From Discovery to Operations: Whole Atmosphere-Ionosphere Models for Space Weather Application

- a new paradigm in thermosphere ionosphere modeling -

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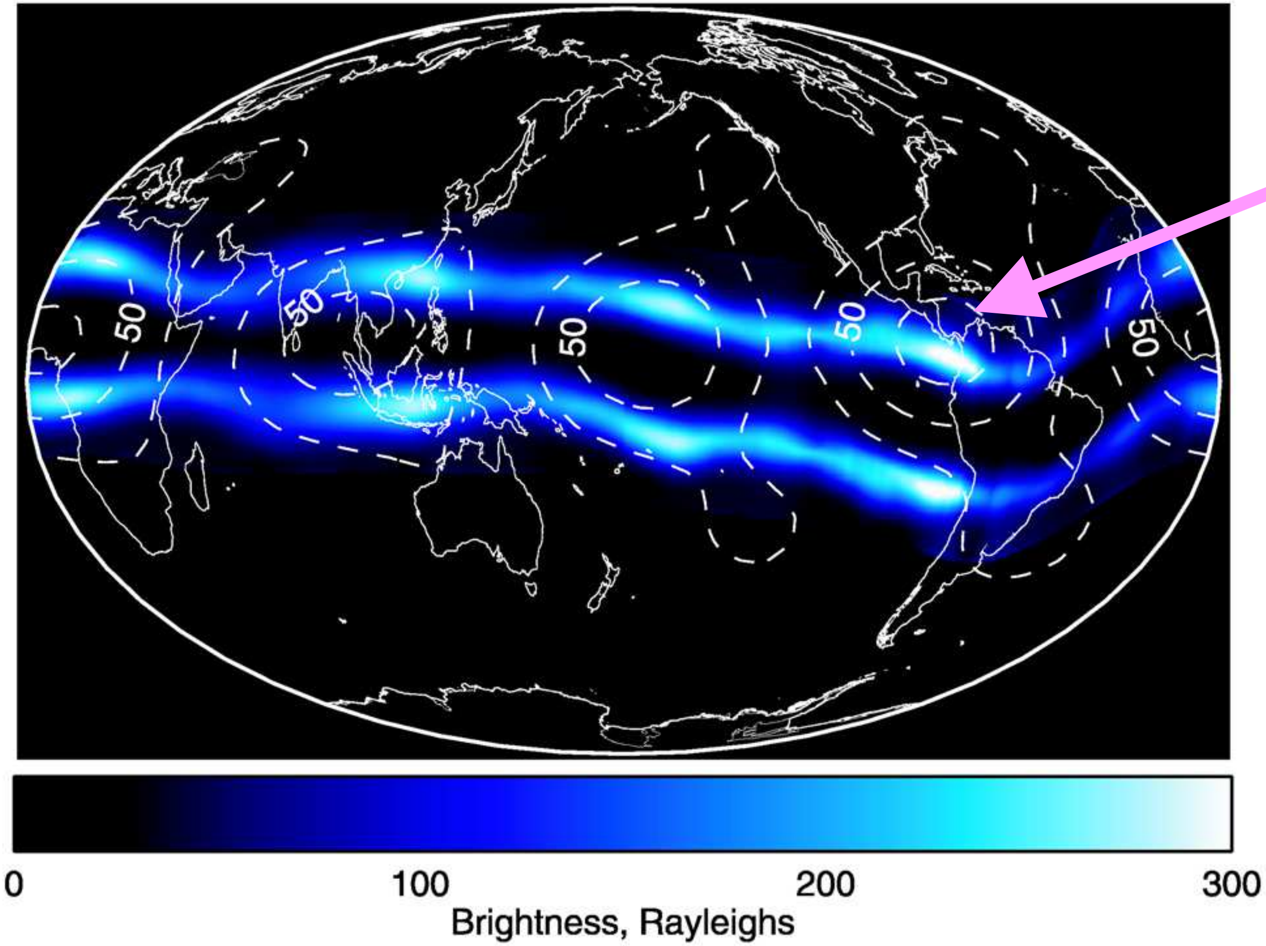
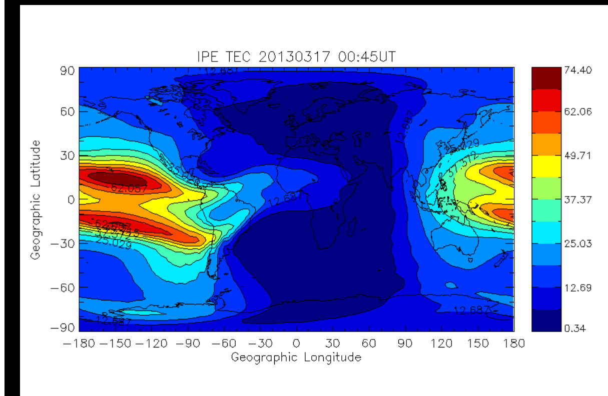
Four peak longitude structures in the ionosphere



The four peaks driven by nonmigrating eastward propagating tidal mode with zonal wavenumber 3 (DE3) in dynamo region.



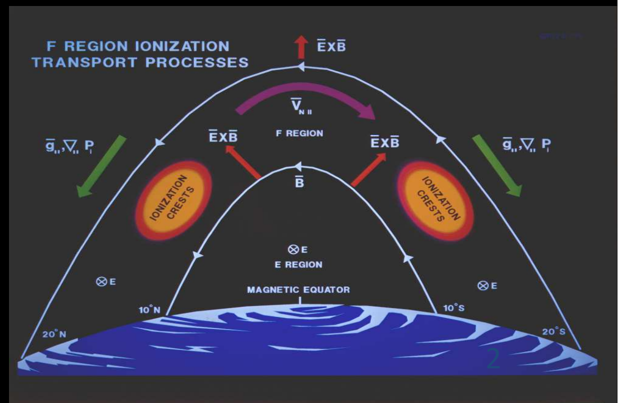
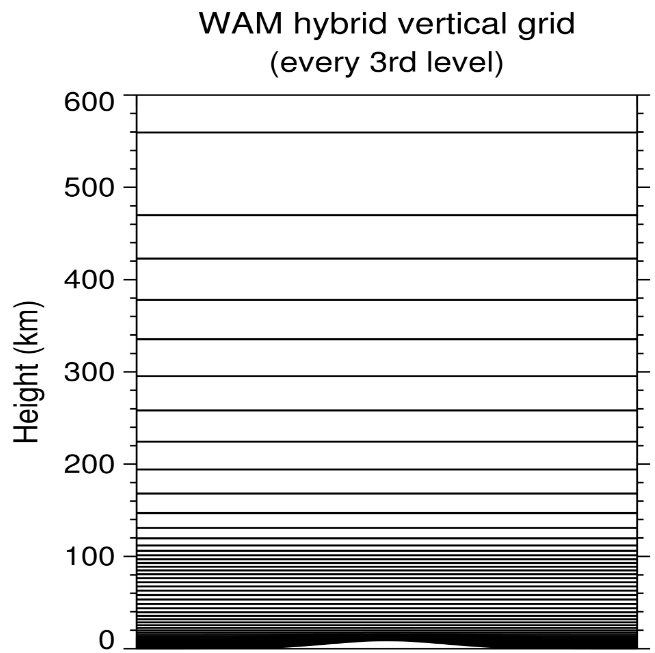
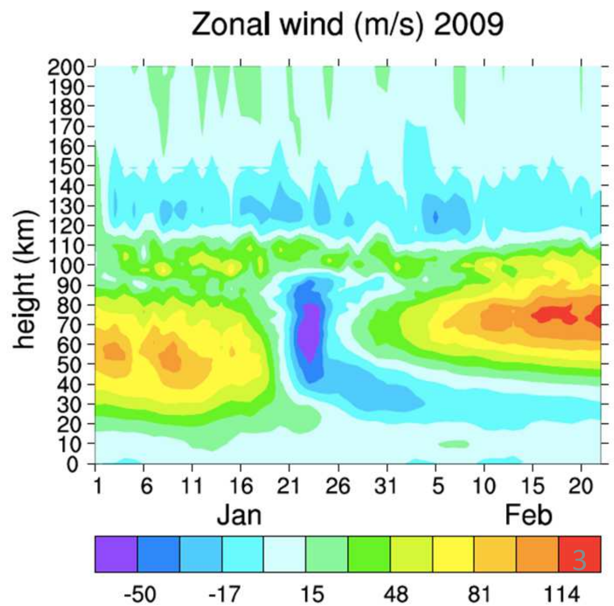


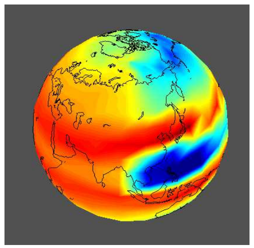
IMAGE composite of 135.6-nm O airglow (350–400 km) in March–April 2002 for 20:00 LT and amplitude of modeled diurnal temperature oscillation @ 115 km (Immel et al., 2006).

Whole Atmosphere Model (WAM)

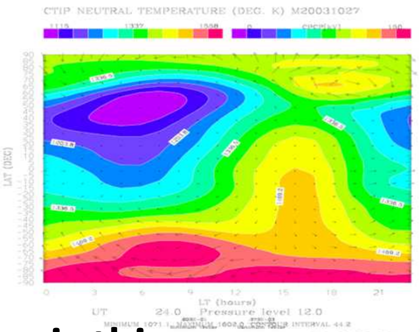
- **Global seamless whole atmosphere model (WAM) 0-600 km, 0.25 scale height, 2° x 2° lat/long, hydrostatic, 10-fold extension of Global Forecasting System (GFS) US weather model.**
- **O_3 chemistry and transport**
- **Radiative heating and cooling**
- **Cloud physics and hydrology**
- **Sea surface temperature field and surface exchange processes**
- **Orographic gravity waves parameterization**
- **Eddy mixing and convection**
- **Diffusive separation of species**
- **Composition dependent C_p**
- **Height dependent g(z)**
- **EUV, UV, and non-LTE IR**
- **Ion drag and Joule heating**





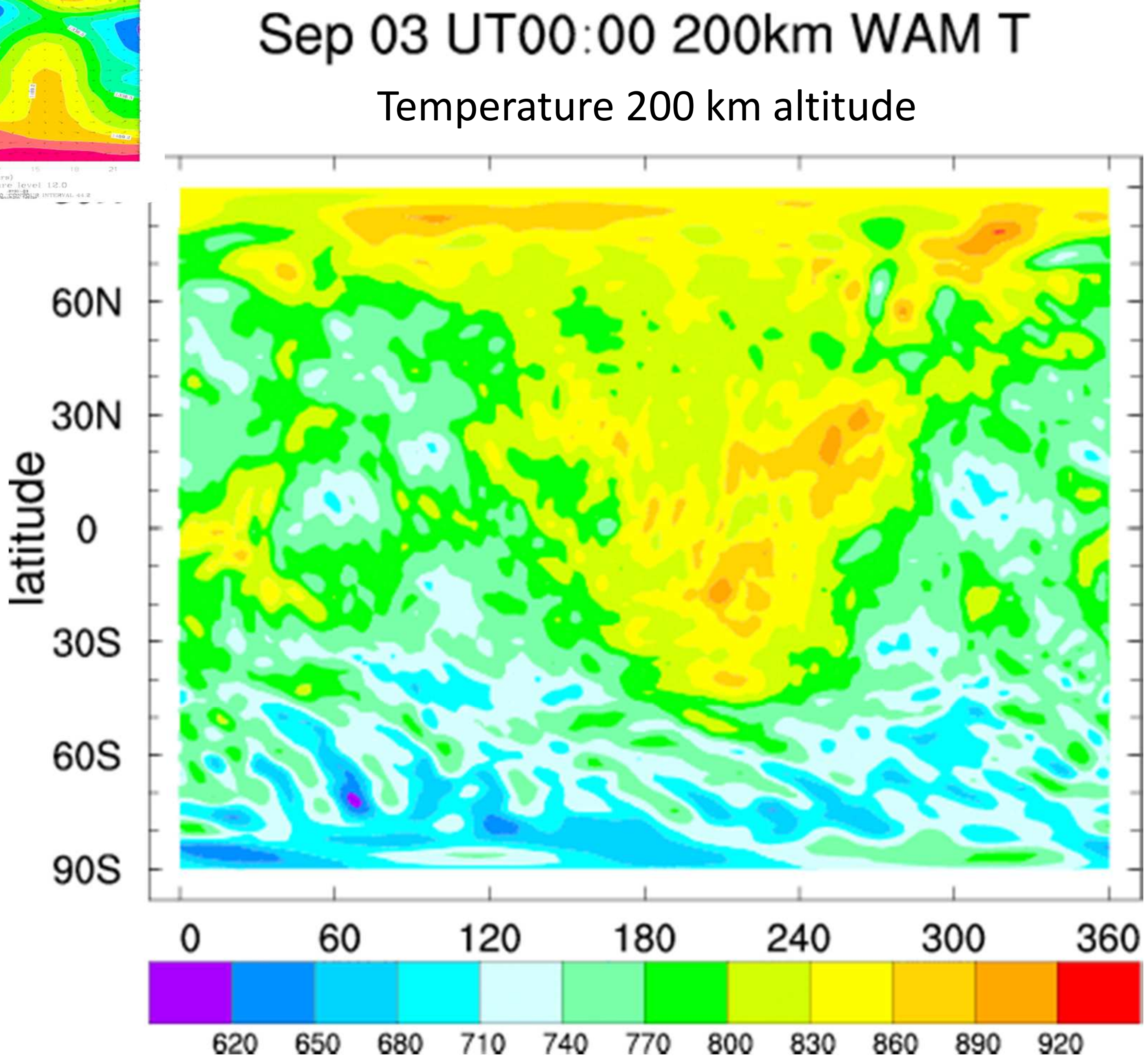


Coupled to an ionosphere and electrodynamics module (CTIPe), working on coupling to IPE (Naomi Maruyama)



....is this reality?

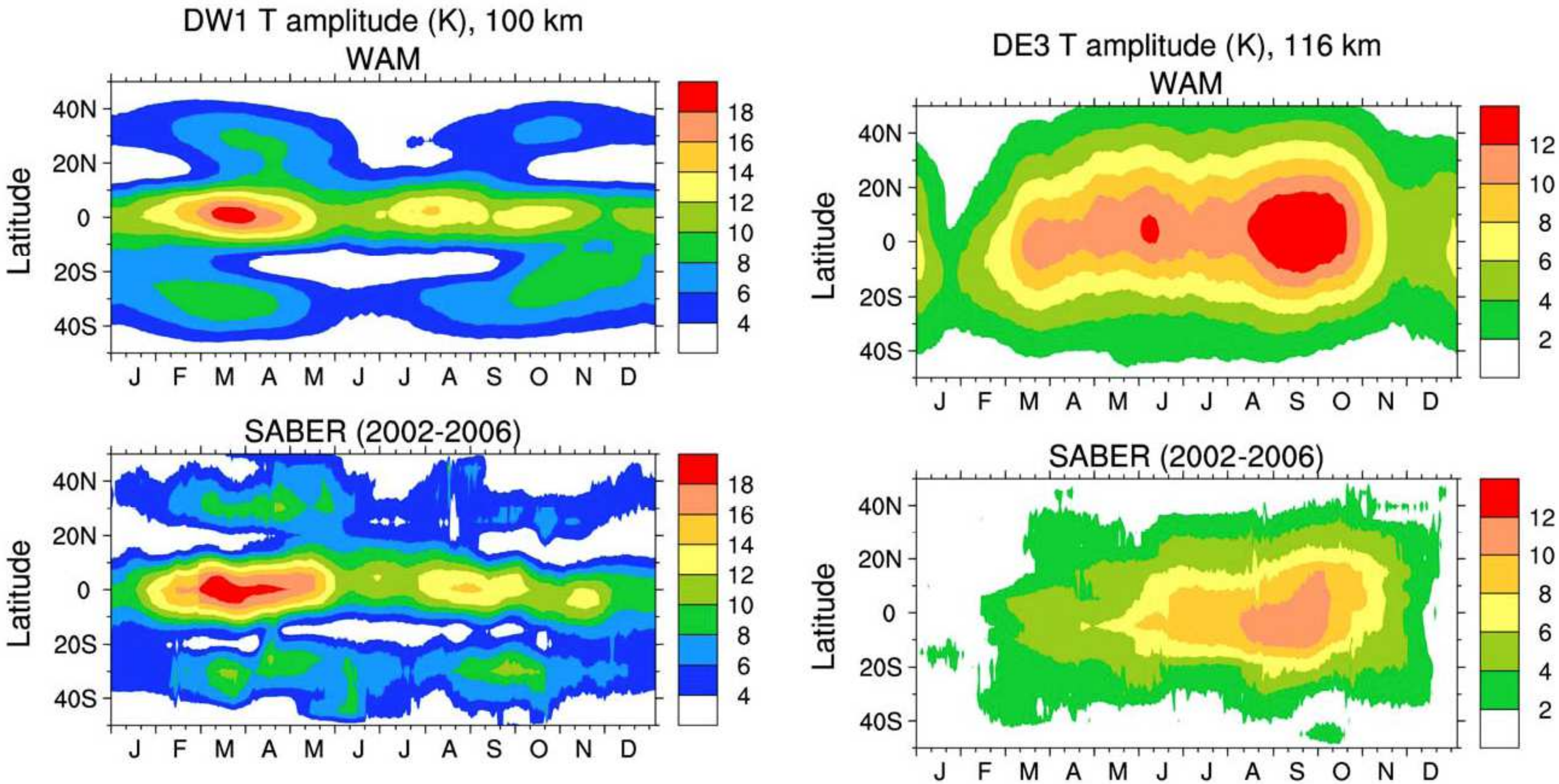
Temperature 200 km altitude



....or is it this ?

WAM agrees well with the diurnal migrating tide DW1 and the famous DE3

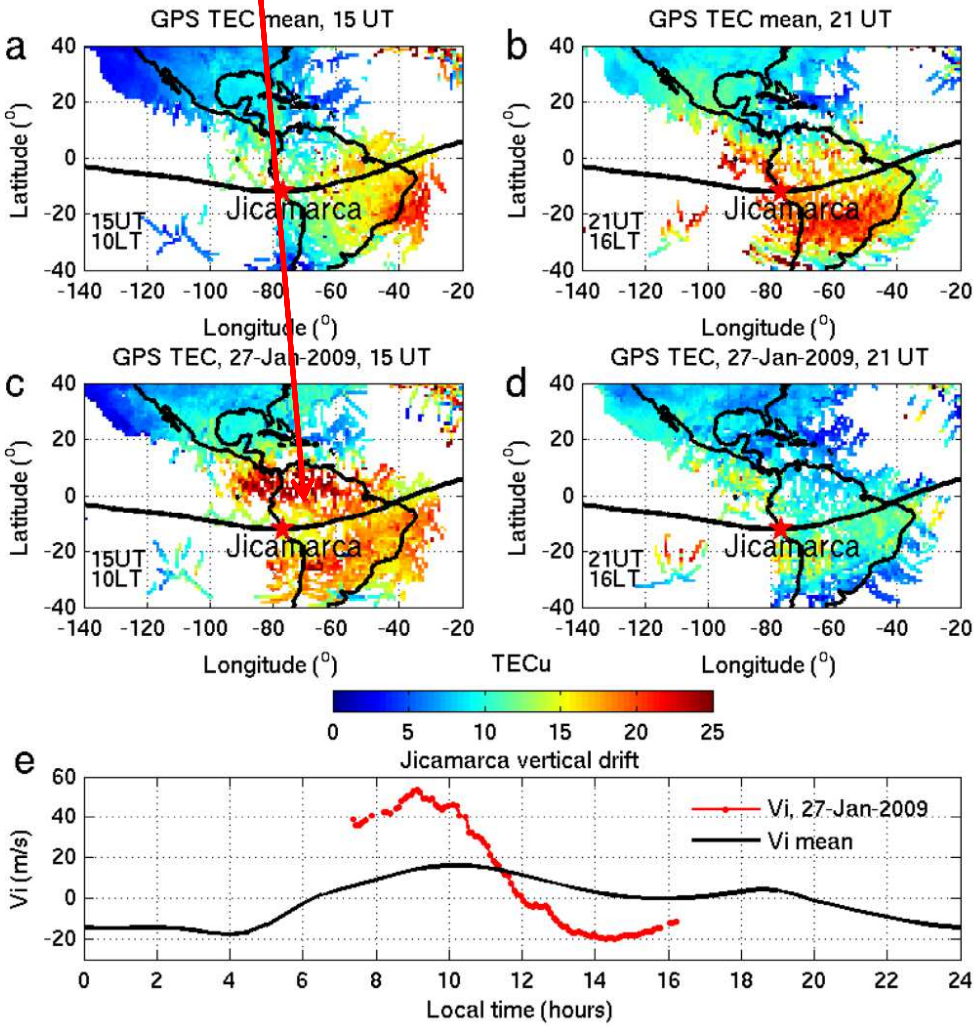
WAM model top: Akmaev et al. 2008



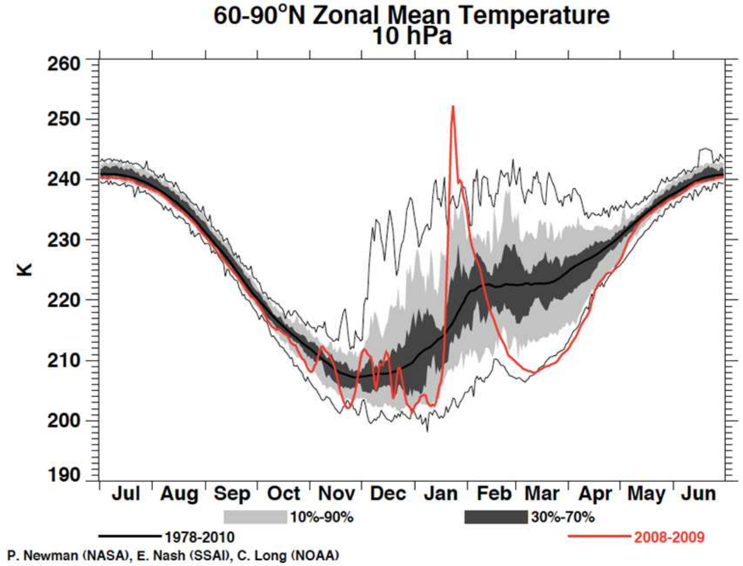
DW1 SABER observations below: Forbes et al. 2008 DE3

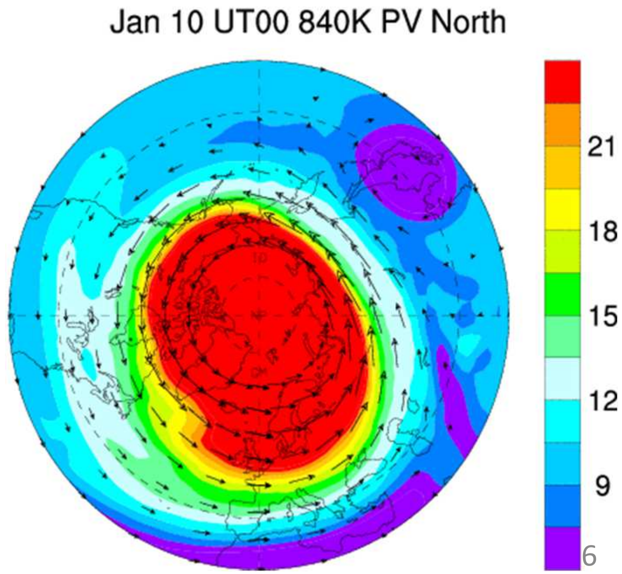
50% increase in TEC in January 2009 when solar and geomagnetic activity were very low

Goncharenko et al. 2010



Is this also a response to changing tidal amplitudes?



