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Whole Atmosphere Community Climate Model with Thermosphere and Ionosphere Extension (WACCM-X): Model Overview

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NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

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NSF

WACCM-X Model Components (from 2010 CEDAR)

Model Framework	Chemistry	Physics	Physics	Resolution
Extension of the NCAR Community Atmosphere Model V.3 (CAM3) Finite Volume Dynamical Core Current version based on WACCM3.5.48 CCSM-Compliant: WACCM-X a build time option.	MOZART+ Ion Chemistry (52 neutral+5 ions+electron) Fully-interactive with dynamics.	Long wave/short wave/EUV IR cooling (LTE/non-LTE) Major/minor species diffusion Molecular viscosity and thermal diff. Species dependent Cp, R, m. Parameterized electric field at high, mid, low latitudes. IGRF geomagnetic field. Auroral processes, ion drag and Joule heating Parameterized GW (including thermosphere)	Ambipolar diffusion Ion/electron transport Ion/electron energy equations Ionospheric dynamo Coupling with plasmasphere/magnetosphere	Horizontal: 1.9° x 2.5° (lat x lon configurable as needed) Vertical: 81 levels (125 levels) 0-~500km • < 1.0km in Upper Troposphere/ Lower Stratosphere • 1-2 km in strat. • 0.5 scale height in mesosphere/ thermosphere (0.25 scale height in mesosphere/thermosphere with 125 levels)

Green: Thermosphere extension.

Red: Ionosphere extension.

Major CESM WACCM/WACCM-X Components

Model Framework	Chemistry	Physics	Physics	Resolution
Atmosphere component of NCAR Community Earth System Model (CESM) Extension of the NCAR Community Atmosphere Model (CAM) Finite Volume Dynamical Core (modified to consider species dependent Cp, R, m) Spectral Element Dynamical Core	MOZART+ Ion Chemistry (~60+ species) Fully-interactive with dynamics.	Long wave/short wave/EUV RRTMG IR cooling (LTE/non-LTE) Modal Aerosal CARMA Convection, precip., and cloud param. Parameterized GW Major/minor species diffusion (+UBC) Molecular viscosity and thermal conductivity (+UBC) Species dependent Cp, R, m.	Parameterized electric field at high, mid, low latitudes. IGRF geomagnetic field. Auroral processes, ion drag and Joule heating Ion/electron energy equations Ambipolar diffusion Ion/electron transport Ionospheric dynamo Coupling with plasmasphere/magnetosphere	Horizontal: 1.9° x 2.5° (lat x lon configurable as needed) Vertical: 66 levels (0-140km) 81/126 levels 0-~600km Mesoscale-resolving version:0.25 deg/0.1 scale height.

What's New In CESM2/WACCM-X

- Interactive Ionosphere Modules
  - Interactive electric wind dynamo.
  - F region O+ transport.
  - Time dependent Te/Ti solver, and thermal electron heating of neutral atmosphere.
  - $O^+(^2P)$ and $O^+(^2D)$ included in ion chemistry and energetics.
- High-latitude ionosphere:
  - Heelis model (default)
  - Assimilative Mapping of Ionospheric Electrodynamics (AMIE)
- Thermosphere Modules
  - Ability to take flare time EUV input.
  - $O(^3P)$ cooling.
  - H escape flux parameterization implemented.
- Dynamic core: Species dependent specific heats and gas constant.
- Model domain extended to 4×10^{-10} hPa, with ¼ scale height resolution.
- Reduced divergence damping improves tides.
- WACCM-X with specified dynamics.
- Data Assimilation with WACCM/WACCM-X DART.
- Improved model throughput: 0.57 model year/1 wallclock day with 144 processors on cheyenne.
- **WACCM-X now on the trunk of CESM2**

Ionospheric Electric Dynamo

Ionospheric electrostatic potential is solved by using Ohm's Law and current continuity condition (Richmond, 1983)

$$\nabla \bullet (\sigma : \nabla\Phi) = \nabla \bullet (\sigma : (\vec{V} \times \vec{B}))$$ **+ Highlatitude electric potential**

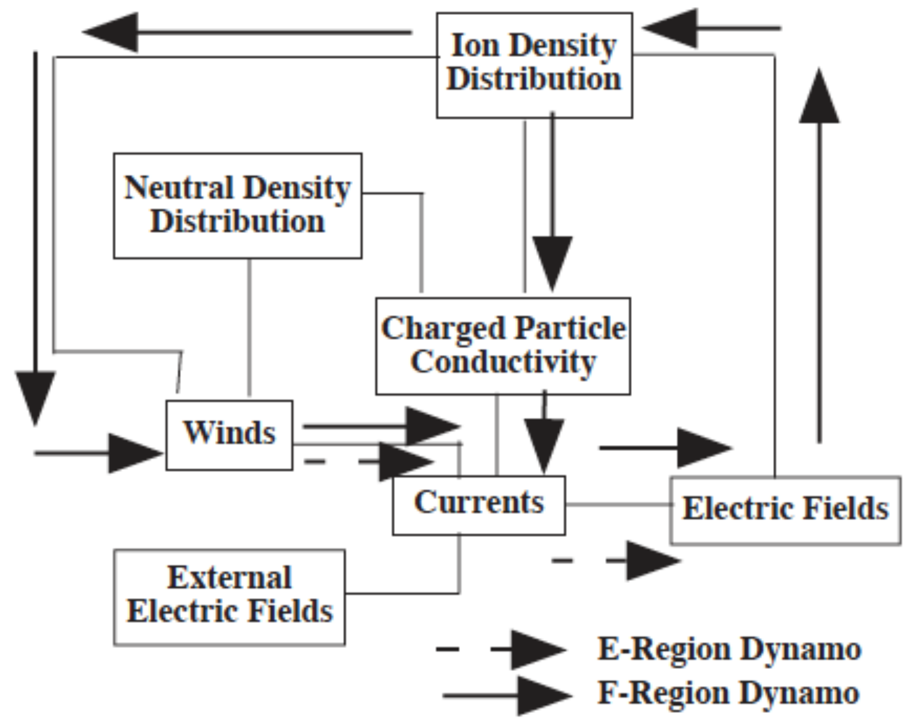


Fig. 6. Block diagram connecting the physical attributes at work in the E- and F-region dynamos.

Heelis, 2004 (CEDAR Tutorial)

F-region O^+ Transport

- O+ transport determined by field aligned ambipolar diffusion and ExB drifts.

$$\frac{\partial n_{O+}}{\partial t} = P - L + \nabla \cdot n_{O+}(\vec{V}_{\parallel} + \vec{V}_{\perp})$$

- O+ production/loss solved by the interactive chemistry module.
- Ambipolar diffusion depends on collision coefficients, plasma pressure, and field aligned winds.
- Collision coefficients and plasma pressure depend on electron and ion temperatures.

Electron and Ion Temperatures

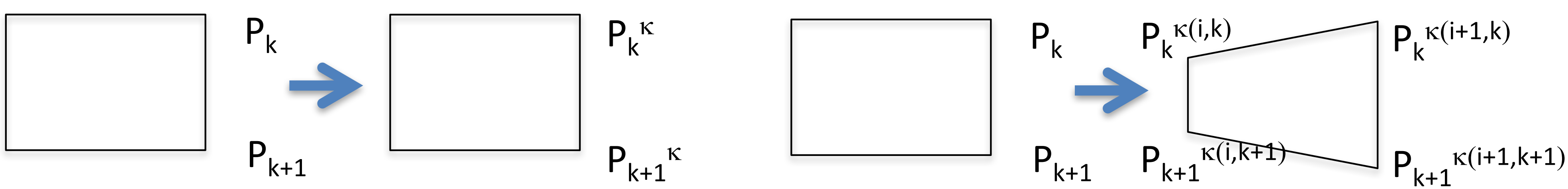
- Te tendency considered: vertical component of electron heat conduction along field-line and heating/cooling.

$$\frac{3}{2}n_e k\frac{\partial T_e}{\partial t} = \sin^2 I\frac{\partial}{\partial z}(K^e\frac{\partial T_e}{\partial z}) + \sum Q_e - \sum L_e$$

- Heating from ionization reactions. Loss rates include loss to neutrals and ions through elastic collisions and vibrational, rotational and fine-structure excitations.
- Ti solved by equilibrium assumption.
- Heating of neutrals by thermal electrons and ions are now included in the model.

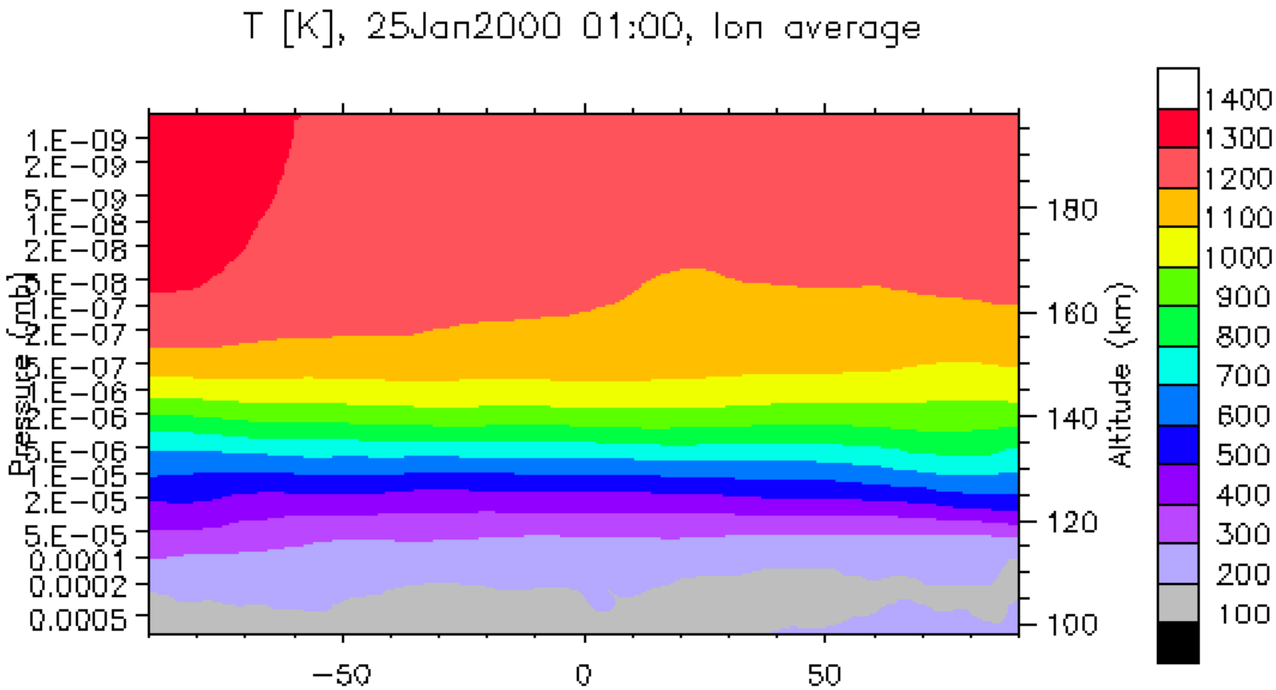
Adapting FV Dycore for Variable Species: Momentum Equations

- Treatment of pressure gradients in horizontal momentum equations.
  - Standard FV core uses Exner function (p^{κ}) as the vertical coordinate for the contour integral of the pressure gradient terms (κ=R/C_p).
  - When κ is a variable, Exner function is not a constant on an isobaric surface, so can't be used as a vertical coordinate.
  - Use pressure or log-pressure instead for computing the contour integral (latter has been used in our implementation).



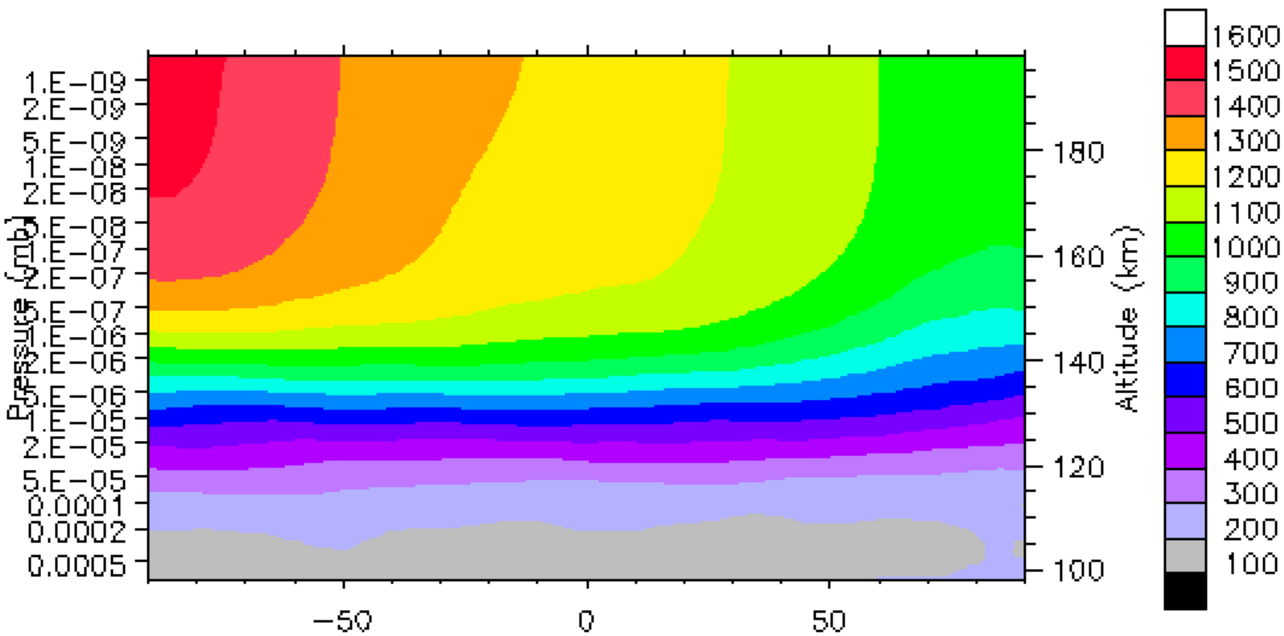
κ constant

κ variable



p$^{\kappa}$ used as vertical coordinate (standard FV dycore)

Tmax = 1372 K



ln(p) used as vertical coordinate (modified FV dycore)

Tmax = 1523 K

Horizontal winds and divergence are solved incorrectly (and often become too strong) with the standard formulation. Causes excessive upwelling in the summer and downwelling in the winter.

