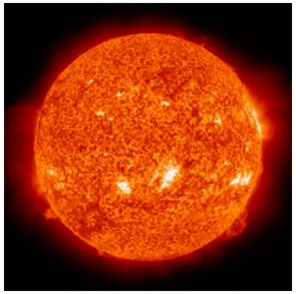
# Integrated Dynamics through Earth's Atmosphere (IDEA): predicting ionosphere-thermosphere space weather under all condition


Tim Fuller-Rowell, Rashid Akmaev, Fei Wu, Houjun Wang, Tzu-Wei Fang, Naomi Maruyama, Tomoko Matsuo, Mihail Codrescu, Yang-Yi Sun, Catalin Negrea, Leslie Meyer, Jun Wang, Mark Iredell, Shrinivas Moorthi, John Derber, Henry Juang, Yu-Tai Hou, Misha Rancic, Daryl Kleist, Ming Hu, Phil Richards, Art Richmond, and Astrid Maute




CIRES University of Colorado
NOAA Space Weather Prediction Center
NOAA Environmental Modeling Center
National Center for Atmospheric Research
George Mason University


Sponsors: NASA Heliophysics Theory and Geospace Programs, AFOSR MURI, NOAA SWPC and EMC

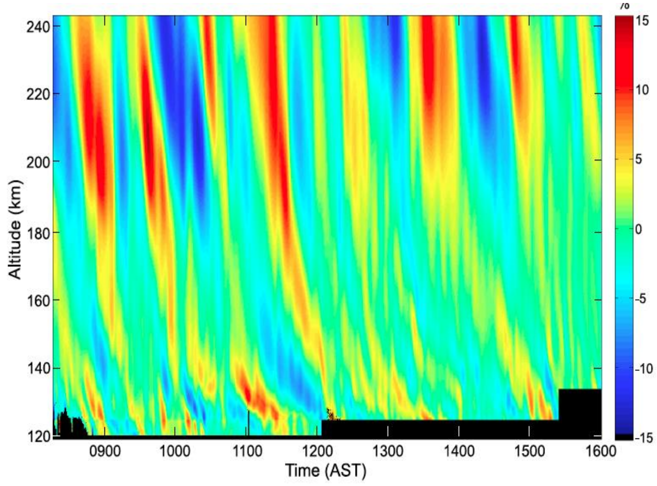

With figures from:
Koki Chau, Larisa Goncharenko, John Retterer,

# IDEA: Integrated Dynamics through Earth's Atmosphere

## Coupled WAM, IPE, and data assimilation

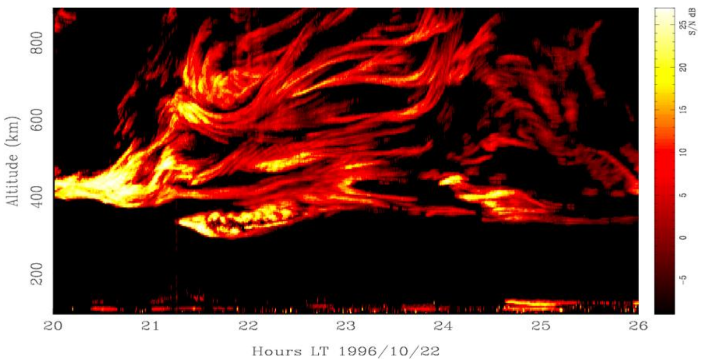
- WAM: Whole Atmosphere Model – provides neutral dynamics, temperature, composition, and minor species for the ionosphere
- IPE: Ionosphere-Plasmasphere-Electrodynamics - provides Joule heating, ion drag, solar heating and dissociation rates to WAM
- Data assimilation (extended NCEP GSI; Ensemble Kalman Filter, Hybrid)
- Potentially a community resource

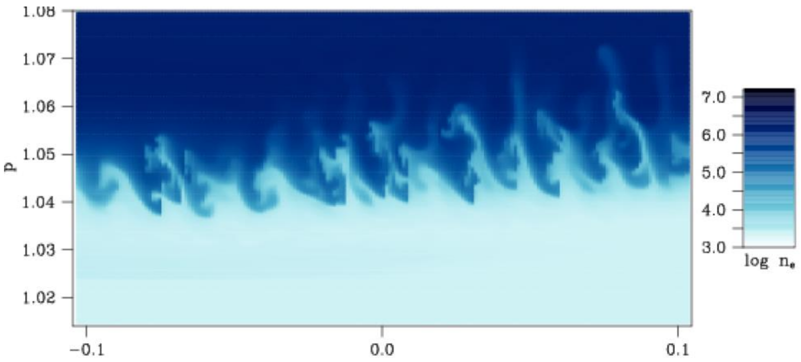
# Day-to-day ionospheric structure




Waves in the ionosphere over
Arecibo, Puerto Rico
Djuth et al., JGR, 2010

Residual plasma density after
de-trending +/-15%

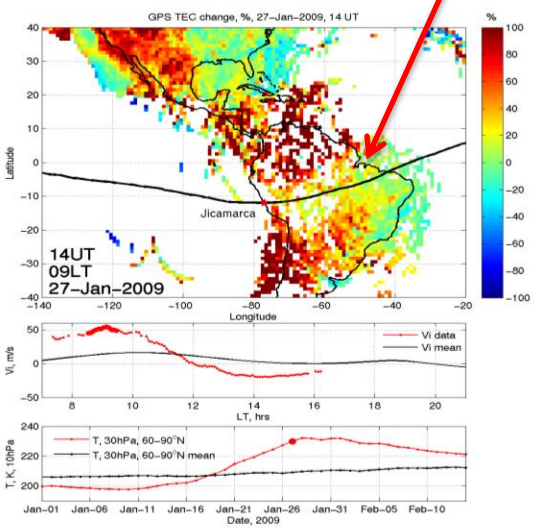


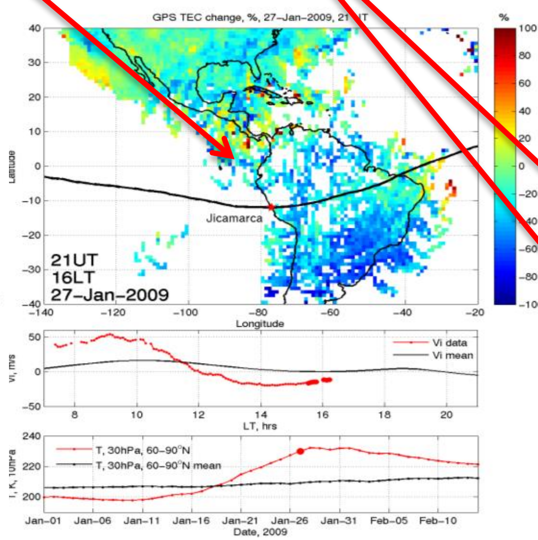



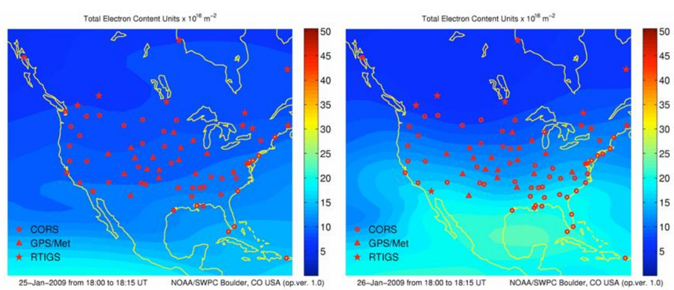

Ionosphere iregularities over
Jicamarca, Peru
Hysell and Burcham., JGR, 1998

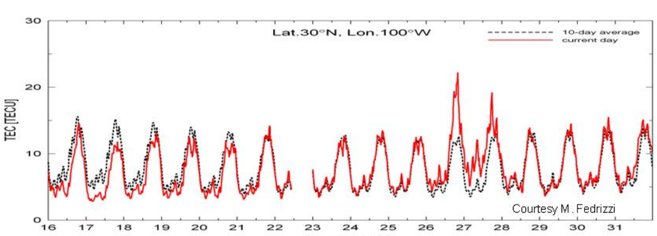
Ionospheric structure impacts satellite communication and navigation, and ground-based radar signals

