Whole Atmosphere Community Climate Model with Thermosphere/Ionosphere Extension (WACCM-X): Model Requirements, Structure, Capabilities and Validation

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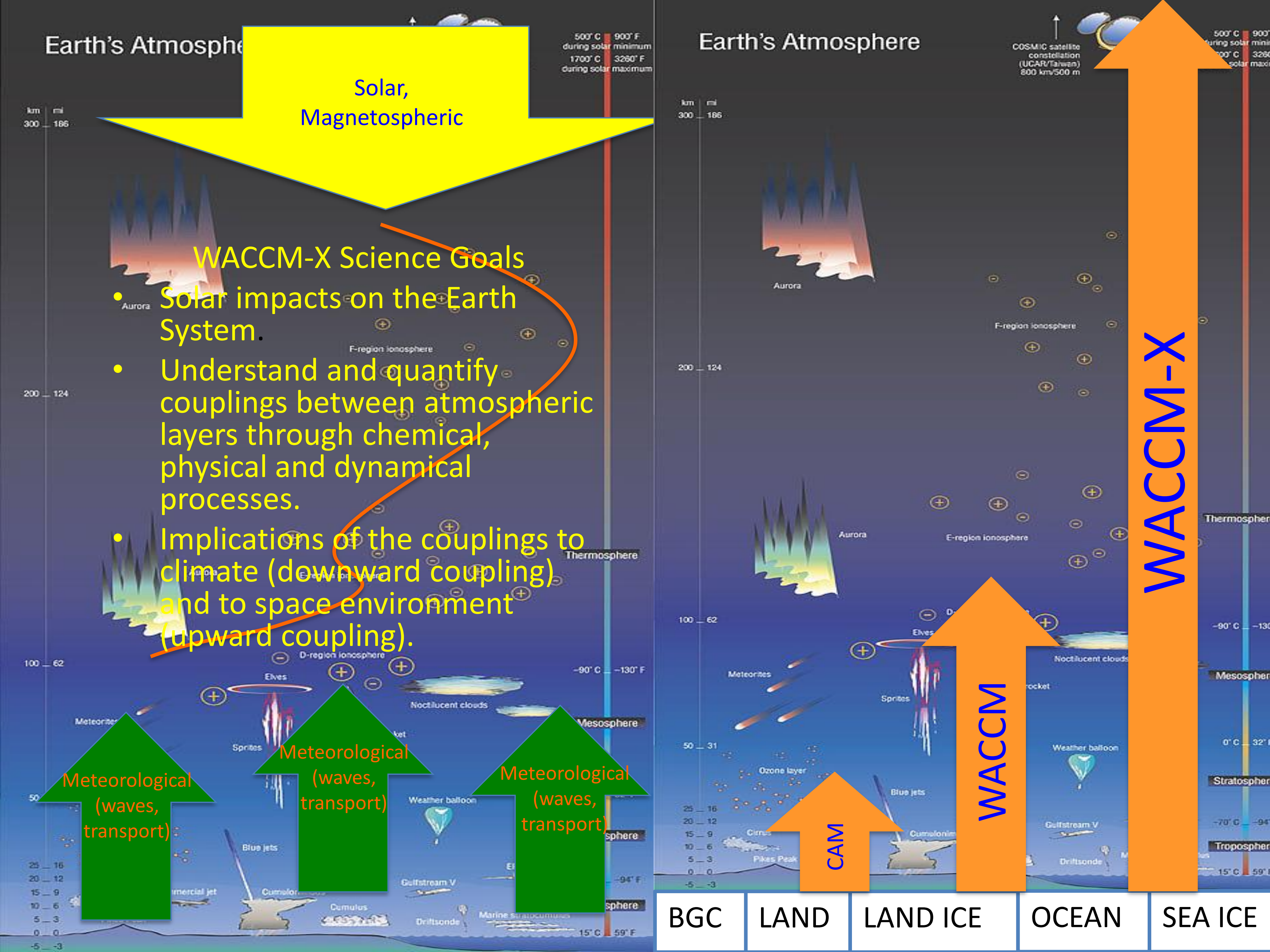

Earth's Atmosphere
Solar, Magnetospheric
WACCM-X Science Goals
• Solar impacts on the Earth System.
• Understand and quantify couplings between atmospheric layers through chemical, physical and dynamical processes.
• Implications of the couplings to climate (downward coupling) and to space environment (upward coupling).
Meteorological (waves, transport)
Meteorological (waves, transport)
Meteorological (waves, transport)
Earth's Atmosphere
CAM
WACCM
WACCM-X
BGC
LAND
LAND ICE
OCEAN
SEA ICE

Important Physical Properties

- Deep: 10% of Earth radius, ~29 scale-heights, 10^{13} change in density from Earth surface to exobase.
- Diffusive separation above the homopause.
- Ion-neutral coupling
  – Different transport processes of neutral species and ionospheric plasma (oriented along magnetic field lines).
- Coupling between dynamics and photochemistry.
- Short temporal and spatial scales
  – Increasing significance of gravity waves and tides.
  – Large wind (~300m/s) and acoustic speed (~800m/s).
  – Geomagnetic storms and fine ionospheric structures.
  – Ionospheric irregularities.
  – Large molecular viscosity and diffusion (both vertically and horizontally).

Implications for Mathematical and Numerical Formulation (1)

- Diffusive separation above the homopause:
  - Specific heats and mean molecular weight (thus gas "constant" of dry air) are dependent on major species (O, O_2, N_2, He, H), thus vary spatially and temporally.
  - Potential temperature becomes an ill-posed quantity: the mixing ratios of the major species are different from those at reference levels.
  - Variable gravity affects the scale height (thus the vertical distribution) of individual species.

Implications for Mathematical and Numerical Formulation (2)

- Coupling between dynamics and photochemistry.
  - Conservative and efficient computation of advective transport of large number of chemical species.
- Ion-neutral coupling:
  - Frequent mapping between dycore grid and geomagnetic grid.
  - Transport routines that can handle different advective velocities (neutral winds and ion velocities).

Implications for Mathematical and Numerical Formulation (3)

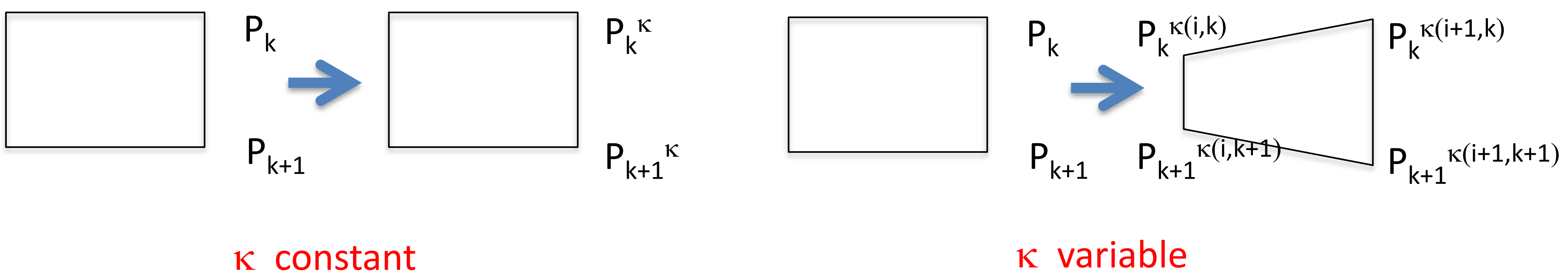
- Short temporal/spatial scales of physical processes:
  - Parameterization schemes that can accommodate short time steps (5 minutes or less).
  - Code design that is capable of subcycling and super-cycling.
  - Mesh refinement capability.
  - Non-hydrostatic dynamics.
  - Horizontal diffusion should be included with increasing spatial resolution.
  - Would require short time steps or sub-cycling, or implicit treatment.
  - Efficient scaling for high-resolution simulations.