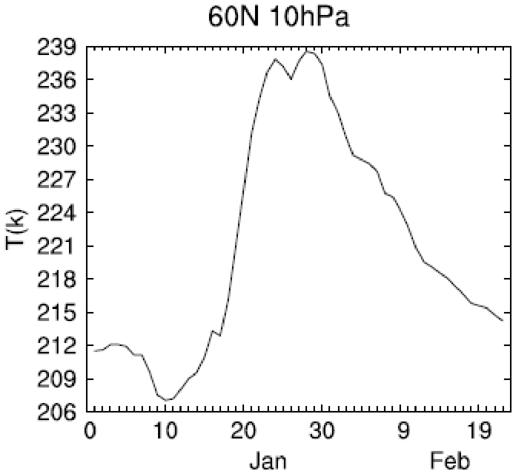


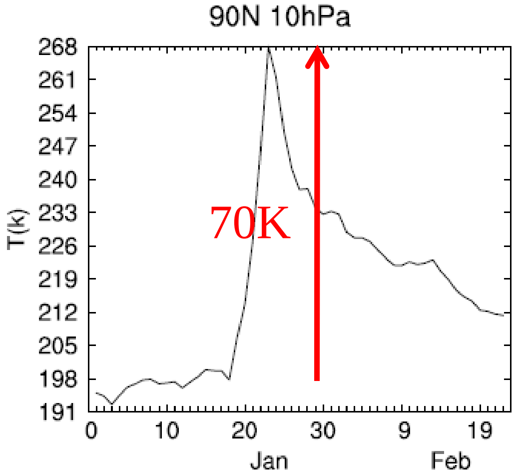
Sudden stratospheric warming

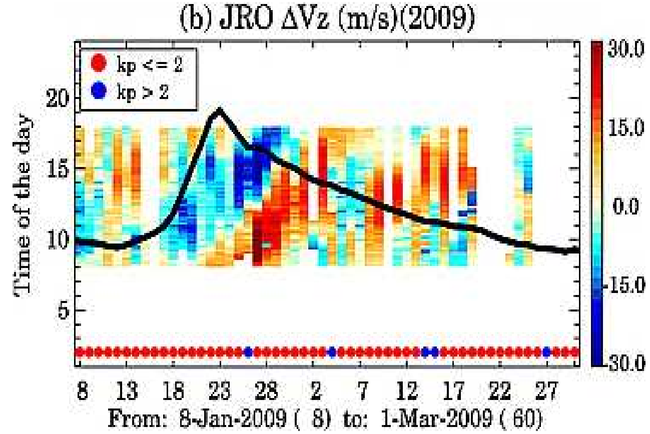
Benefits of WAM

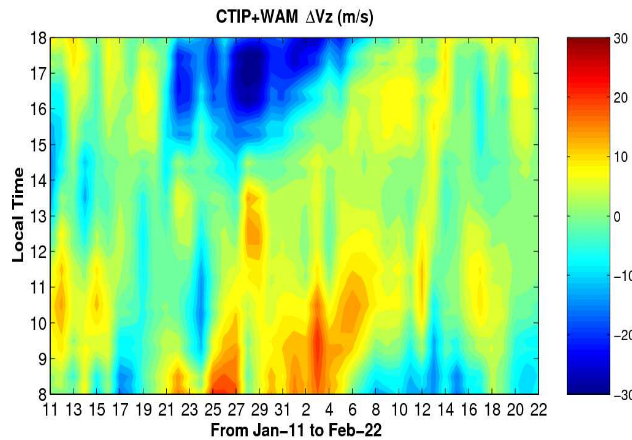
- Compatible with the US weather model already running operationally
- Can implement the operational Gridpoint Statistical Interpolation (GSI) data assimilation system, utilizing the lower atmosphere data
- Able to follow real lower atmosphere weather events and their impact on the upper atmosphere and ionosphere (such as hurricanes, tornados, planetary waves, sudden stratospheric warming, tropical convection, longitude structure in migrating and non-migrating tides)

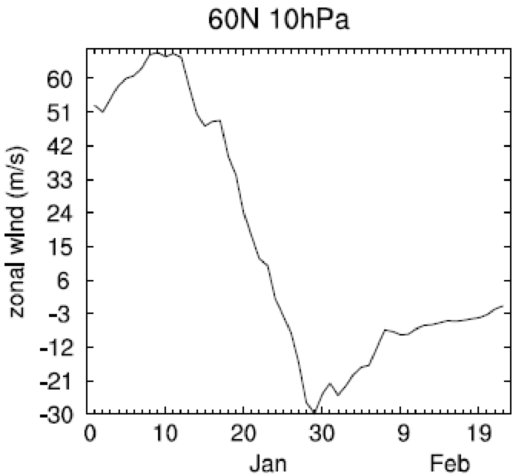
WAM simulations of the January 2009 sudden stratospheric warming

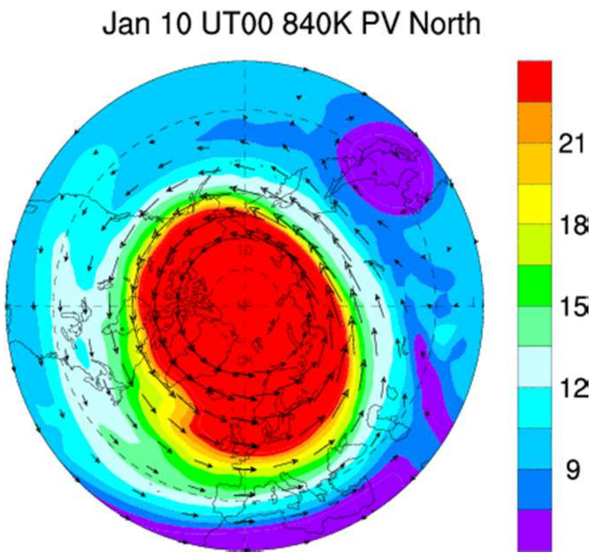


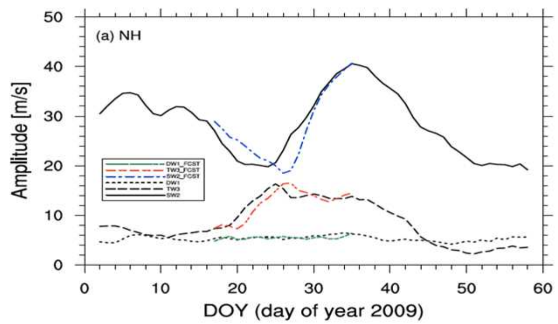






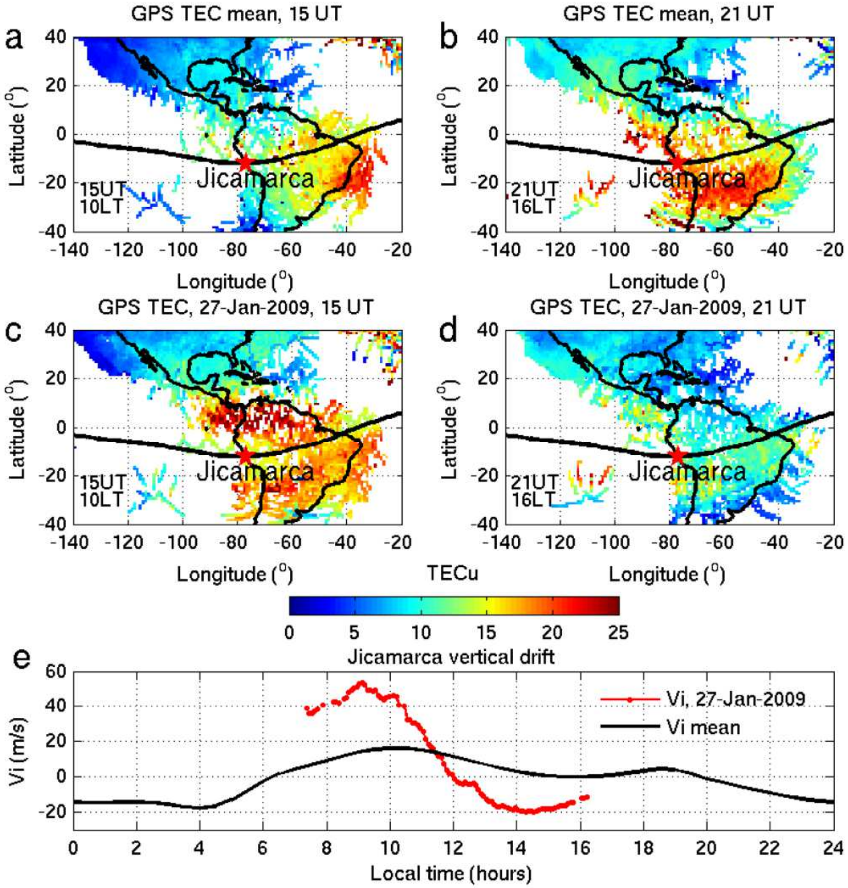






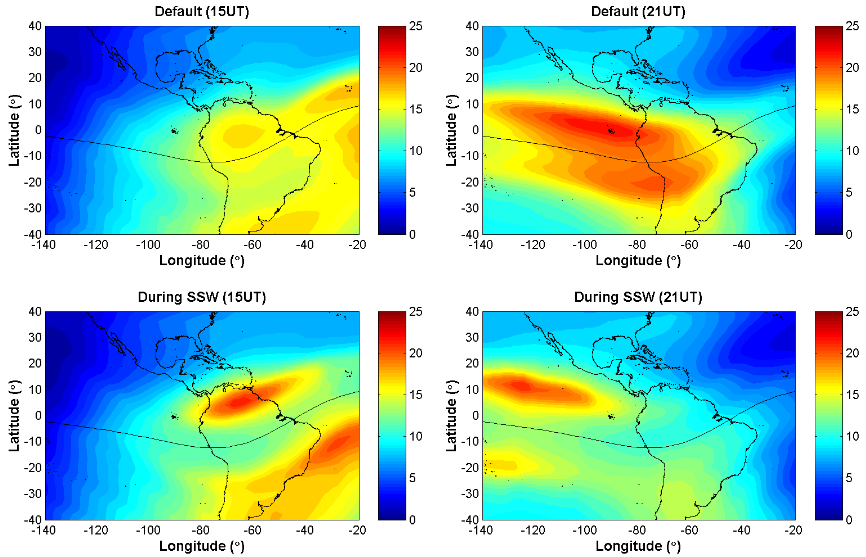
January 2009 Stratospheric Warming impact on EIA

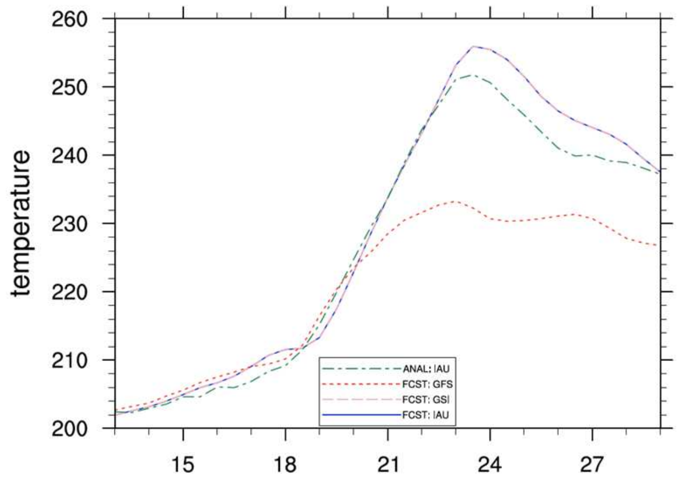
GPS-TEC observation
before and after SSW
Goncharenko et al. (2010)



SSW vertical plasma drift
Jicamarca (Chau et al., 2010)

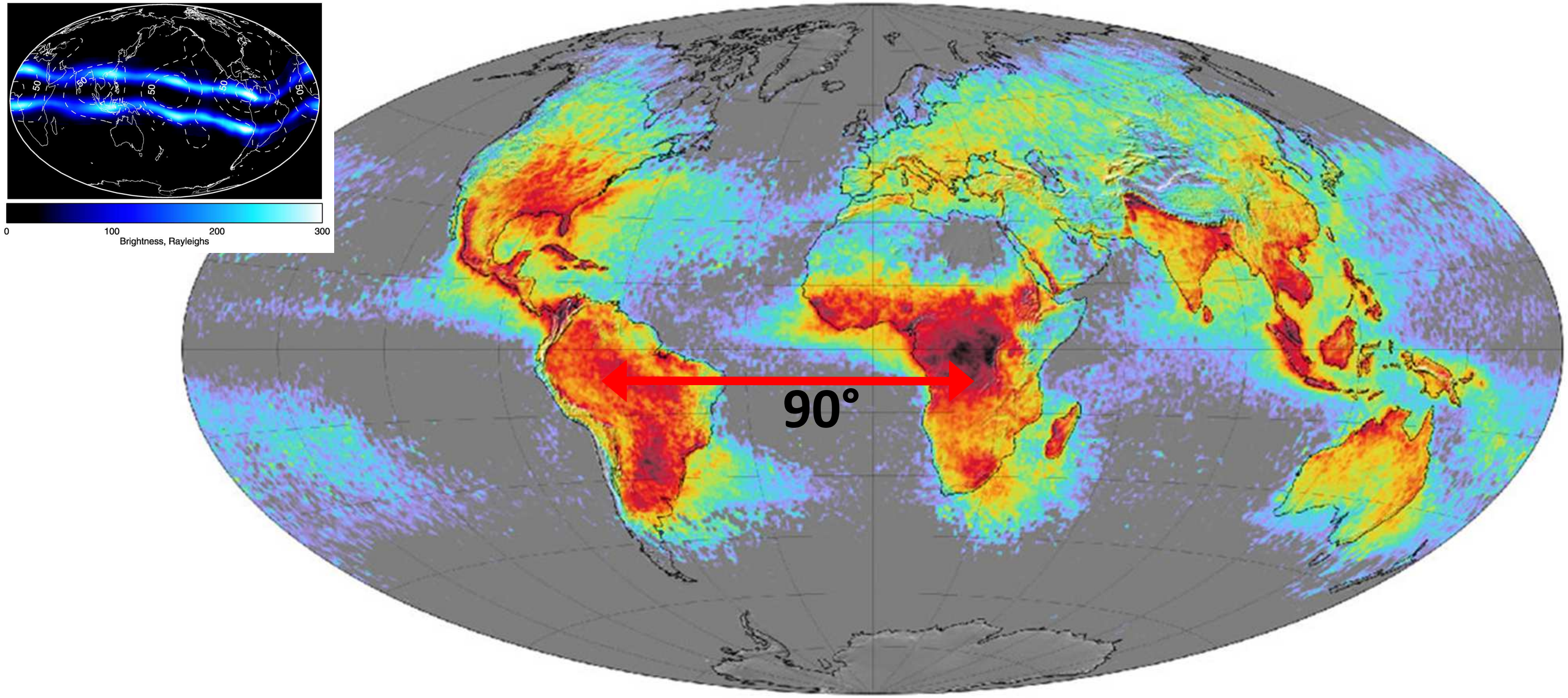
WAM-GIP
before and after SSW





Can be forecast more than a week ahead

Driver of the Immel longitude structure



Lightning strikes from convective storms, signature of latent heat release:
Either three or four peaks in longitude: wave 3 or 4
Illuminated by the Sun every 24 hours: diurnal

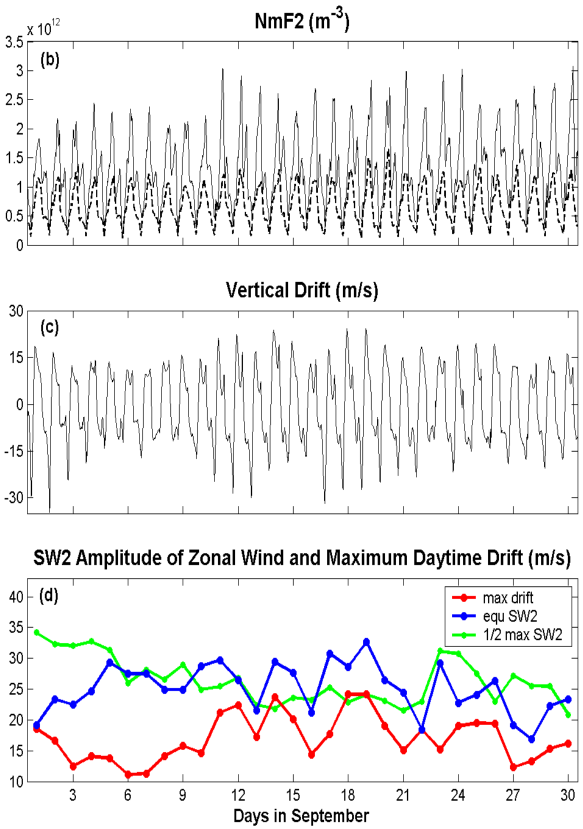
$$\cos(\Omega t + \lambda)\cos 4\lambda \quad \text{--->} \quad \cos(\Omega t + 5\lambda) + \cos(\Omega t - 3\lambda)$$

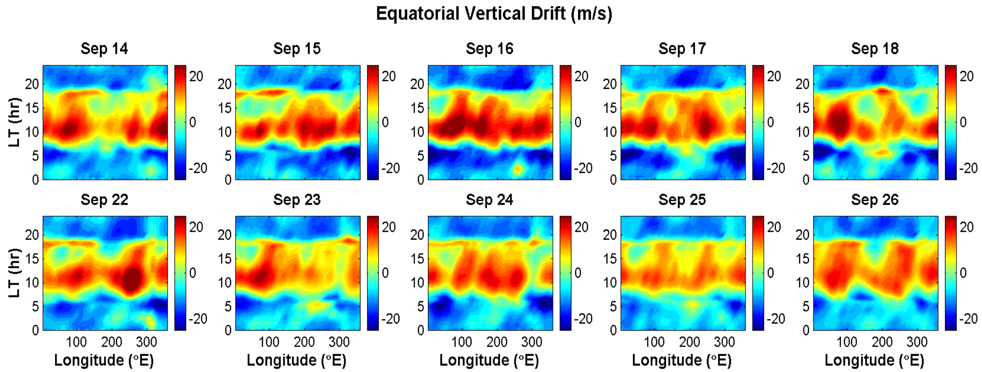
$$\cos(\Omega t + \lambda)\cos 3\lambda \quad \text{--->} \quad \cos(\Omega t + 4\lambda) + \cos(\Omega t - 2\lambda)$$

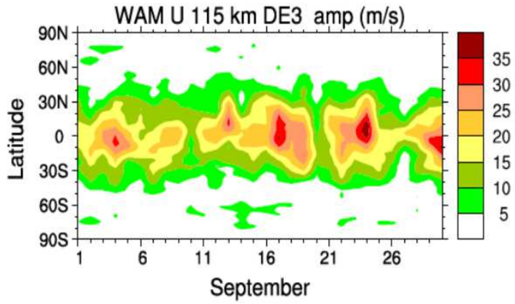
Can create a diurnal eastward propagating W2 or W3 DE2 and DE3

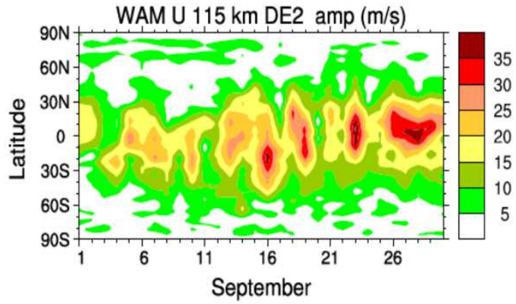
Example of impact of tidal variability

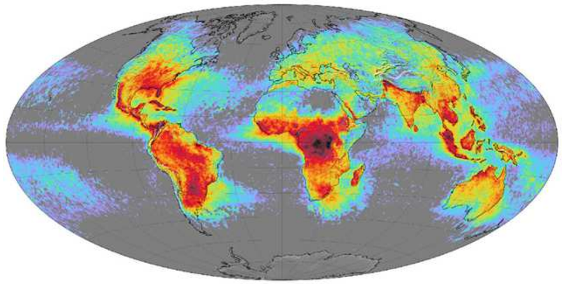
Tzu-Wei Fang et al. 2013 from WAM-GIP model simulation