# TEC response to 2009 Sudden Stratospheric Warming (SSW) Goncharenko et al. 2010




NOAA US-TEC

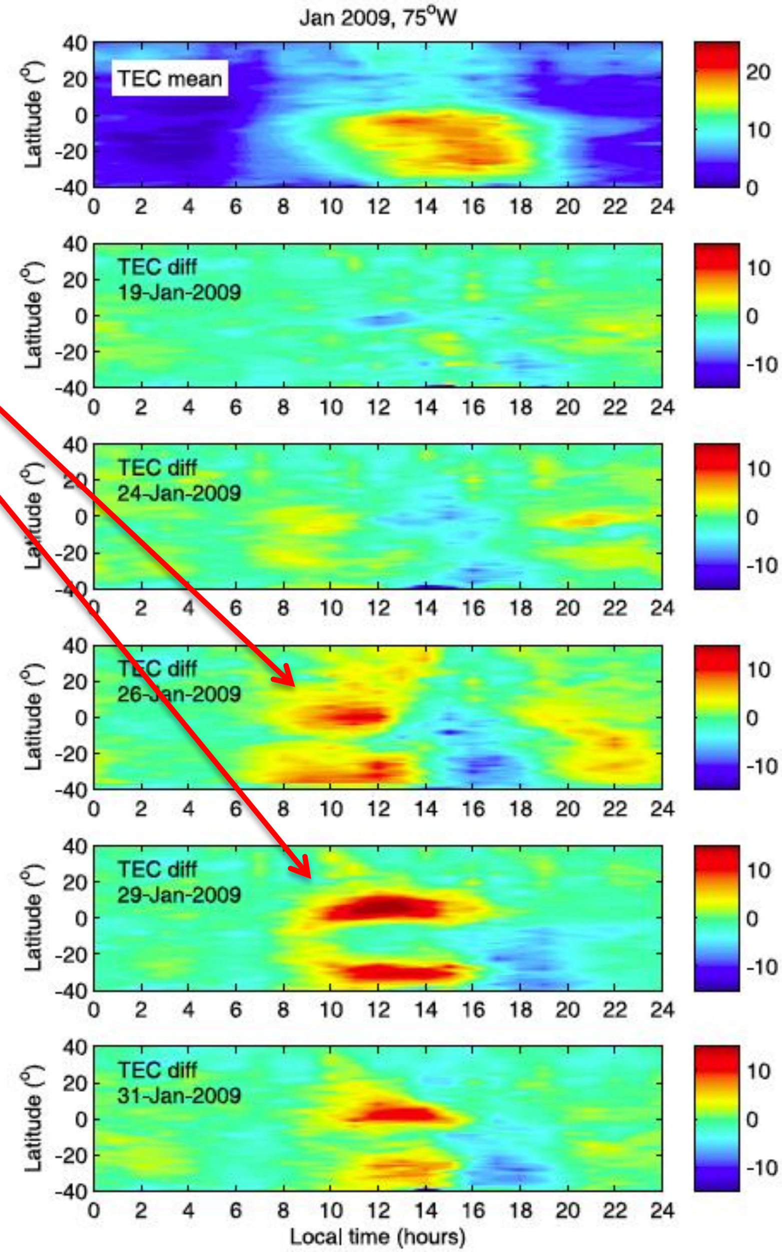
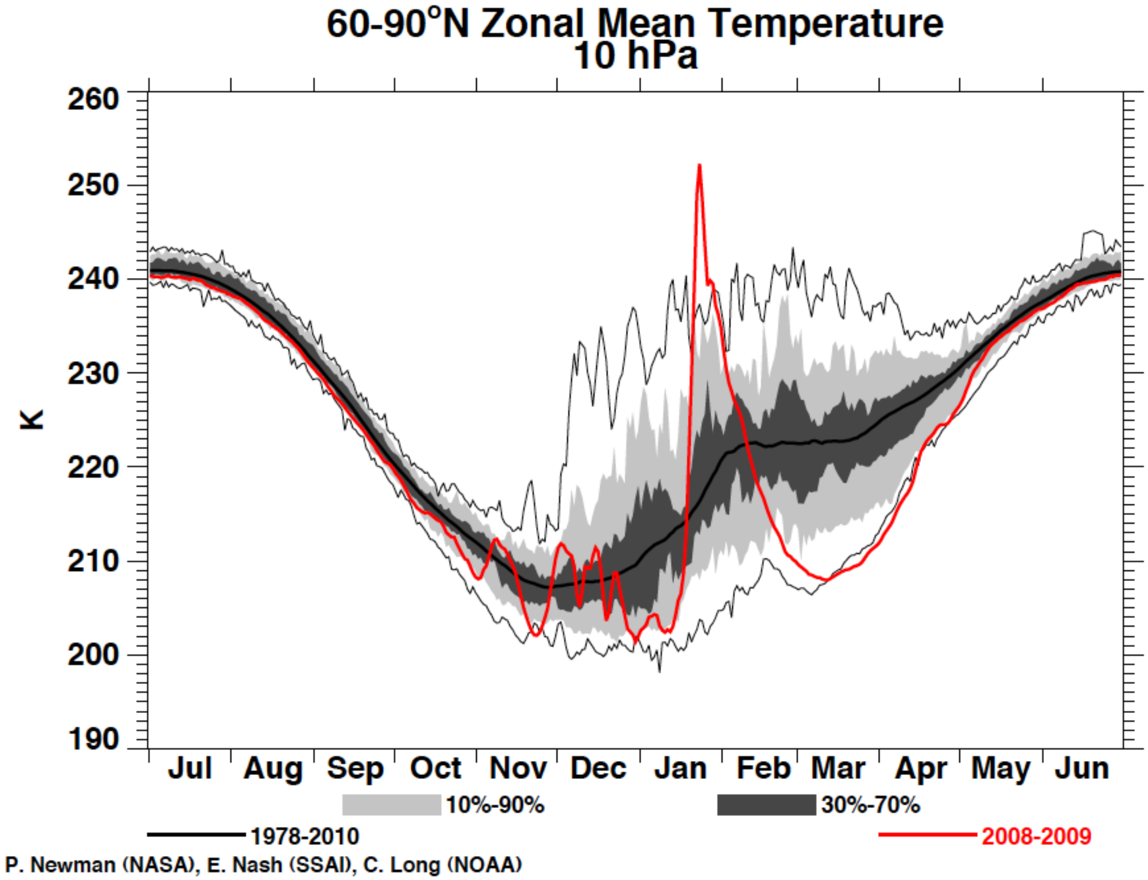


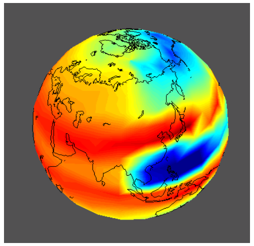

**Figure 3.** TEC variation at 75°W in local time and latitude during the January 2009 SSW. (top) The 10 day mean TEC prior to SSW. (lower) Differences in TEC from the mean state during the SSW.

# 2009 sudden stratospheric warming

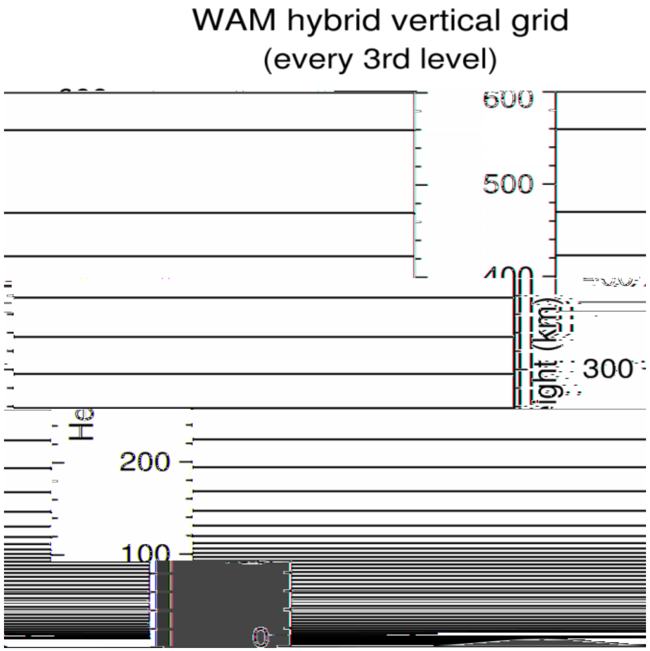


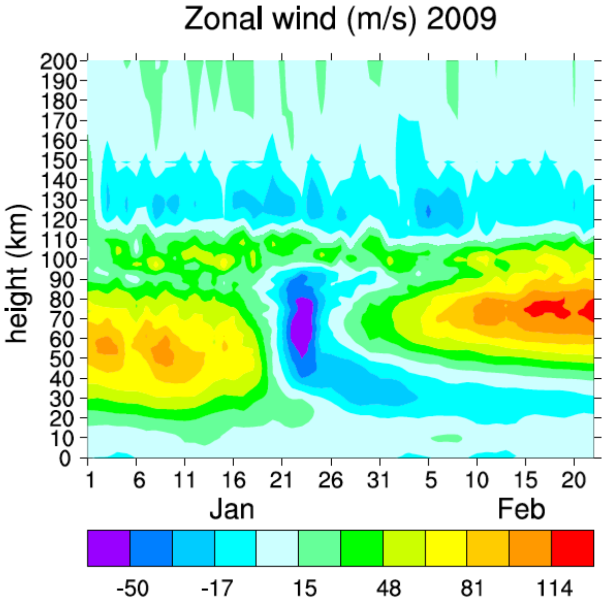
# Whole Atmosphere Model (WAM)

- 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)