Adapting FV Dycore for Variable Species: Thermal Equation and Hydrostatic Equation

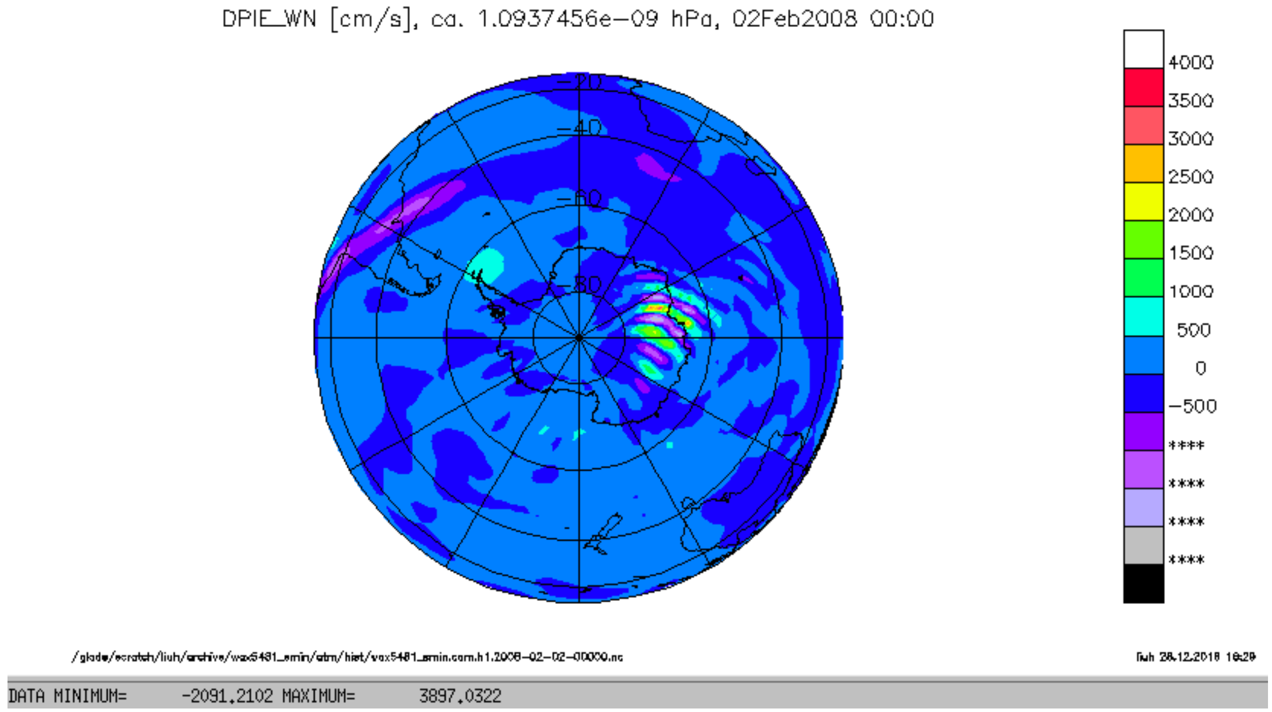
- Thermal equation using potential temperature:

$$\frac{\partial(\Theta\delta p)}{\partial t}+\nabla_H\cdot(\vec{V}_H\Theta\delta p)=\Theta\ln(p/p_0)\left(\frac{\partial(\kappa\delta p)}{\partial t}+\nabla_H\cdot(\vec{V}_H\kappa\delta p)\right)$$

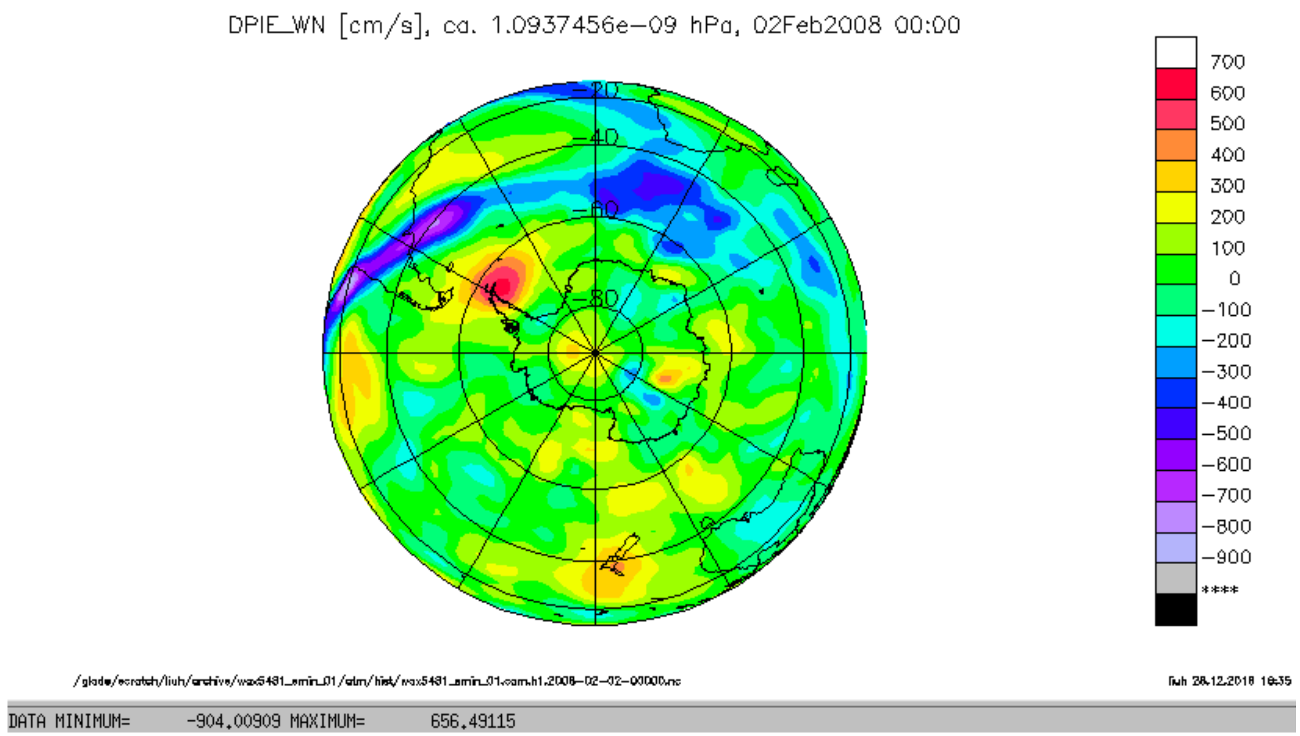
advection of κ should be considered.

- Hydrostatic relation $\delta\phi=C_p\Theta\delta(p^\kappa)$ is used in rebuilding geopotential. This is correct if κ is a constant, but yields an extra term if κ is variable. Should use $\delta\phi=C_p\kappa p^\kappa\Theta\delta(\ln p)$.