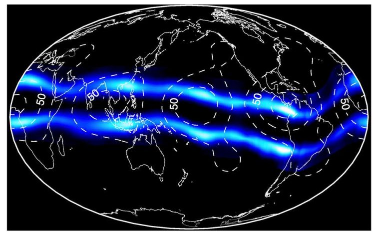












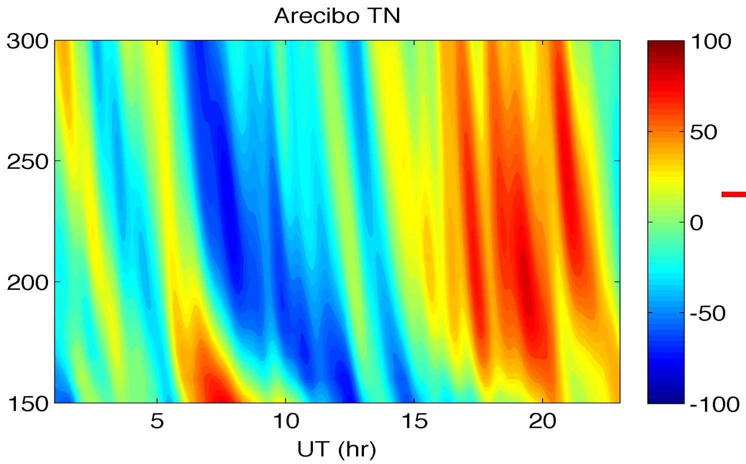
Modulation of semi-diurnal tide SW2 correlates with increases in peak vertical plasma drift and N_mF2

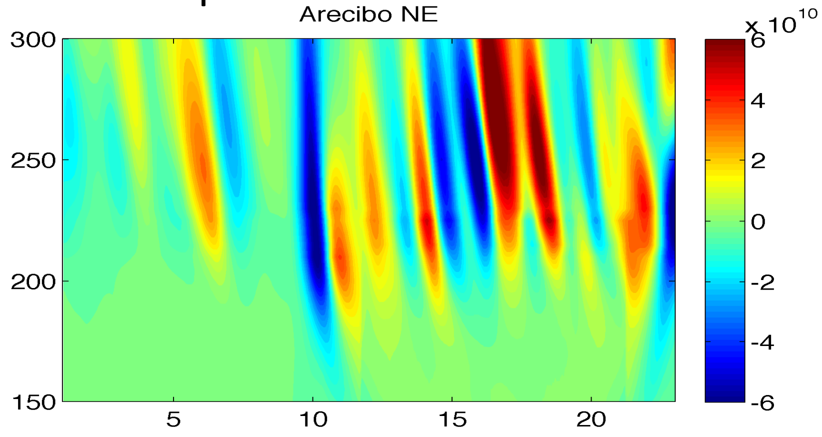
Modulation of DE3 and DE2 tidal amplitudes correlates with number of peaks in longitude structure of vertical plasma drift

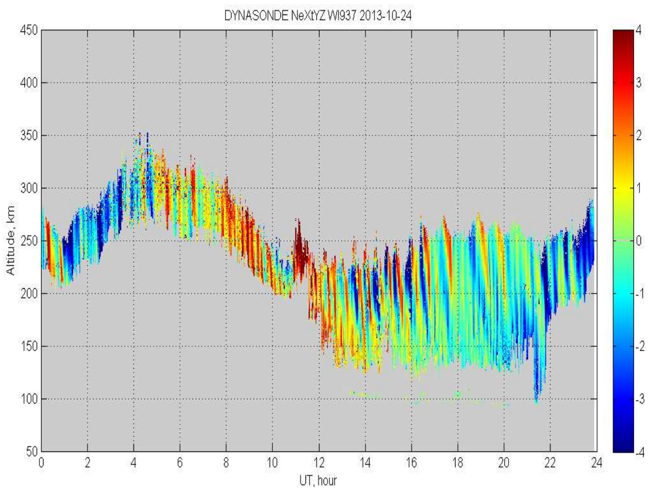
Use WAM winds, composition, density to drive GIP plasma density
- agrees well with Arecibo ISR observations by Djuth et al. -

WAM temperature perturbations at Arecibo

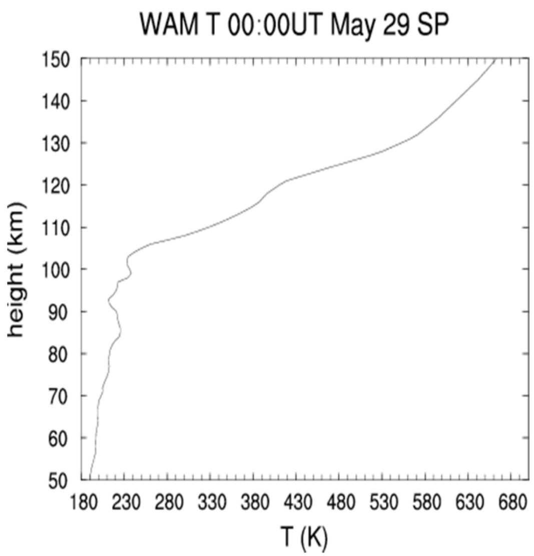
WAM-GIP ~20% plasma density perturbations at Arecibo



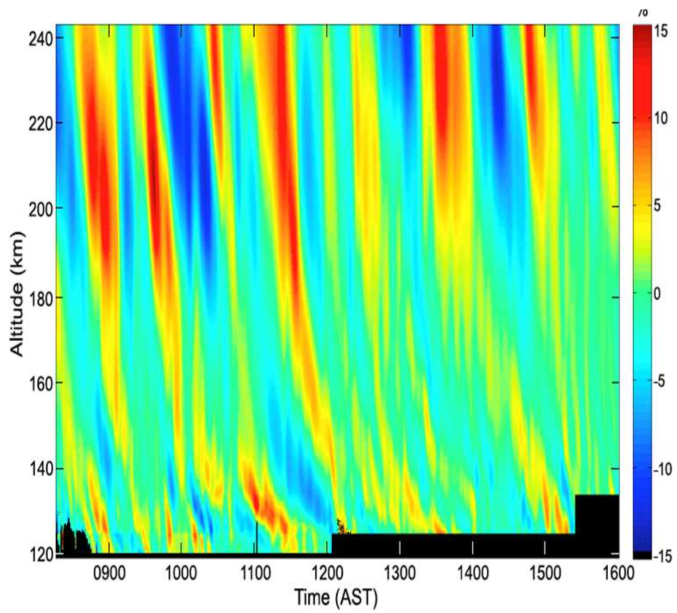




Dynasonde - vertical velocity and tilts, Nikolay Zabotin



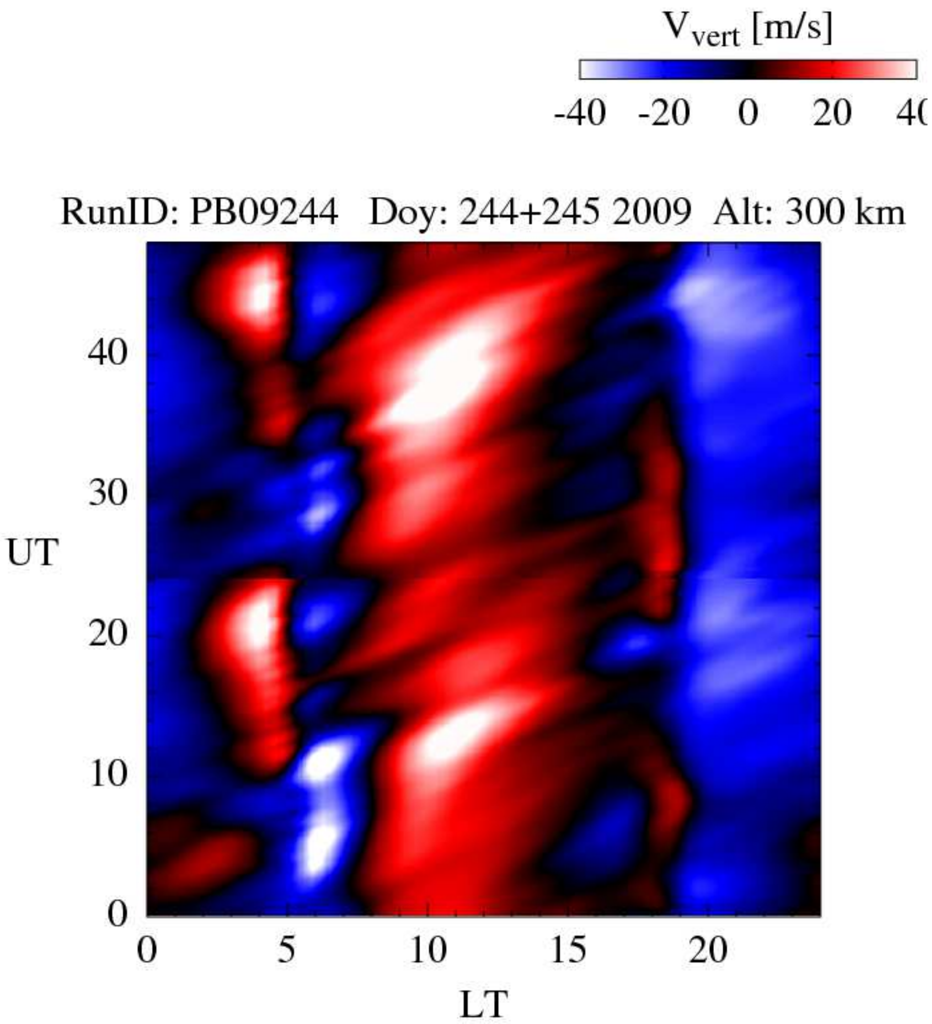
WAM temperature



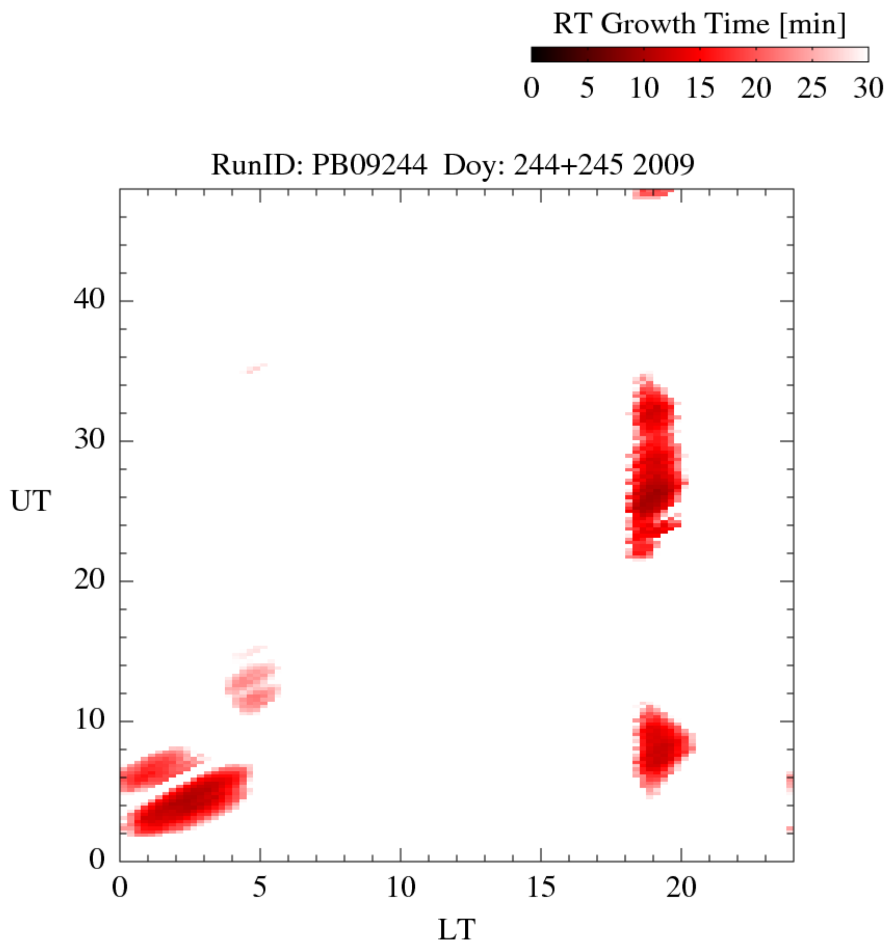
De-trended ISR observations of N_e perturbations, Djuth et al.

Variability of Electrodynamics

GIP Plasma Drift

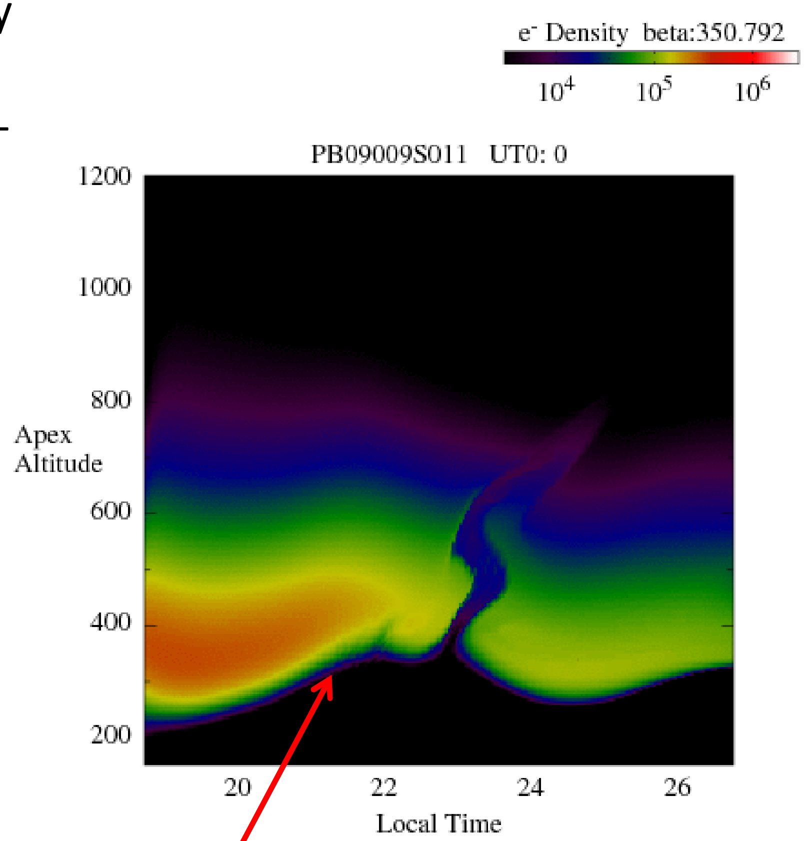


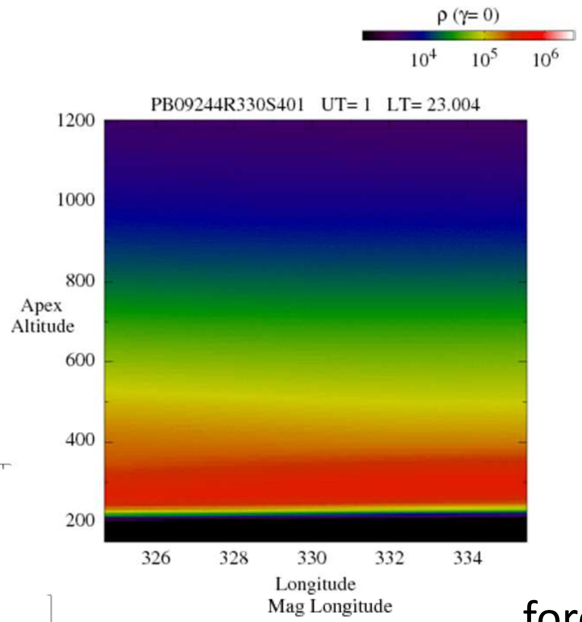
RT Growth Timescale

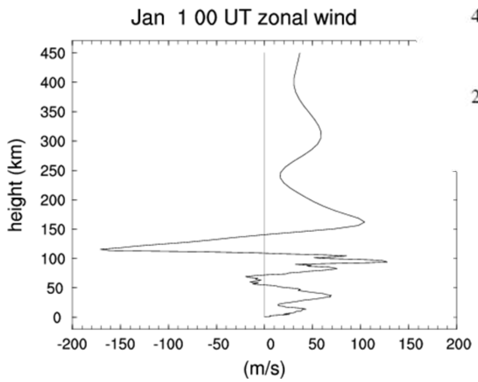


Days 244 and 245

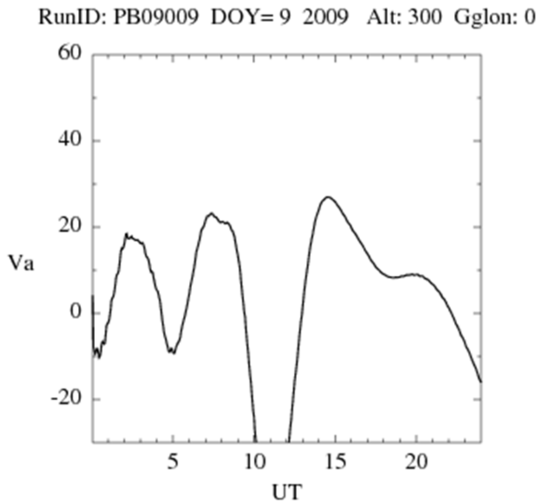
Bubble development in physics-based irregularity model (PBMOD) with WAM fields (180 km horizontal. resolution, ¼ scale-height vertical, ~2-5km) with no additional seeding Retterer et al.

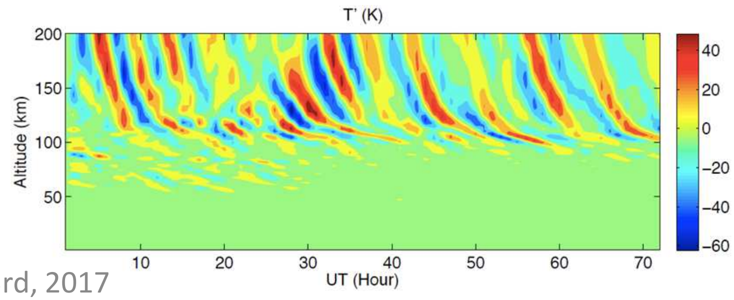






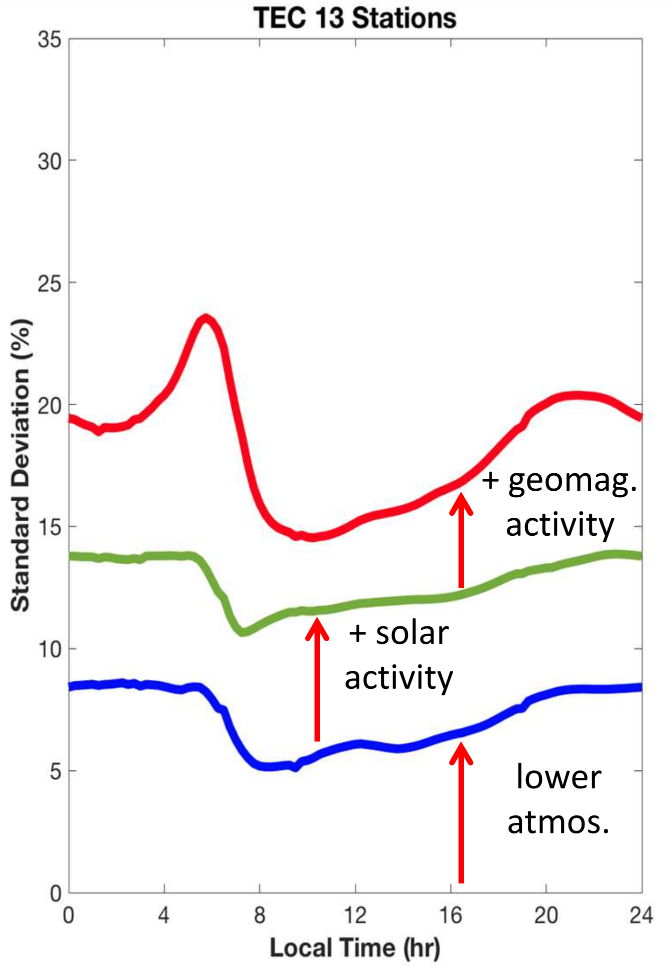
forecasting large scale wave structure, (LSWS) on bottomside