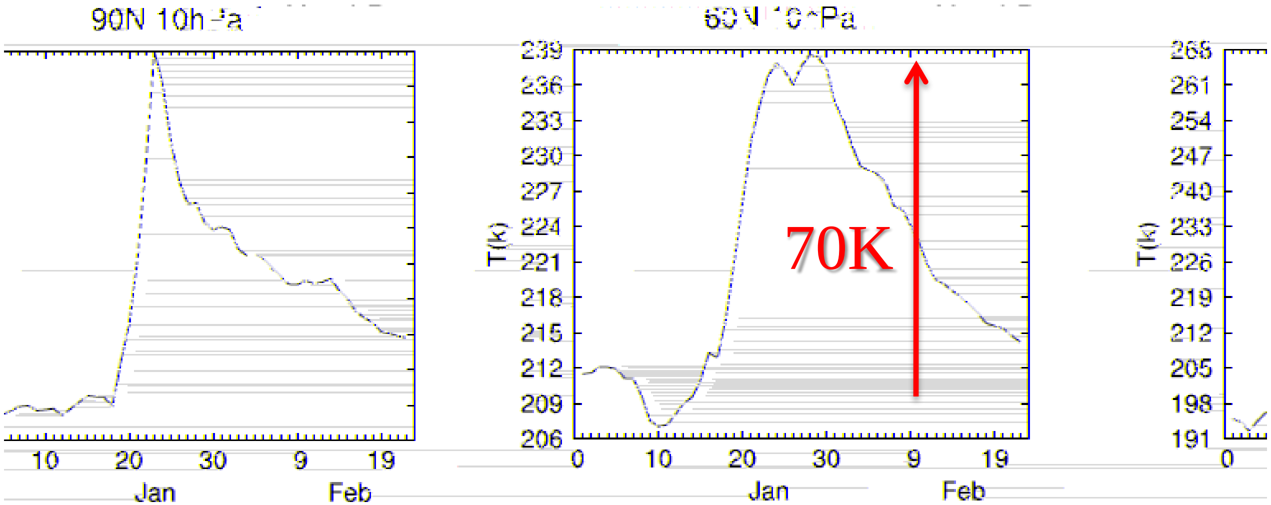


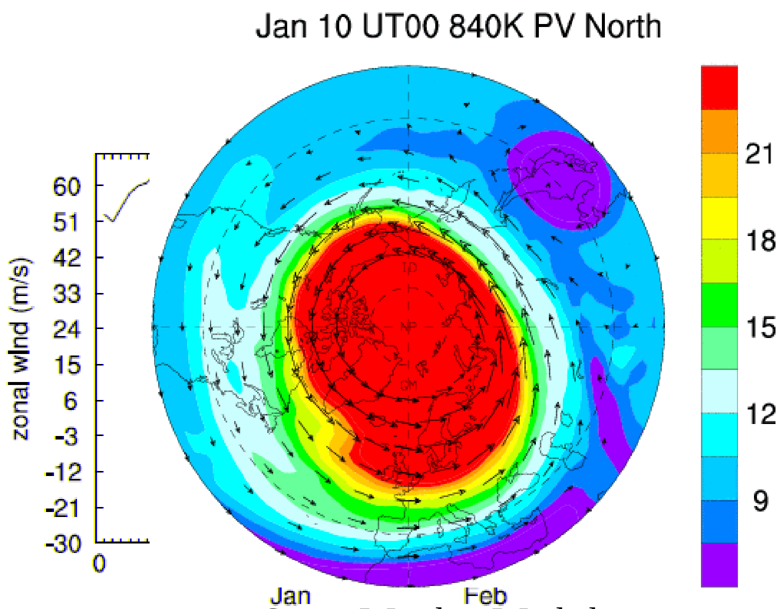



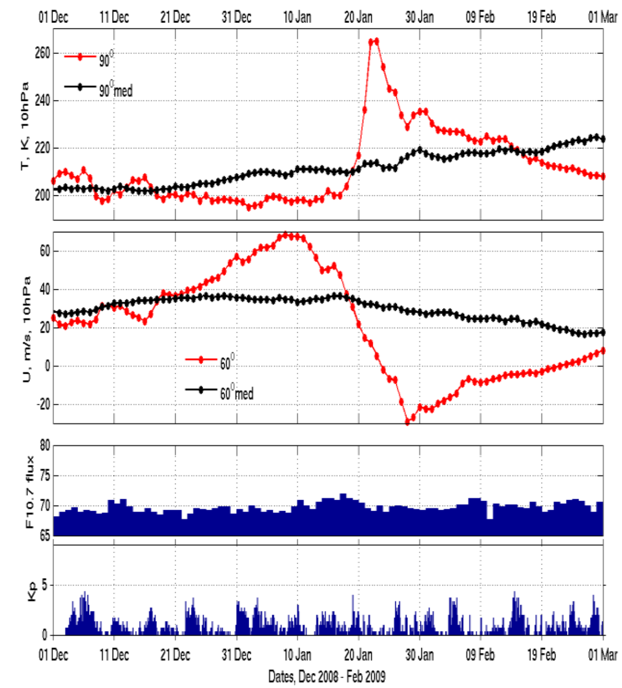
# WAM-GSI Analysis System with Incremental Analysis Updates (IAU) Wang et al. 2011

- WAM produced SSW naturally without need for external forcing (one year - minor warming, multi-year could produce major warming)
- GFS-GSI is the NCEP 3DVAR operational data analysis system for global and regional NWP (GFS: Global Forecast System, GSI: Grid-point Statistical Interpolation)
- Replace GFS with WAM to follow real SSW events
- Analysis system modified to use IAU to avoid use of digital filter, which excessively damps tidal propagation to the thermosphere
- Uses data in GSI up to ~60 km to simulate January 2009 period during large SSW

# WAM simulations of the January 2009 sudden stratospheric warming



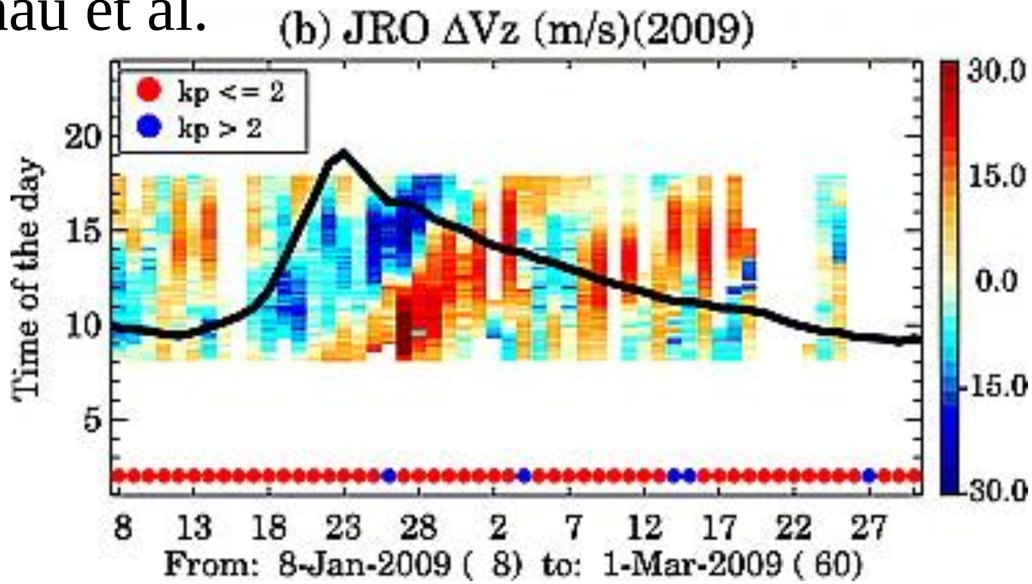




Same as ECMWF

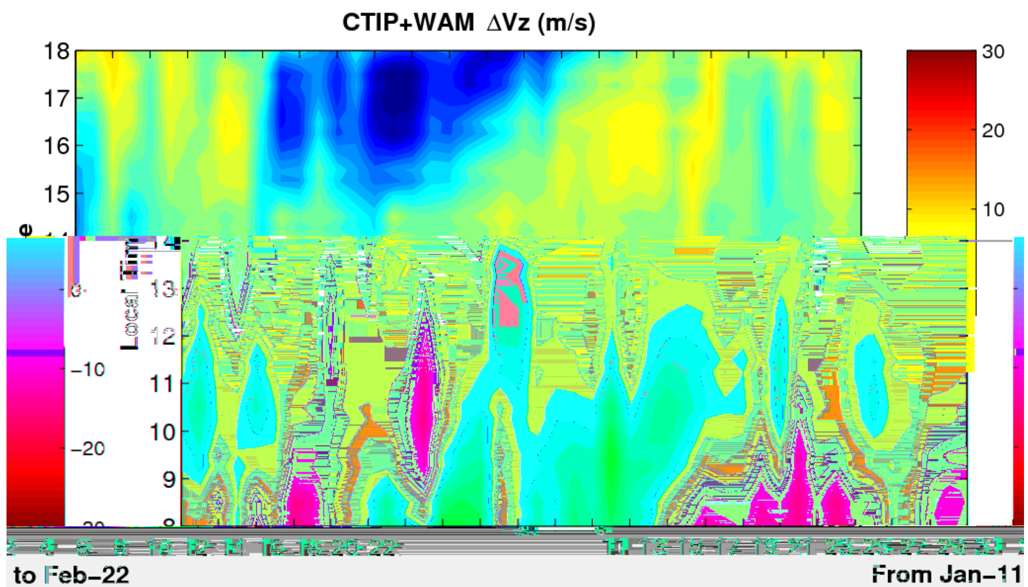
“validation”

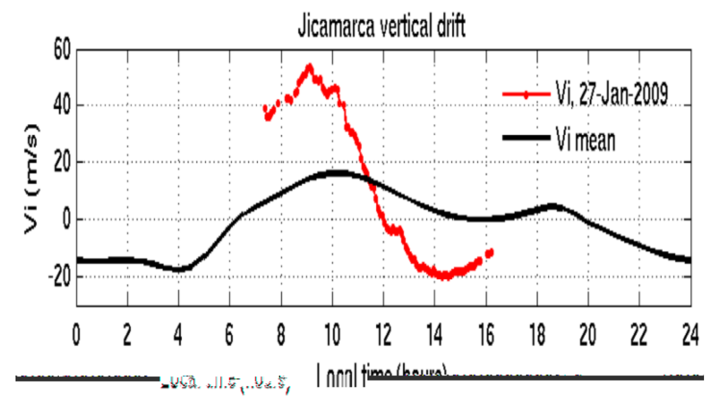
# Electrodynamic comparison JRO vs WAM-CTIPe

Chau et al.




- **CTIPe simulations with WAM winds (lower panel) 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**



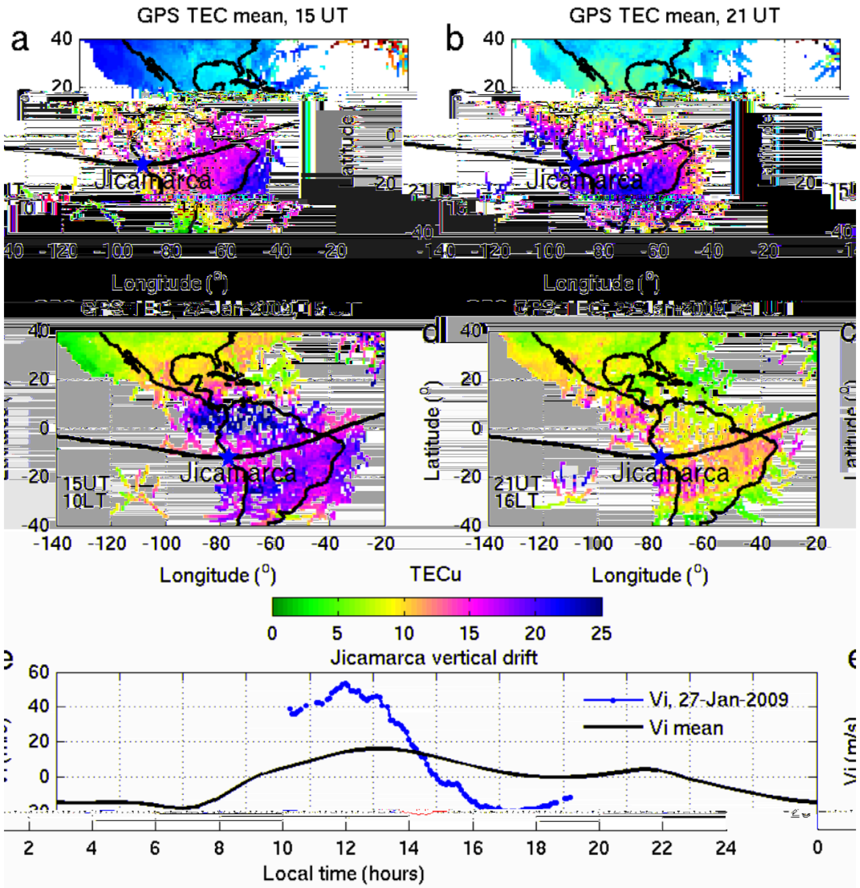




Fuller-Rowell et al. 2011

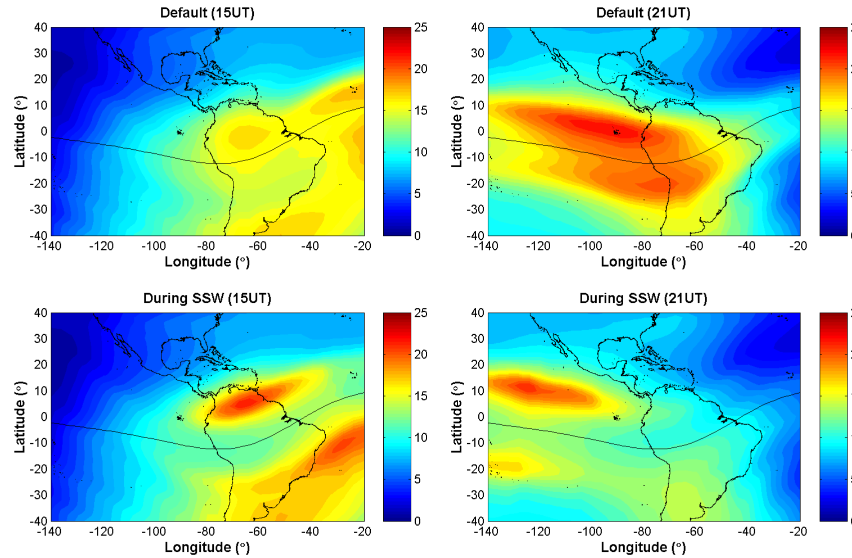
# January 2009 Stratospheric Warming impact on EIA