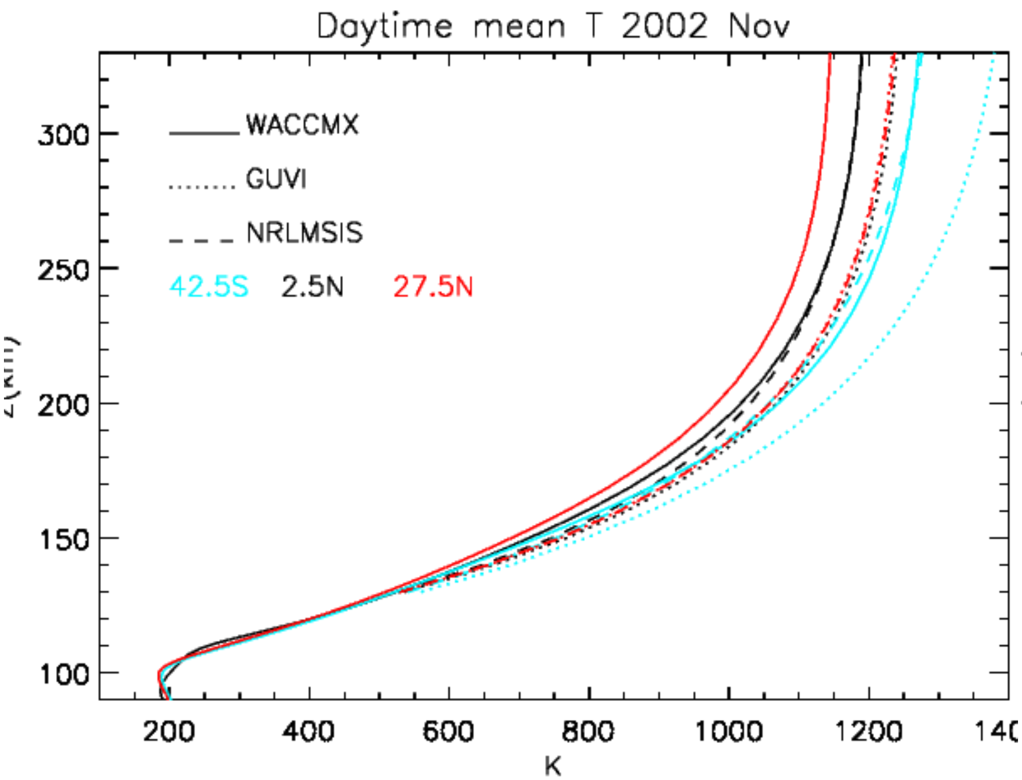
Without advecting κ

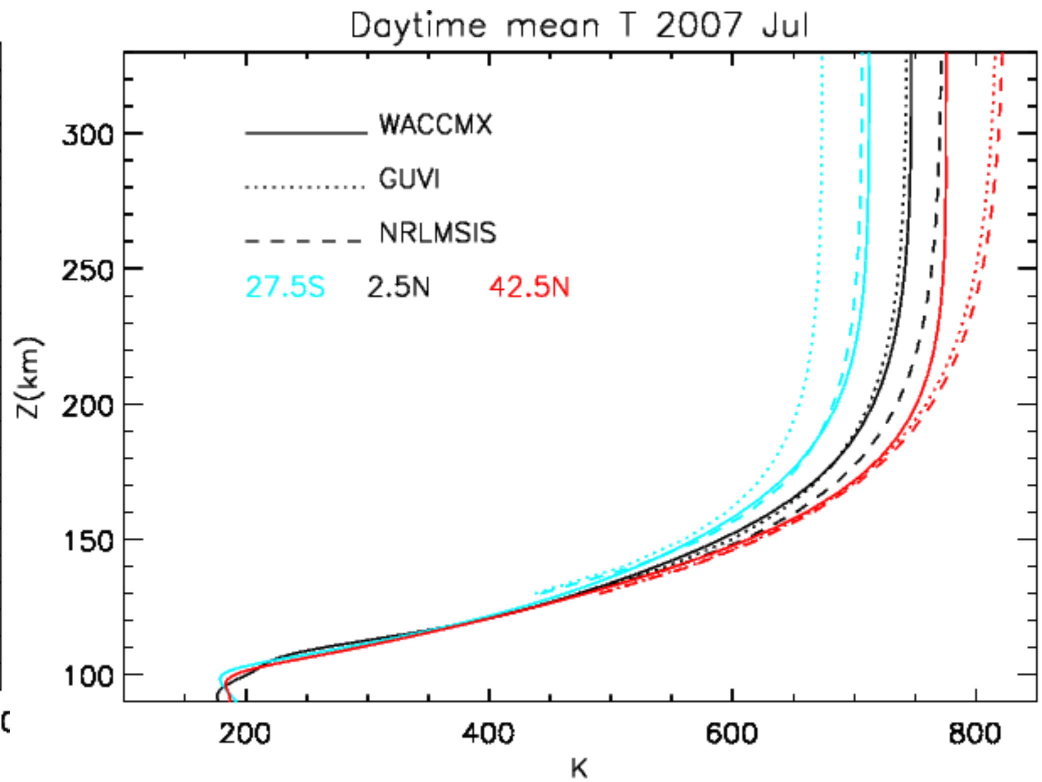


With κ advection



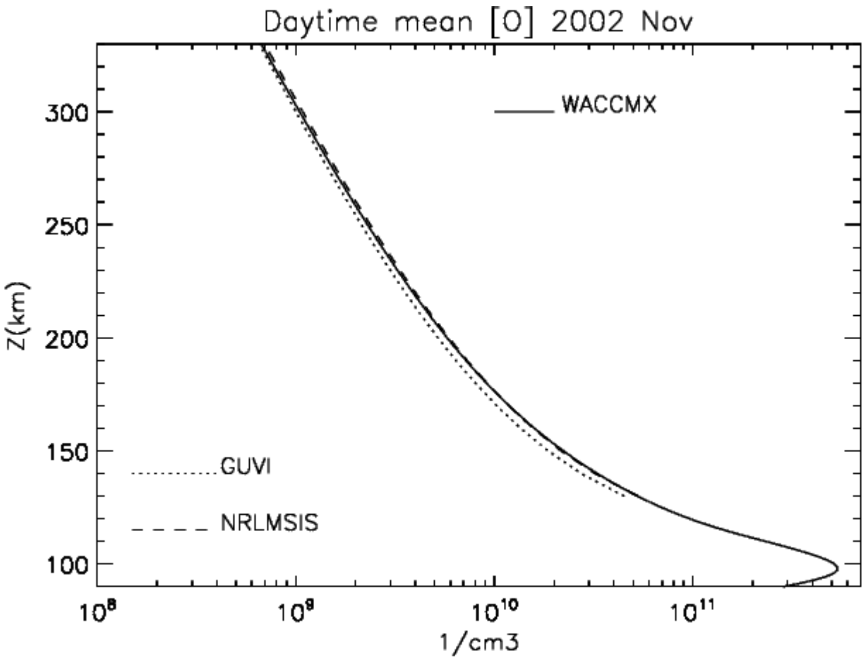
Thermal Structures

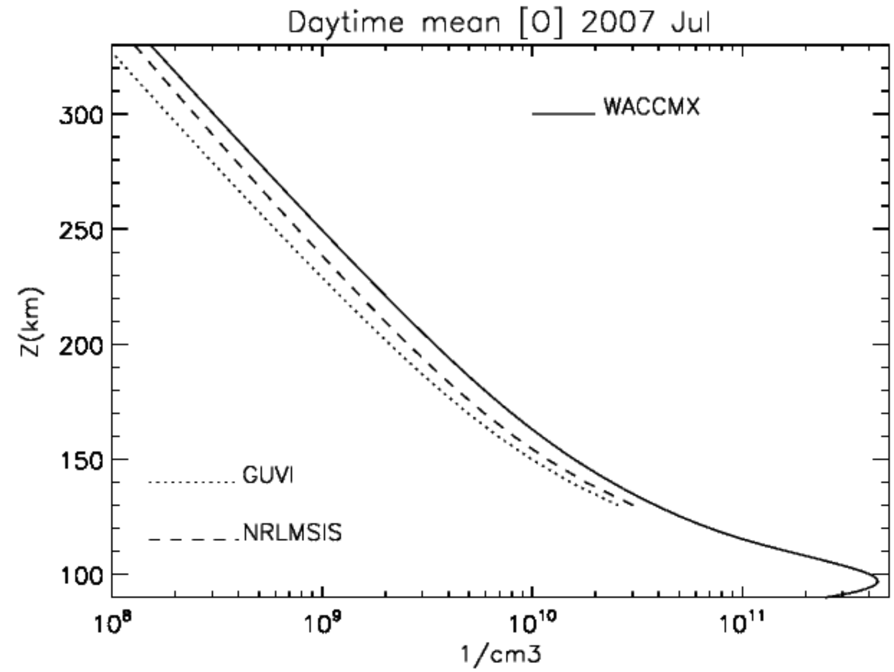


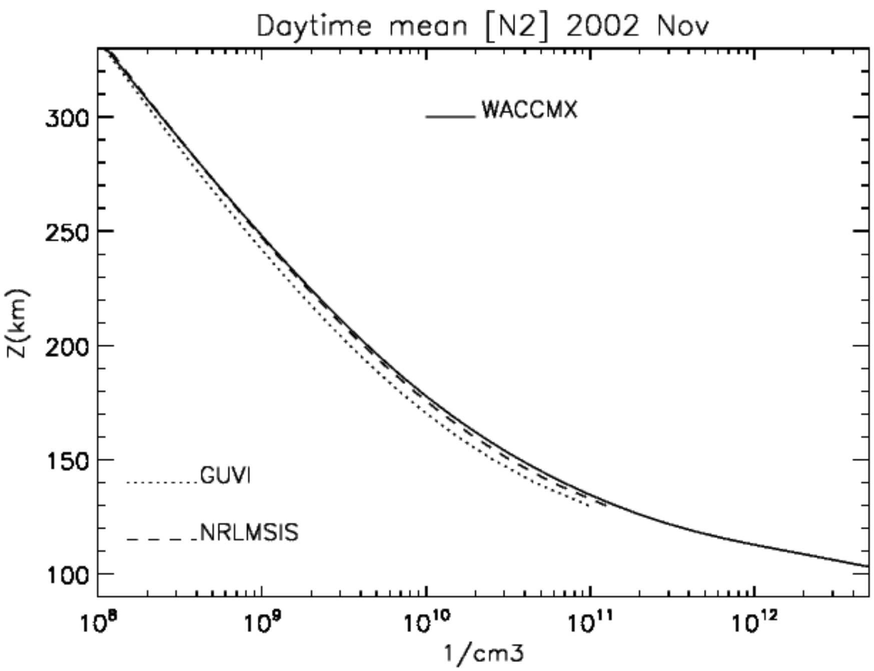


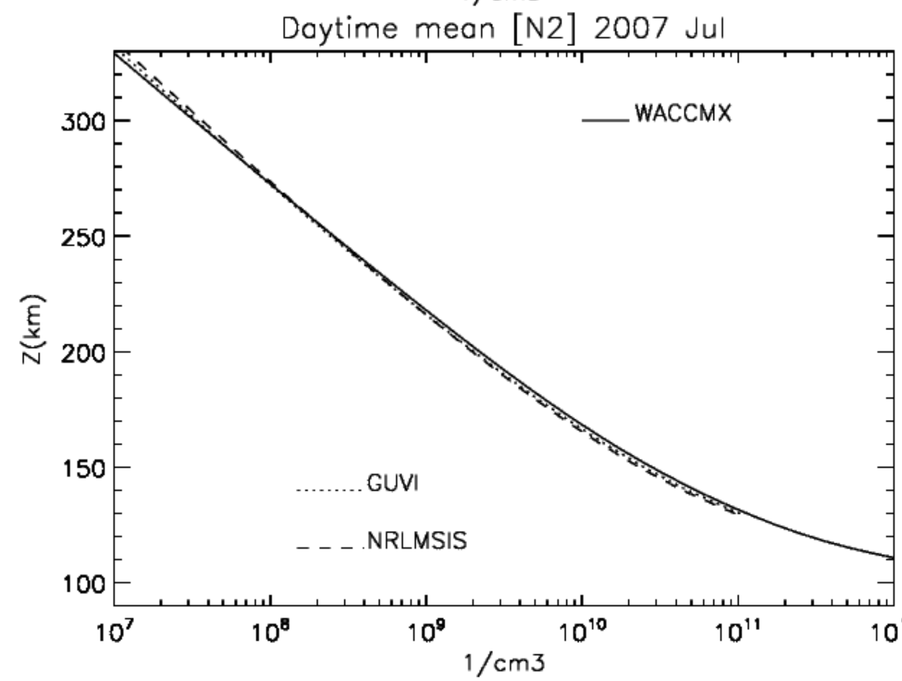
GUVI/NRLMSIS Courtesy of Bob Meier

O And N2

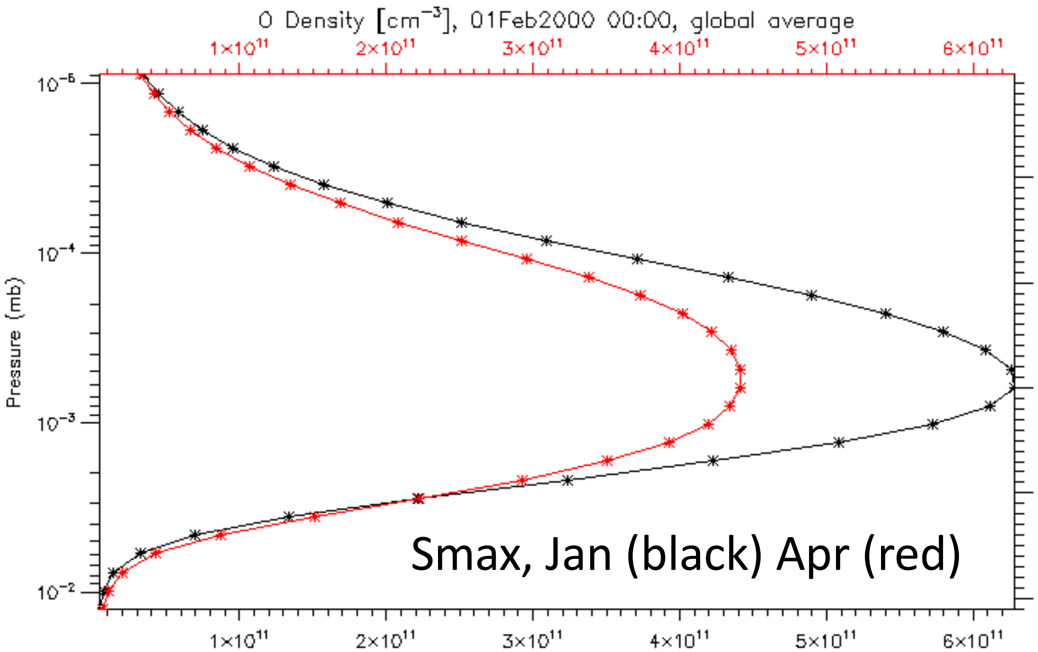

Daytime mean [O] 2002 Nov
WACCMX
GUVI
NRLMSIS
Z(km)
300
250
200
150
100
10^8
10^9
10^{10}
10^{11}
1/cm3

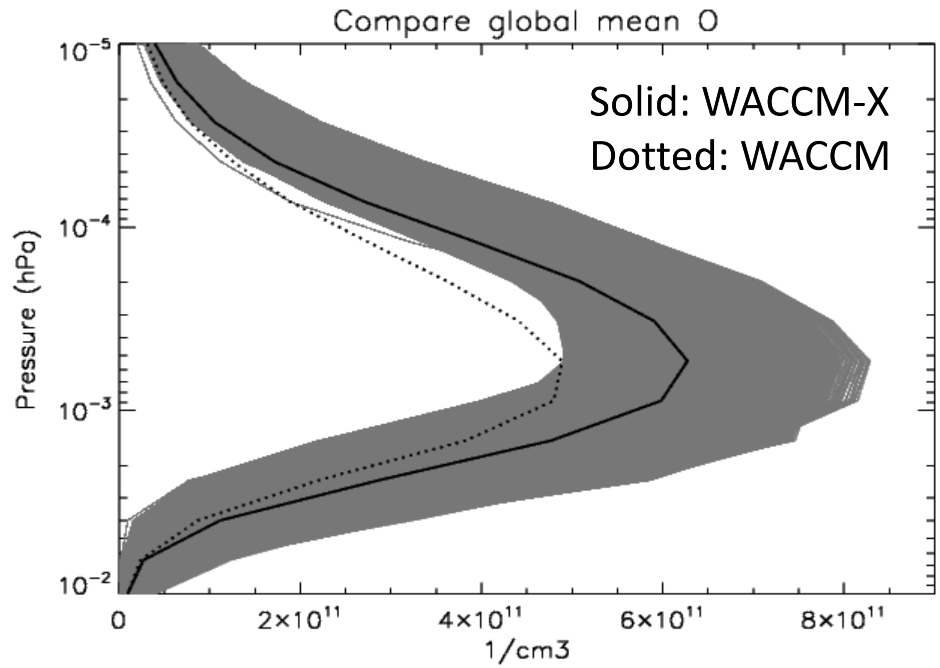

Daytime mean [O] 2007 Jul
WACCMX
GUVI
NRLMSIS
Z(km)
300
250
200
150
100
10^8
10^9
10^{10}
10^{11}
1/cm3


Daytime mean [N2] 2002 Nov
WACCMX
GUVI
NRLMSIS
Z(km)
300
250
200
150
100
10^8
10^9
10^{10}
10^{11}
10^{12}
1/cm3


Daytime mean [N2] 2007 Jul
WACCMX
GUVI
NRLMSIS
Z(km)
300
250
200
150
100
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
1/cm3

O Peak in MLT

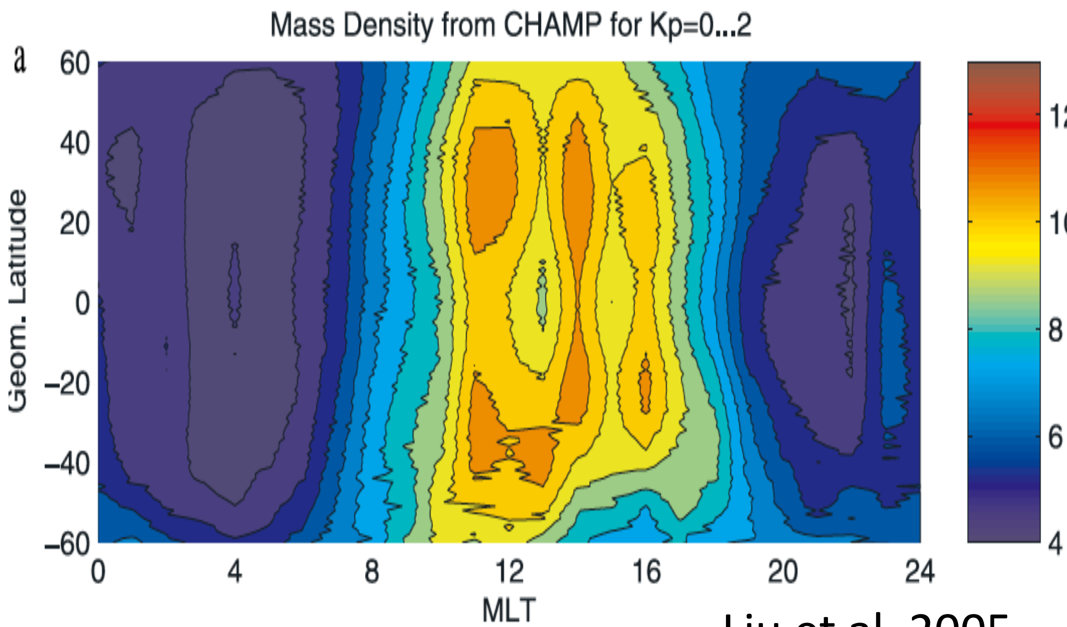




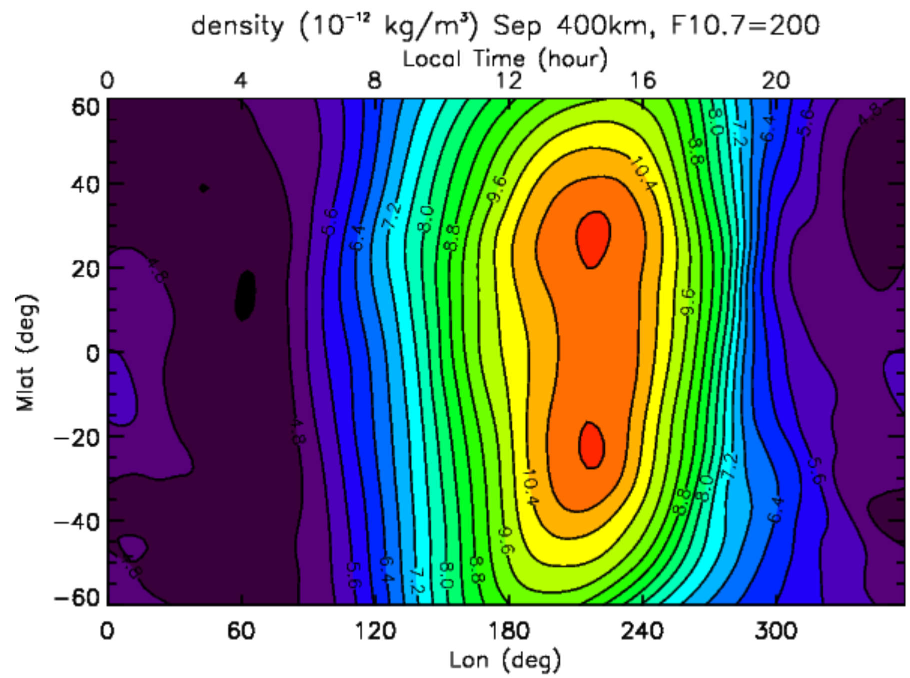
	Pressure			
	0.01 hPa	0.003 hPa	0.001 hPa	0.0004 hPa ~~0.004 hPa~~
Mean altitude (km)	79.2	86.2	92.7	97.9
Day O density (cm^{-3})	1.58 e+10	1.43 e+11	6.22 e+11	7.66 e+11
Night O density (cm^{-3})	5.44 e+09	2.23 e+11	6.56 e+11	5.58 e+11