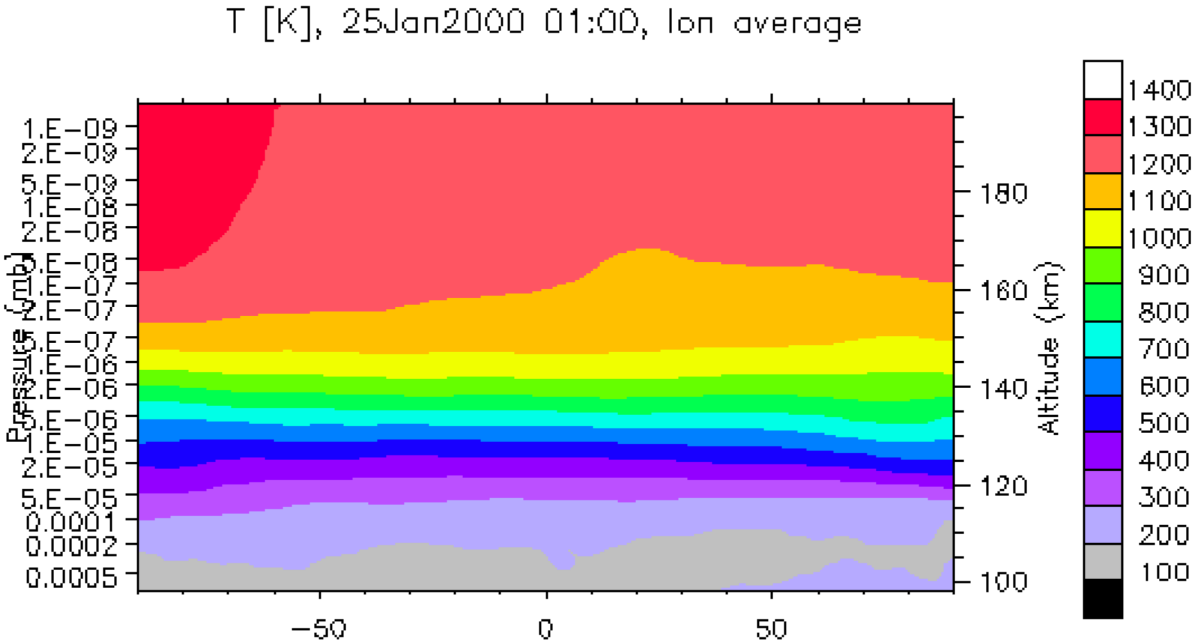
Major CESM WACCM/WACCM-X Components

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.

Adapting FV Dycore for Variable Species: Momentum Equations

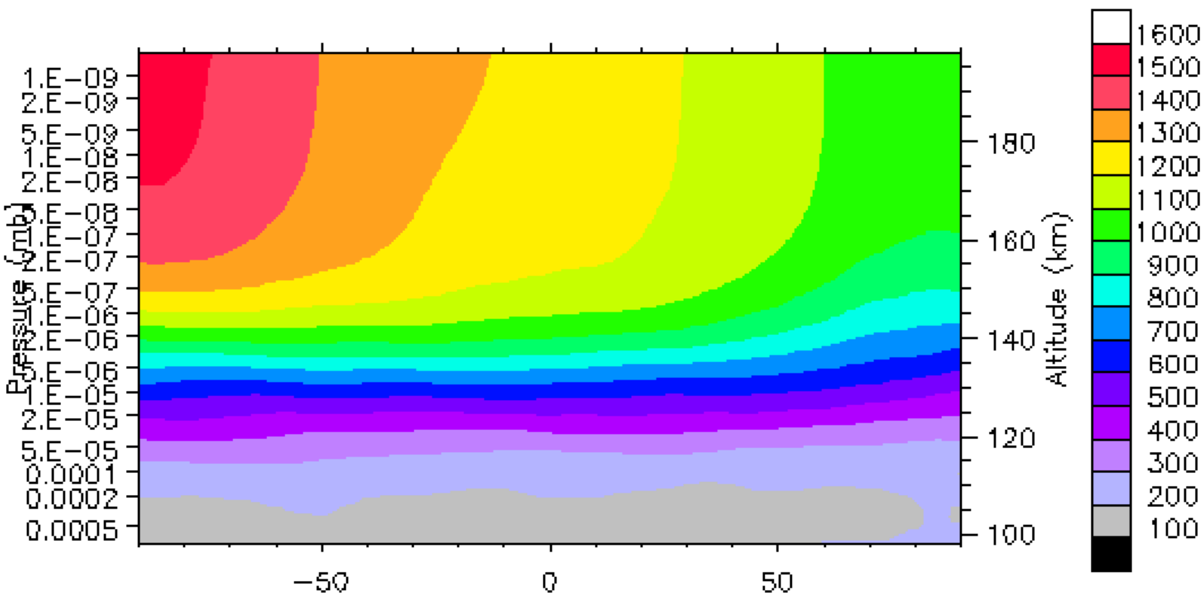
- Treatment of pressure gradients in horizontal momentum equations.
  - Standard FV core uses Exner function (p^{κ}) as the vertical coordinate for the contour integral of the pressure gradient terms (κ=R/C_p).
  - When κ is a variable, Exner function is not a constant on an isobaric surface, so can't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





p^{κ} 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

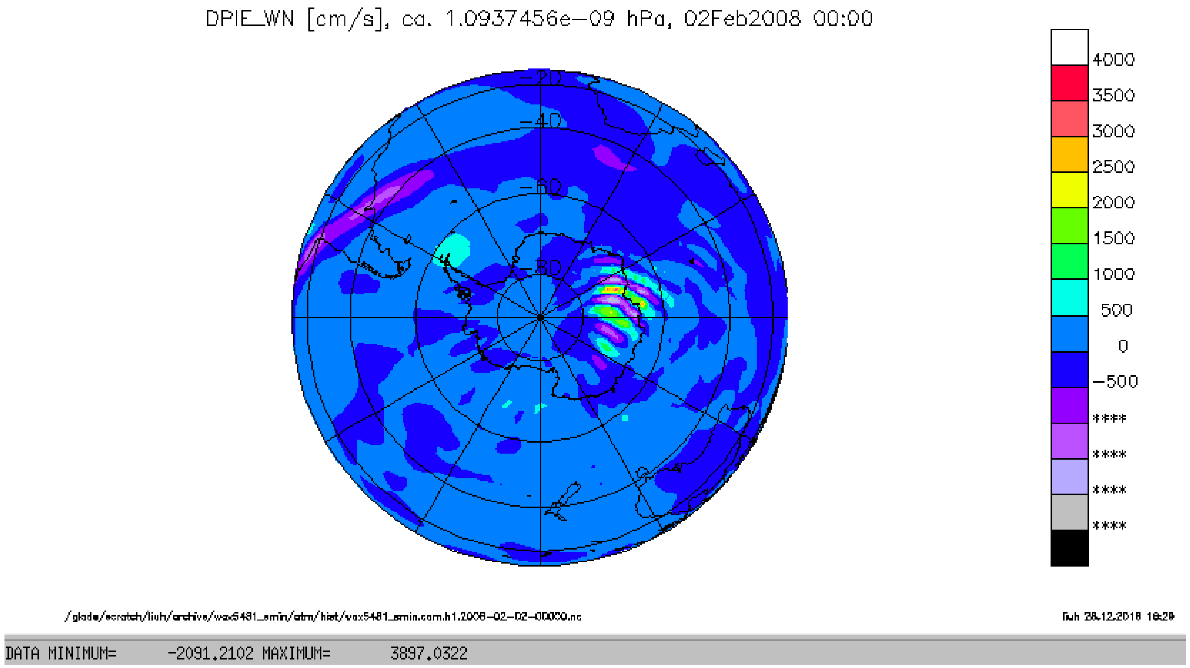
- Thermal equation using potential temperature:

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

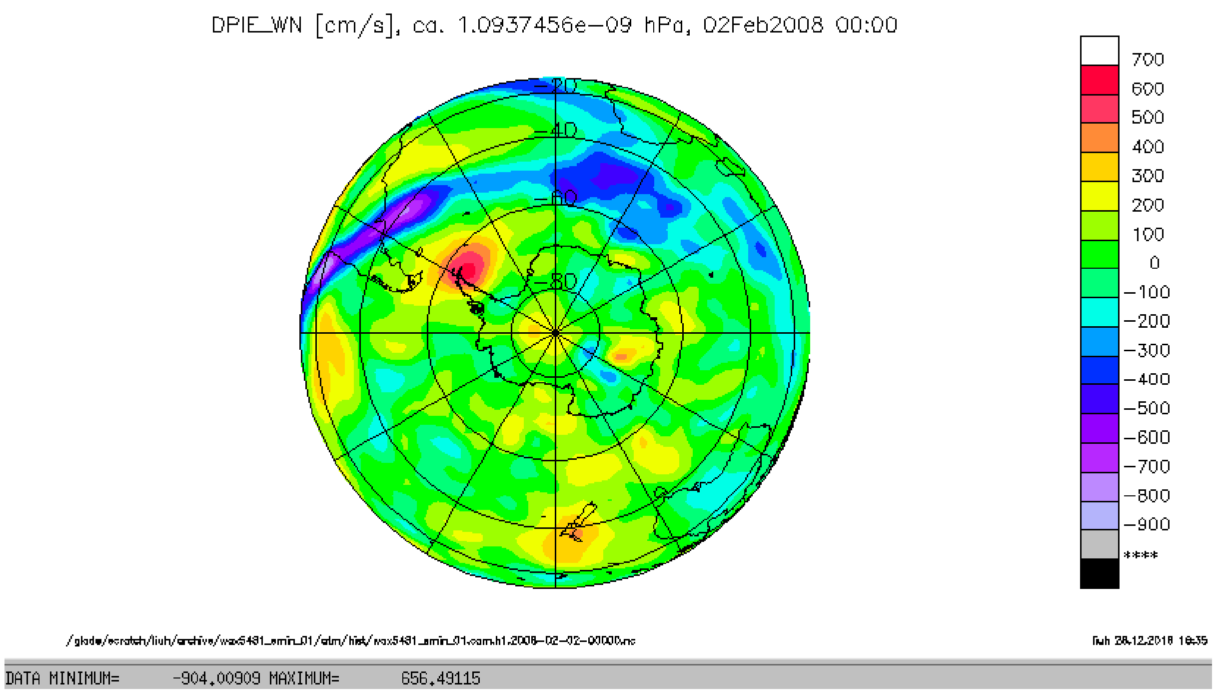
advection of κ should be considered.

- 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



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**

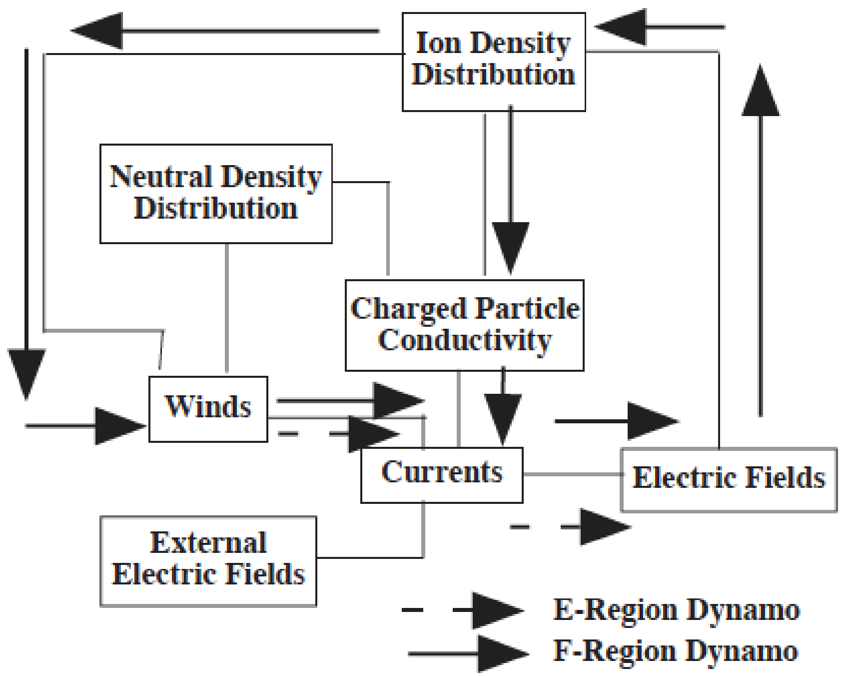


Fig. 6. Block diagram connecting the physical attributes at work in the E- and F-region dynamos.

Heelis, 2004 (CEDAR Tutorial)

F-region O^+ Transport and Electron/Ion Temperatures

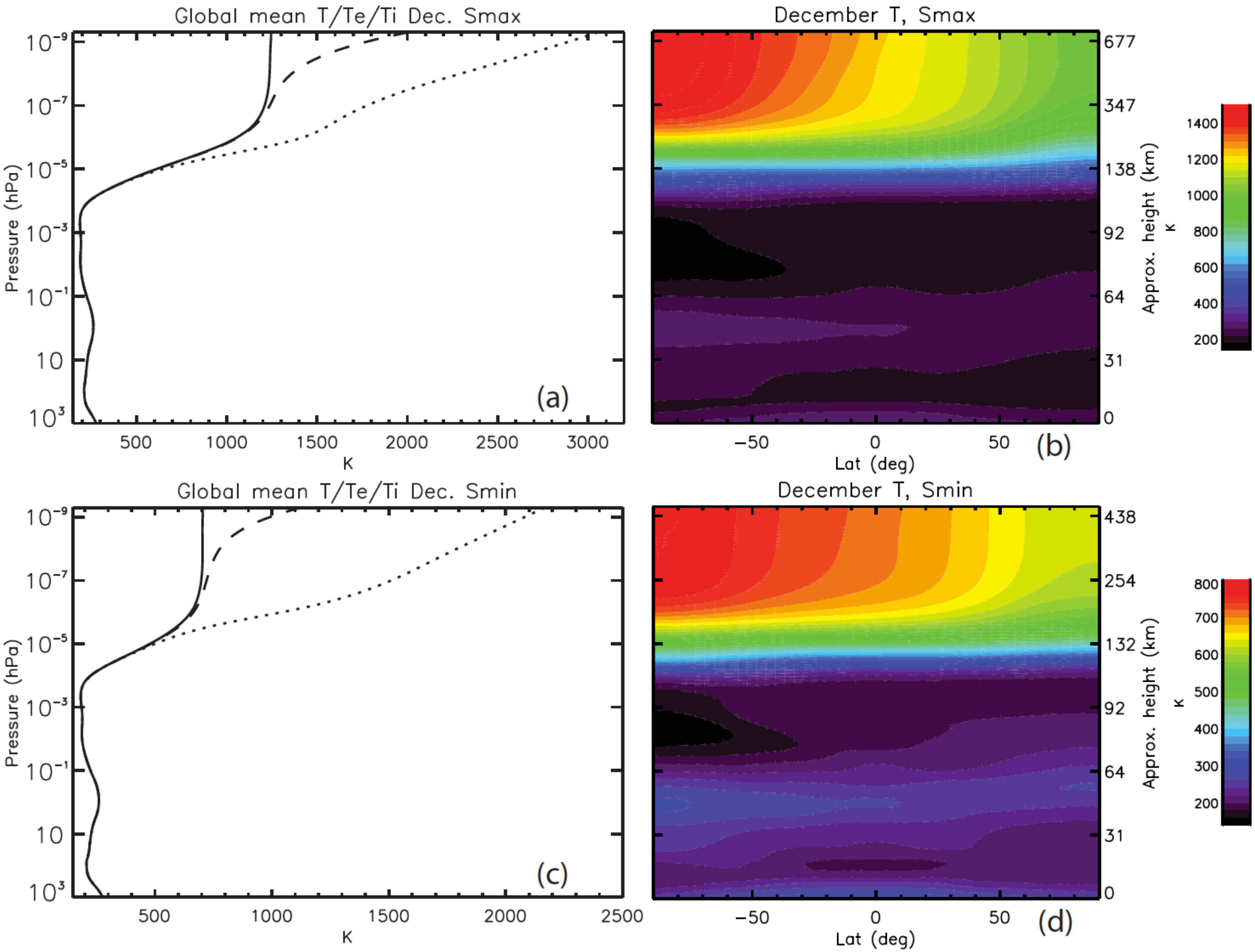
- O+ transport determined by field aligned ambipolar diffusion and ExB drifts.
- Ambipolar diffusion depends on electron and ion temperatures.
- Te tendency considered: vertical component of electron heat conduction along field-line and heating/cooling.
- Heating of neutrals by thermal electrons and ions are now included in the model.