## GPS-TEC observation before and after SSW

## WAM-GIP before and after SSW

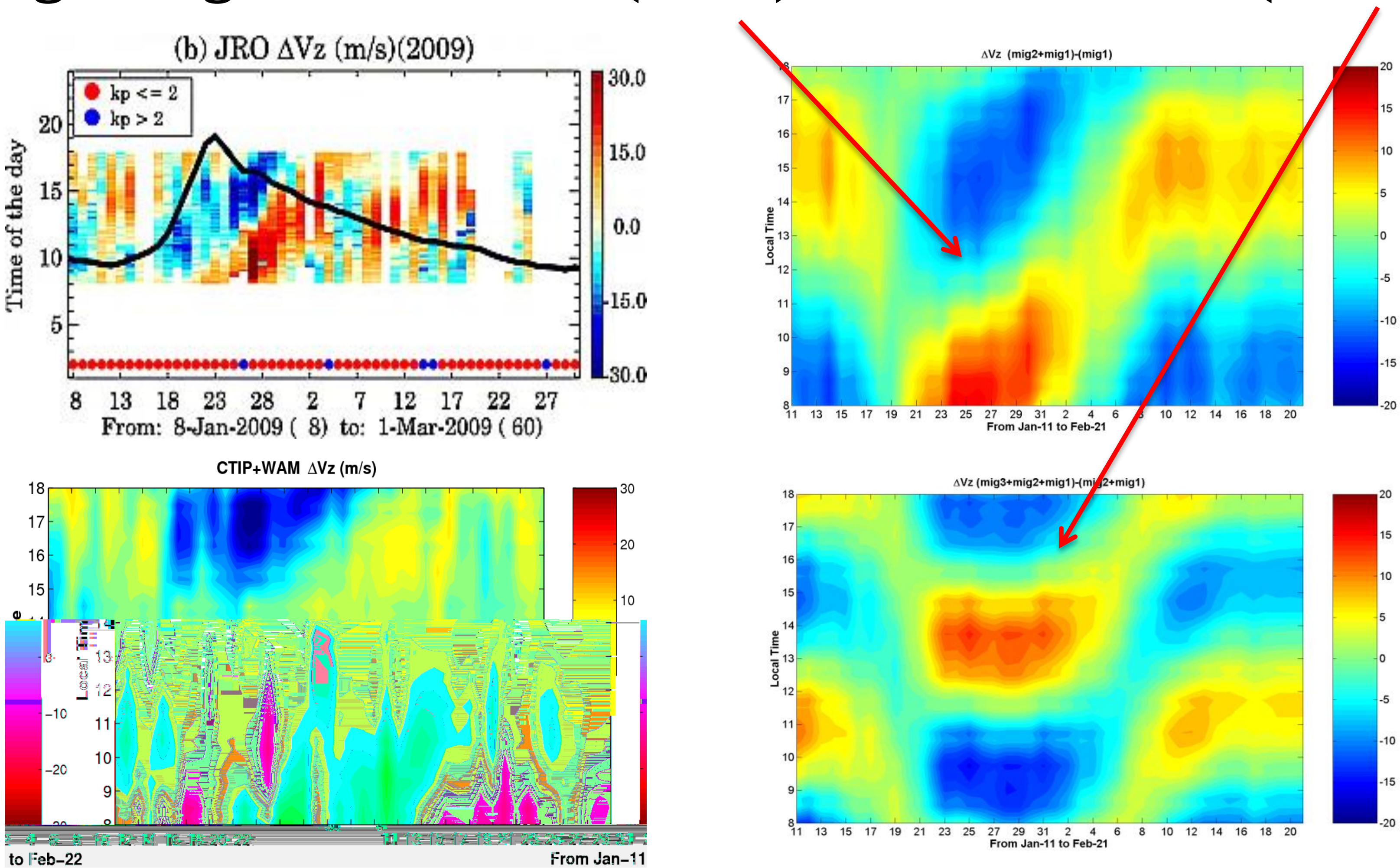



SSW vertical plasma drift
Jicamarca (Chau et al., 2010)




Good agreement between GIP and Goncharenko et al. (2010) on Jan 27th, 15 and 21 UT, 10 and 16 LT

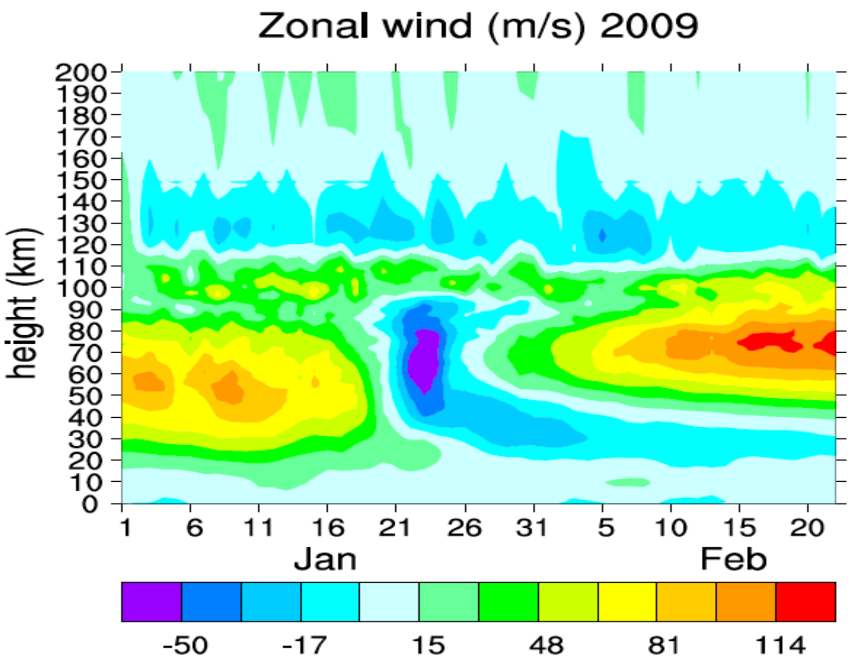
# Electrodynamic Response – driven by changes in migrating semi-diurnal (SW2) and ter-diurnal (TW3)

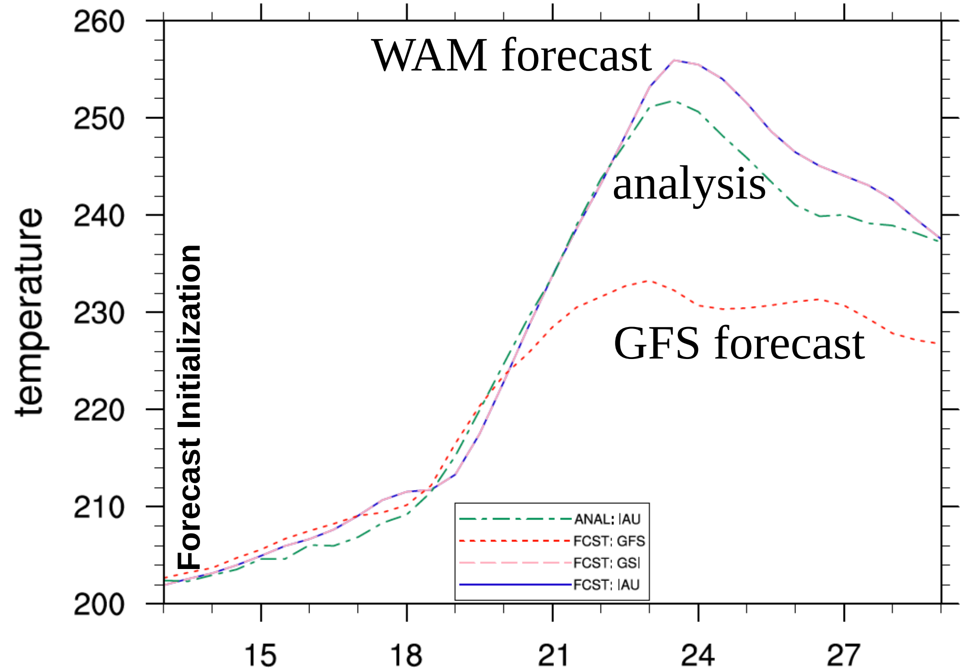


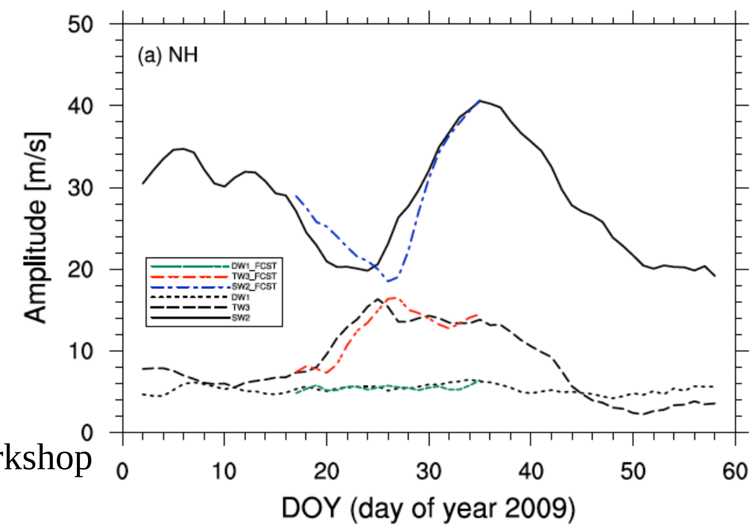

CTIPe simulations with WAM winds appear to reproduce the main features in vertical plasma drift during a SSW with SW2 and TW3 only, including longitude dependence