Smith et al., 2010

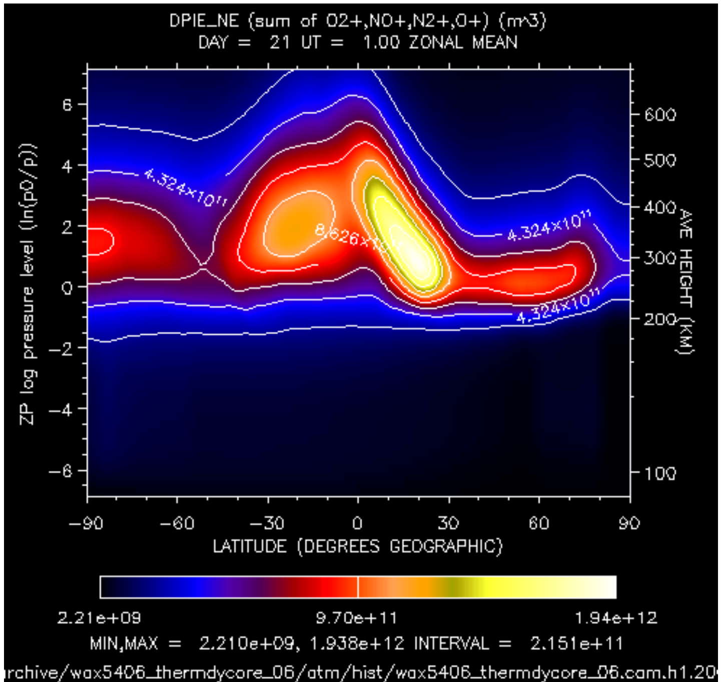
Thermospheric Density at 400km



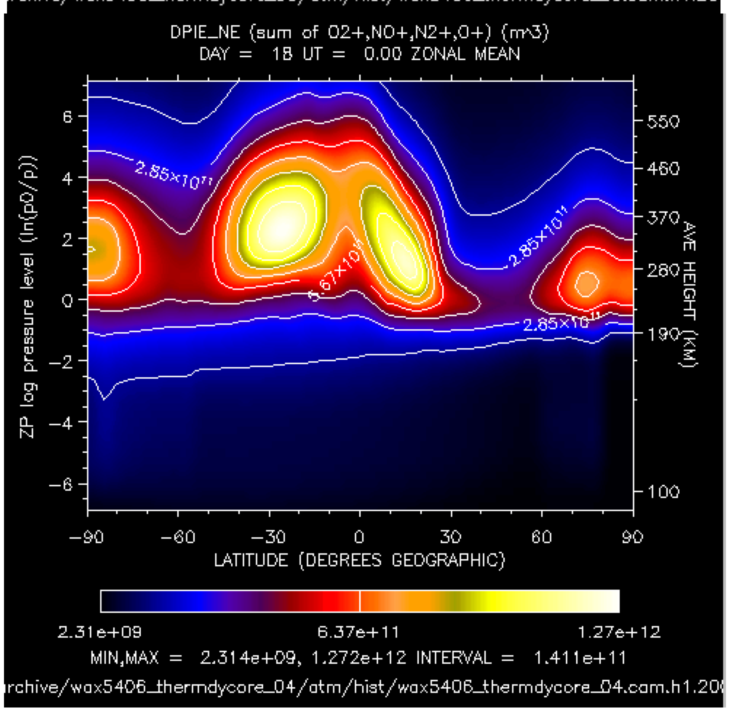
Liu et al. 2005



O+ in WACCM-X and TIME-GCM

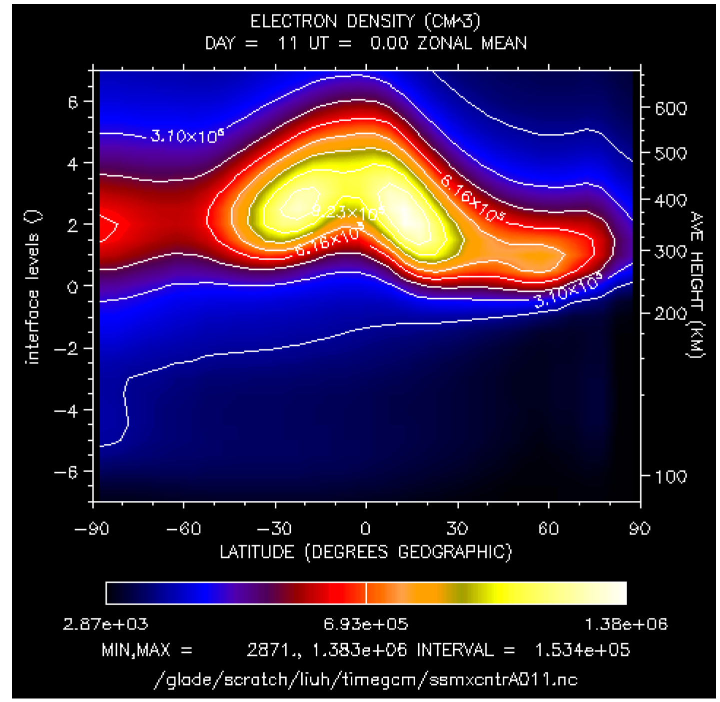


WACCM-X with new dycore



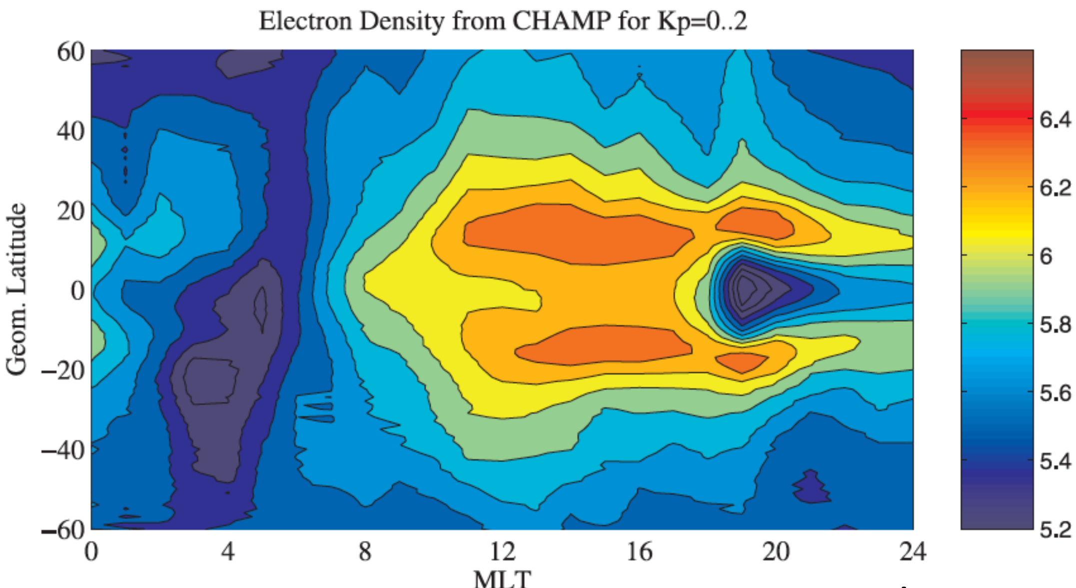
WACCM-X with old dycore

TIME-GCM

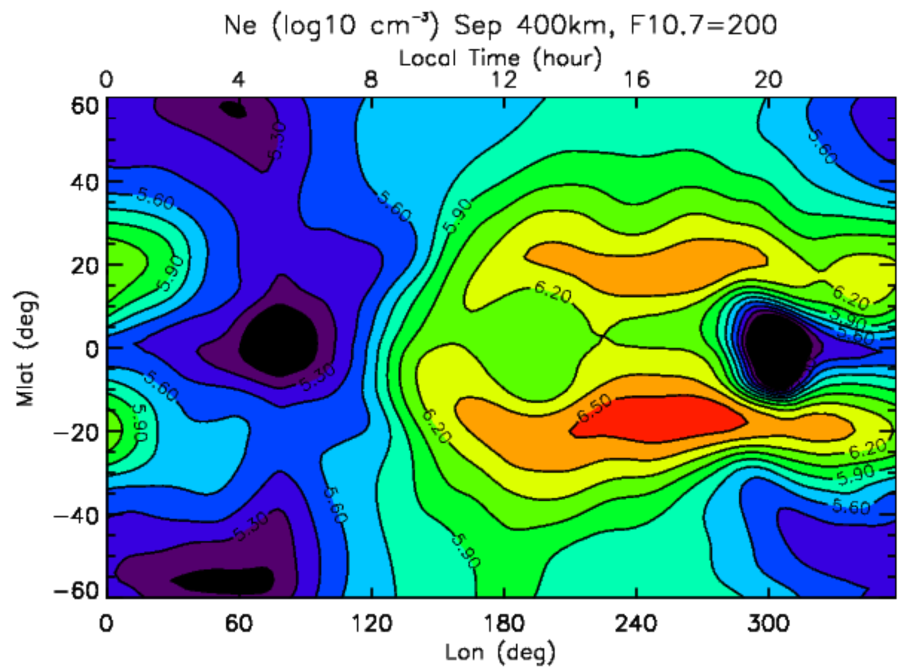


The spurious accumulation of O+ at high laitutdes is gone after the dycore fix.