Key WACCM-X Capabilities

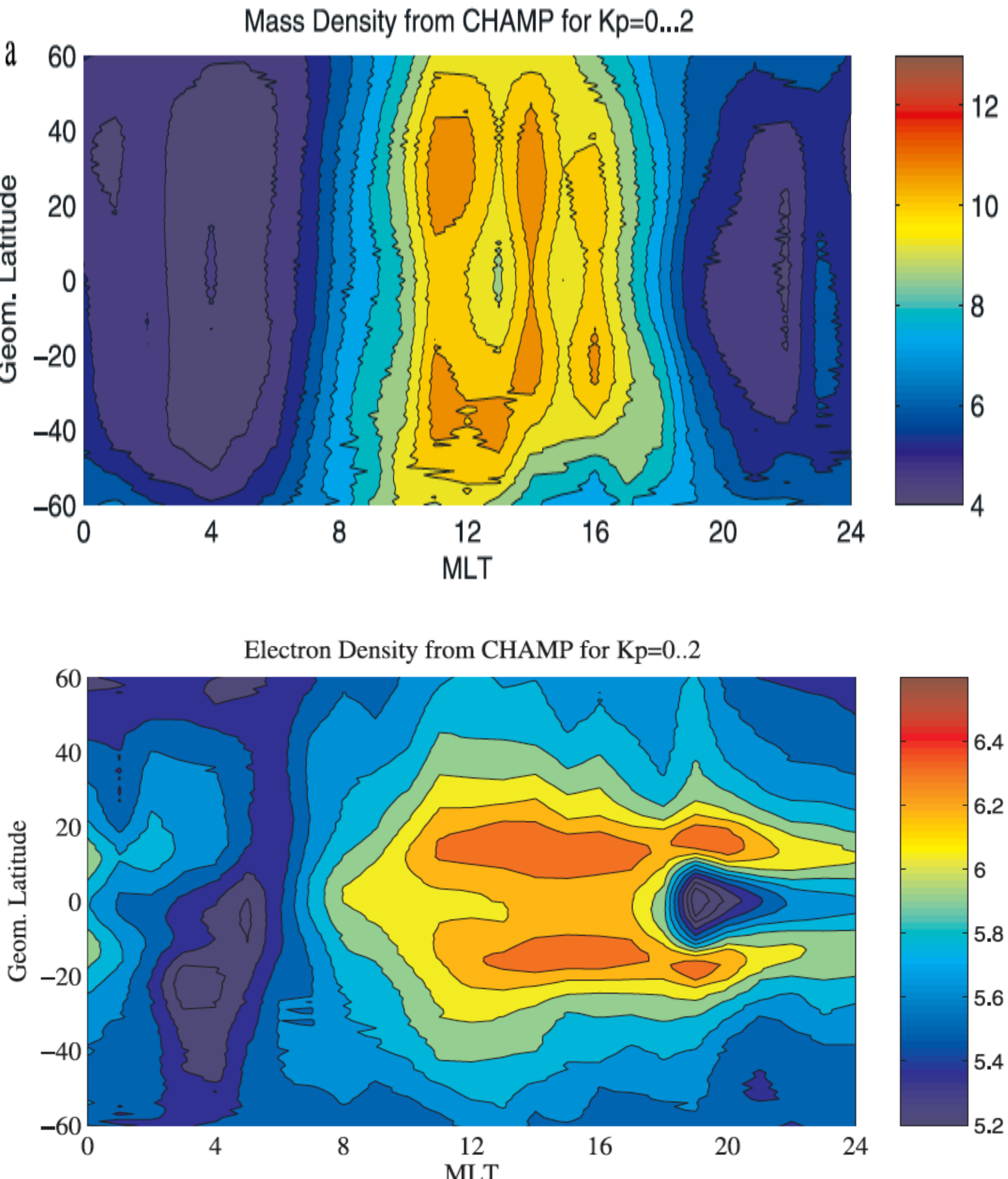
- Physics-based whole atmosphere general circulation model (0-700km)
- Solves dynamics, radiative transfer, photolysis and energetics
- Fully interactive chemistry, including ion chemistry.
- Ionospheric electrodynamics using fully interactive dynamo.
- Ion transport in the *F*-region.
- Magnetospheric inputs using empirical or specifications, including AMIE.
- Coupling with a plasmasphere model (NRL).
- Meteorology can be constrained by reanalysis data (MERRA).
- Whole atmosphere data assimilation for specification and forecast.

  - WACCM-X Tutorial during 2017 CEDAR Workshop
  - WACCM-X released as part of CESM2 on June 8, 2018.