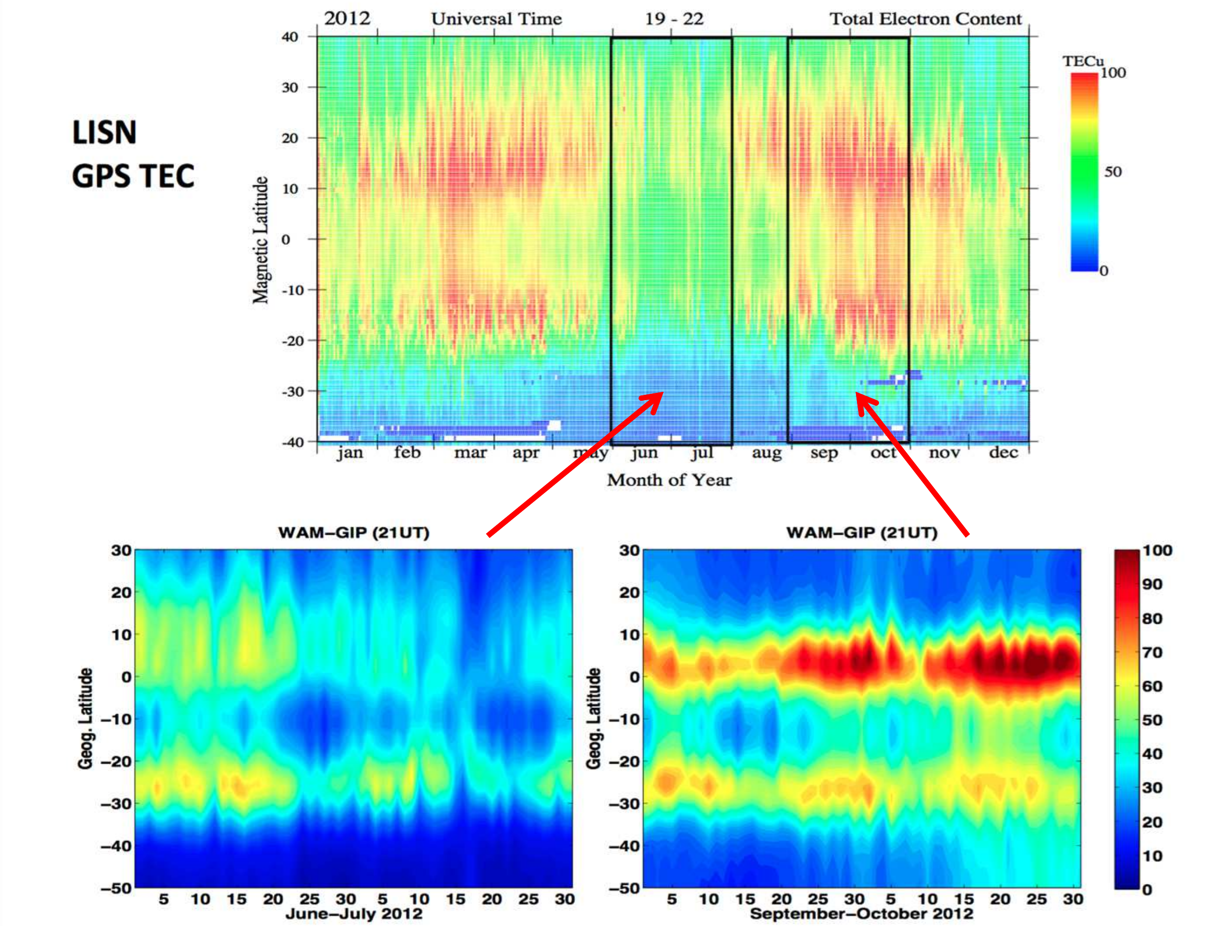




Ionospheric Variability (TEC) and Sources in American Sector

(Model: Tzu-Wei Fang, SAIR project; GPS TEC data: Cesar Valadares, LISN)

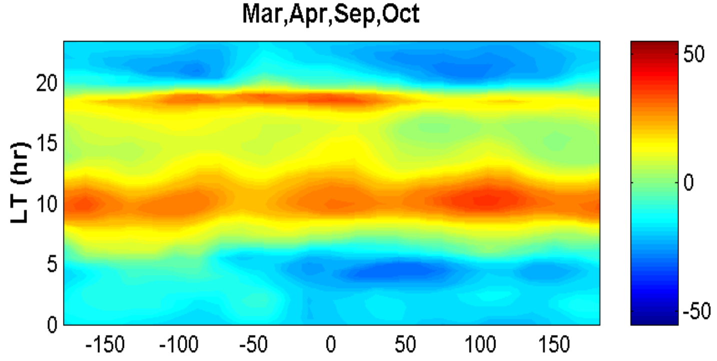




NOAA Operational Models

- WSA-ENLIL and the Michigan Geospace physical models have been transitioned to NOAA operations and are now providing real-time space weather products
- National Weather Service is committed to raising the lid of the US weather model to improve long-range seasonal and sub-seasonal terrestrial weather forecasts
- Presents an opportunity to include an operational thermosphere ionosphere physical model - specifying and forecasting space weather in the upper atmosphere

DE3 winds drives E-region dynamo to produce tidal signatures in nightside Equatorial Ionospheric Anomaly (EIA) Why 4 peaks at fixed local time?



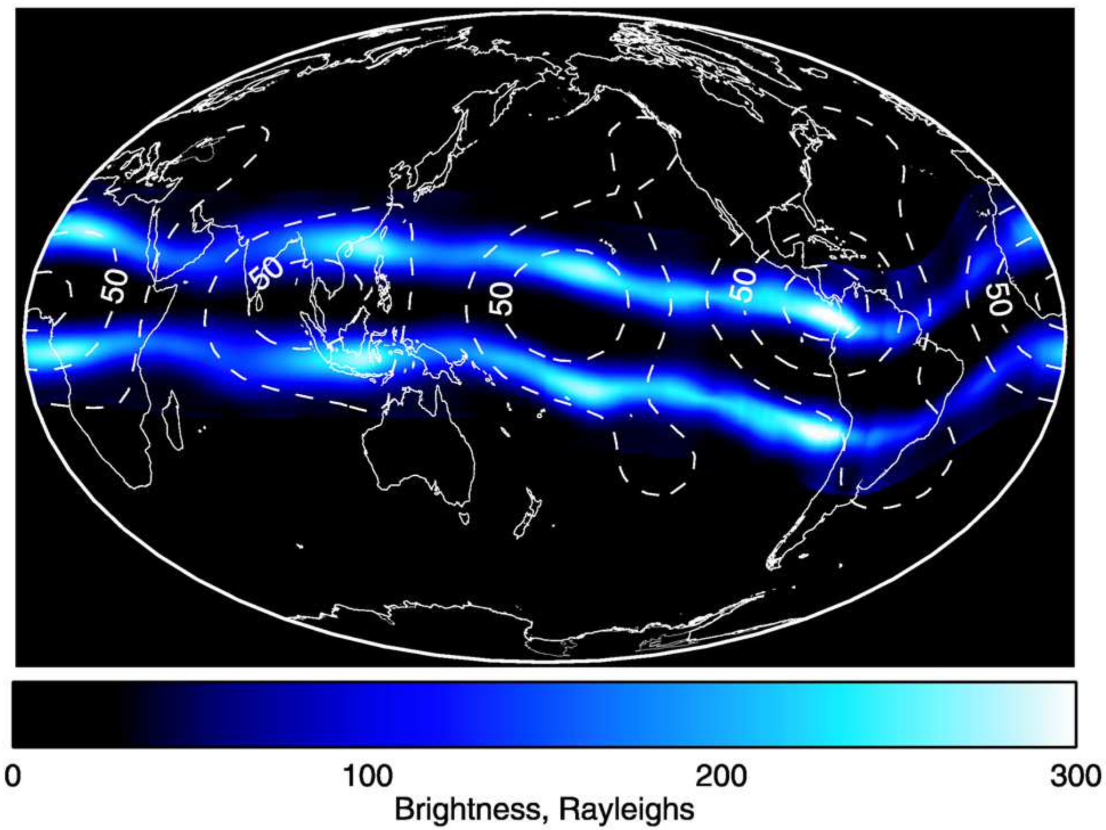
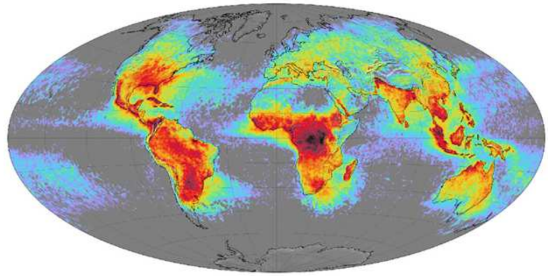
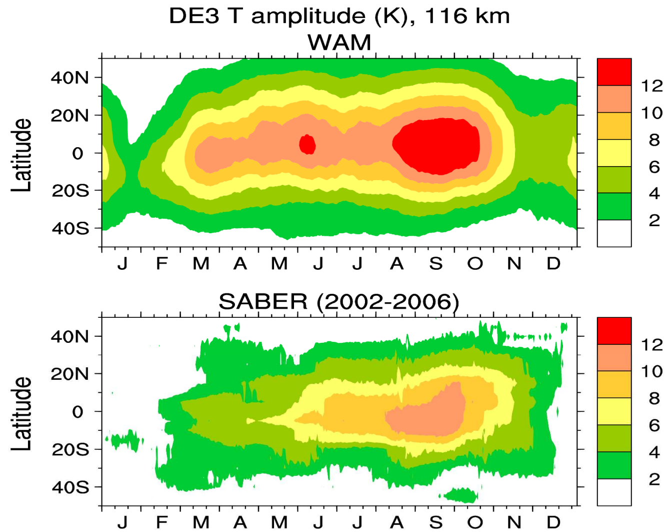


IMAGE composite of 135.6-nm O airglow (350-400 km) for March-April 2002 and magnitude of tidal temperature oscillations at 115 km (Immel et al., 2006).

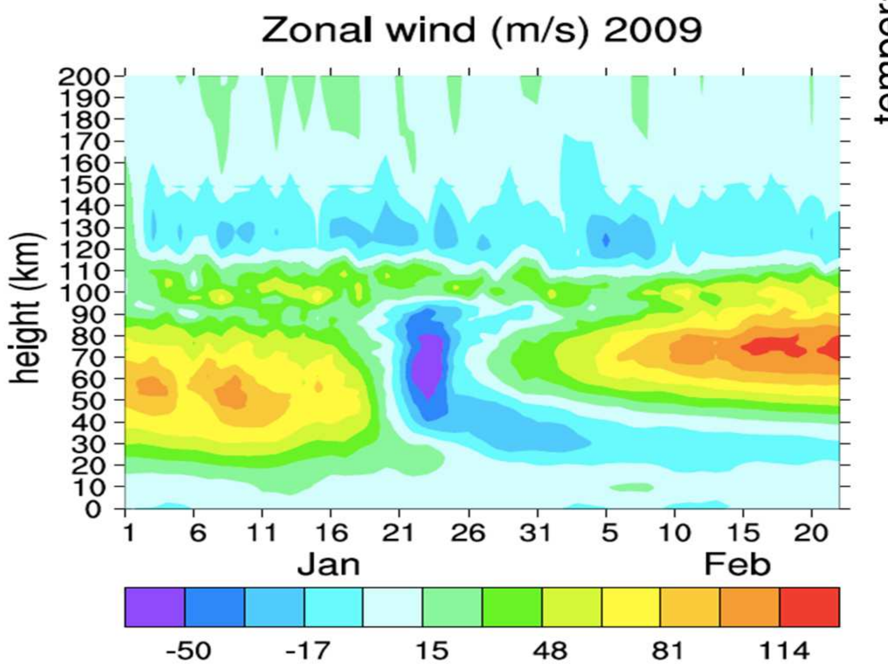
3 peaks of wave 3
Move one peak eastward in 24 hours



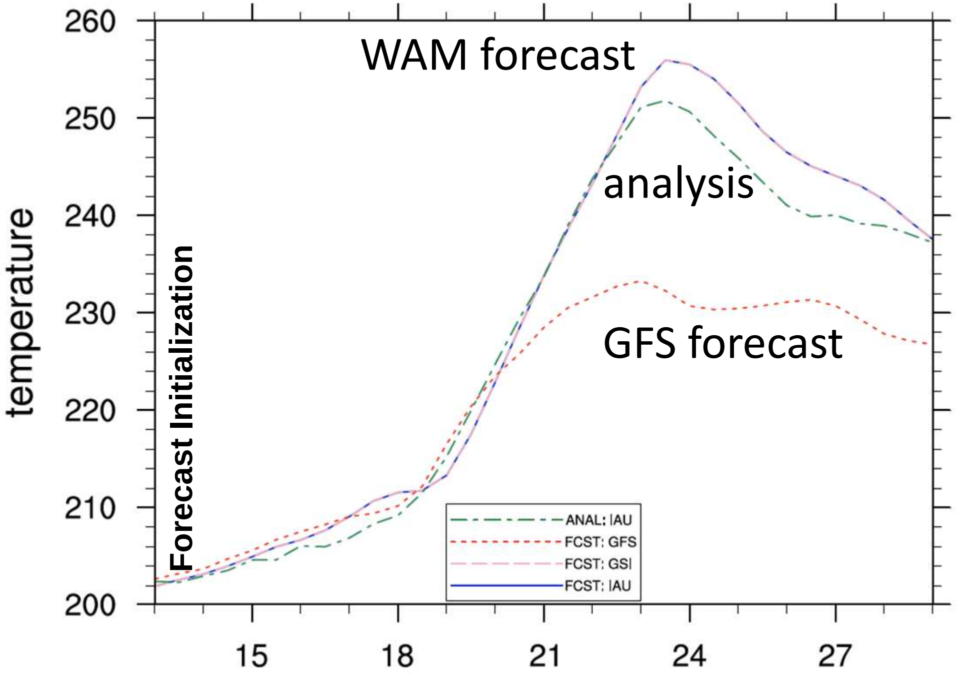


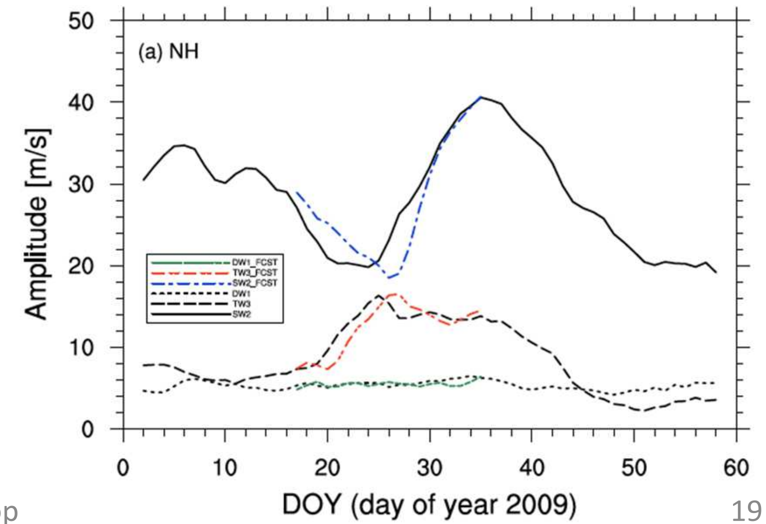
Ionosphere, electrodynamic, and tidal response can be forecast at least a week ahead (Wang et al., 2011)

Initialized with analysis using operational data on Jan 13th, WAM is able to forecast the warming and tidal response several days in advance (Wang et al. 2011), farther ahead than the NWS GFS operational model

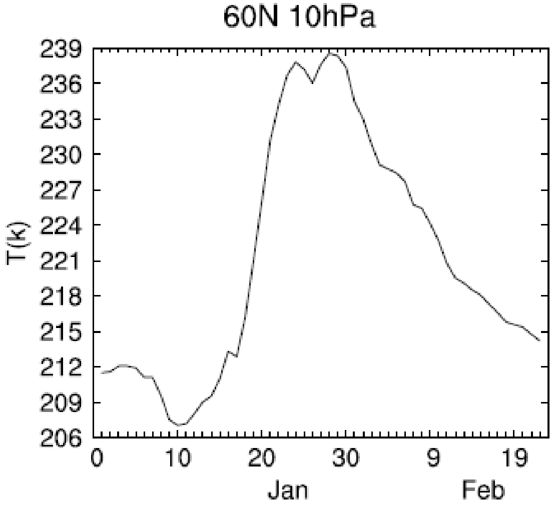


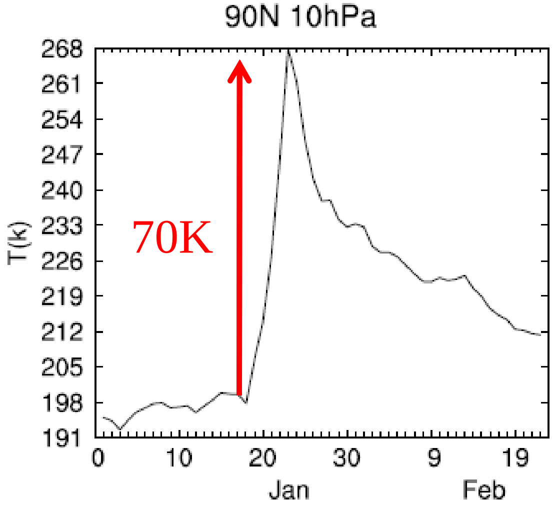
WAM also has potential to improve long-range tropospheric weather forecasting – so-called “downward control”

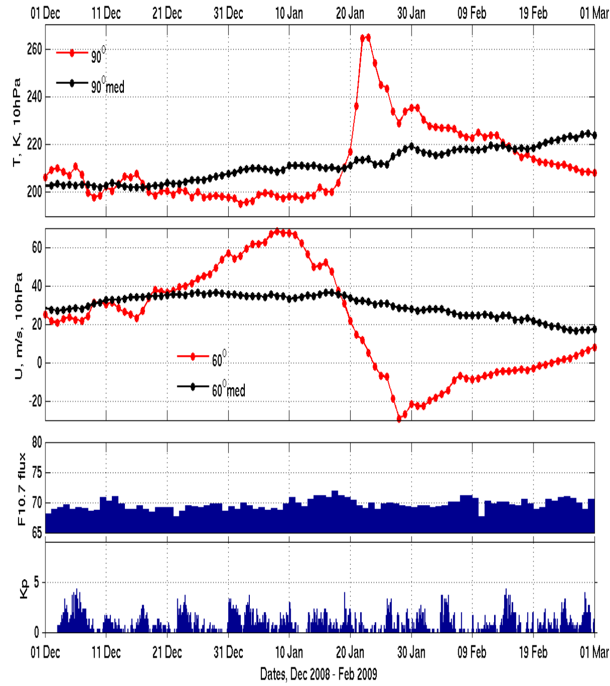


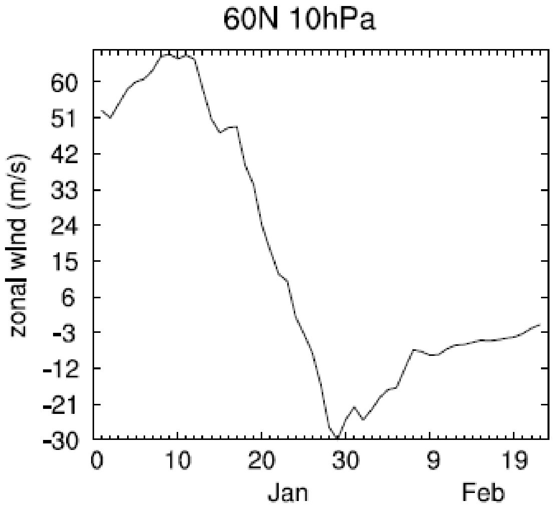


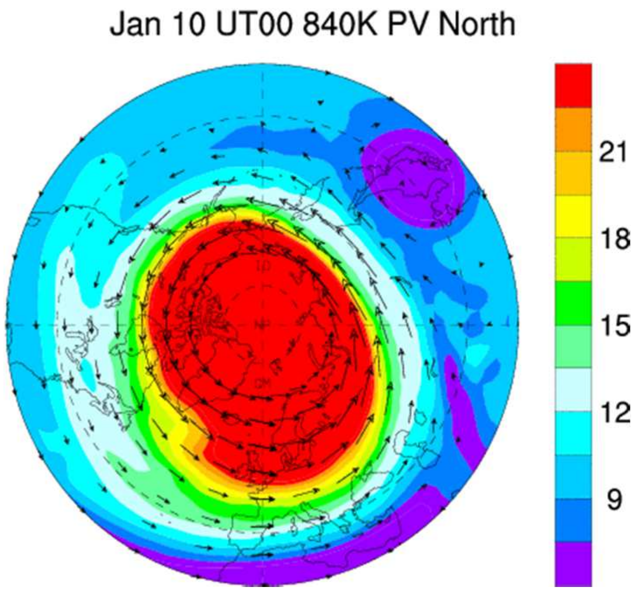
WAM simulations of the January 2009 sudden stratospheric warming









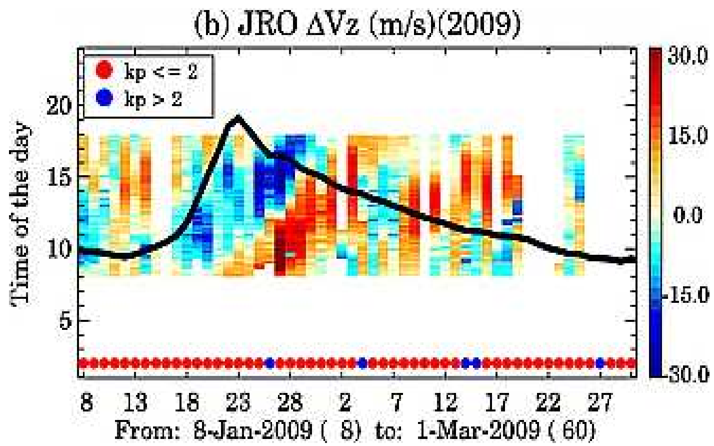


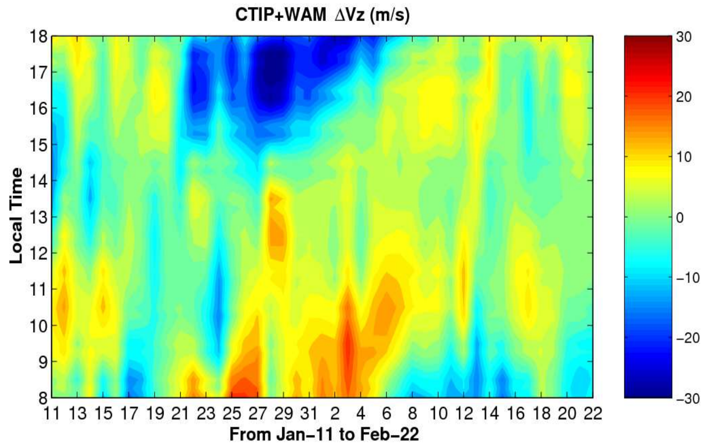
Same as ECMWF

"validation"

Electrodynamic comparison JRO vs WAM-CTIPe

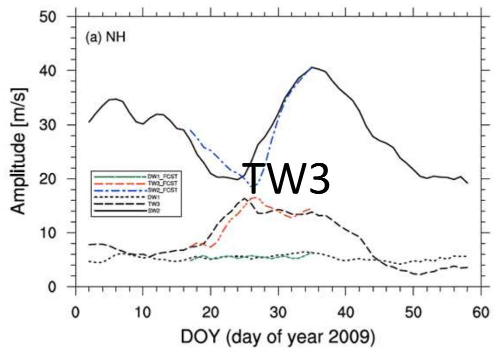
Chau et al.