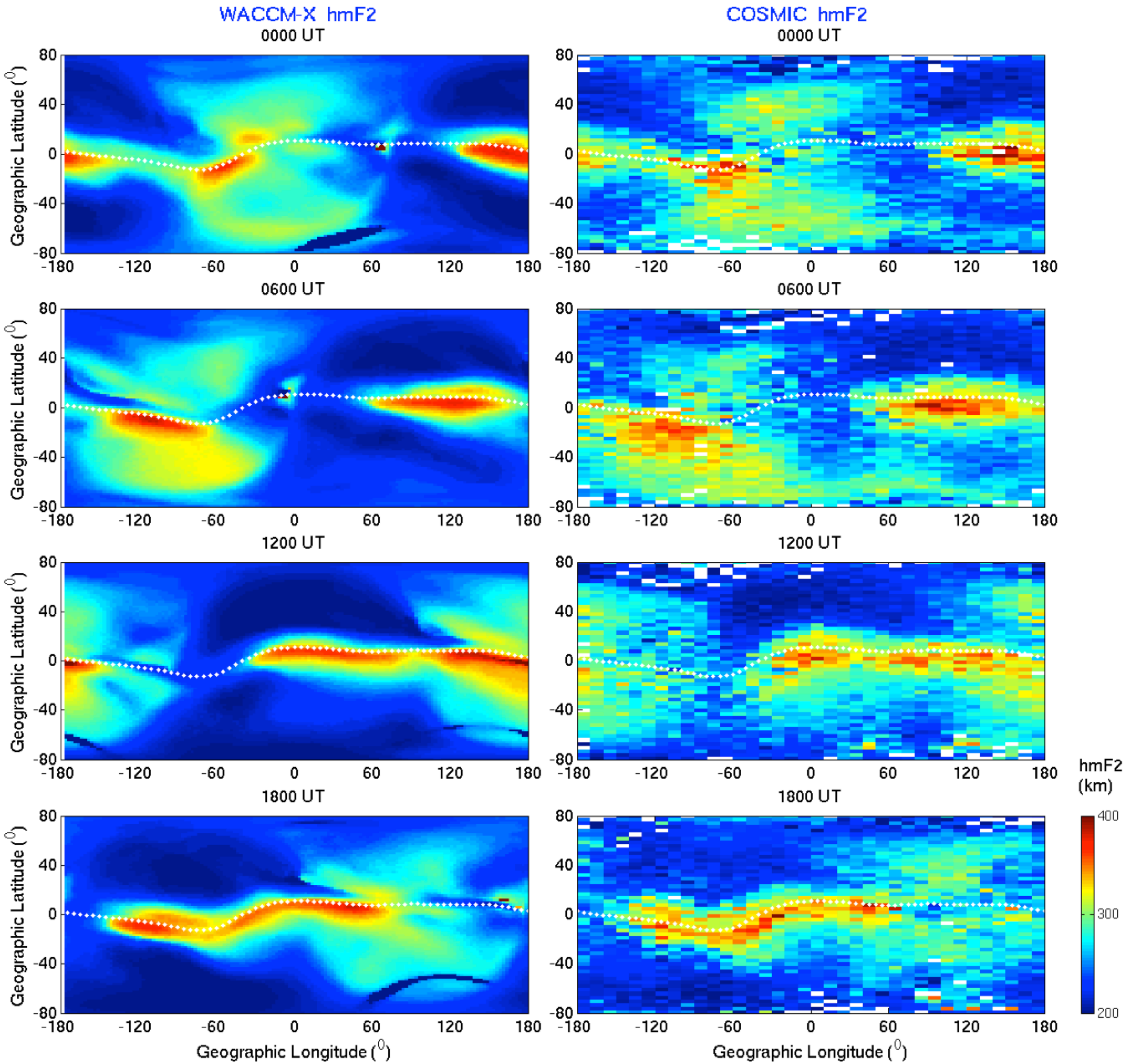
Electron Density at 400km



Liu et al., 2005



Comparison with COSMIC 2008 Jan-Feb



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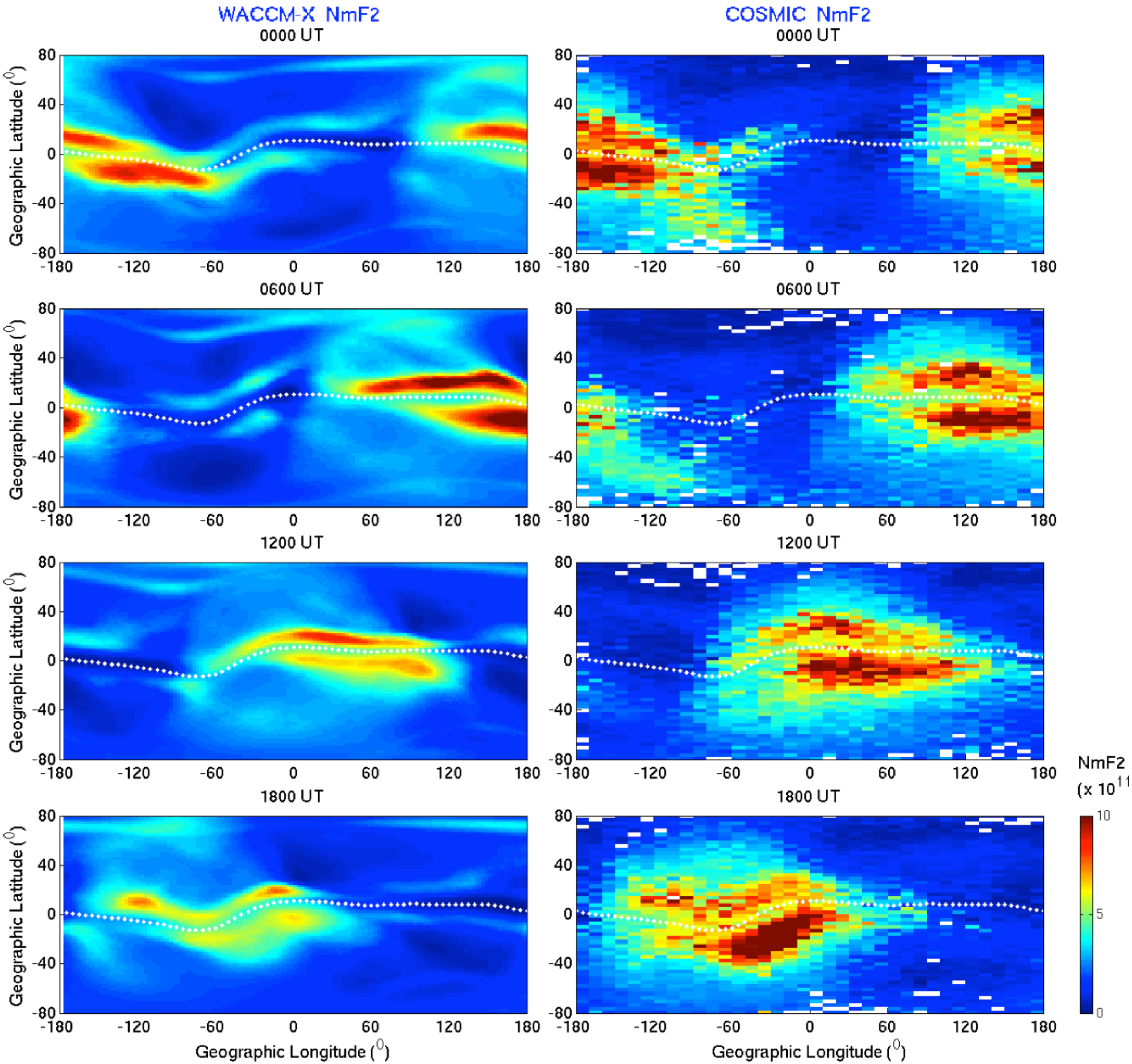
Comparison with COSMIC 2008 Jan-Feb



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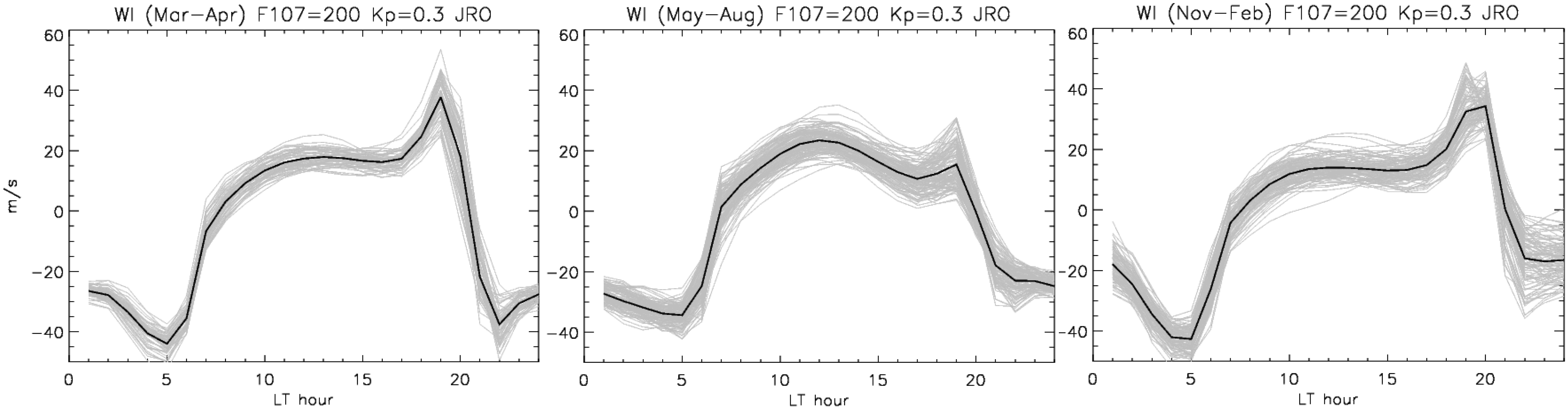
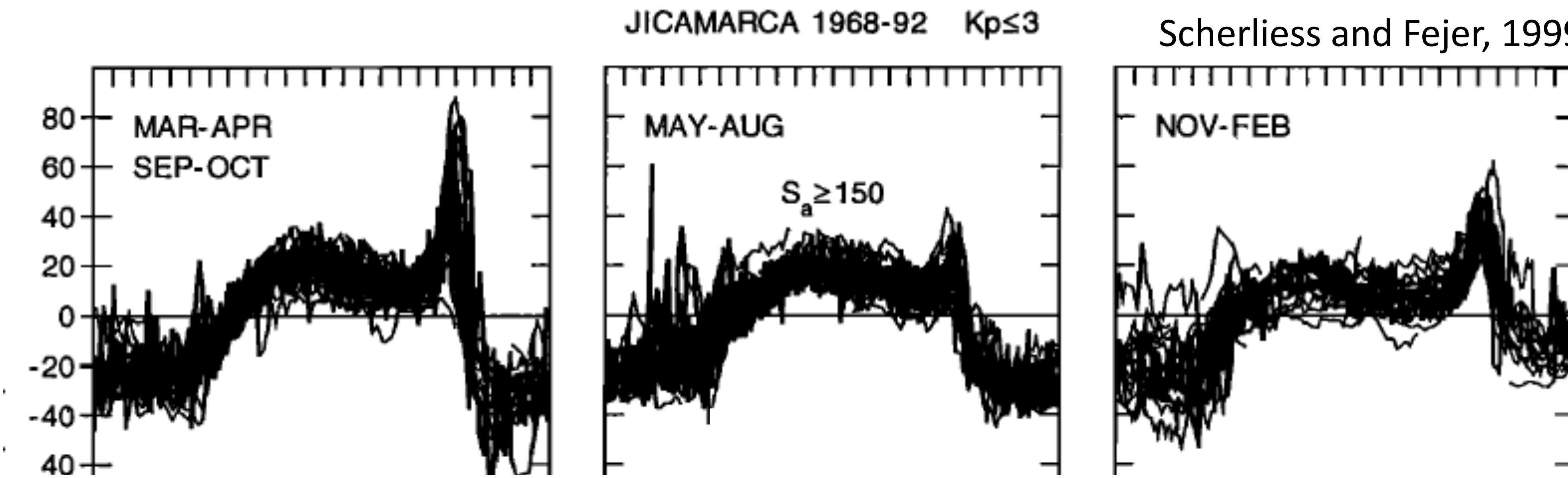
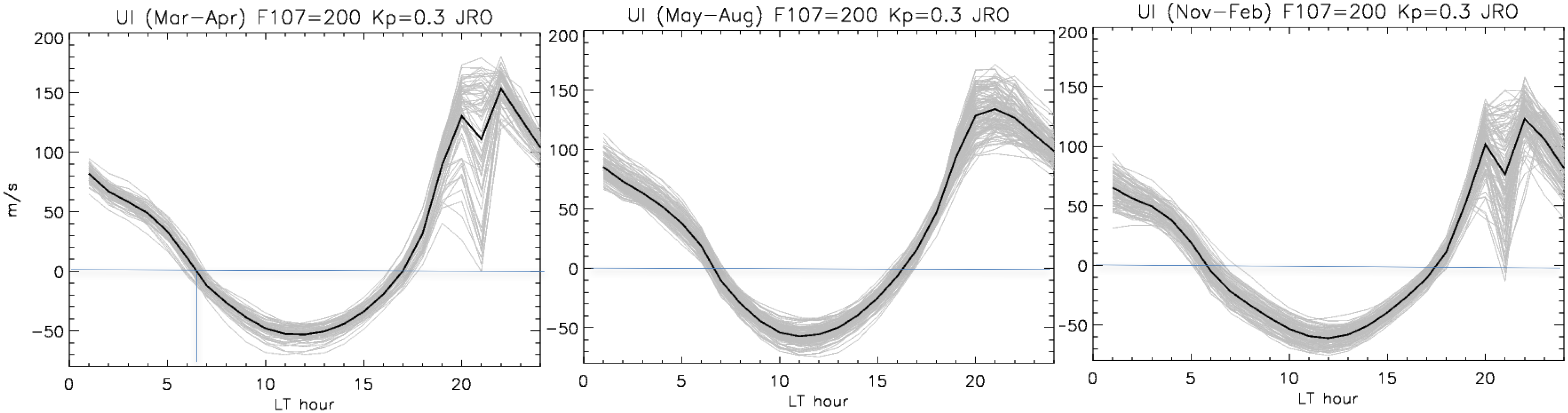
Vertical ExB Drift: Comparison with Smax Climatology



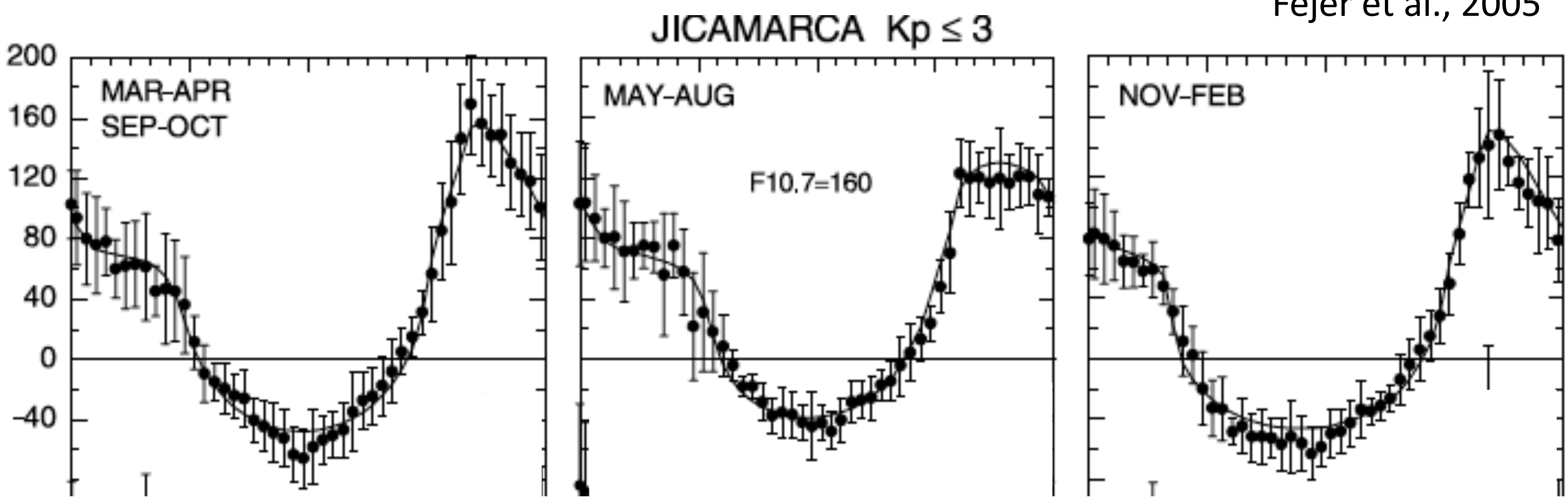


Scherliess and Fejer, 1999

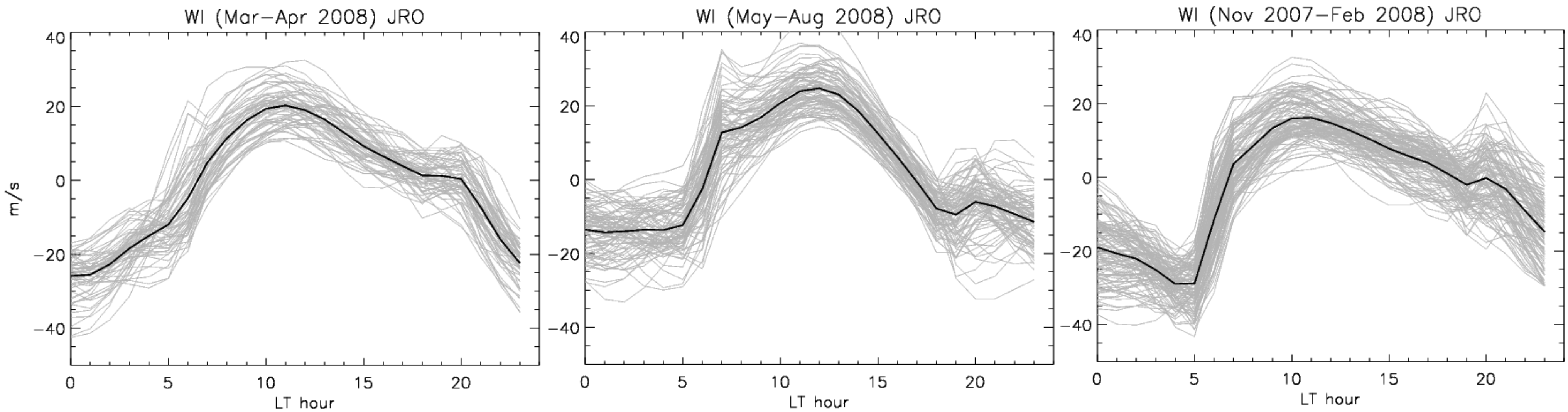
Zonal ExB Drift: Comparison with Smax Climatology