# 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

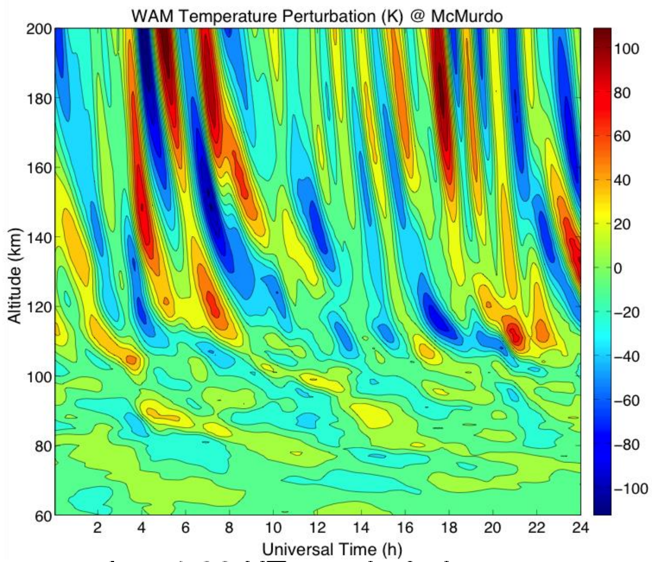


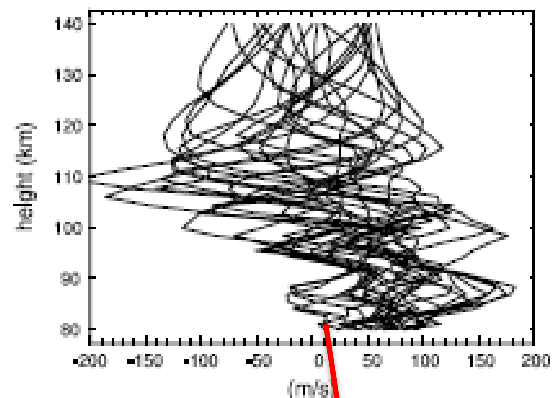



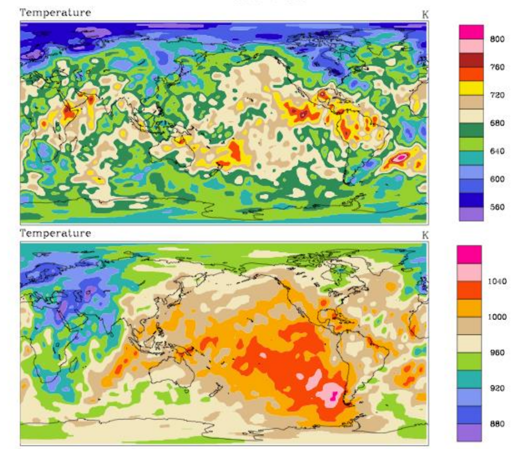

WAM also has potential to improve long-range tropospheric weather forecasting – so-called "downward control"

# A rich spectrum of waves propagate from the lower atmosphere impacting the ionosphere

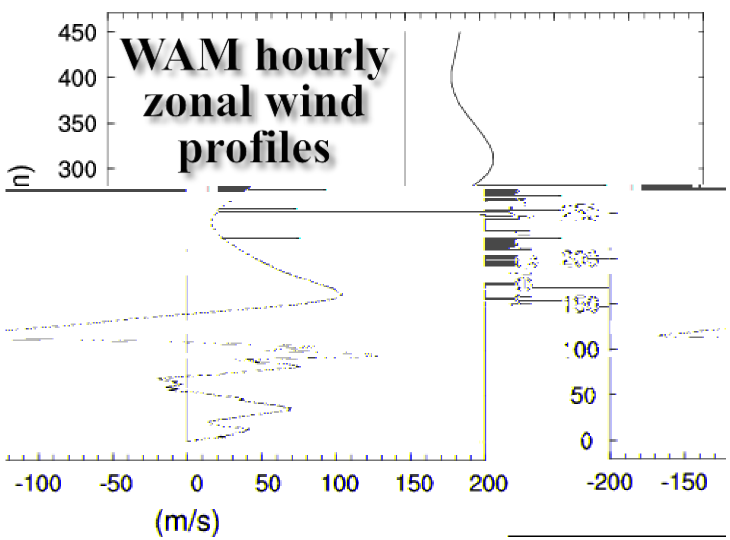


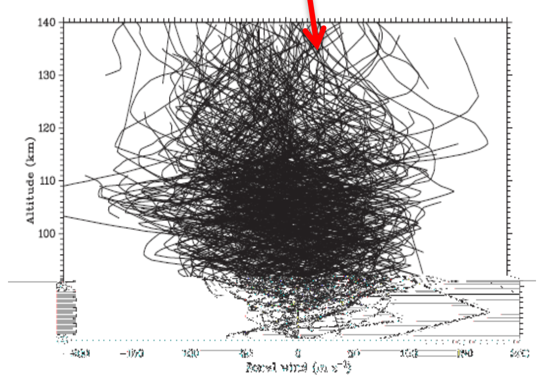

**WAM 1-day**



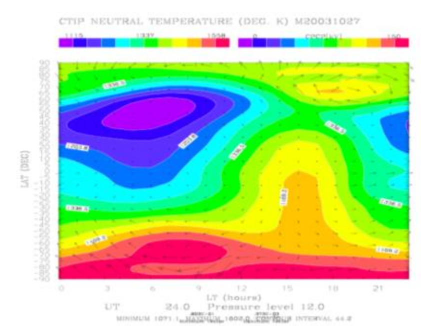

Jan 1 00 UT zonal wind



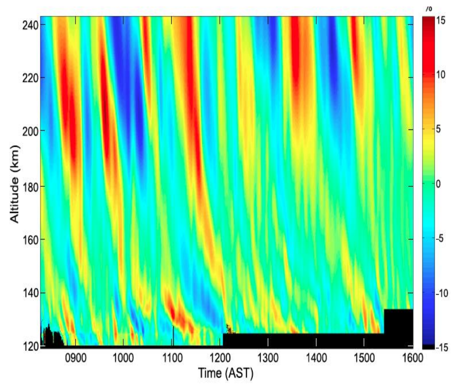




**Observed mid and low latitude zonal winds Larsen (2002)**

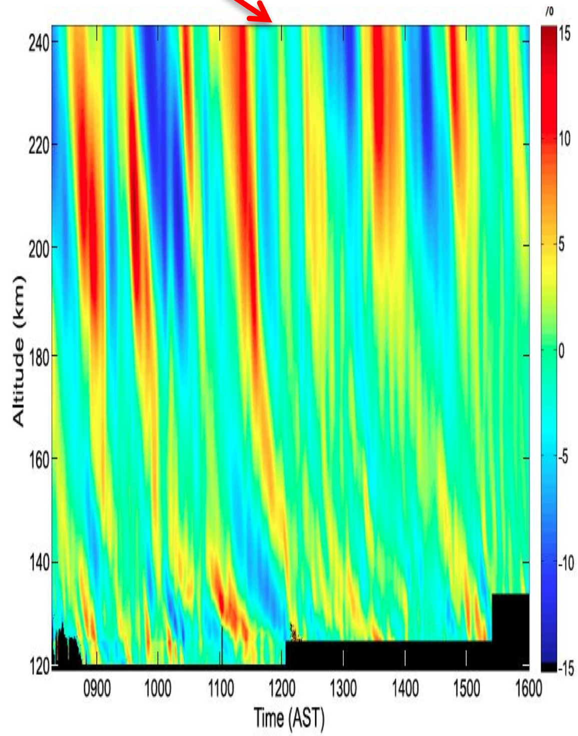
**A new paradigm in ionospheric modeling**



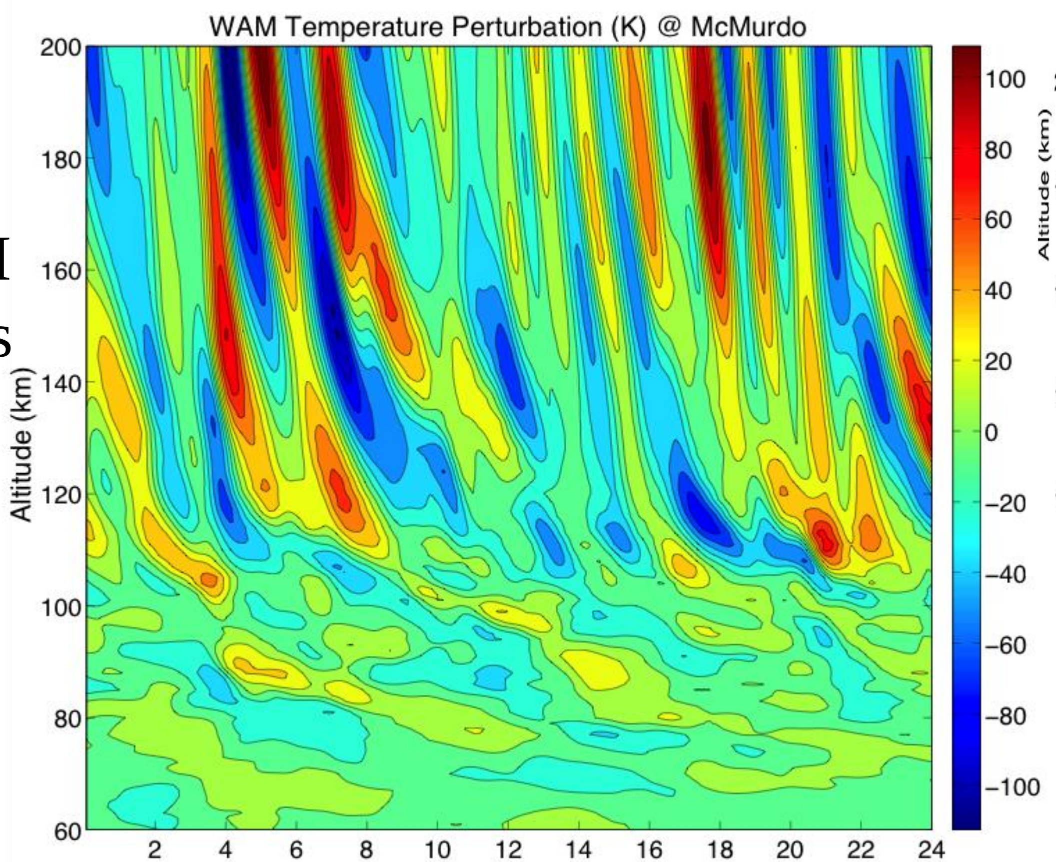
# WAM waves compared to Arecibo ISR waves