- CTIPe simulations with WAM winds (lower panesl) appear to reproduce the main features in the observed vertical plasma drift (upper panel) during a SSW, including the stronger upward drift early in the morning and reversal to downward in the afternoon
- Largest tidal changes during interval are in SW2 and TW3

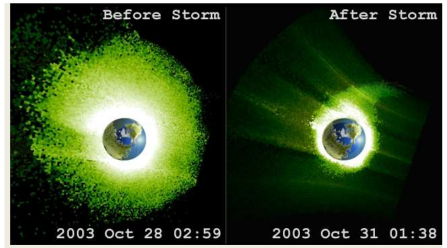
SW2

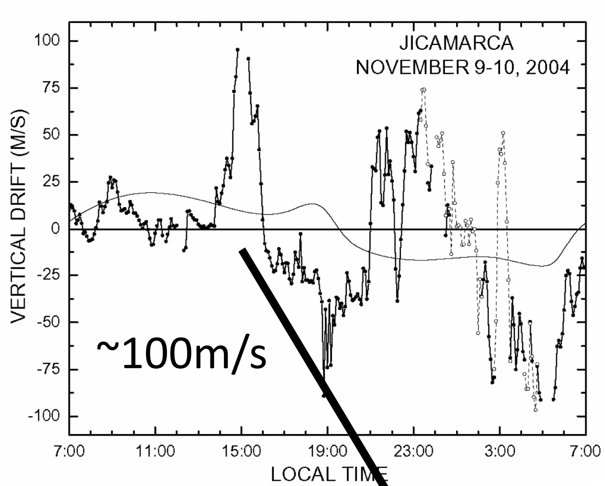


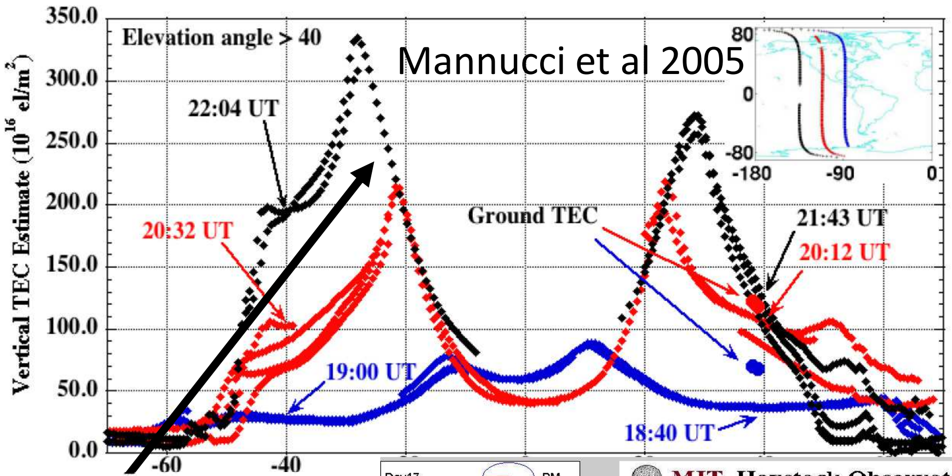
average 95-155km, 20 – 60° north

Fuller-Rowell et al. 2011

Combination of poleward movement of Equatorial Ionospheric Anomalies (EIA) due to penetration electric field and build-up of mid-lat plasma by the Heelis effect







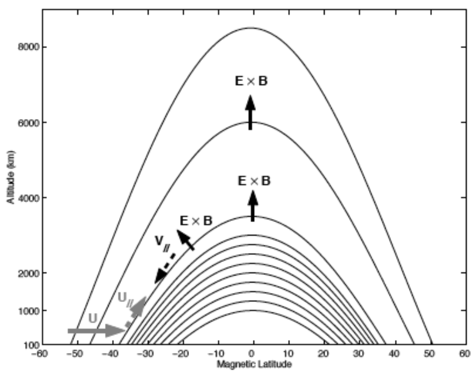


Figure 6. Schematic of the competing effect of the downward field-aligned diffusion and the upward movement of the plasma produced by an equatorward neutral wind at mid latitudes.

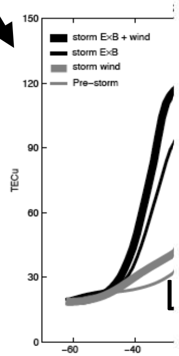
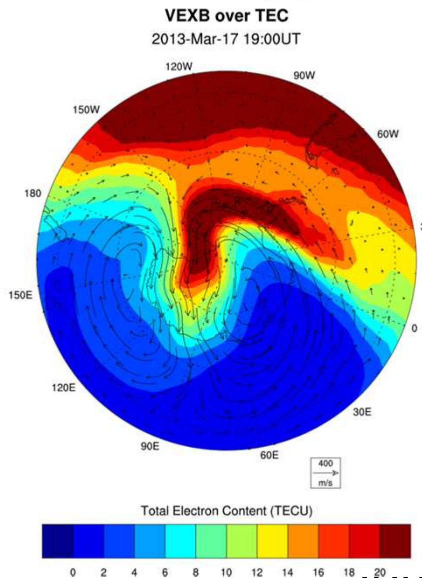
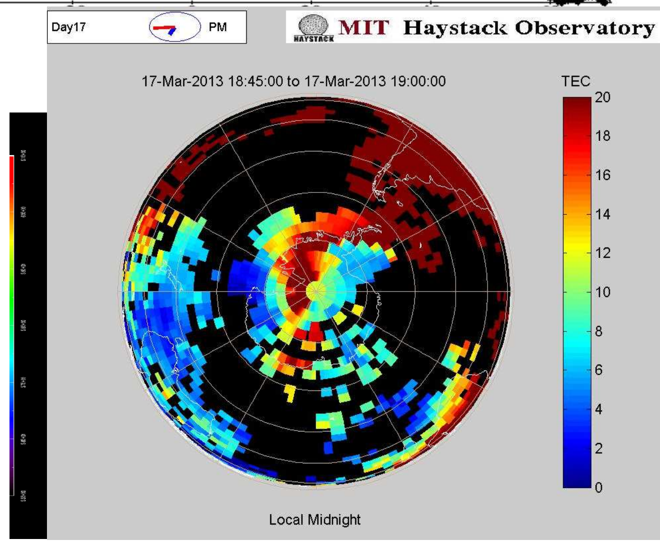


Figure 10. The total electro SUPIM results at 23:30 UT (thin gray line), case 1 (bold line).





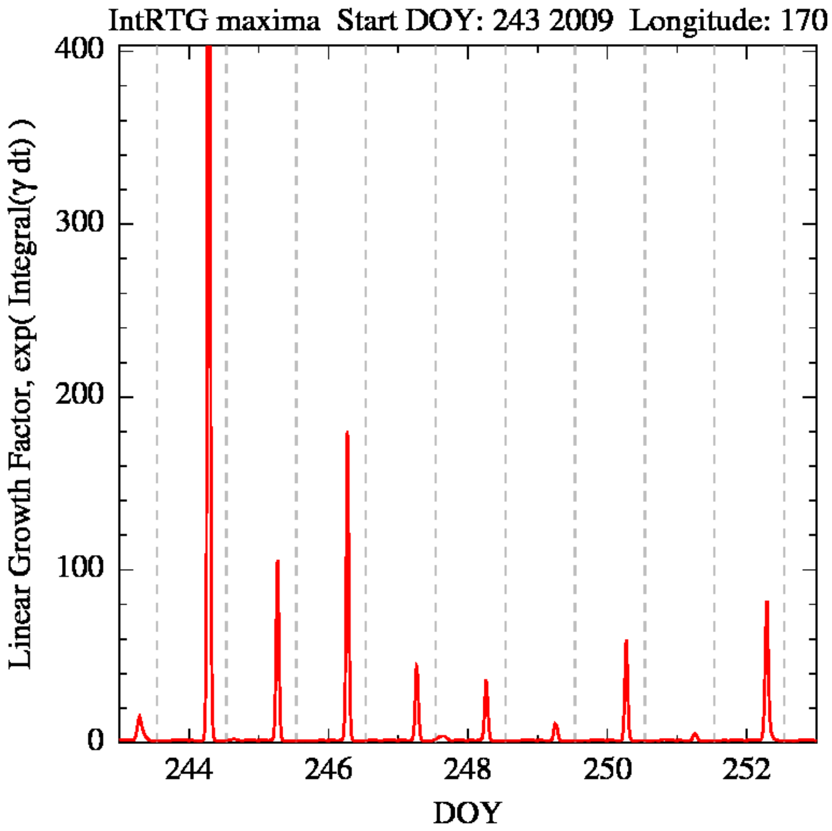
Penetration electric field and plasma drift at the magnetic equator

Ionospheric positive storm due to expanded convection, Heelis mechanism

RT Growth Rates

Calculated using WAM winds and electric fields to drive ionospheric structure

Kwajalein longitude sector



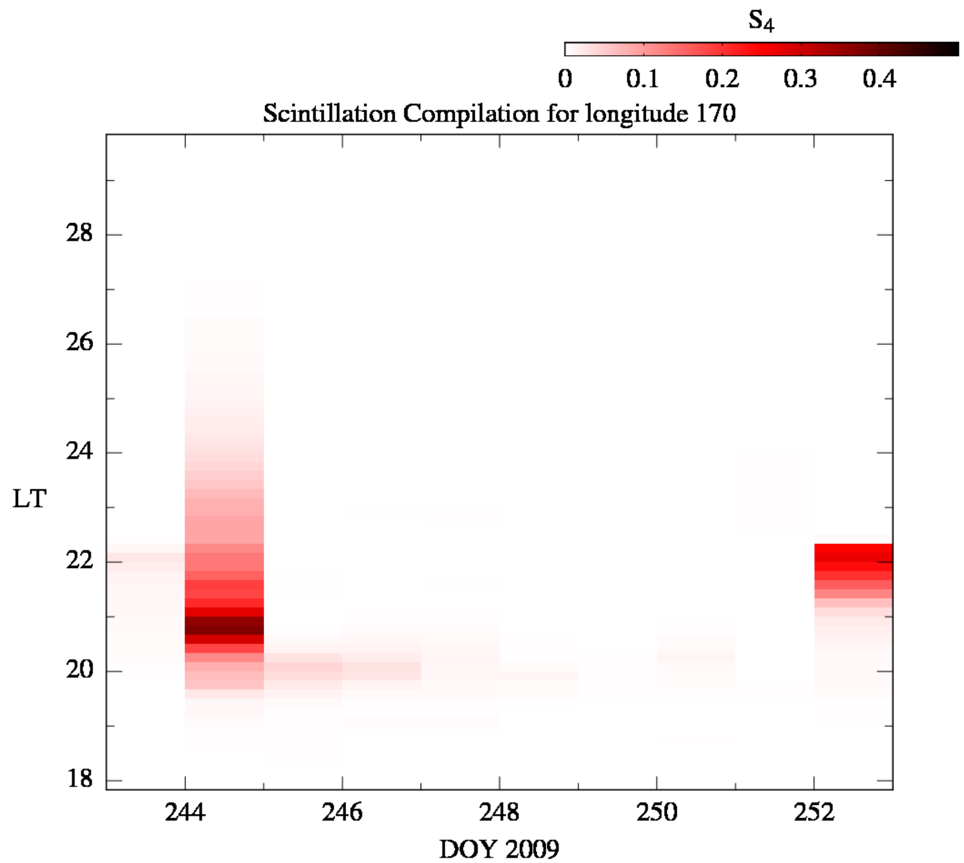
Red: Exponential of integrated growth rate, giving the linear amplification factor for the amplitude of an unstable mode

Gray dashed lines mark local midnight

Certainly demonstrates significant day-to-day variability of strength of instability

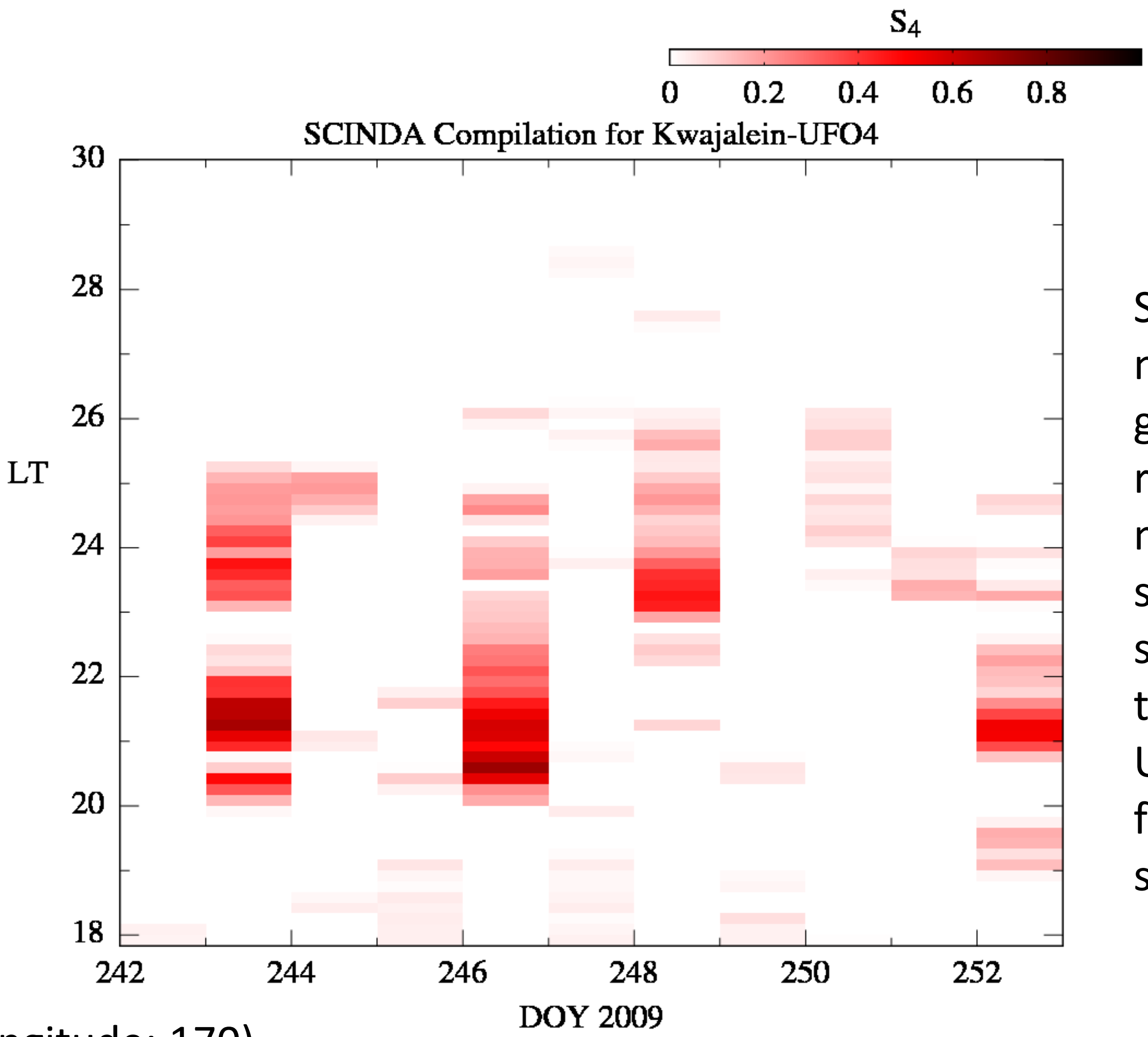
Linear growth factor is large (i.e., exceeds 50) on 5 days out of 10

Scintillation History, Longitude 170



Certainly captures day-to-day variability of irregularities; frequency of occurrence (4/10) is similar to SCINDA rate

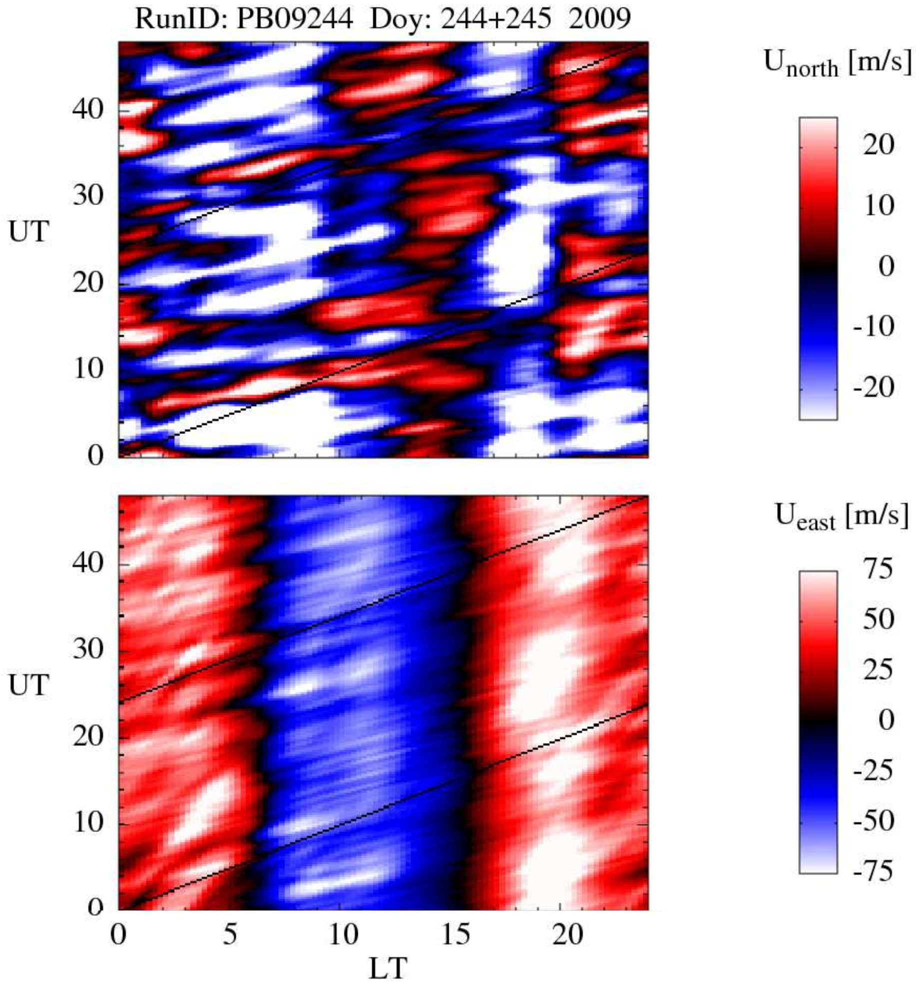
Baseline Observations

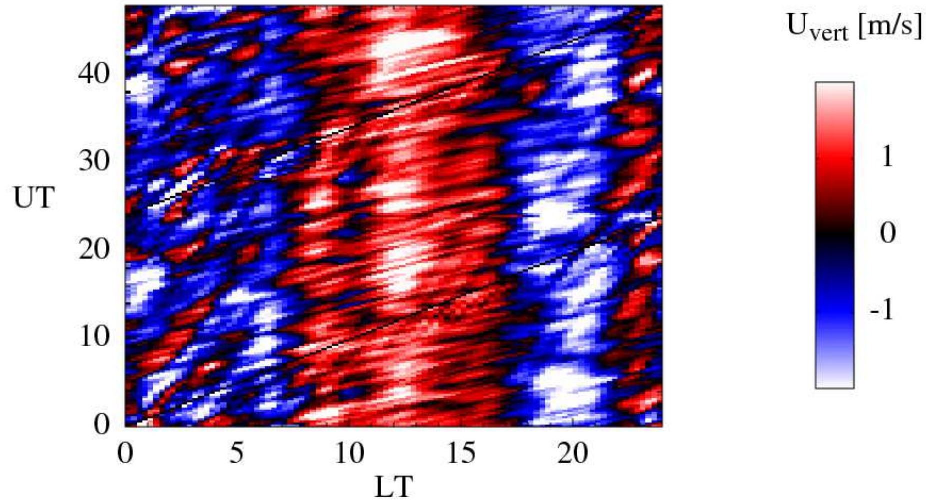


SCINDA: USAF network of ground-based receivers monitoring the strength of satellite transmitters at UHF radio frequencies for scintillation

Kwajalein (longitude: 170)
Significant scintillation occurs 4 out of 10 evenings: frequency = 40 %
T_{onset} usually around 20 LT; peak S_4 around 0.5