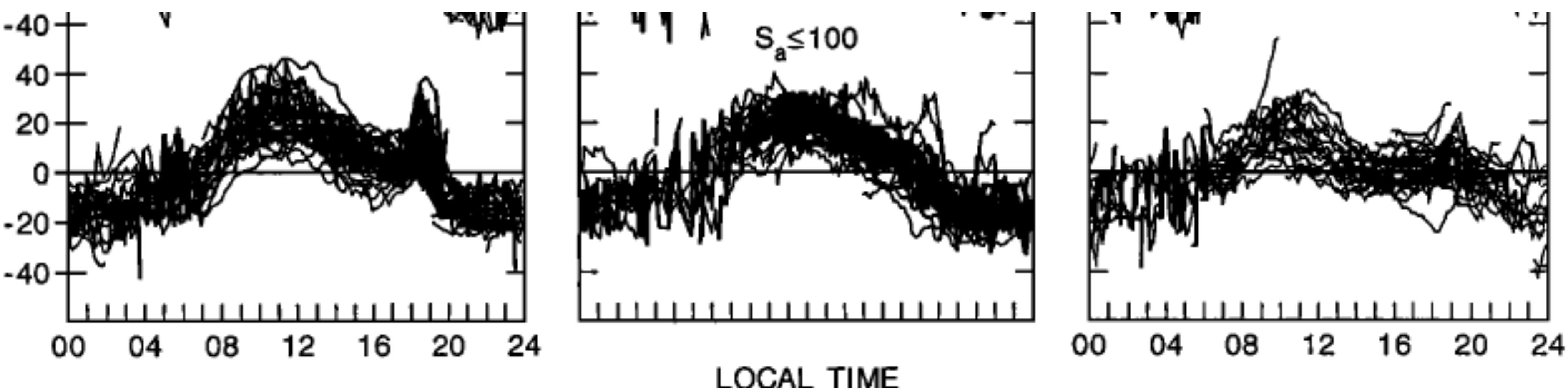
Fejer et al., 2005



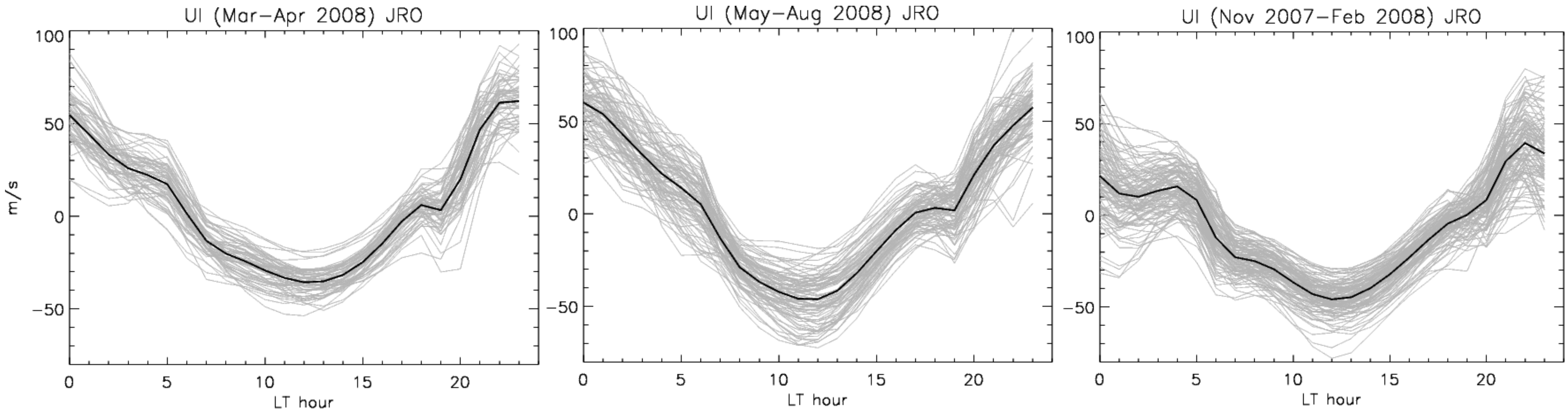
Vertical ExB Drift: Comparison with Smin Climatology



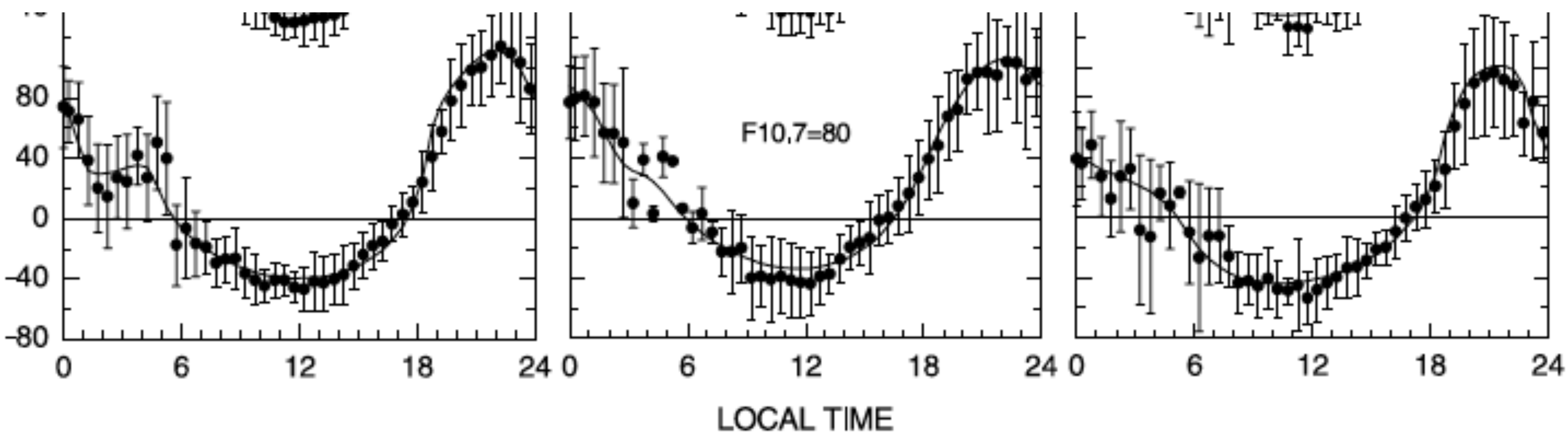
Scherliess and Fejer, 1999



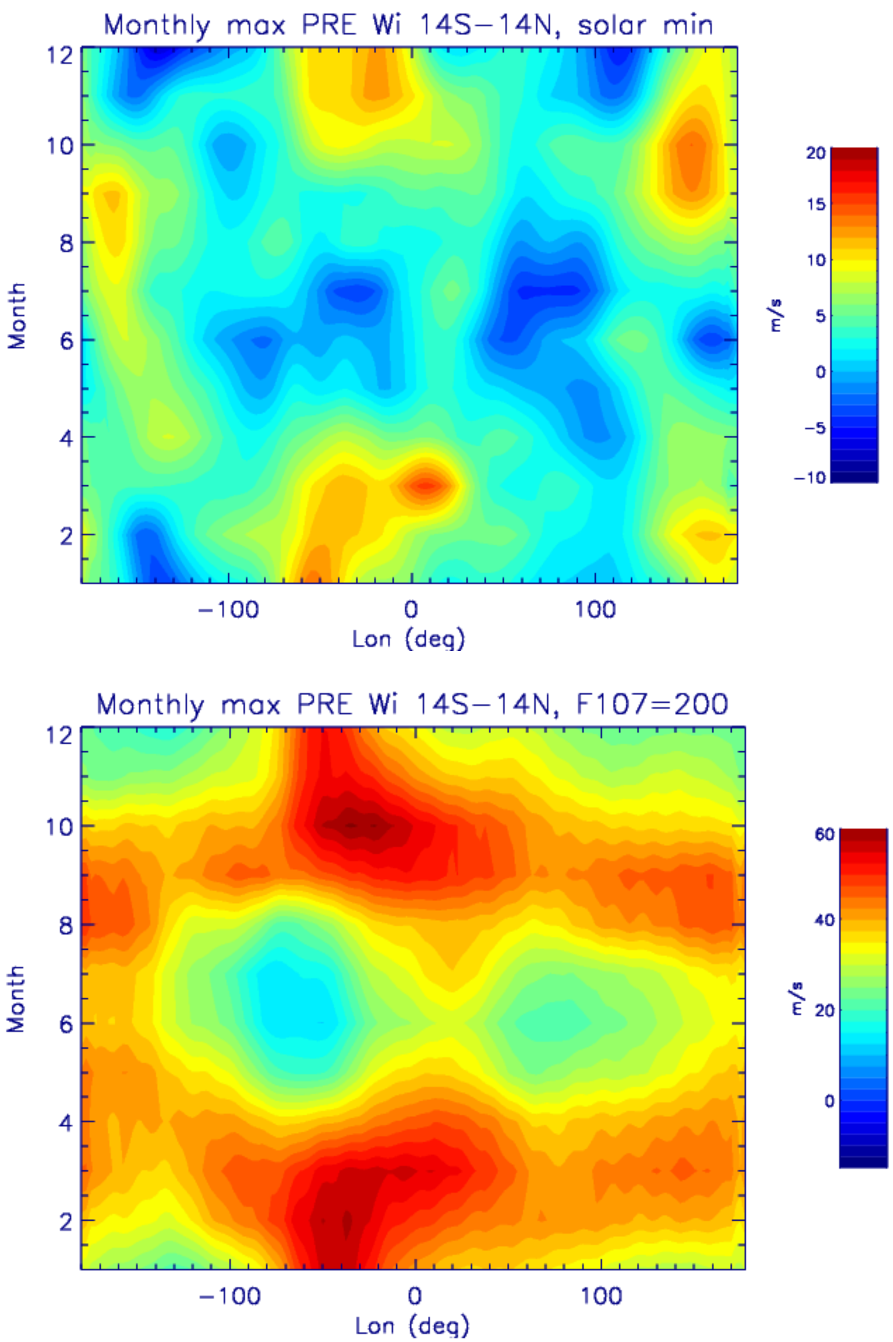
Zonal ExB Drift: Comparison with Smin Climatology