**Waves in the ionosphere at Arecibo [Djuth et al., JGR, 2010]**

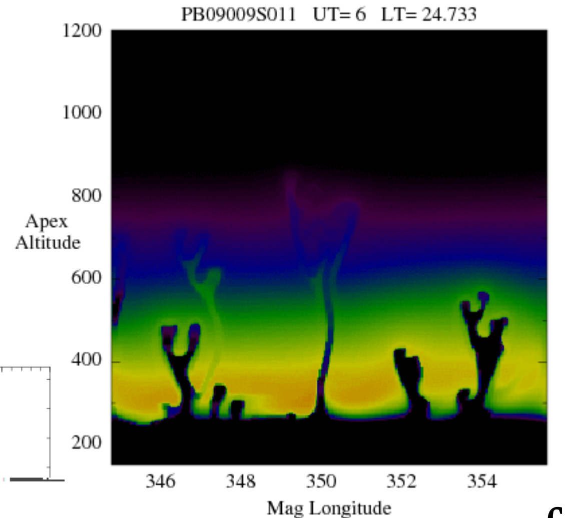


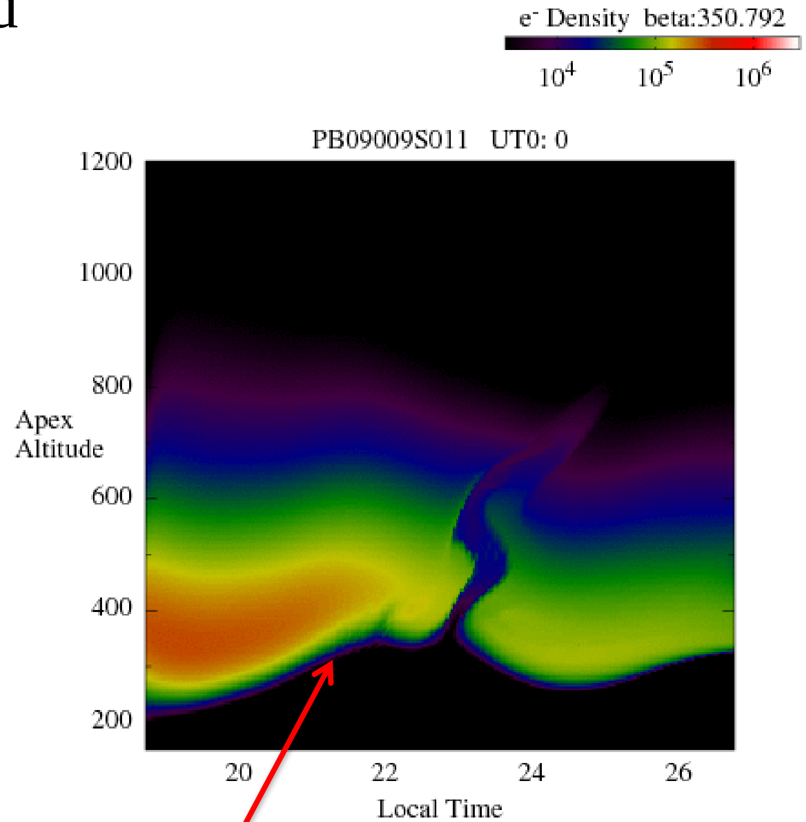

WAM waves

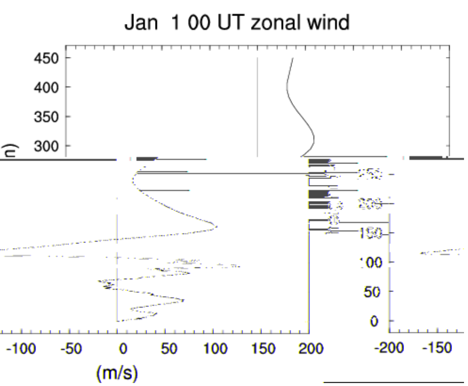


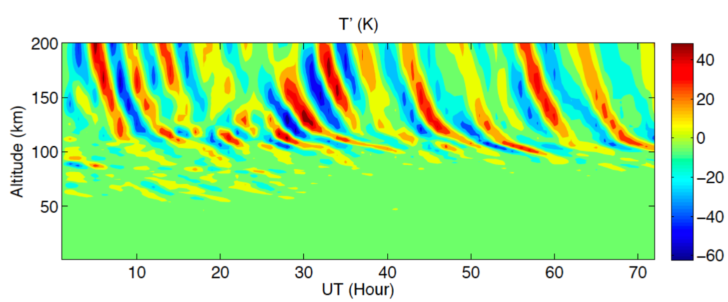
# Bubble development in physics-based irregularity model (PBMOD) with WAM fields (180 km horizontal. resolution, ¼ scale-height vertical, ~2-5km) with no additional seeding

F




forecasting large scale wave structure, (LSWS) on bottomside

# New ionosphere-plasmasphere-electrodynamics IPE model (Lead: Maruyama et al., 2013)

- Solves for ion species ($O^+$, $H^+$, $He^+$, $NO^+$, $N_2^+$, $O_2^+$, $N^+$), electron temperature, and ion temperature in a coordinate system defined by Earth's geomagnetic field
- Sophisticated photo-chemistry and flux-tube solver based on Phil Richards (GMU) Field Line Inter-hemispheric Plasmasphere (FLIP) model
- Solves for two stream photoelectron flux, includes pitch angle scattering
- International Geomagnetic Reference Atmosphere (IGRF): APEX coordinate system [Richmond 1995]
- Global coverage / seamless transport, flexible resolution
- Time-dependent polar cap boundary for plasma outflow and refilling
- Self consistent calculation of ionospheric electrodynamics on the same grid (Richmond/Maute, NCAR/HAO), merged with magnetospheric electric fields (e.g., Weimer, Raeder OpenGGCM MHD)
- Information exchange between WAM and IPE through interpolation across very different 3-D grid structures (fixed grid or ESMF re-gridding)
- MPI compatible, SMS implemented, distributed memory, (Middlecoff, GSD)

# NCEP's operational DA system

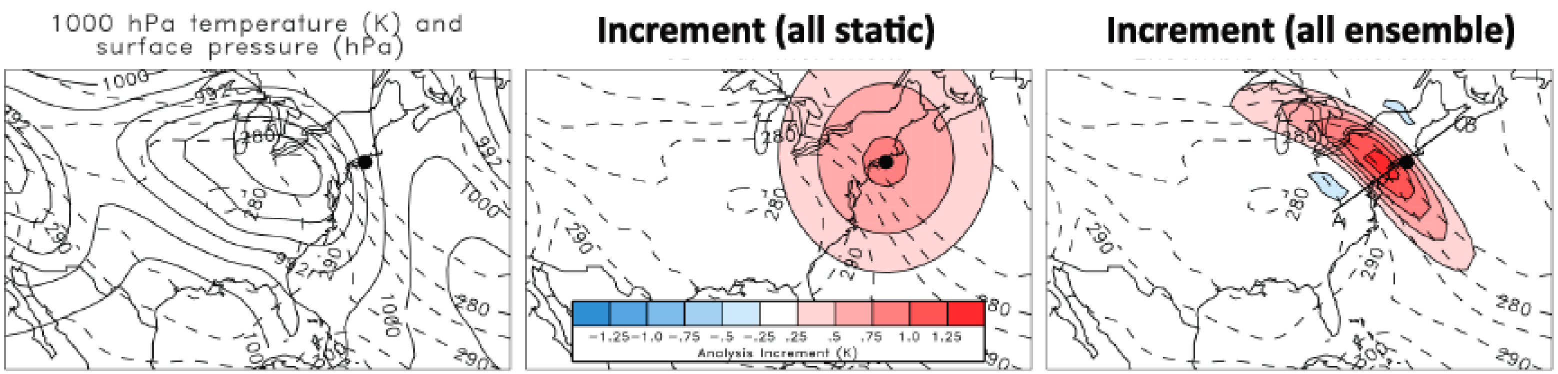
Operational implementation of "**hybrid** (= GSI+ensemble) data assimilation system" at NCEP, 22 May 2012

$$\mathbf{J}(\mathbf{x}') = \frac{\beta}{2}(\mathbf{x}')^T \mathbf{B}_f{}^{-1}(\mathbf{x}') + \frac{1-\beta}{2}(\mathbf{x}')^T \mathbf{B}_{ens}{}^{-1}(\mathbf{x}') + \frac{1}{2}(\mathbf{H}\mathbf{x}' - \mathbf{y}')^T \mathbf{R}^{-1}(\mathbf{H}\mathbf{x}' - \mathbf{y}')$$

$\mathbf{B}_f$ Stationary (isotropic/homogeneous) forecast-error covariance

$\mathbf{B}_{ens}$ "Flow-dependent" forecast-error covariance (estimated from ensemble – EnKF)

$\beta$ Weighing factor




(From Jeff Whitaker's tutorial at DTC Aug 23, 2012)

# IDEA Status, Plans, and Timeline

- WAM is an extension of the National Weather Service operational weather forecasting model GFS (Global Forecast System)
- WAM has been integrated into the NOAA Environmental Modeling System (NEMS)
- WAM in NEMS will be able to follow the natural development cycle of GFS (e.g., non-hydrostatic, semi-Lagrangian transport, updates in radiation, updates on gravity wave parameterization, increase in resolution, fully ESMF compatible, etc….)
- NEMS-WAM will be integrated into NWS GFS data assimilation system (GSI), and also follow the natural NCEP development cycle (e.g., GSI/ensemble Kalman Filter hybrid data assimilation scheme)
- NEMS-WAM and WDAS operational model protocol will be defined (e.g., 16-day forecasts, every 6 hours, at 1 hour temporal resolution, etc.) and model protocol delivered to NCO Q4 2013 and implemented Q4 2014
- Forecast fields will be available FY2015 for community use (e.g., tidal wind fields to drive electrodynamic models, variability, etc.)