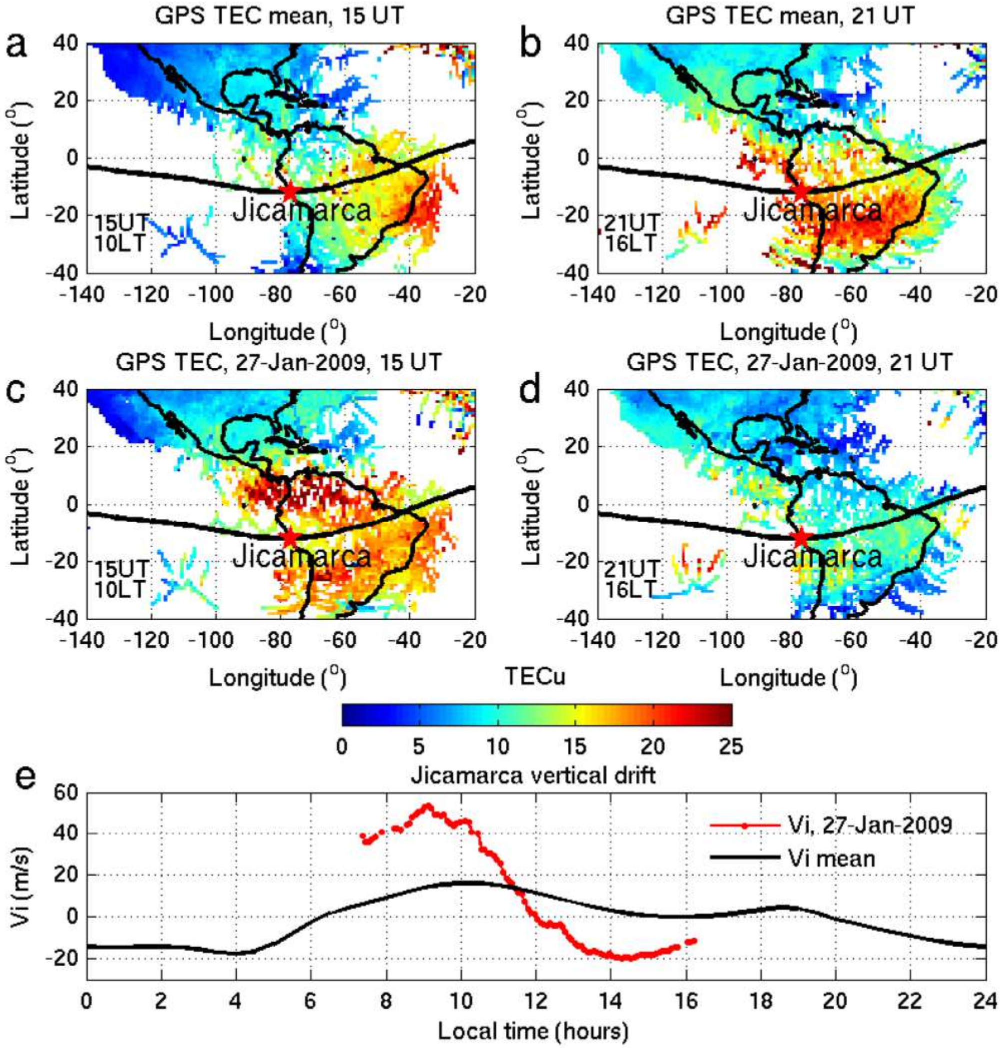
Variability/Structure of WAM Winds





The mean winds on Days 244 and 245

2009 Strat-warm Impact on Ionosphere and Space Weather



Goncharenko et al. (2010):

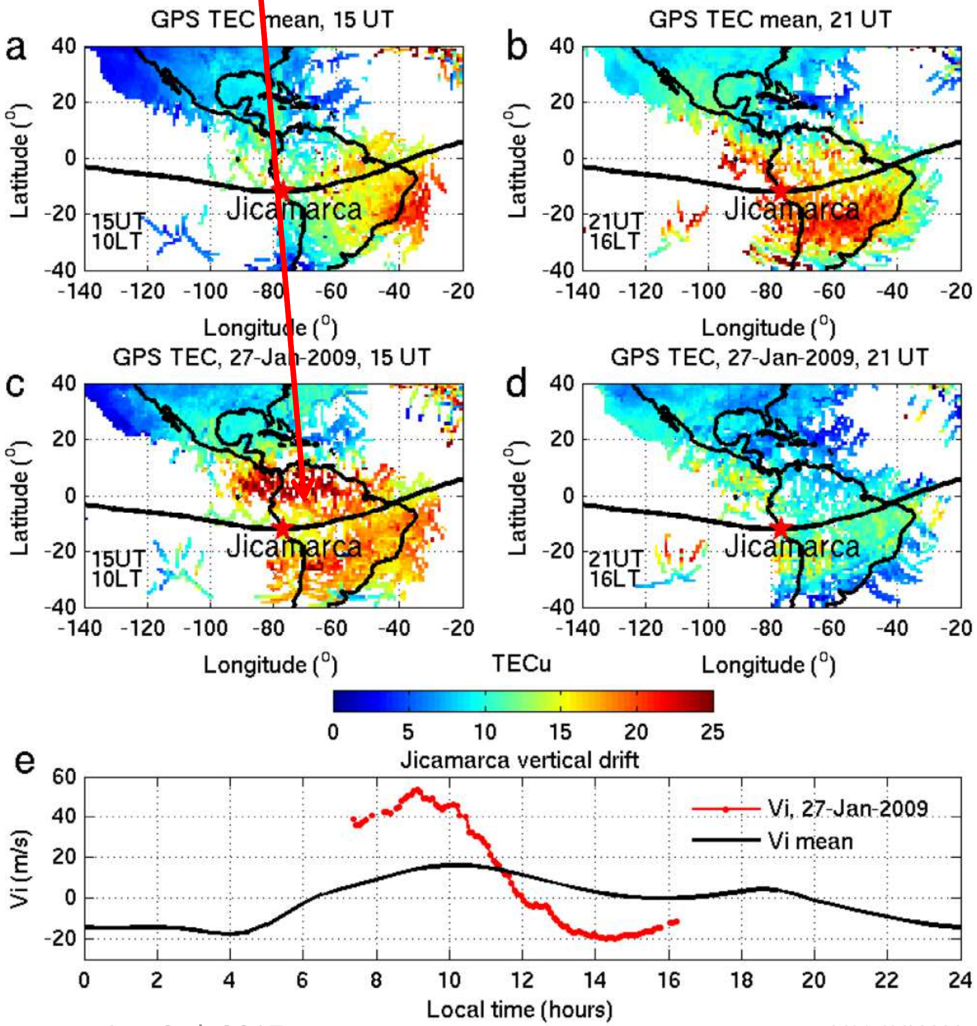
Climatological TEC @ 10 and 16 LT from ground GPS observations.

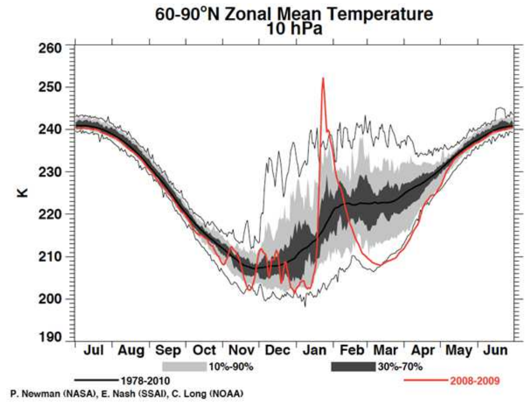
Same on January 27, after the peak of the warming.

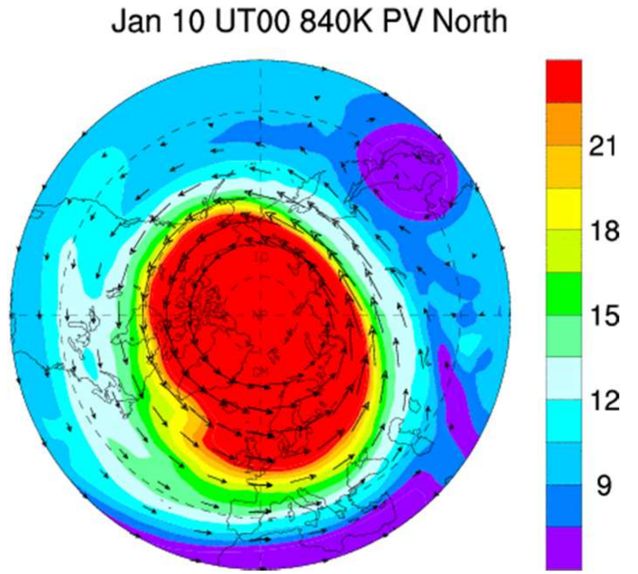
Comparison of plasma drift climatology with observations on Jan. 27.

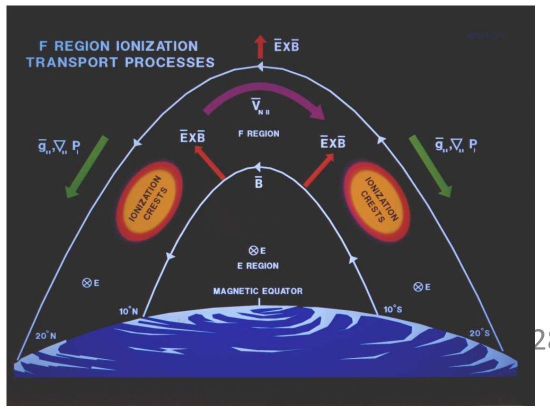
50% increase in TEC in January 2009 when solar and geomagnetic activity were very low

Goncharenko et al. 2010





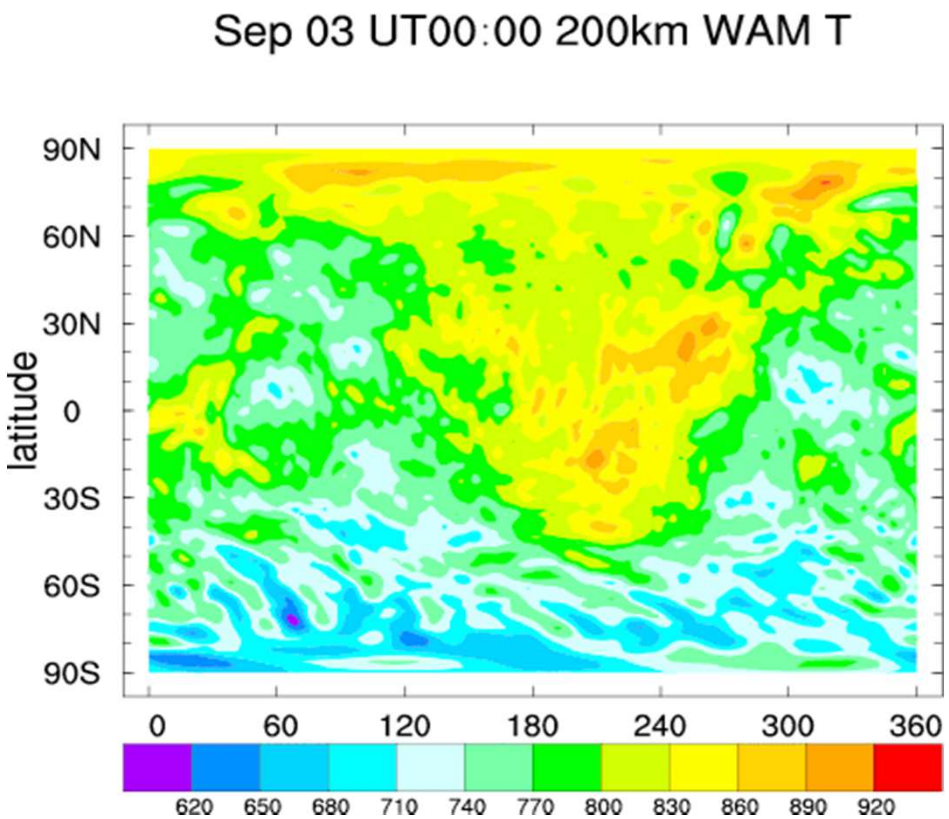




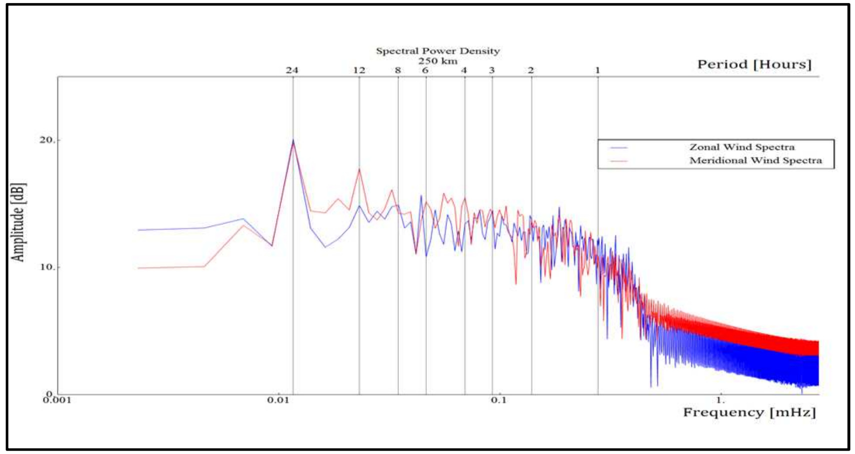
A response to changing vertical plasma drift driven by tides

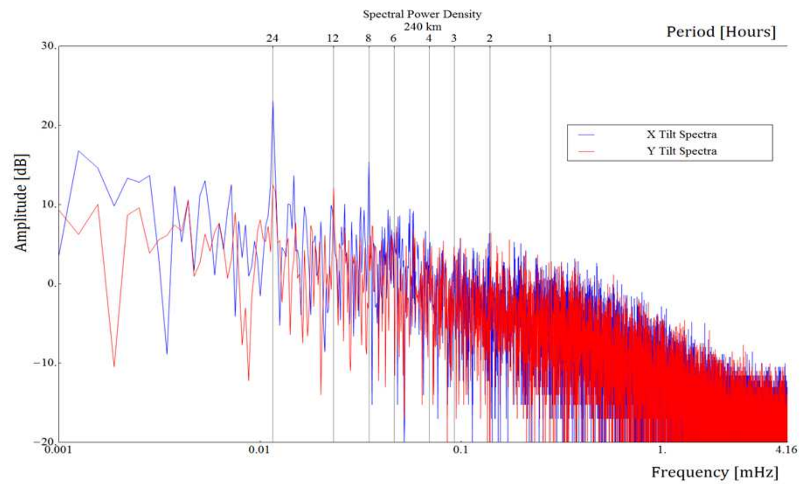
Whole Atmosphere Model (WAM) with coupled ionosphere

WAM spectrum with 180 km grid – cuts off at about 25 minute period



WAM spectrum of waves

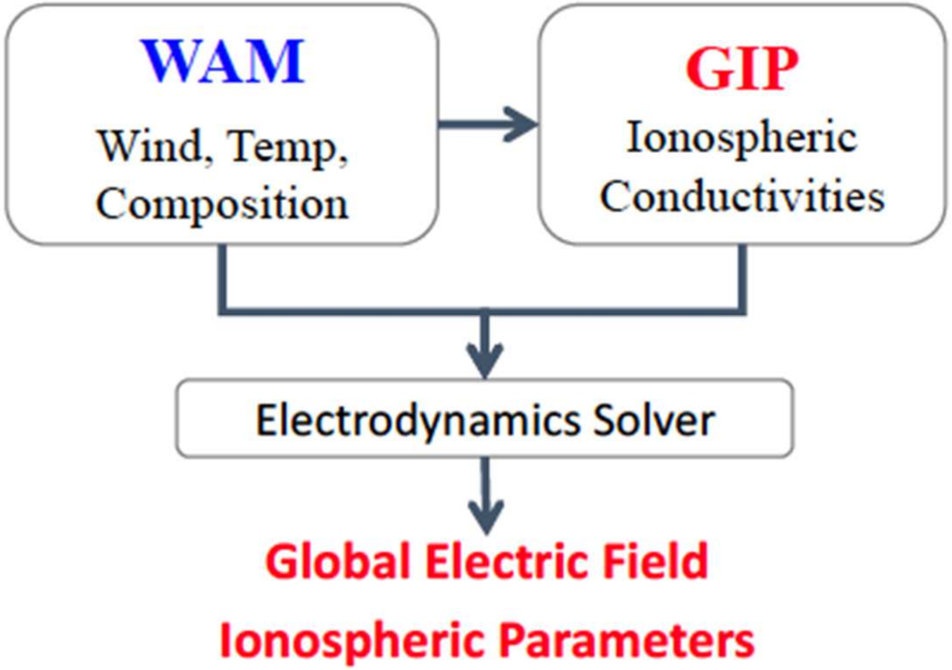




Dynasonde tilt spectrum Catalin Negrea

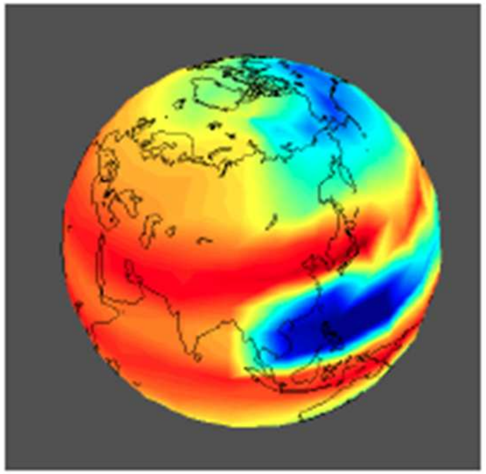
Whole Atmosphere Model (WAM)

- Extended Global Forecast System (GFS) upper boundary from 64 km to 600 km
- Resolution $2^\circ \times 2^\circ$ in latitude-longitude, H/4 in altitude
- Free or forecast runs
- Height dependent g(z)
- Orographic gravity waves parameterization
- Horizontal & vertical mixing
- Radiative heating (EUV & UV) and cooling
- Ion drag & Joule heating
- Major species composition, Eddy mixing
- Non-orographic gravity waves parameterization
- Improved neutral composition
- Daily UV and EUV from SDO-EVE, GOES-XRS, and TIMED-SEE for solar heating and dissociation
- TIROS/NOAA auroral ionization is included
- Real time solar and geomagnetic indexes

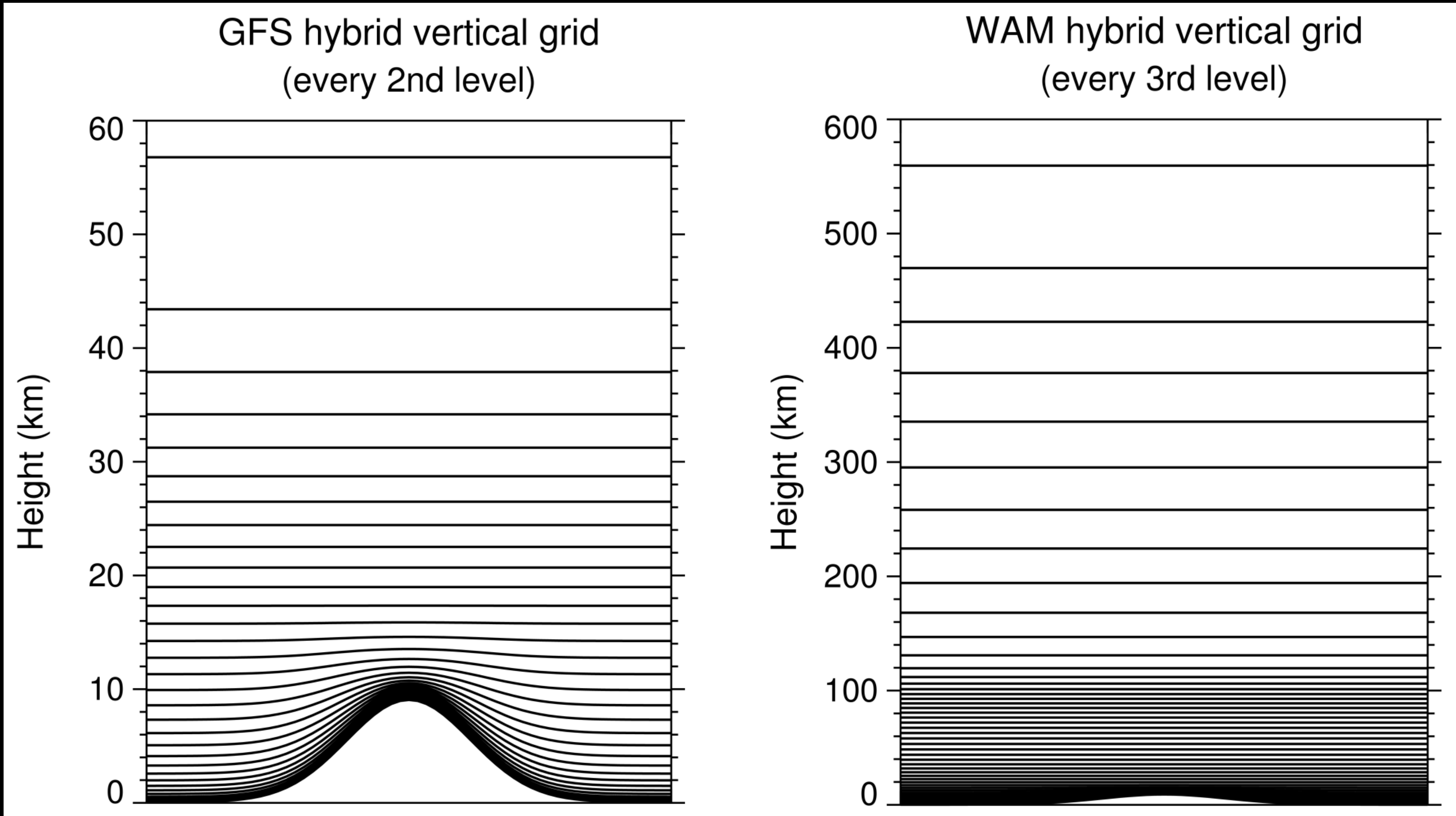


Global Ionosphere and Plasmasphere Model (GIP)

