third.
- Specification and forecasting each of the three drivers is critical to developing an accurate forecast of the I/T system
- Only a coupled atmosphere-ionosphere model will provide adequate forecasts of space weather impacts on the systems communication and navigation systems.

Improved Satellite Drag Forecasts

Requires better gravity wave forcing

Requires better EUV forcing



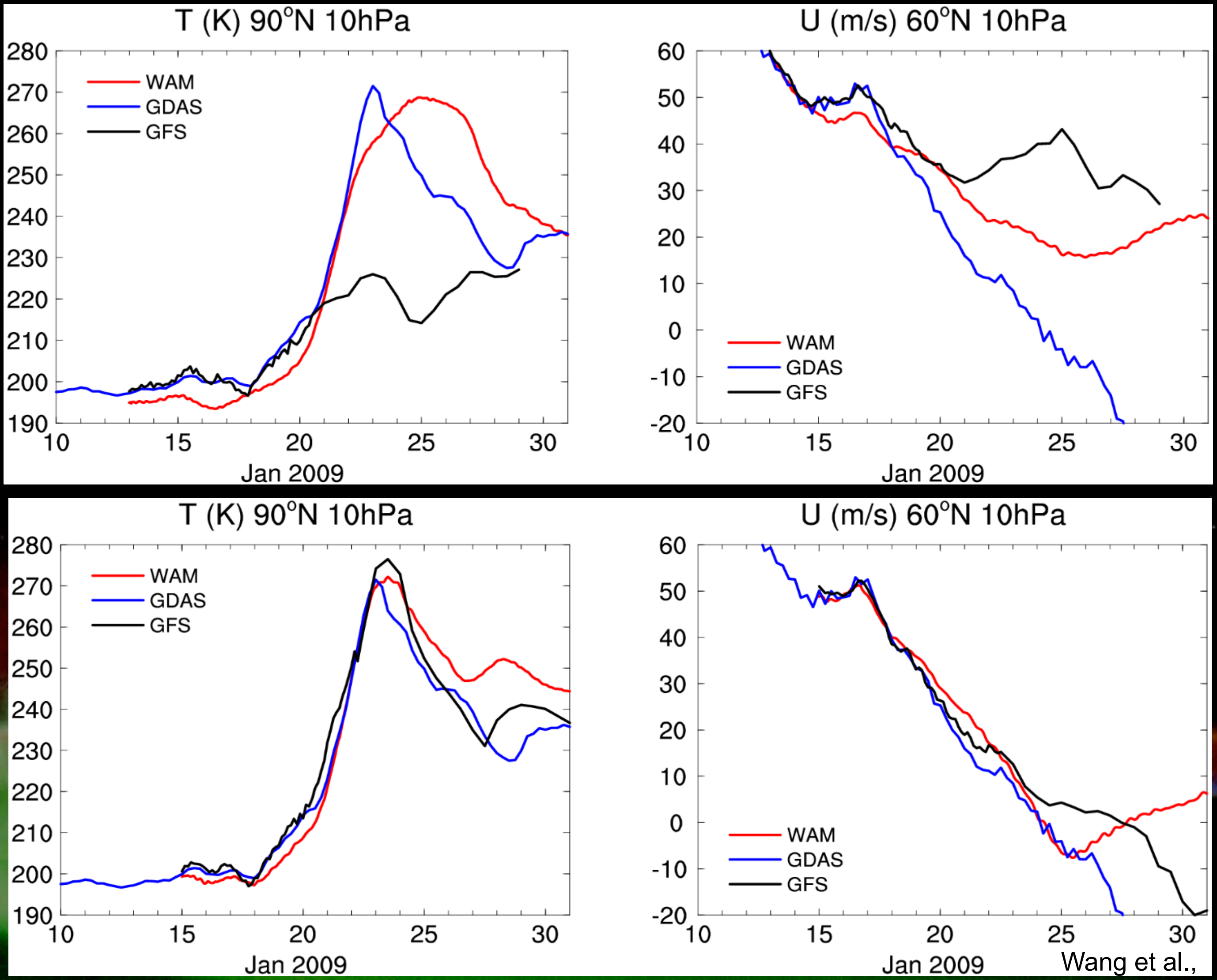
NWS R2O Grant to improve gravity wave parameterization in GFS and WAM (Yudin and Fuller-Rowell)

Bonus: WAM and GFS Stratosphere Forecast

WAM Predicts Strat-Warm 2 Days Before GFS

WAM and GFS forecast from Jan 13, 2009 of T and U @ 10 hPa vs GDAS analysis.

WAM and GFS forecast from Jan 15, 2009 of T and U @ 10 hPa vs GDAS analysis.



The full impact of WAM on tropospheric forecasts needs to be evaluated