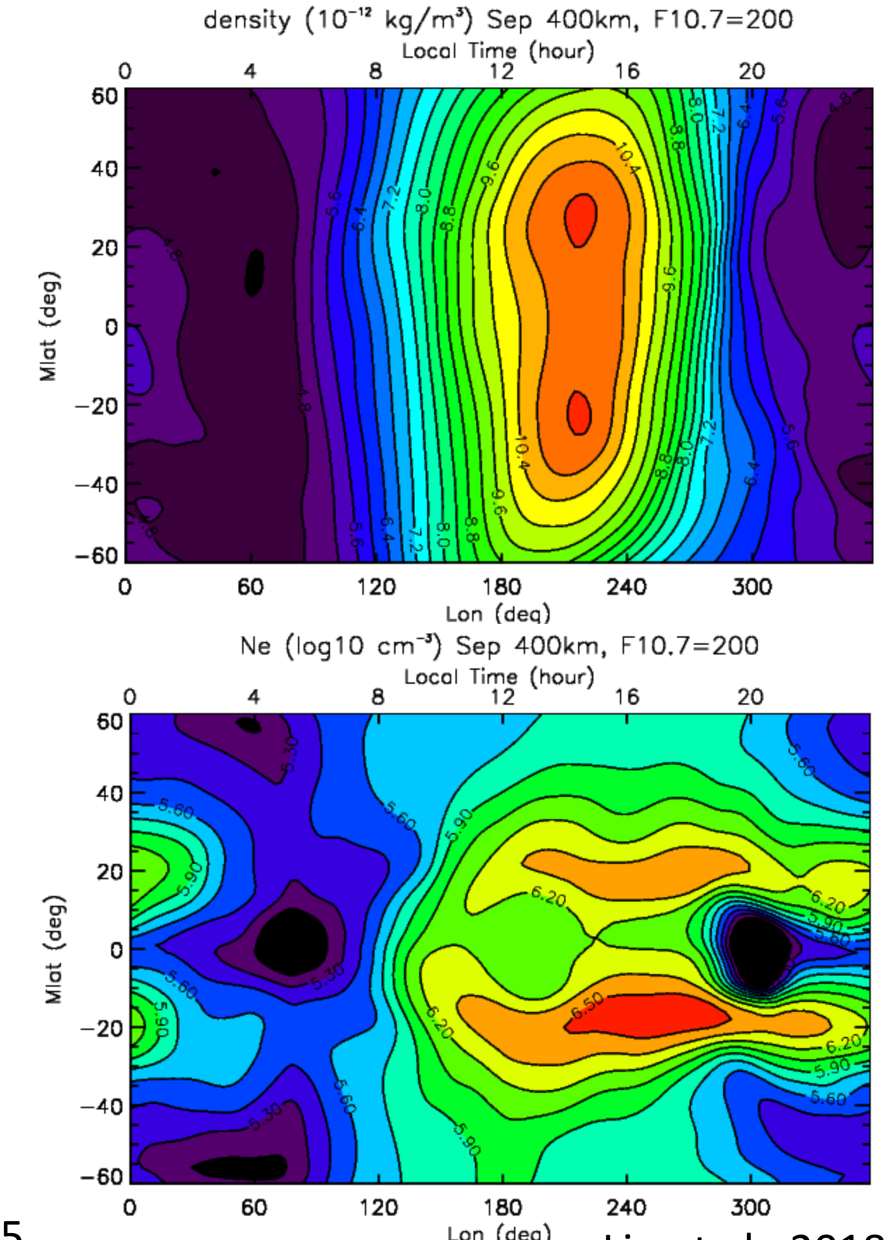
Thermal Structure



Mass and Electron Density at 400km

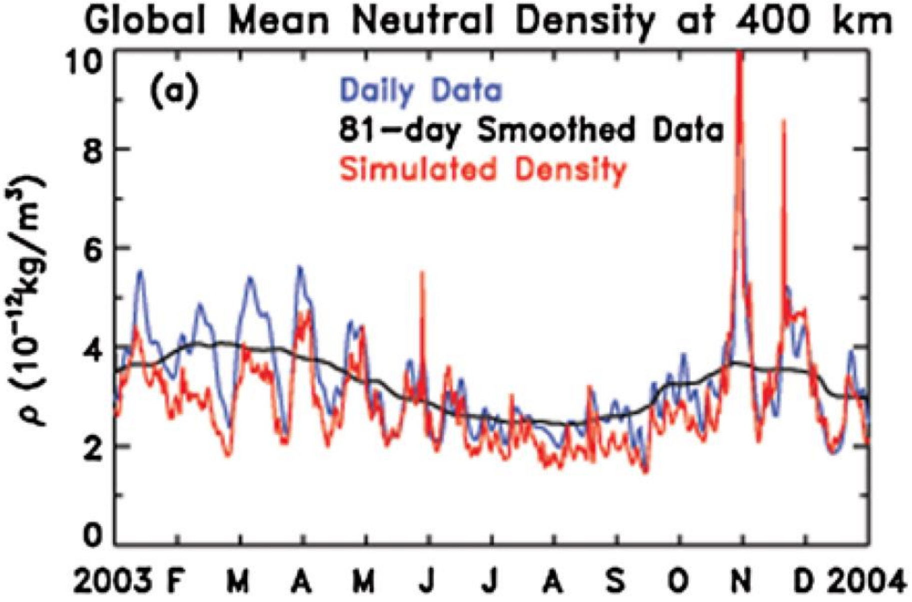


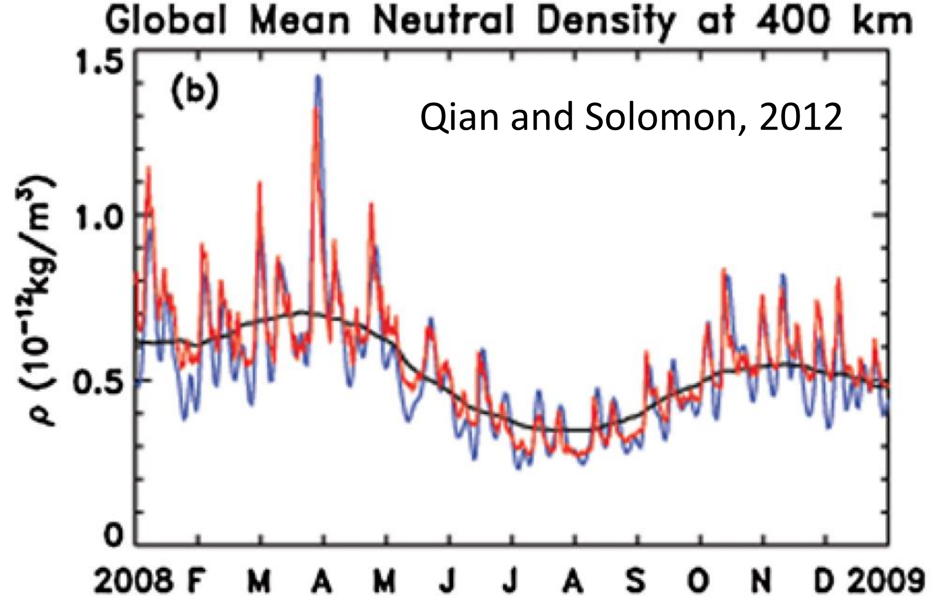
H.X. Liu et al., 2005