- The horizontal resolution in the low-latitude region is about 1° in latitude and 4.5° in longitude. In altitude, it covers the plasmasphere and gives information from 100 km to higher than 20,000 km.
- It solves continuity, momentum, energy equations and outputs are Ni (O^+, H^+, O_2^+, NO^+, N_2^+, N^+), Ne, Ti, Te and Vi.
- The apex coordinate system (*Richmond*, 1995) is adopted in the structure of magnetic field, in which a global three-dimensional grid are created by tracing through the full International Geomagnetic Reference Field (IGRF).
- Daily UV and EUV from SDO-EVE, GOES-XRS, and TIMED-SEE for solar ionization
- Real time solar and geomagnetic indexes

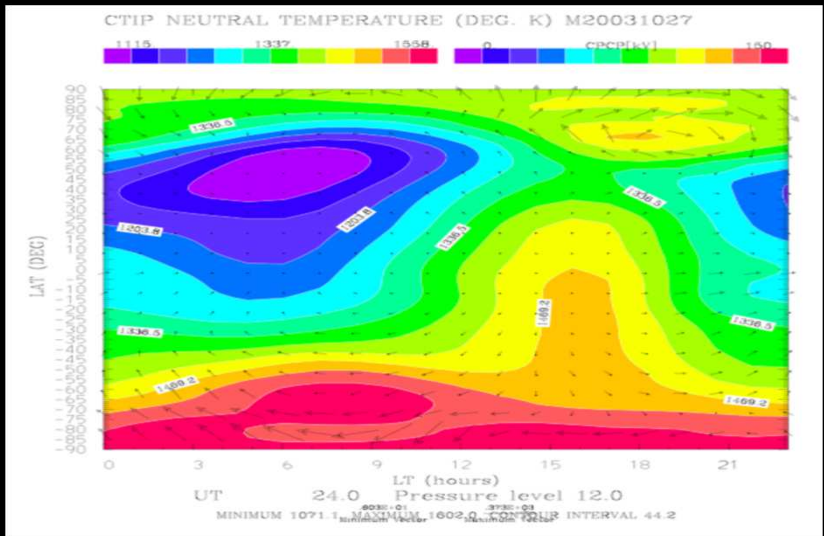


WAM = Extended GFS

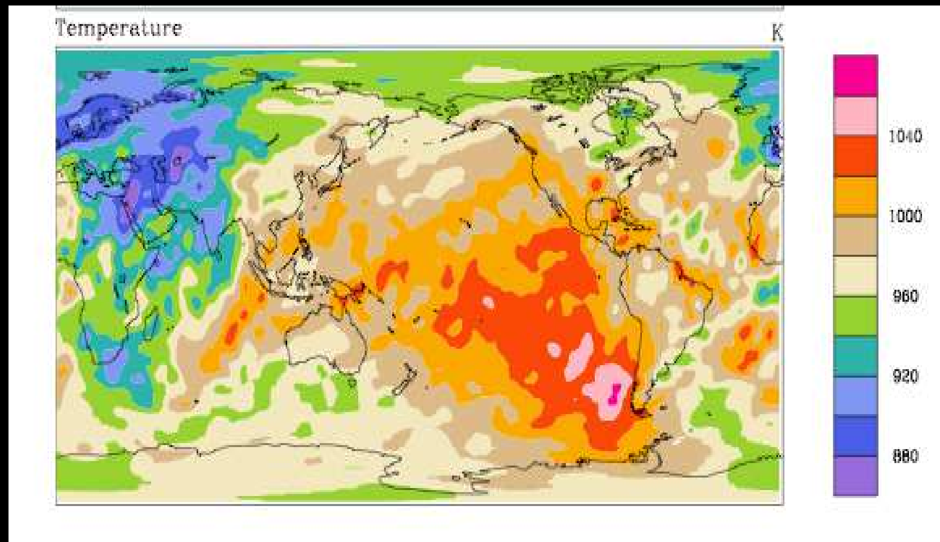


With and Without WAM:
Adding the Lower Atmosphere

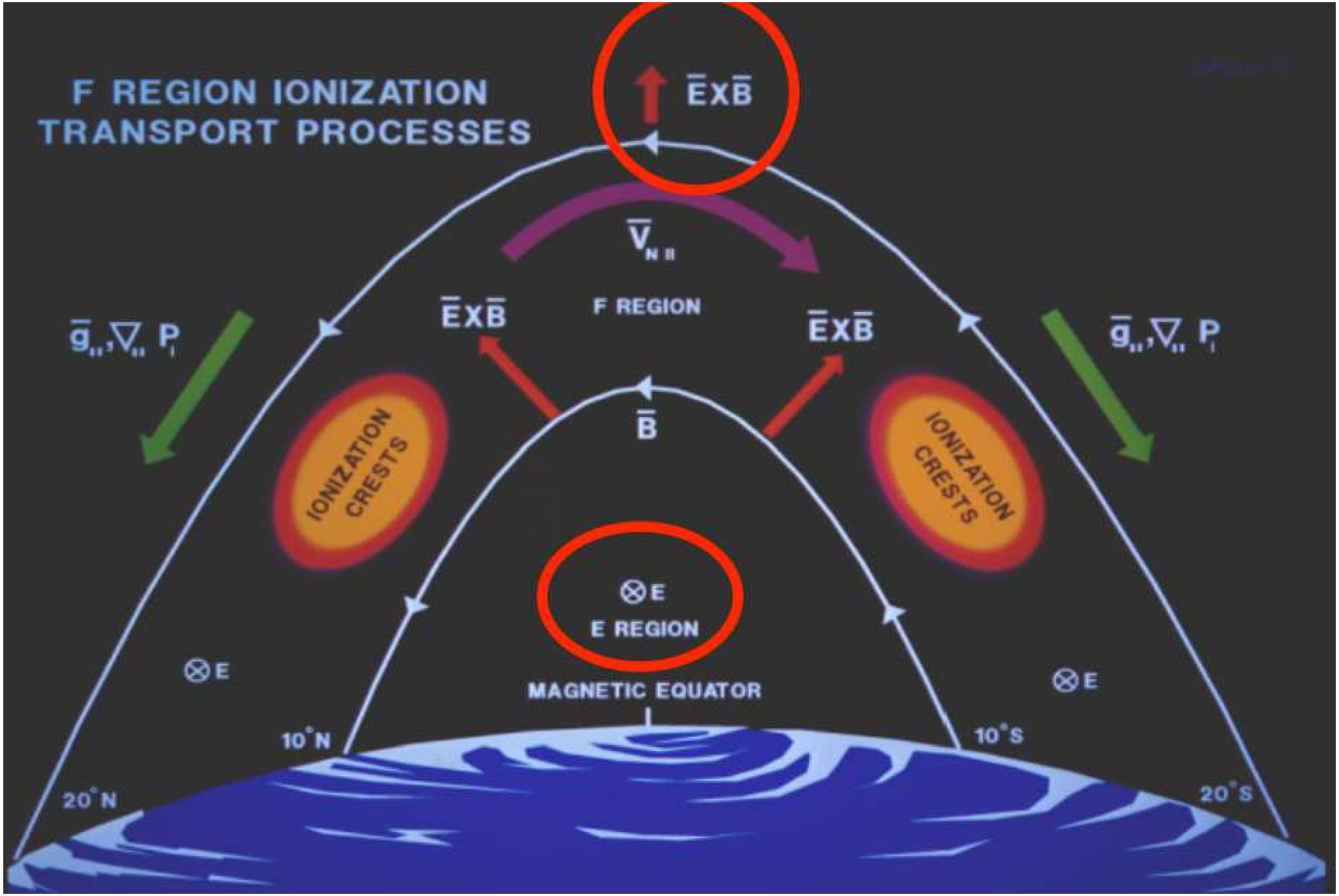
Typical ionosphere-thermosphere model: Global maps show little fine structure



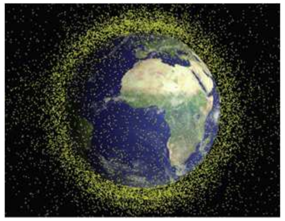
Ionosphere-thermosphere model coupled to the lower atmosphere: Global maps show structure relevant to GPS accuracy and available



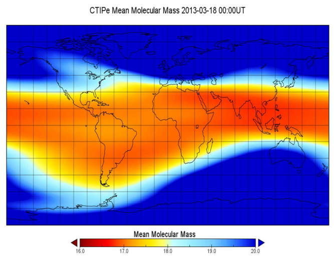
The temperature structure from a stand-alone thermosphere ionosphere plasmasphere model (e.g., CTIPe) is similar to the MSIS empirical model. The Whole Atmosphere Model (WAM) drives variability from the chaotic lower atmosphere which introduces a whole spectrum of variability.


F REGION IONIZATION
TRANSPORT PROCESSES
ExB
V N ||
F REGION
ExB
ExB
g||,∇|| Pi
g||,∇|| Pi
IONIZATION CRESTS
IONIZATION CRESTS
B
⊗E
E REGION
⊗E
⊗E
MAGNETIC EQUATOR
10°N
10°S
20°N
20°S

Contents



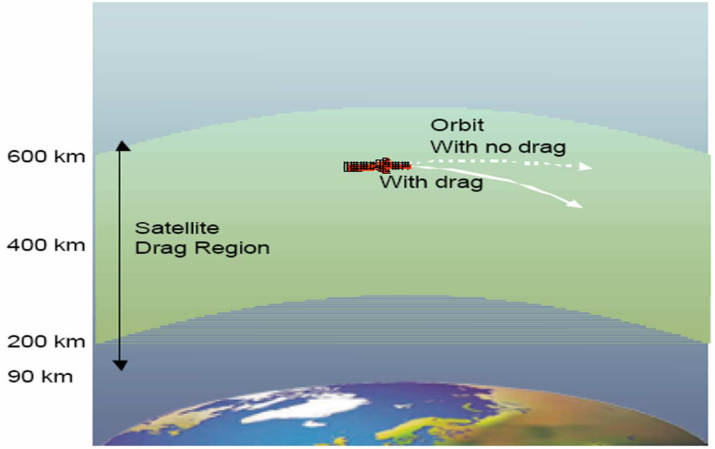
- Neutral density and satellite drag
- Positive and negative phases of ionospheric storms impacting communications and positioning, navigation, etc.



- Other sources of ionospheric variability
- Small-scale waves from the lower atmosphere
- Ionospheric irregularities
- Large scale waves and longitude structure
- Sudden stratospheric warmings

Thermospheric Density Effects on Orbit Prediction and Collision Avoidance

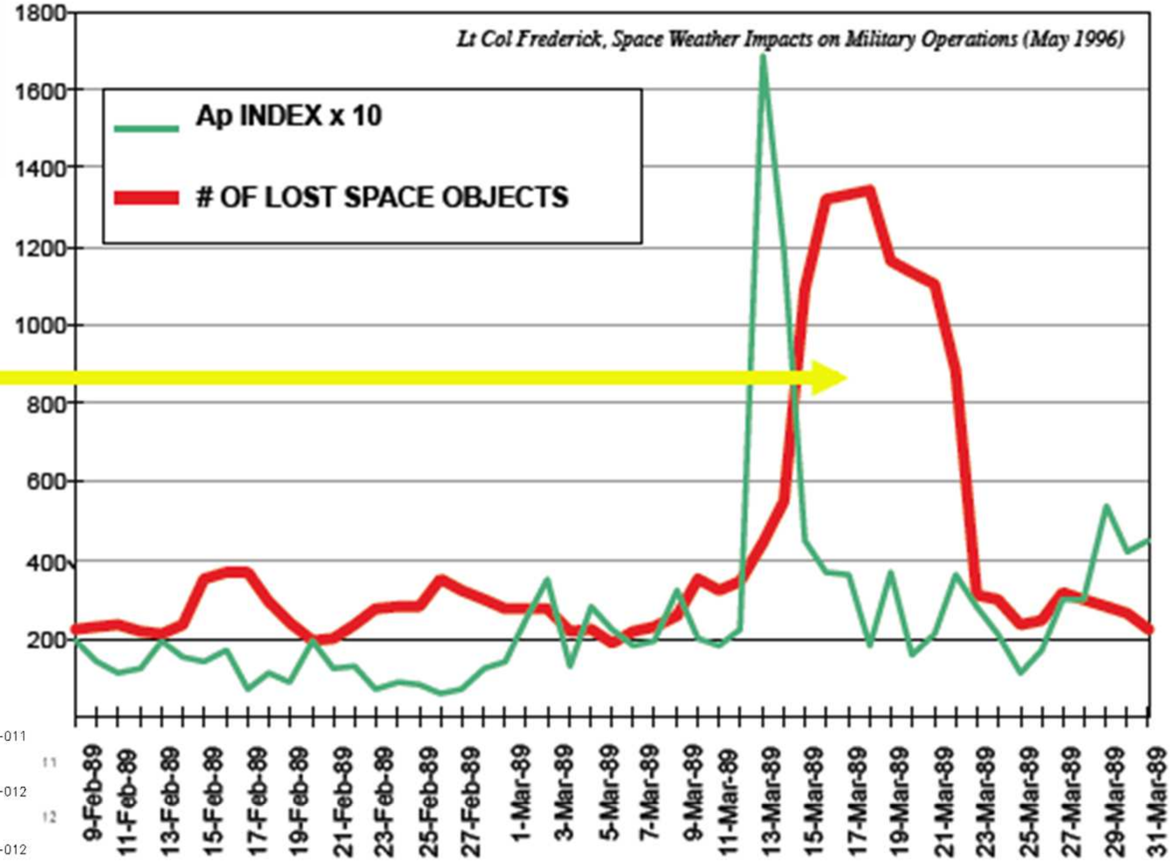
Tracking Space Objects

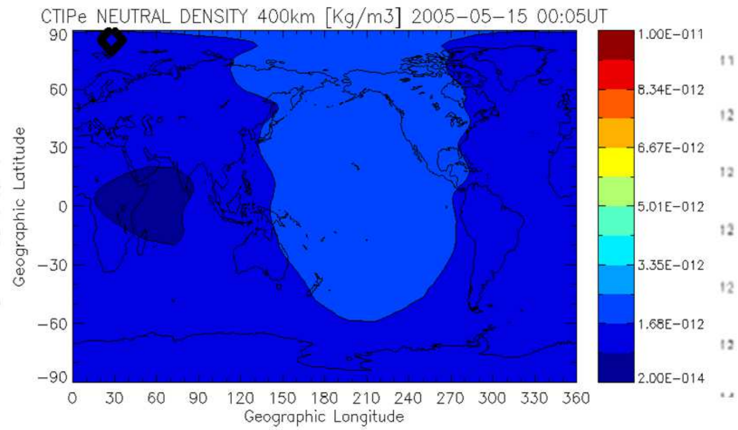


Tracking of Space Objects

During the geomagnetic storm of March 1989, more than 1000 objects were temporarily lost for a period of several days.

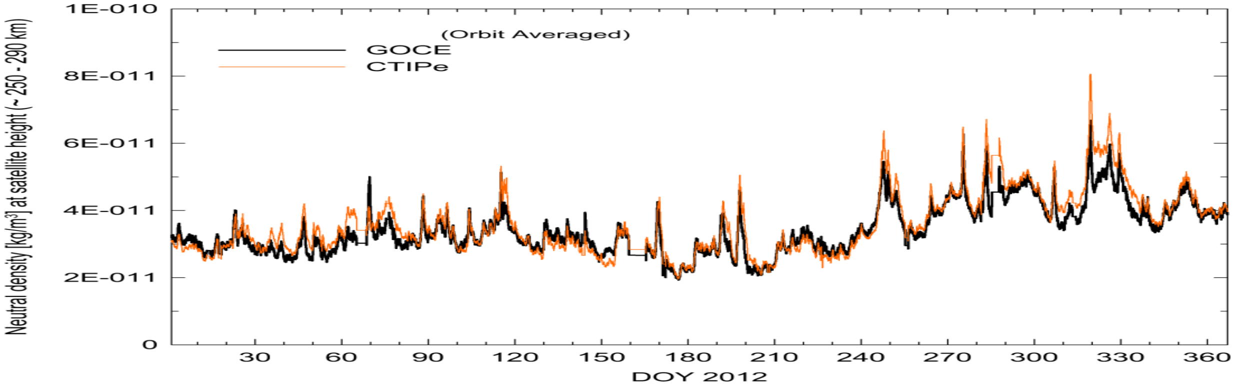
This was a direct effect of increased atmospheric drag on the orbiting objects caused by a severe geomagnetic storm.

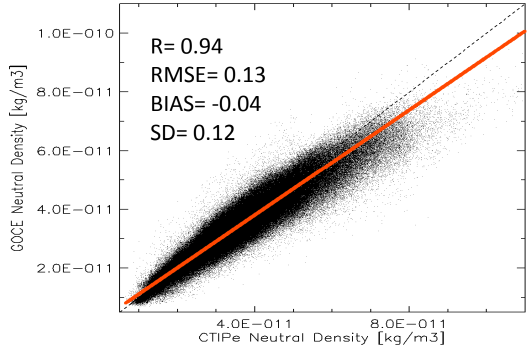


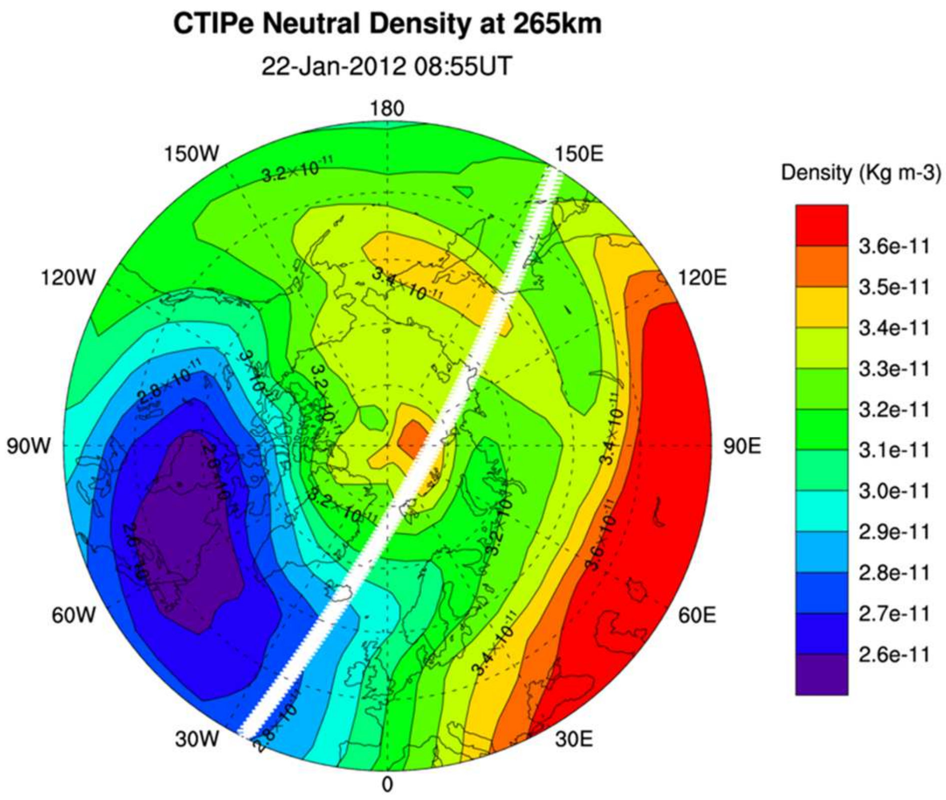


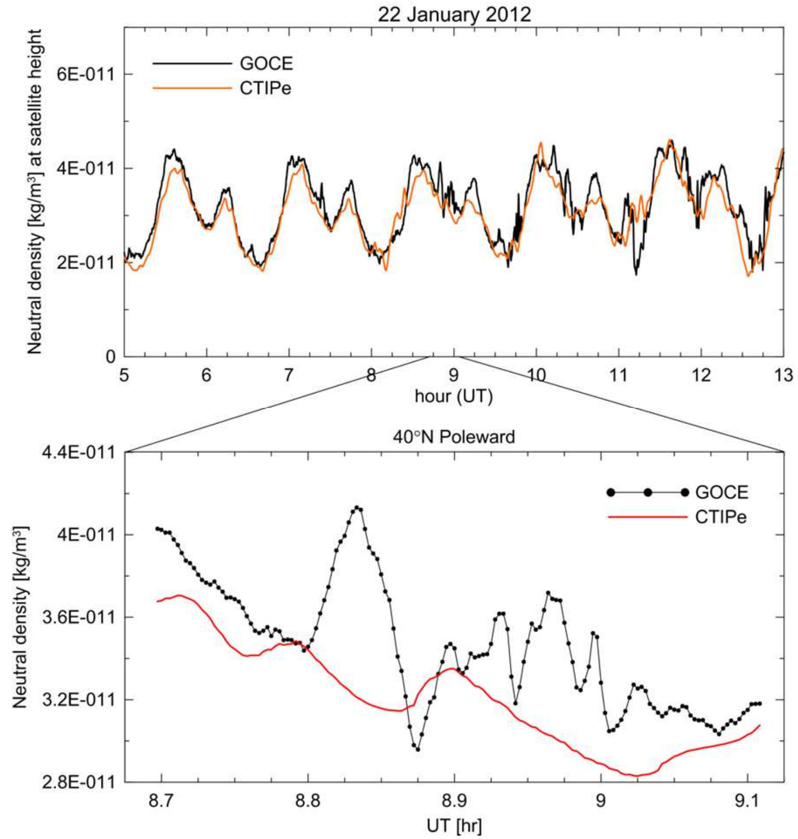
~20,000 pieces of debris > 5 cm are tracked
Collision between spent Russian satellite and Iridium and deliberate destruction of Chinese satellite added 5,000 pieces