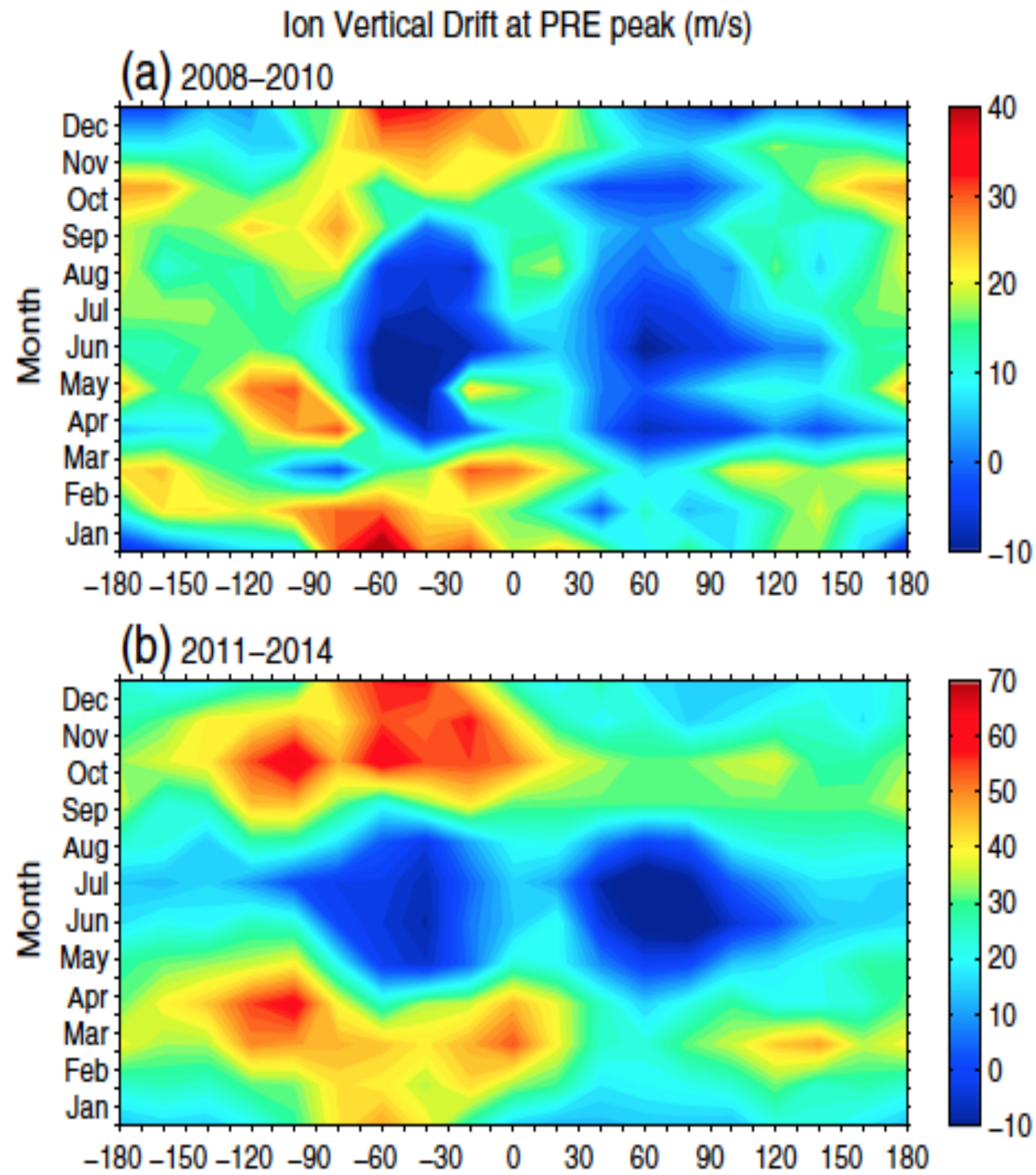


Fejer et al., 2005



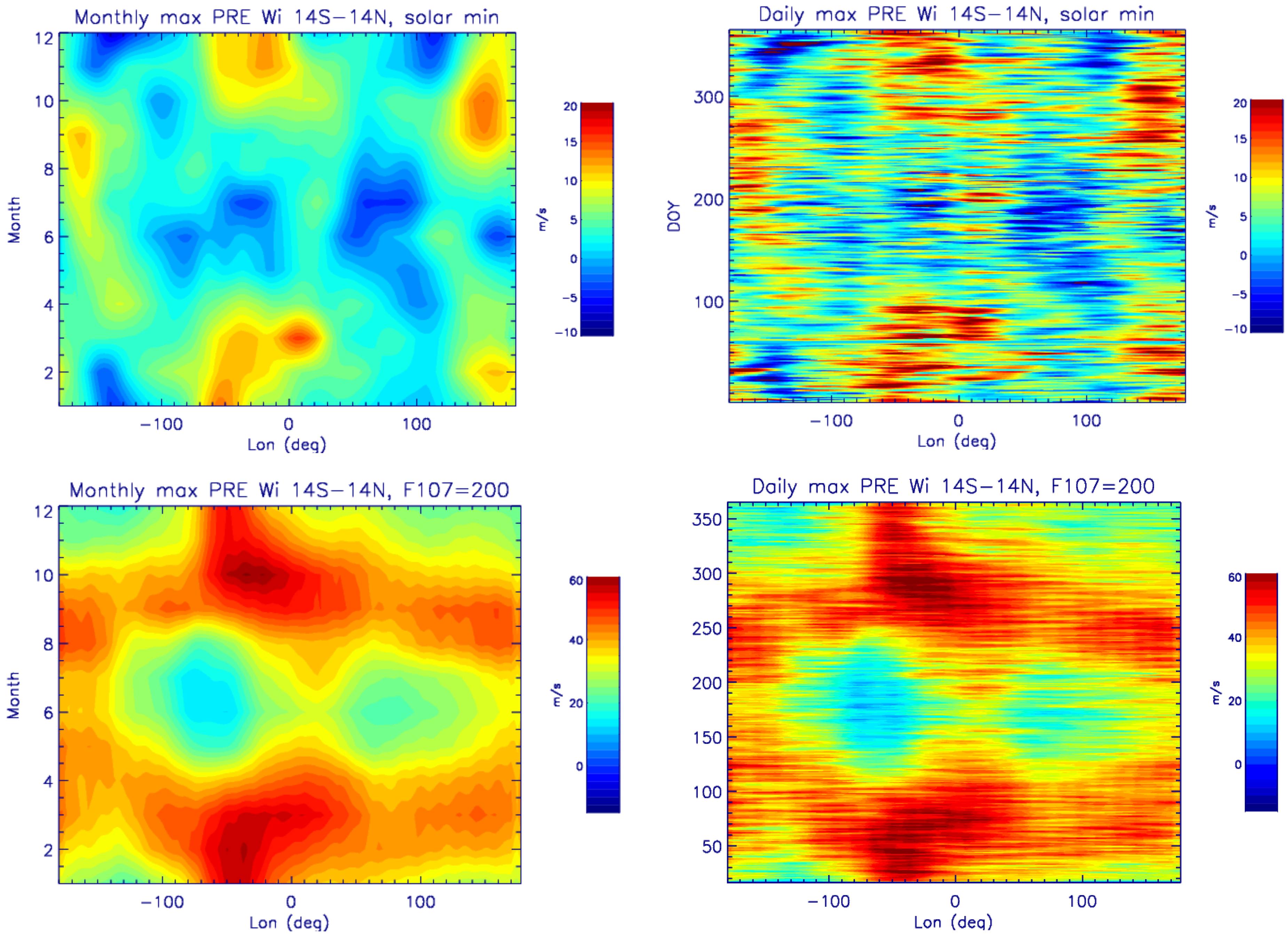
Monthly Mean PRE Peak



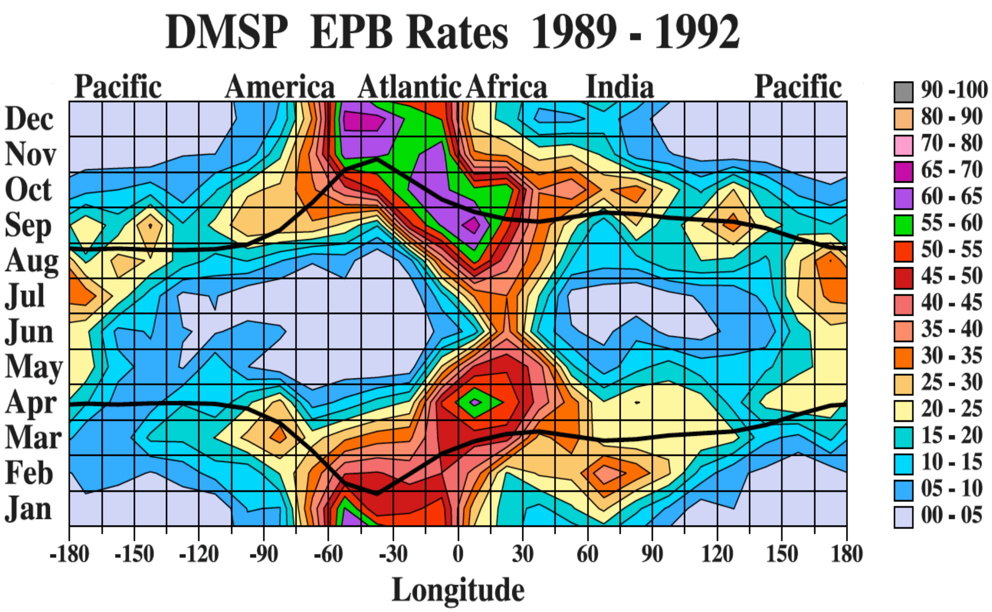


Huang and Hairston, 2015

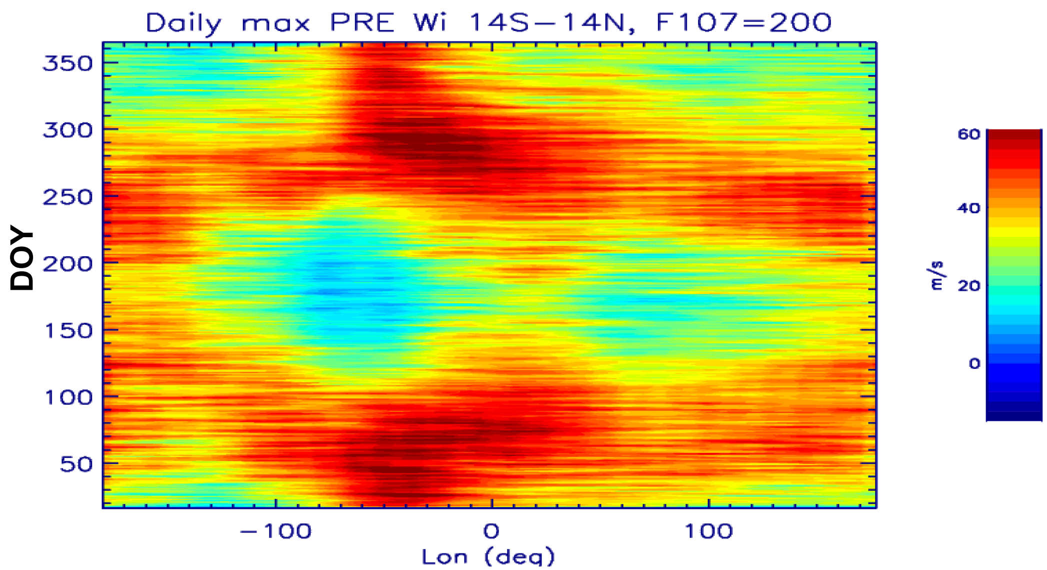
Monthly vs Daily Variability



WACCM-X Ionosphere: PRE Variability

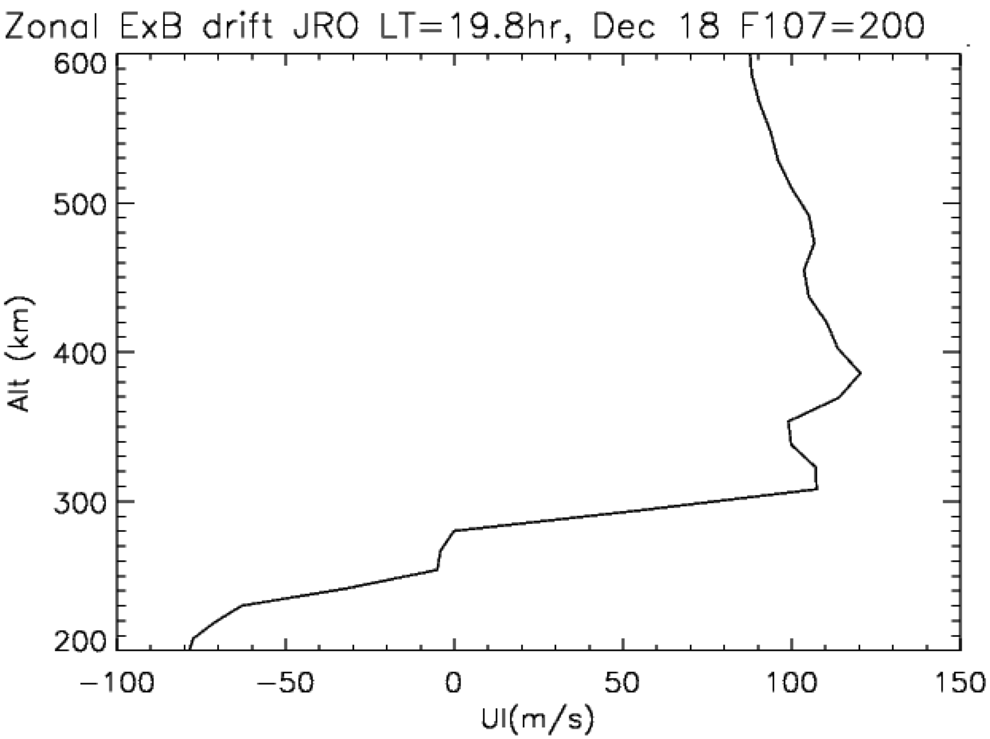


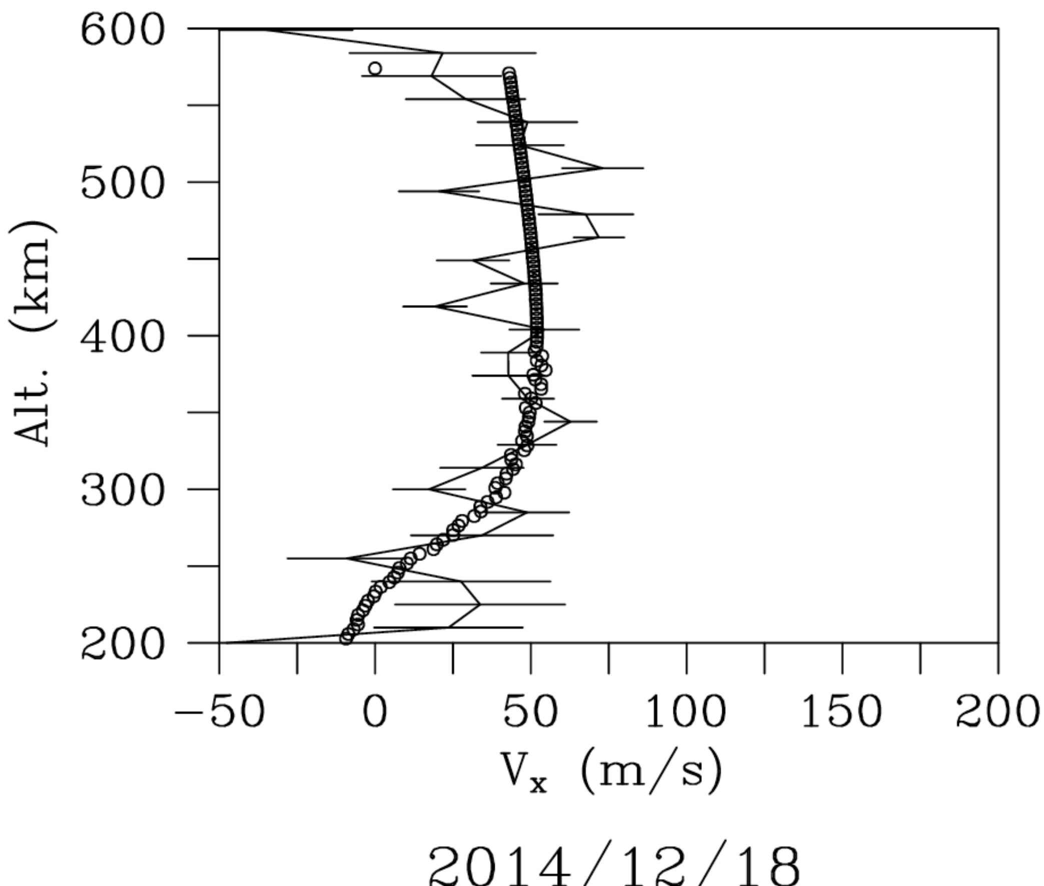
Gentile et al., 2006



WACCM-X Solar Max: Constant F107 and Kp

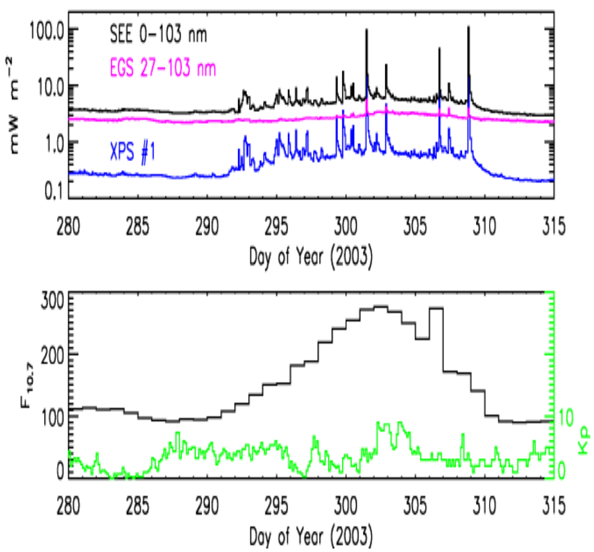
Vertical Profile of Zonal Drift: Smax

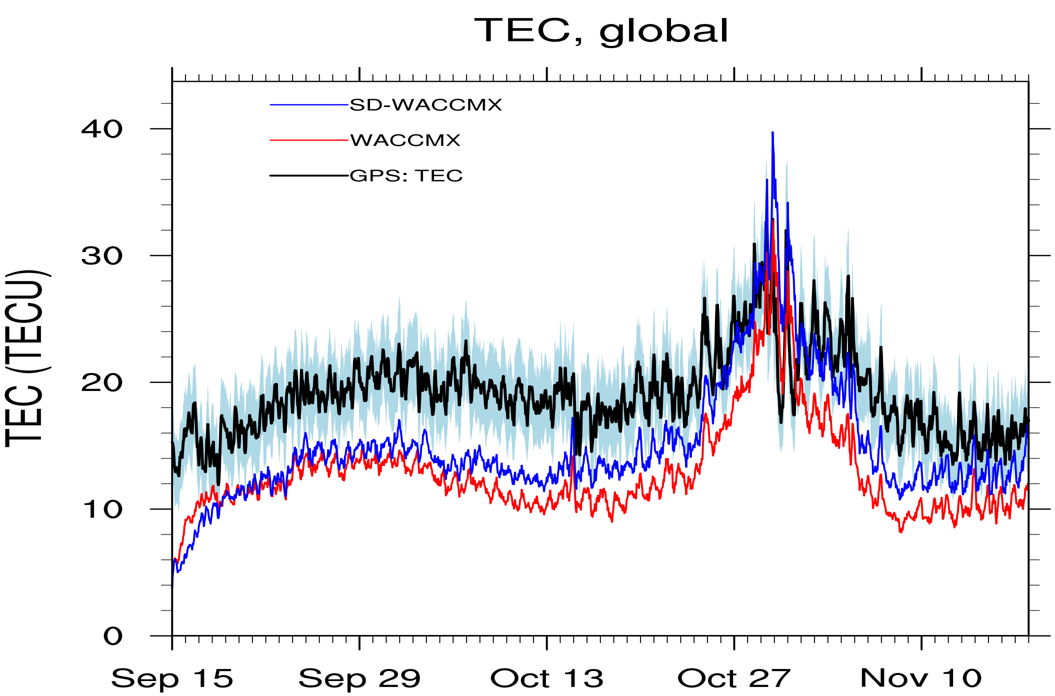




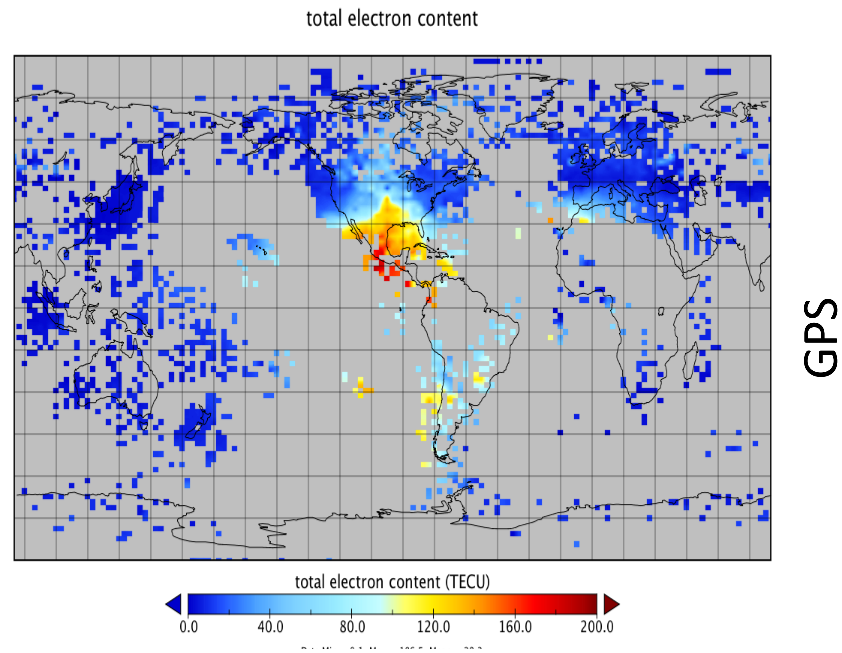
Hysell et al. (2015)

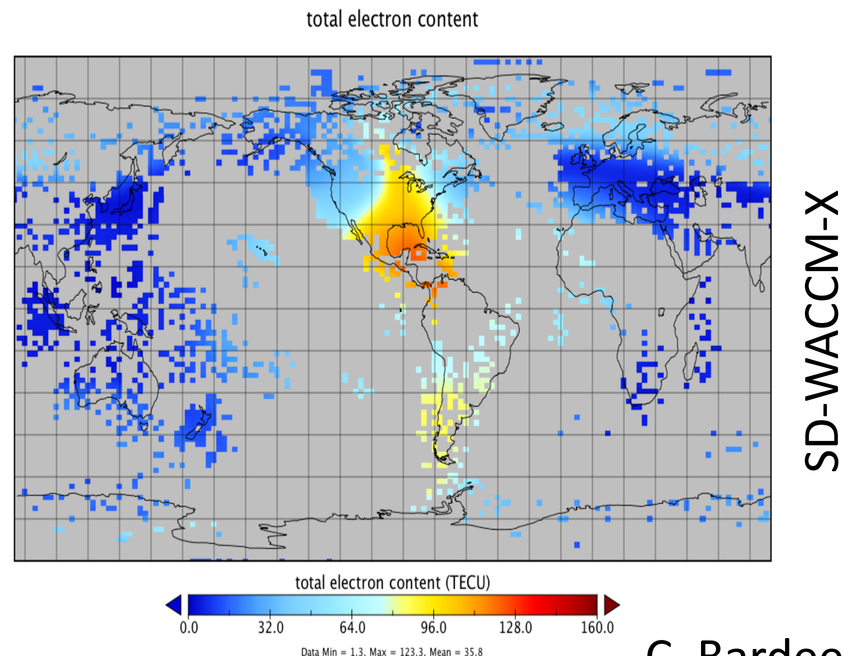
2003 “Halloween” Storms





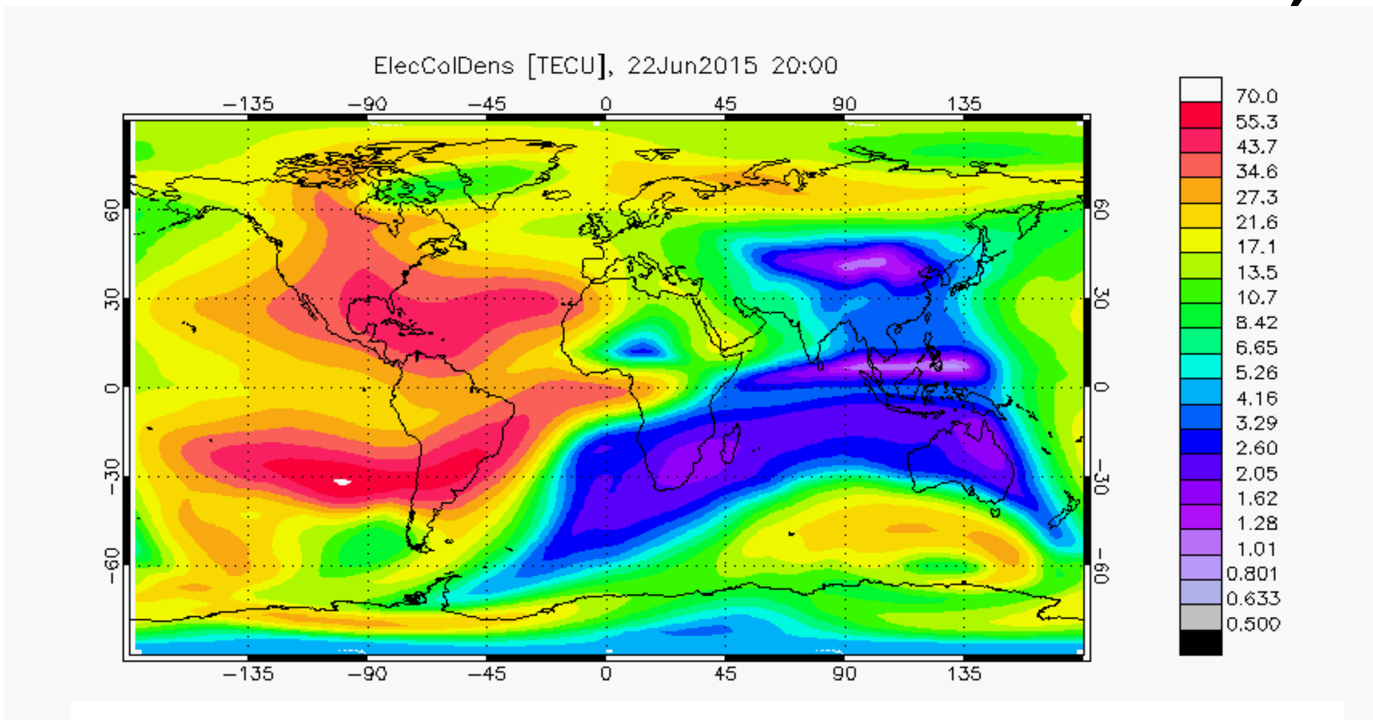
TEC, 29 Oct @ 20:15