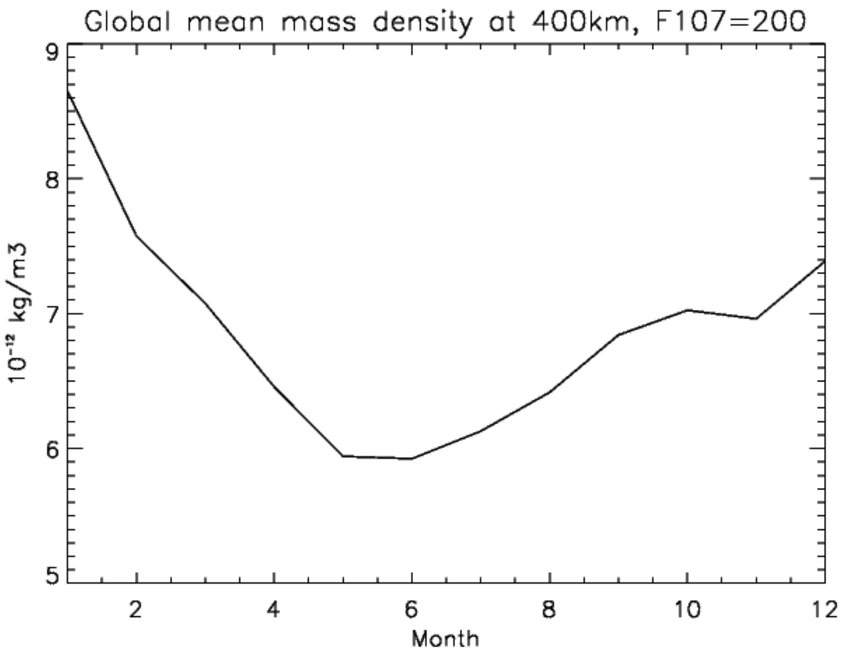


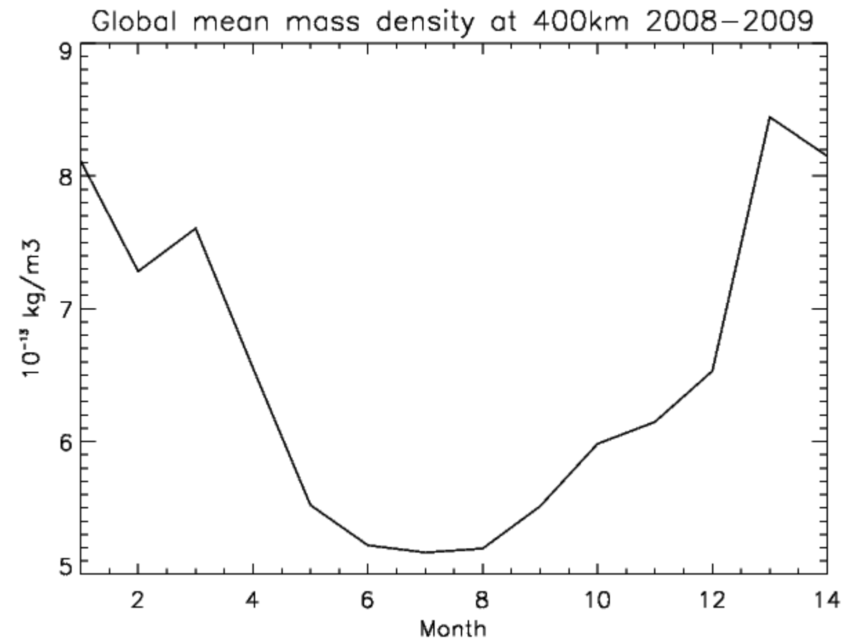
Liu et al., 2018

Annual Variation of Neutral Density

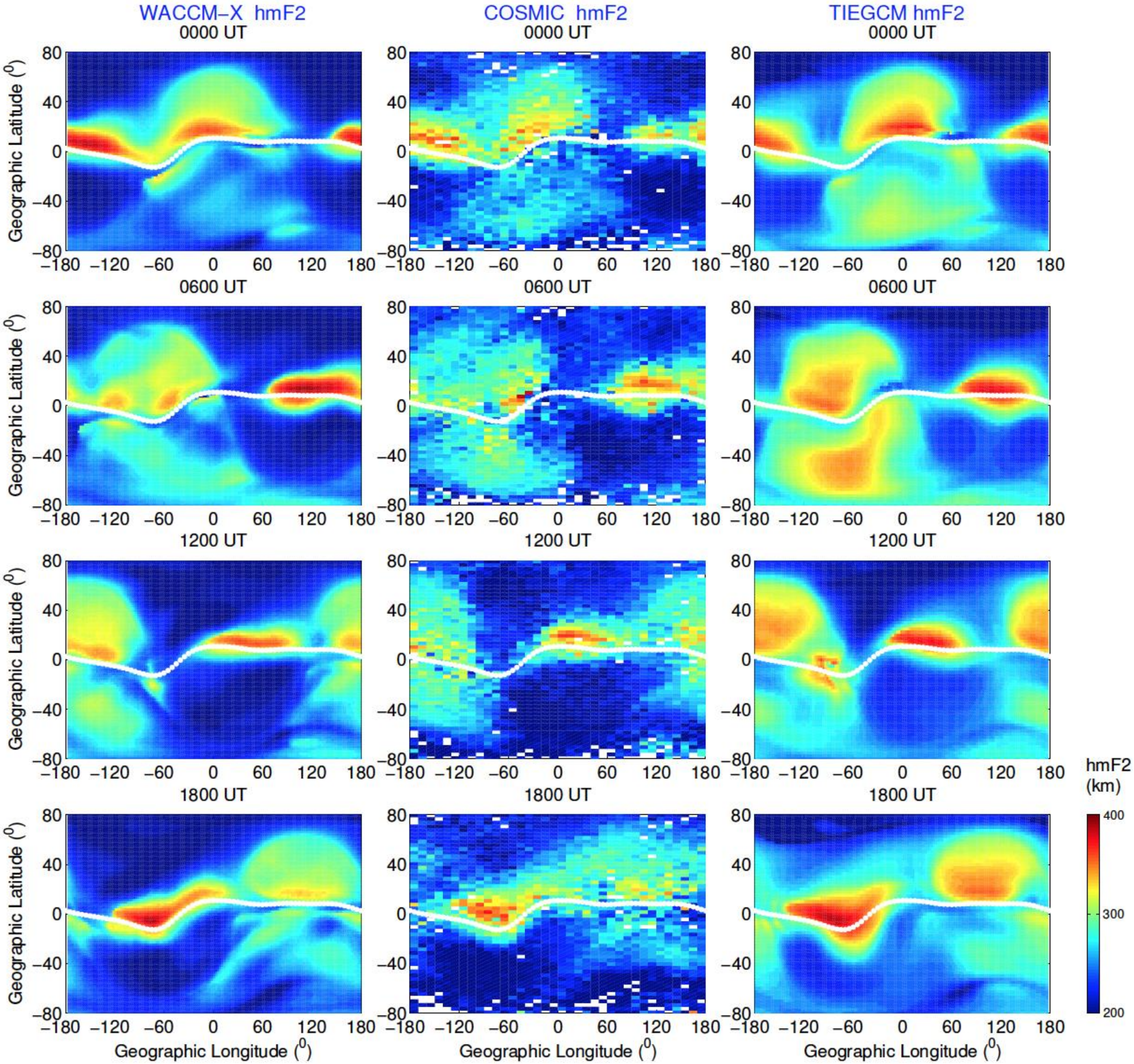






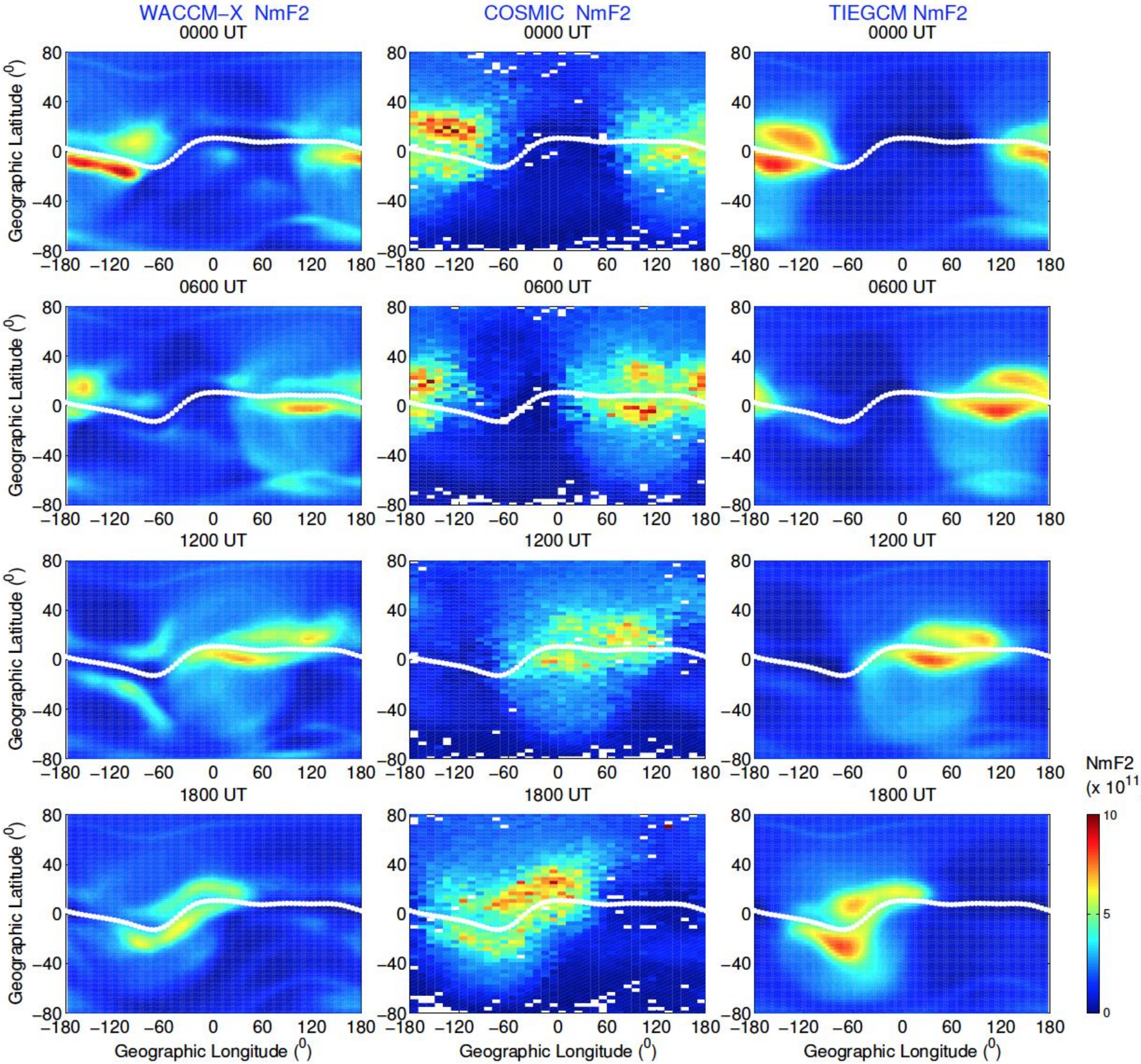