CTIPe vs GOCE quiet

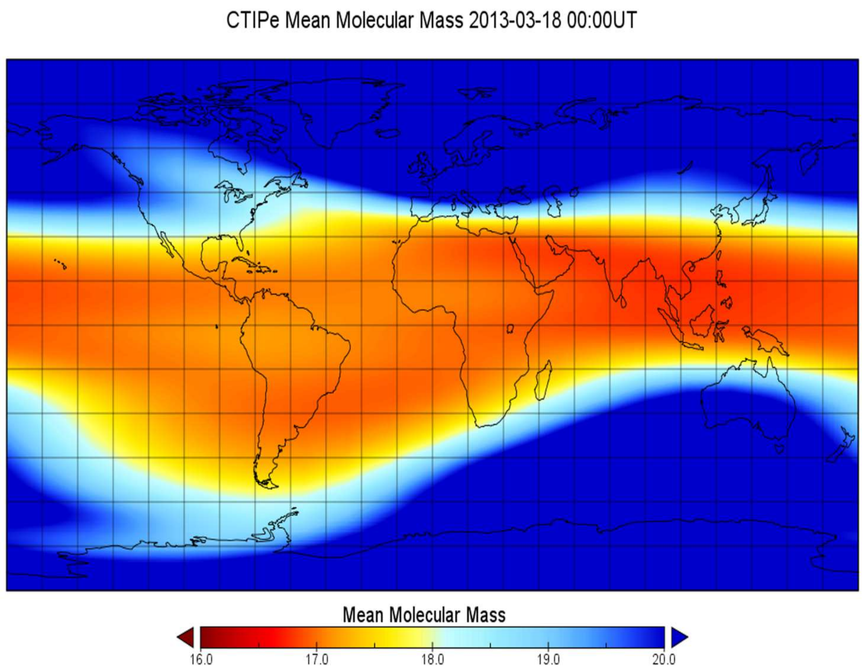


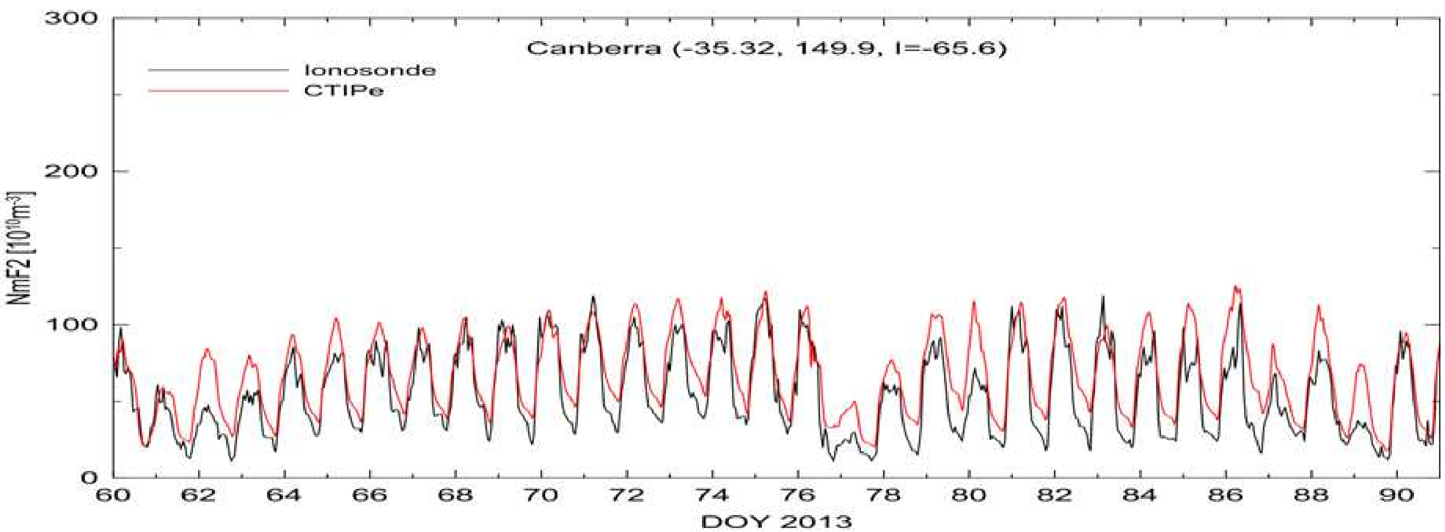




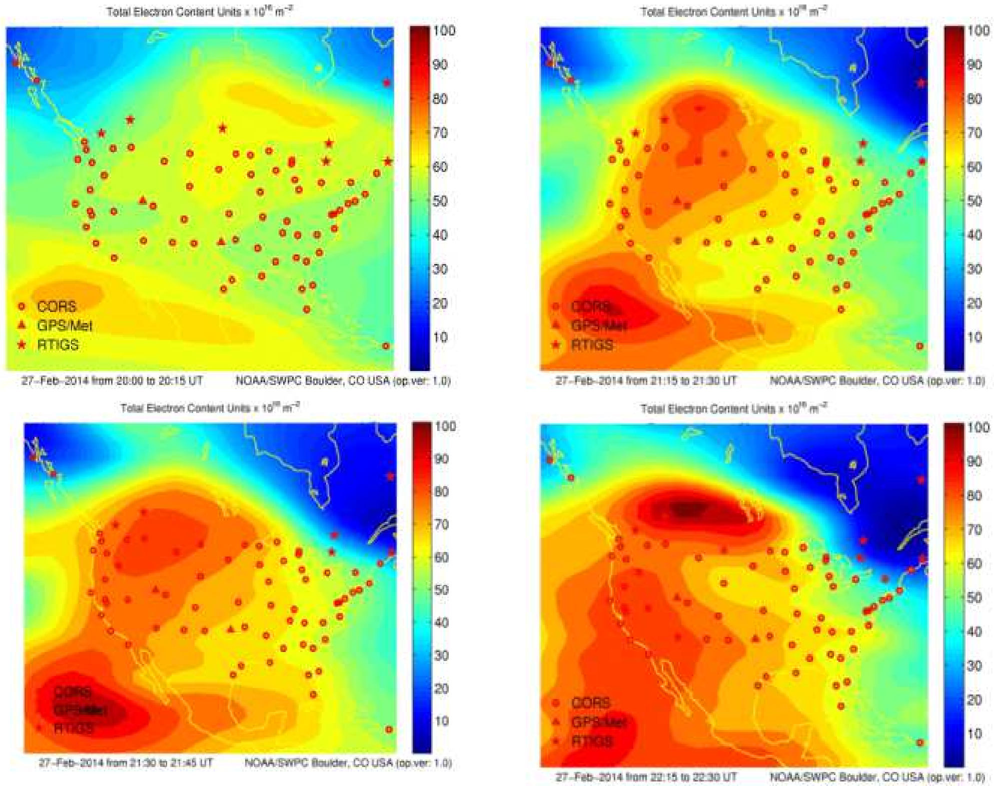


Neutral composition change and the “negative phase”

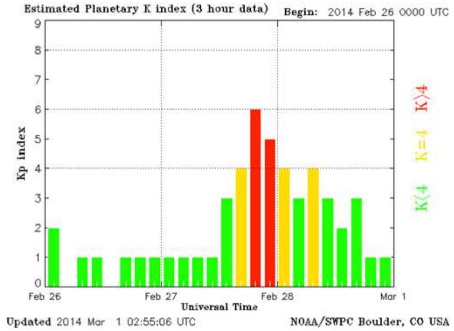


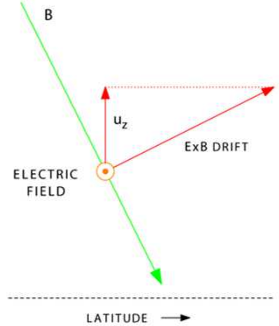


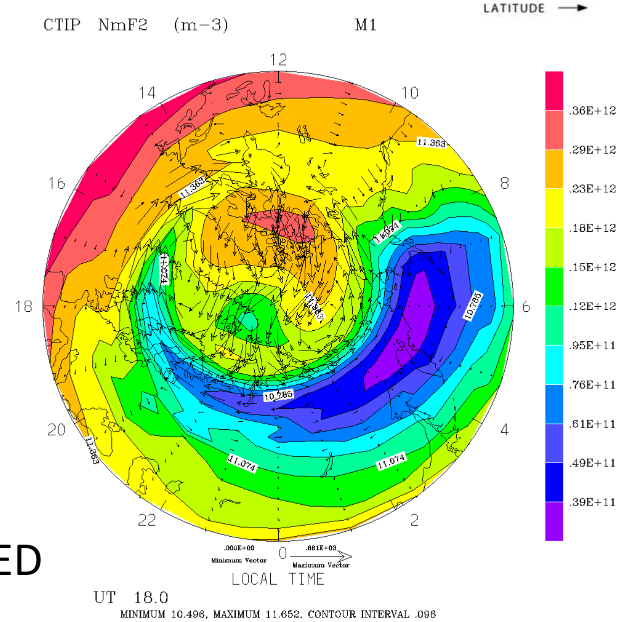
Positive phase -TEC response to expansion of magnetosphere convection

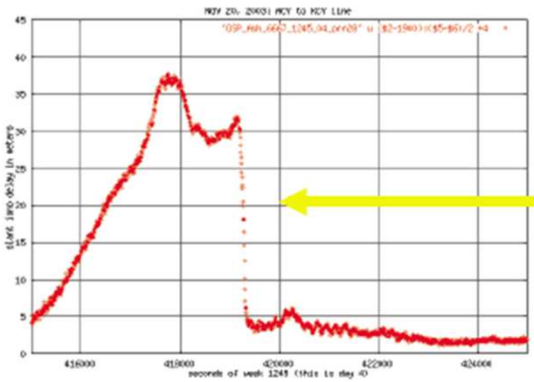


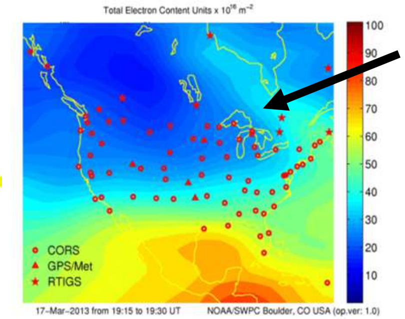
Response of SWPC US-TEC product to modest storm on Feb 27th 2014





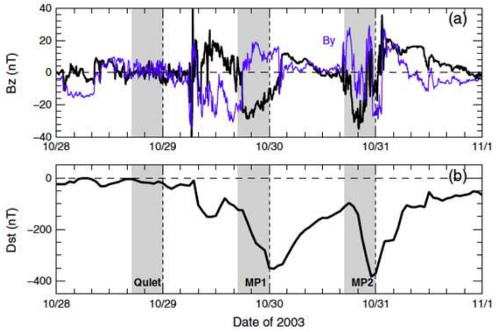




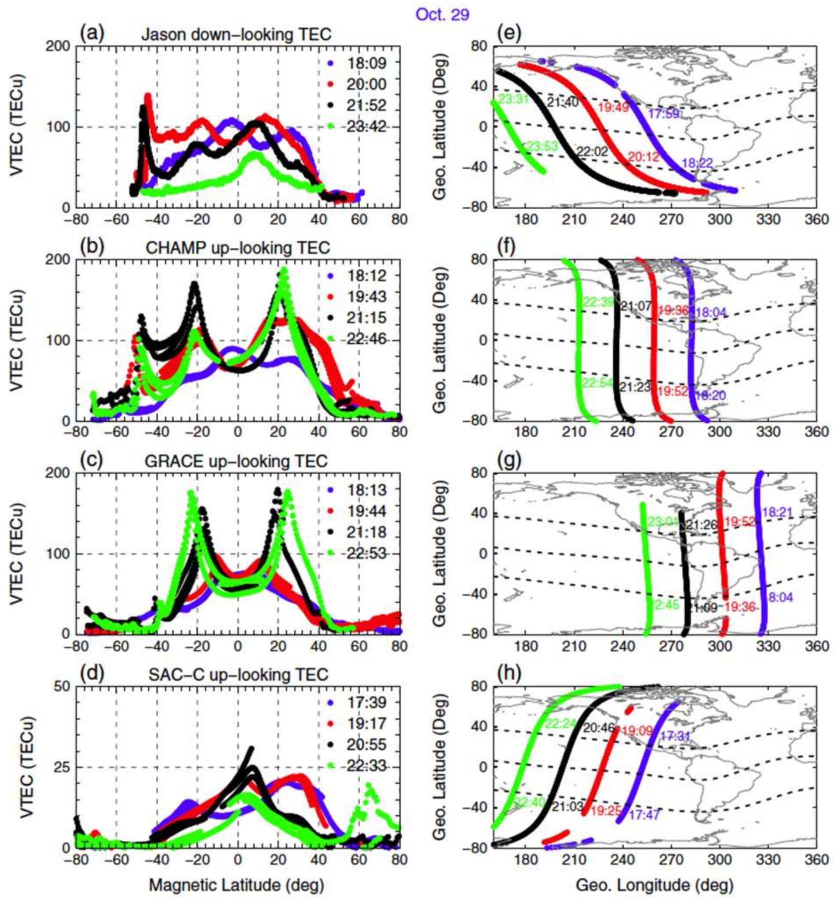


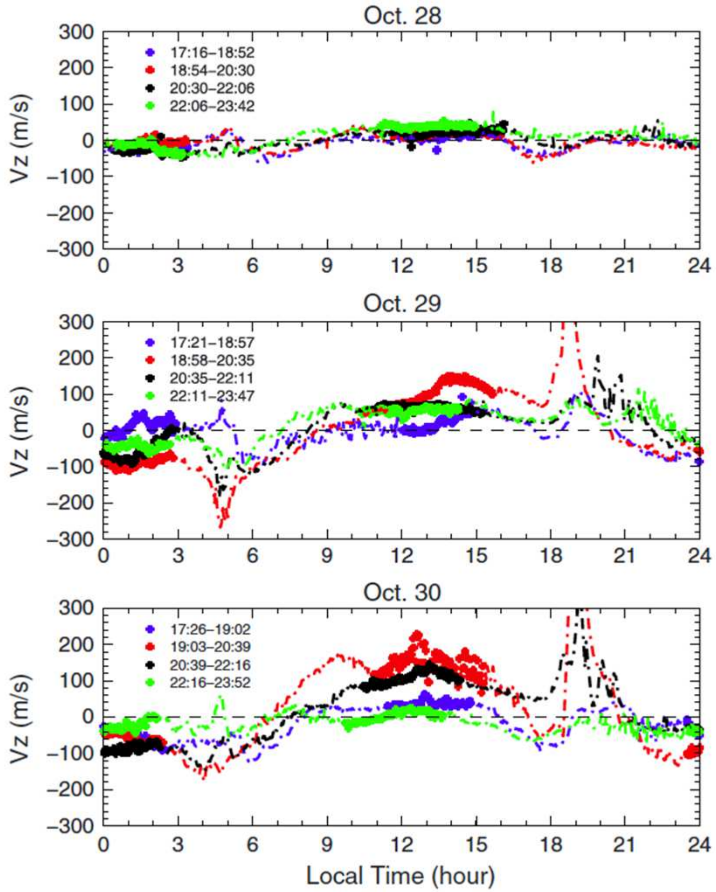
Storm Enhanced Density SED

compromises integrity of WAAS aviation navigation, 130 TEC units over 50 km, causes 20 meters of delay of GPS signals



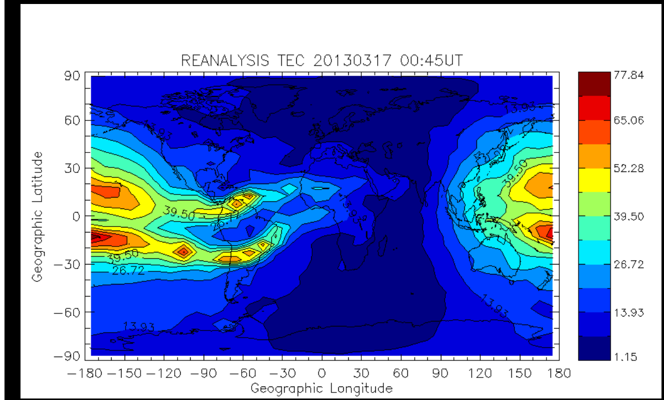
Halloween Storm Lei et al. 2012 Clear distinction between equatorial ionization anomaly peaks and SED

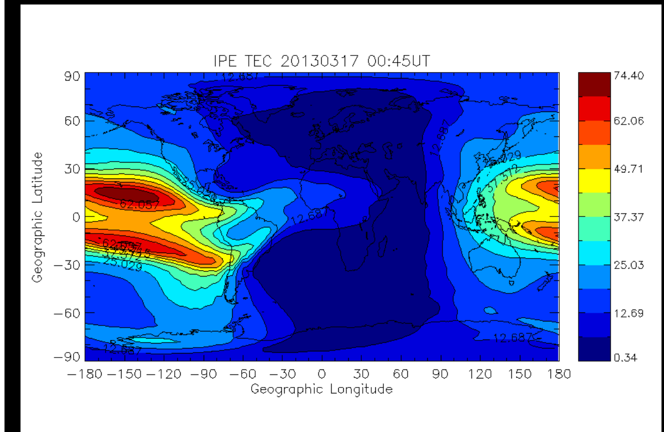


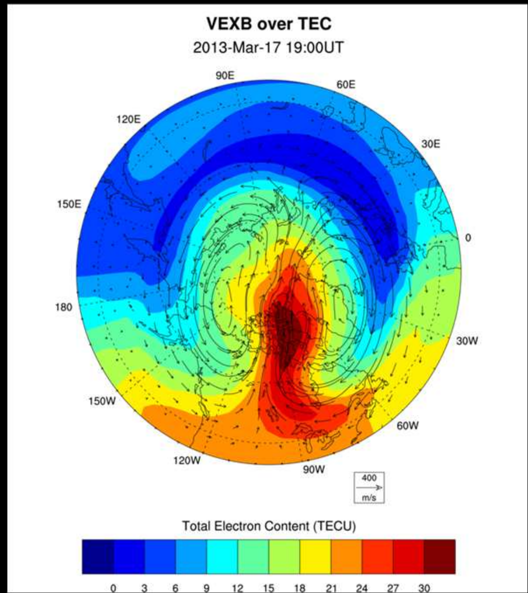


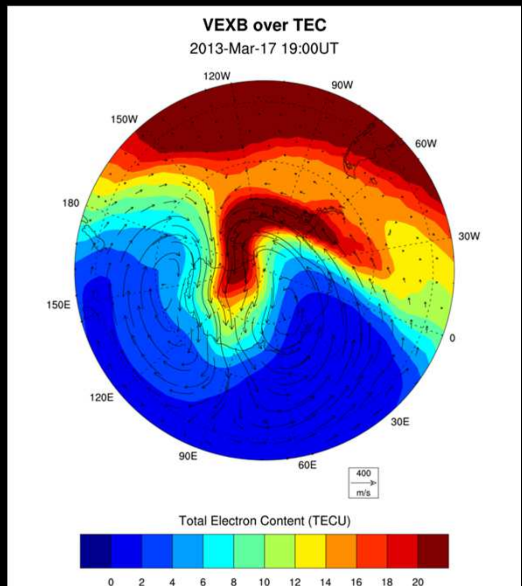
Vertical TEC above satellite altitude illustrates vertical distribution of plasma and storage of plasma in topside ionosphere driven by vertical ion drift

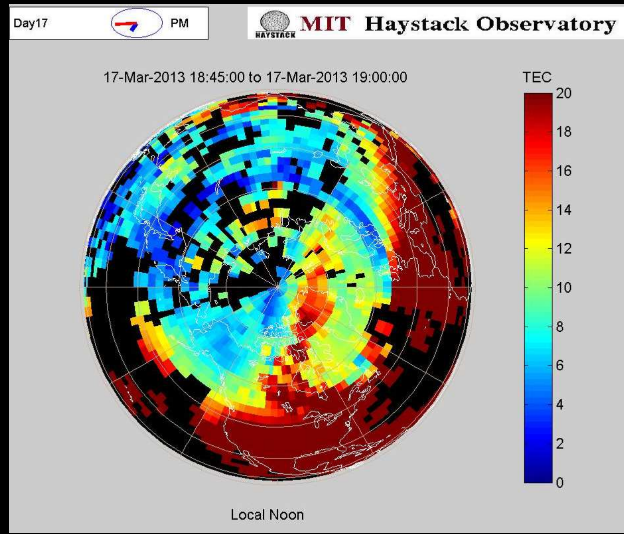
SED - 19UT March 17, 2013 North and South Hemisphere

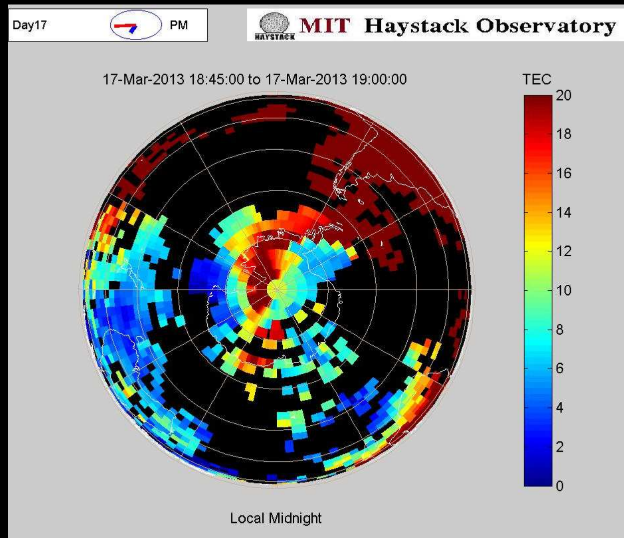












quiet initial conditions
Re-analysis vs IPE

Anthea Coster
TEC maps MIT

Thermosphere Waves in the Bottom-Side Ionosphere