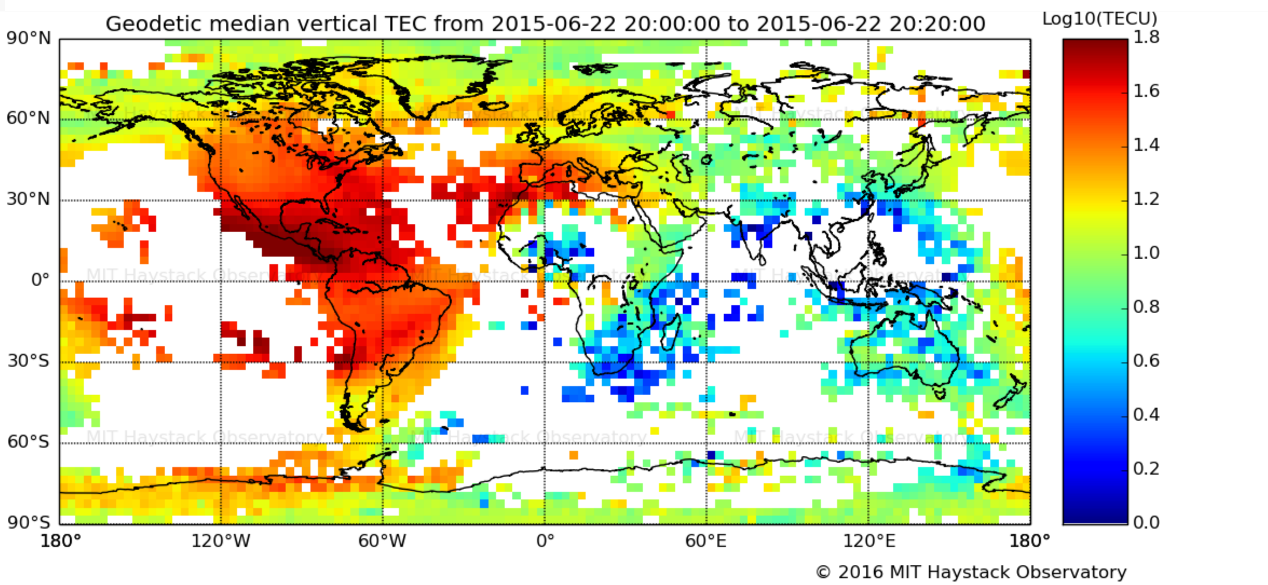




C. Bardeen

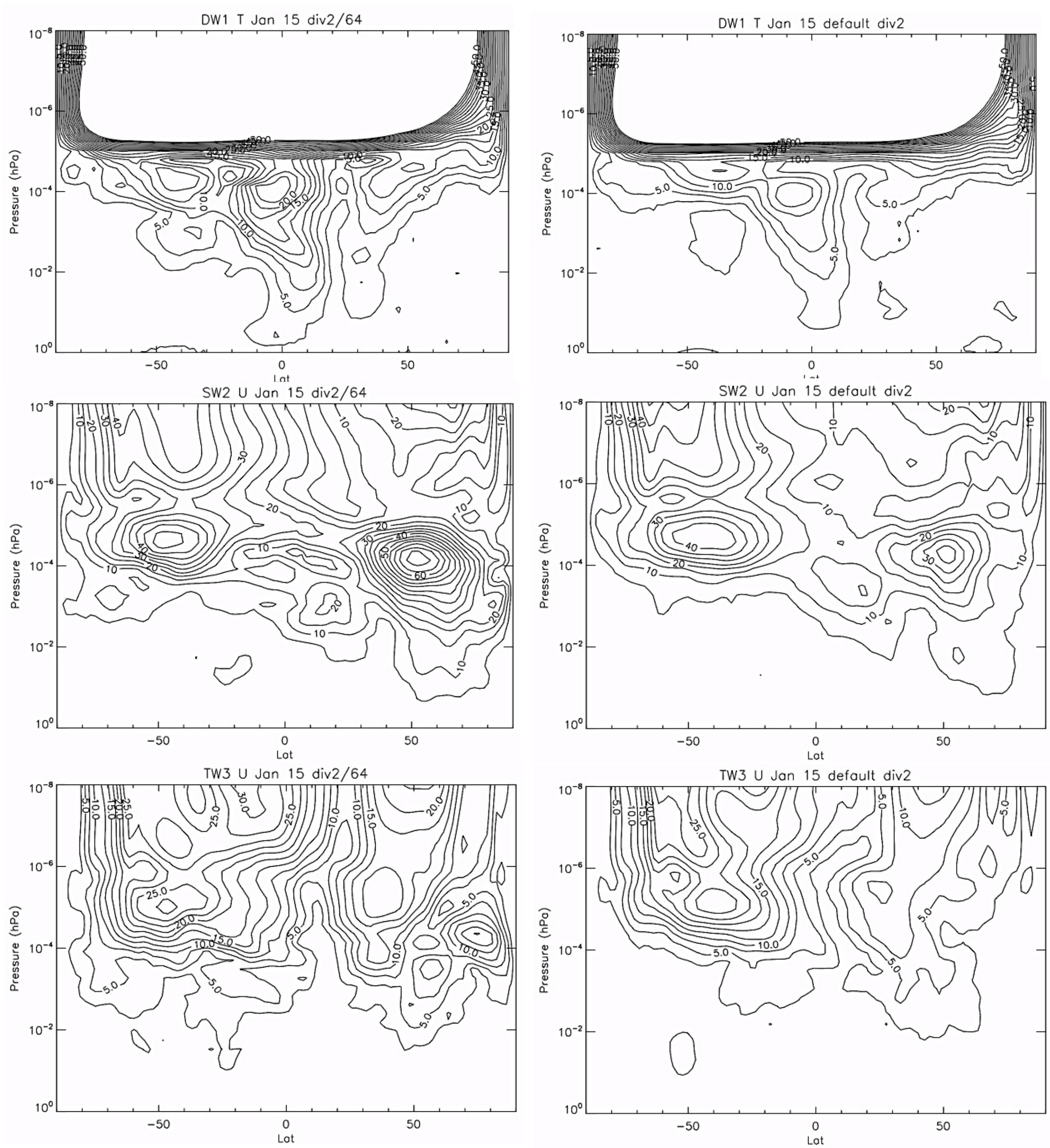
Storm Time Simulation: June 22, 2015





Courtesy of Madrigal Database at Haystack Observatory

WACCM-X Tides



Summary

- WACCM-X now includes interactive ionospheric wind dynamo, O+ transport, as well as ionospheric chemistry.
- Finite volume dynamical core has been improved to consider variable species, and along with it variable specific heats and mean molecular mass.
- Thermospheric temperature and composition are in general agreement with observations.
- Ionosphere plasma density and drifts are in general agreement with observations.
- Storm time ionospheric structure in general agreement with observations.
- WACCM-X+DART produces realistic short-term variability in the ionosphere.