Comparison with COSMIC 2008 June



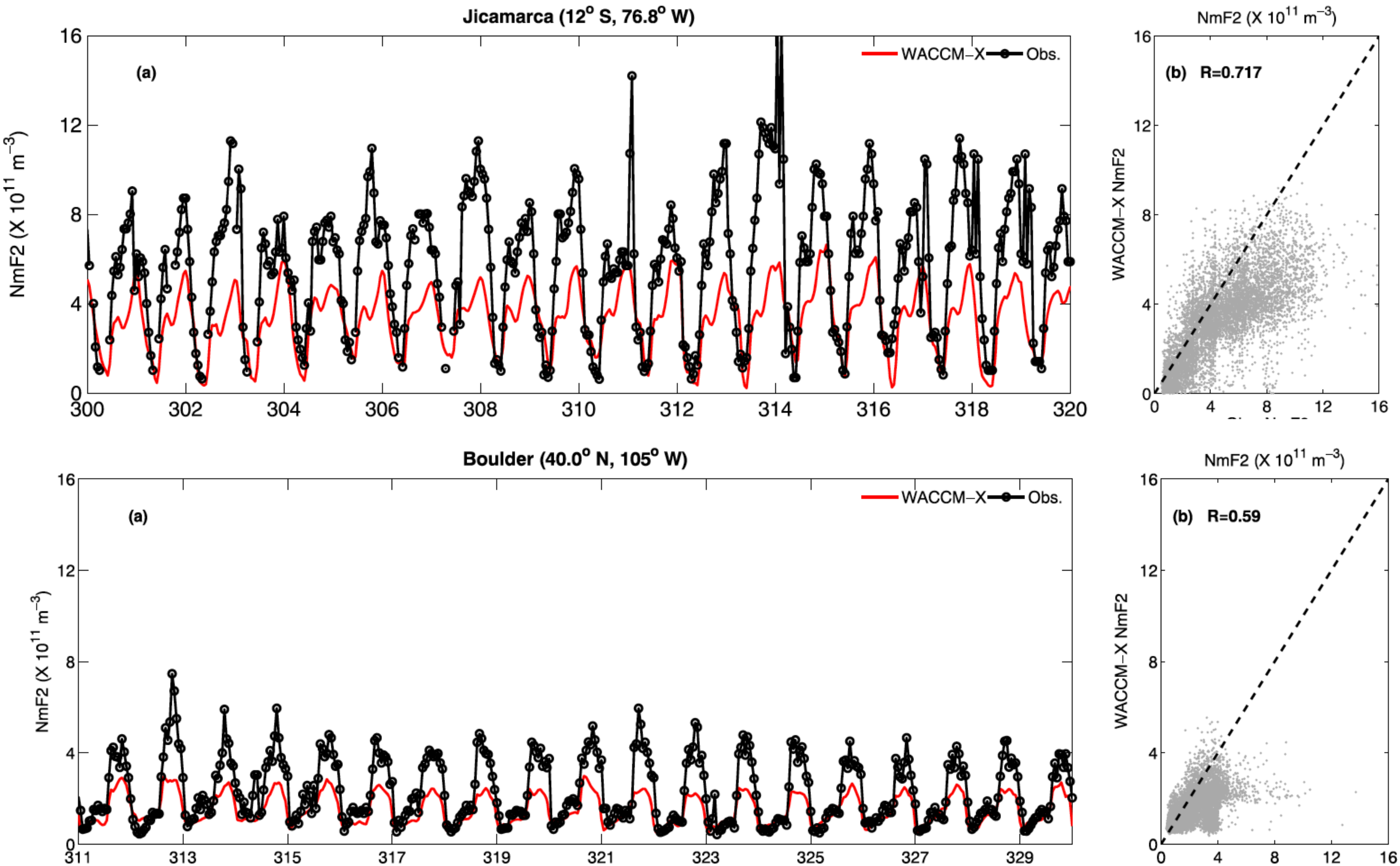
J. Liu et al. 2018

Comparison with COSMIC 2008 June



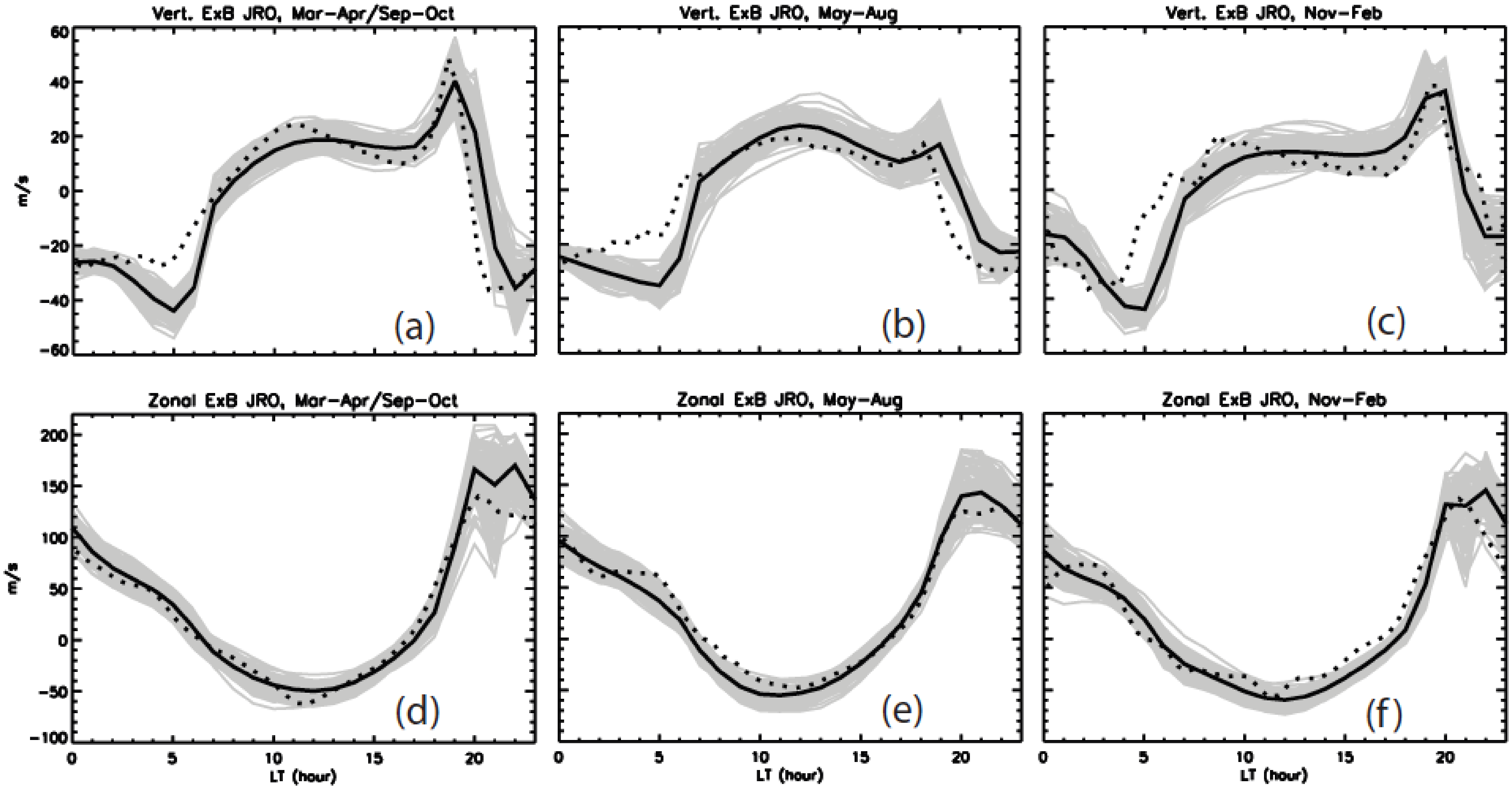
J. Liu et al. 2018

NmF2 From WACCM-X