# IDEA Status, Plans, and Timeline (cont)

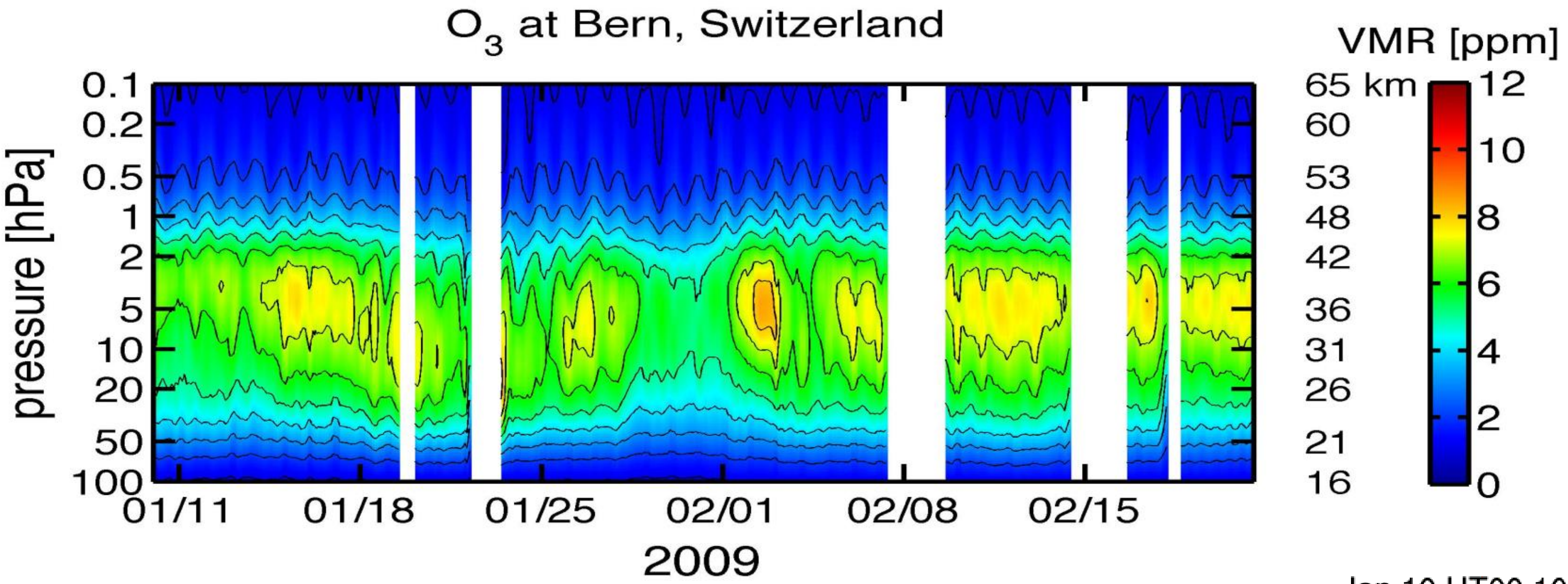
- NCEP Climate Forecast Center ( CFC) to evaluate impact of NEMS-WAM on medium range tropospheric weather forecast (2 weeks – few months)
- Currently testing impact of WAM fields on ionosphere in one-way mode, full two-way coupling in progress
- Initial testing using Global Ionosphere Plasmasphere (GIP, Millward) from CTIPe, cast in magnetic APEX coordinates
- New Ionosphere-Plasmasphere-Electrodynamics (IPE) code to follow
- Extend data assimilation into the strongly forced mesosphere, thermosphere, and ionosphere system, including:
- Extend WAM-GSI to ~120 km and implement NOAA-EnKF, with "flow-dependent" covariance
- Develop IDEA-GSI-EnKF to assimilate thermosphere-ionosphere observations (e.g., g-b GNSS, COSMIC-II radio occultation, ISR, etc.)
- Implement IDEA into NCEP's hybrid data assimilation system
- Define IDEA model protocol and deliver to NCEP NCO in FY2017/18

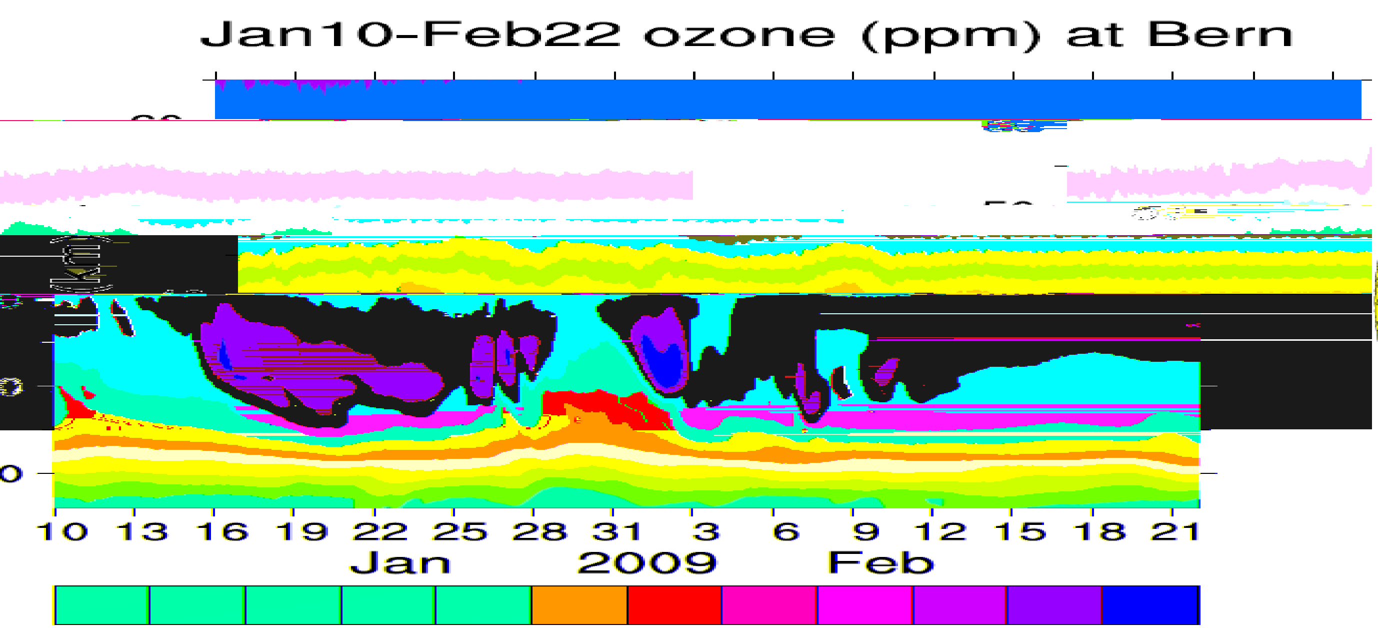
# Summary and Conclusions

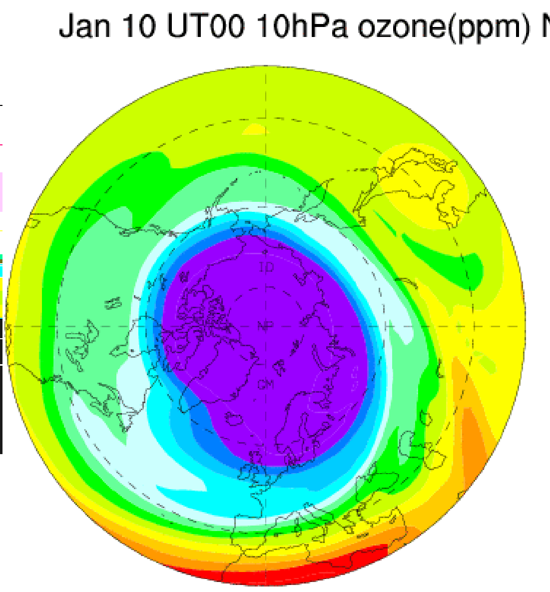
- The lower atmosphere produces a whole spectrum of waves with periods from < 1 hour to days that impact space weather in the thermosphere and ionosphere system
- The shorter periodicities in the neutral dynamics are consistent with the observations from ISR, LIDAR, and dynasondes, and trigger plasma "bubbles" in irregularity models
- WAM-GSI-CTIPe follows the changes in the atmosphere dynamics and appears to follow the observed electrodynamic changes at low latitudes during the sudden stratospheric warmings
- The dynamics and electrodynamics fields driven by the lower atmosphere can be forecast several days ahead
- Entering a new paradigm in atmosphere-ionosphere modeling and data assimilation

# Back up slides

# Observations: Klemens Hocke, Simone Studer, Bern



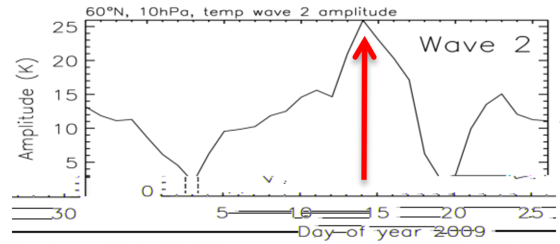





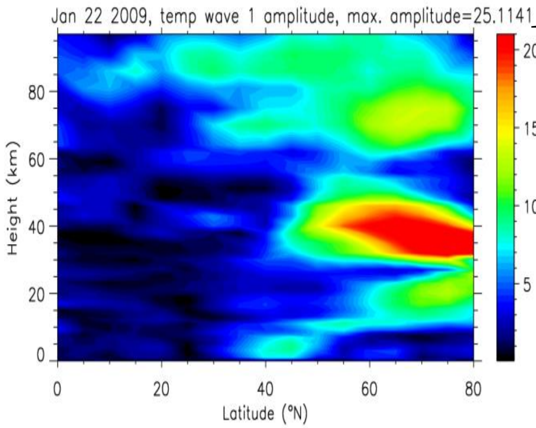

# Modeling: WAM

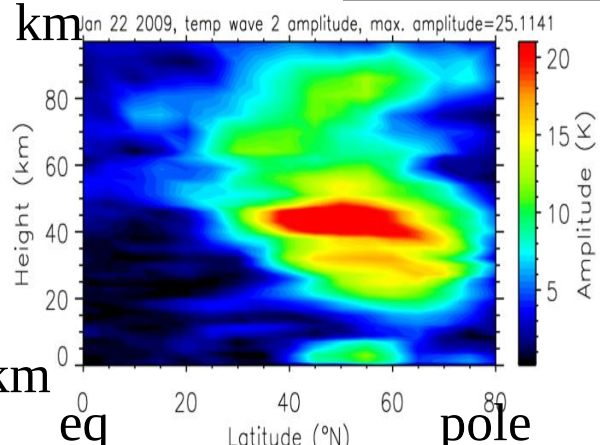
# MLS - upper panels

From Vivien Matthius and Peter Hoffman




SPW2 observed time series



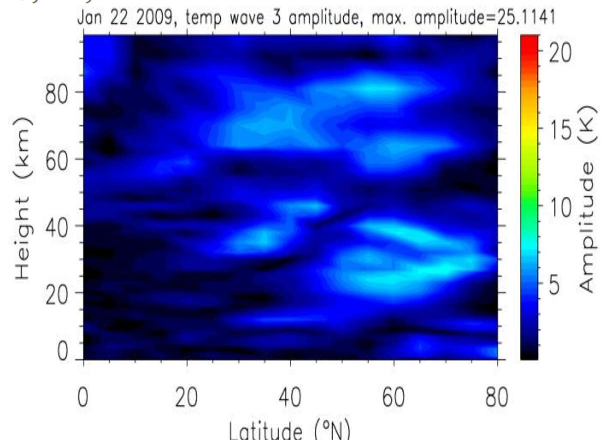




100 km

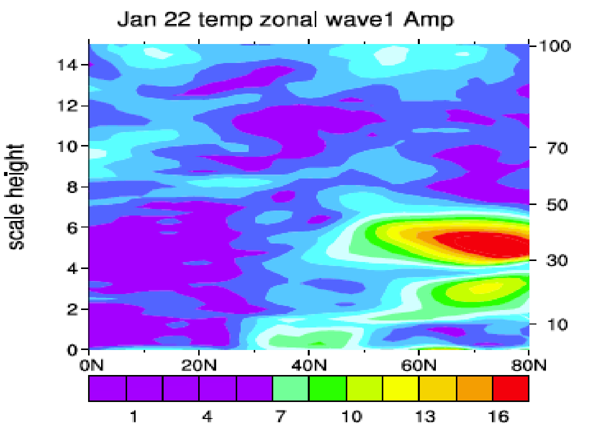
0 km

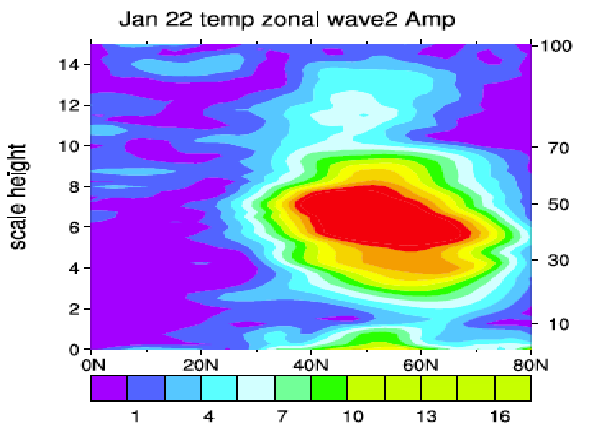
eq

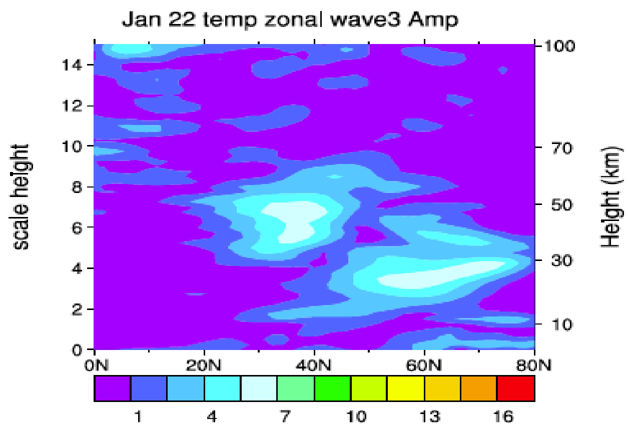
pole



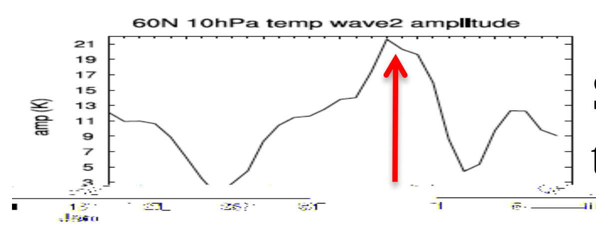

SPW-1 SPW-2 SPW-3




# WAM - lower panels




SPW2 model time series

# Coupled Thermosphere Ionosphere Plasmasphere Model with self-consistent Electrodynamics (CTIPe)

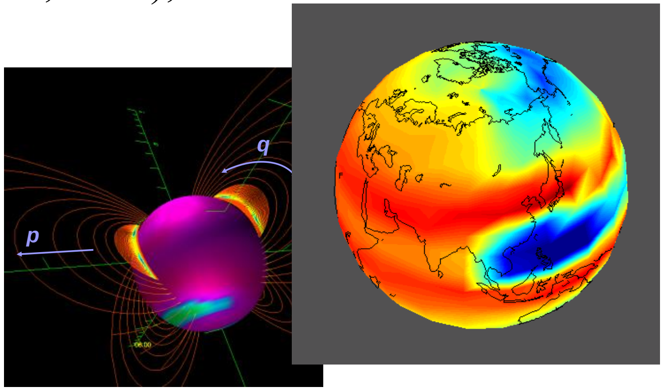
- Global thermosphere 80 - 500 km, solves momentum, energy, composition, etc. Vx, Vy, Vz, Tn, O, O2, N2, … Neutral winds, temperatures and compositions are solved self consistently with the ionosphere (Fuller-Rowell et al., 1996);

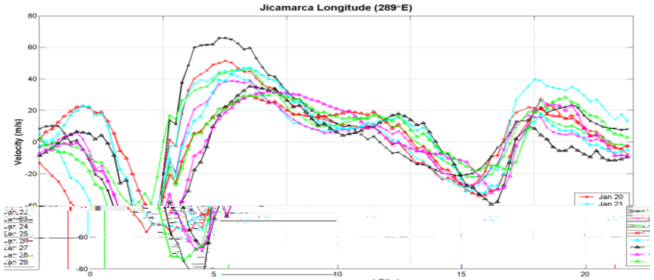
- High latitude ionosphere 80 -10,000 km, solves continuity, momentum, energy, etc. O+, H+, O2+, NO+, N2+, N+, Vi, Ti, …. (open flux tubes, Quegan et al., 1982);

- Plasmasphere, and mid and low latitude ionosphere, closed flux tubes to allow for plasma to be transported between hemispheres (Millward et al., 1996);

- Self-consistent electrodynamics (electrodynamics at mid and low latitudes is solved using conductivities from the ionospheric model and neutral winds from the neutral atmosphere code) (Richmond);

- Forcing: solar UV and EUV, Weimer electric field, TIROS/NOAA auroral precipitation, tidal forcing from WAM.

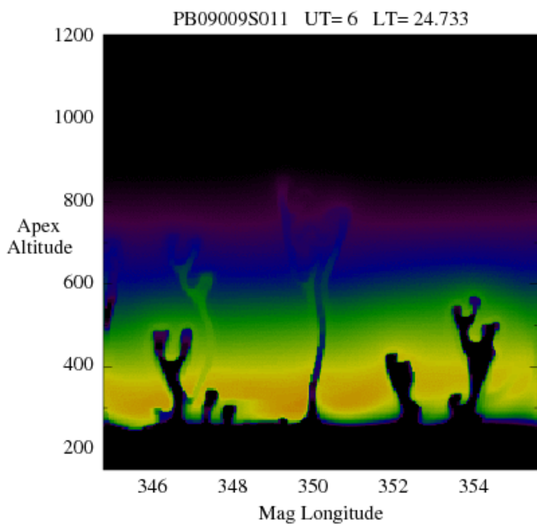


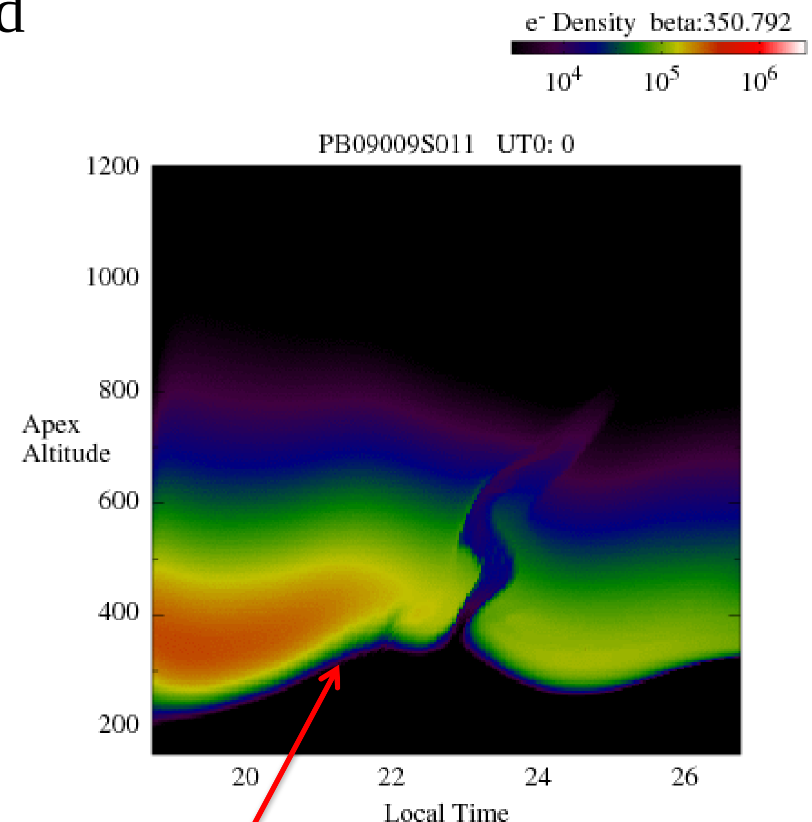



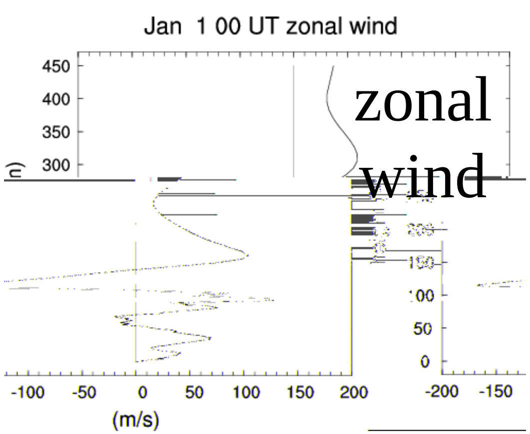

Equatorial vertical plasma drift

# 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

F




zonal wind

forecasting large scale wave structure, (LSWS) on bottomside