J. Liu et al., 2018

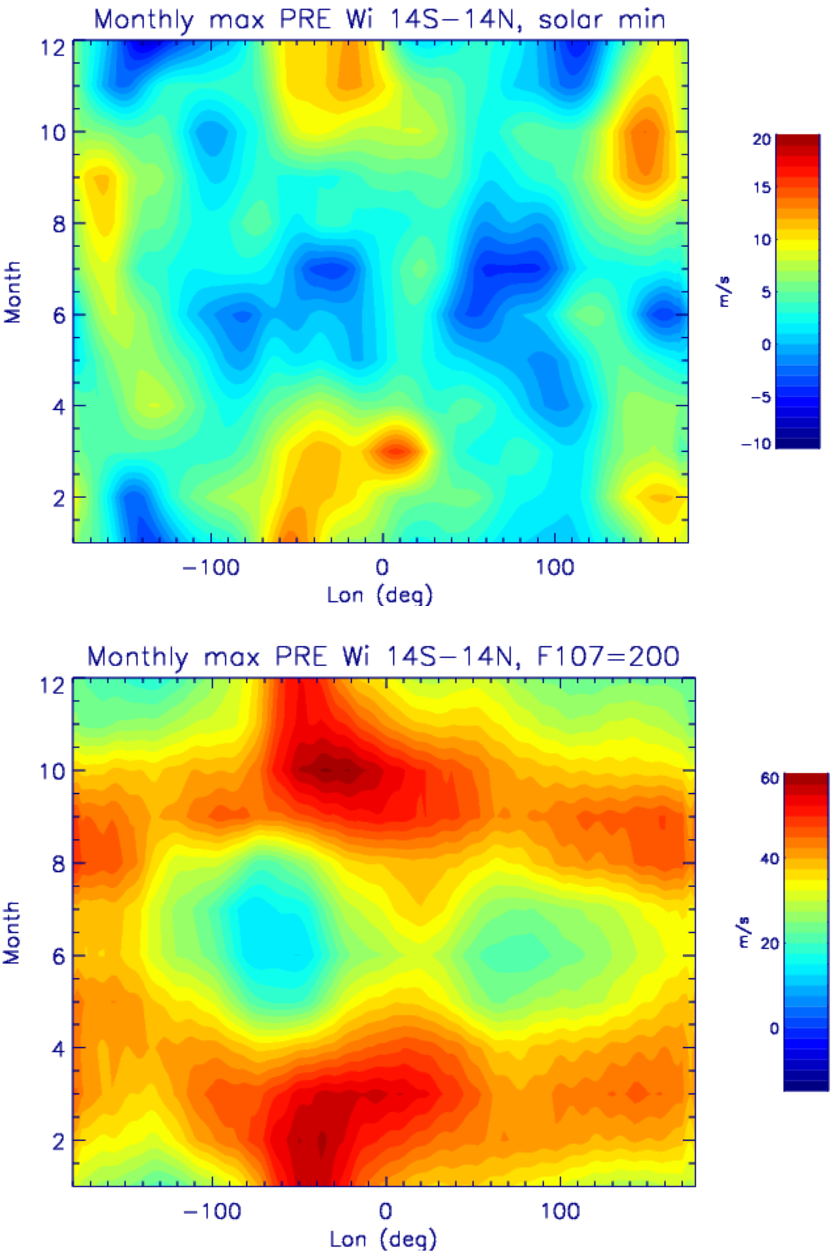
ExB Drifts: WACCM-X vs Climatology

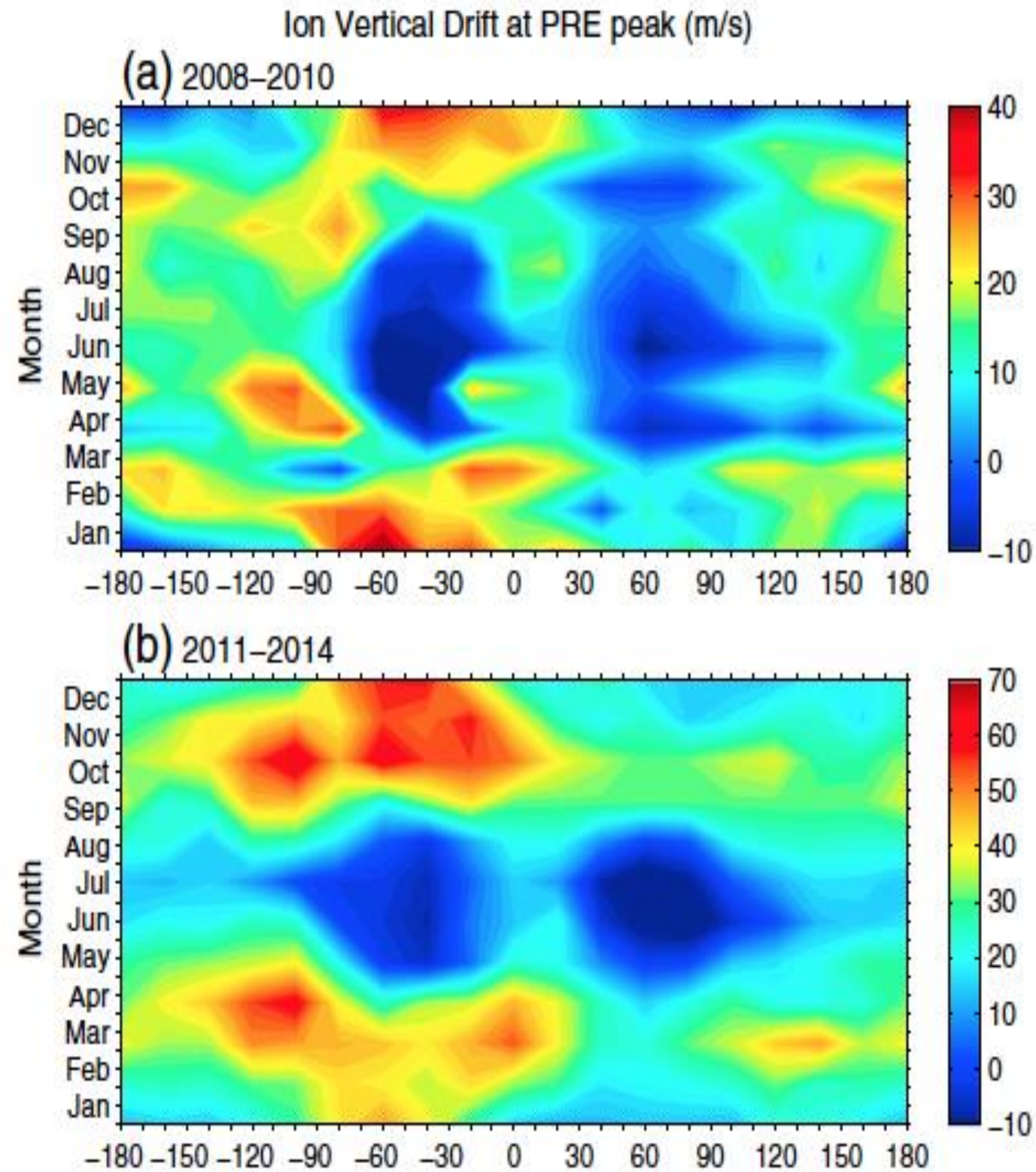


Liu et al., 2018

Dotted line: JRO climatology (Fejer et al., 1991)

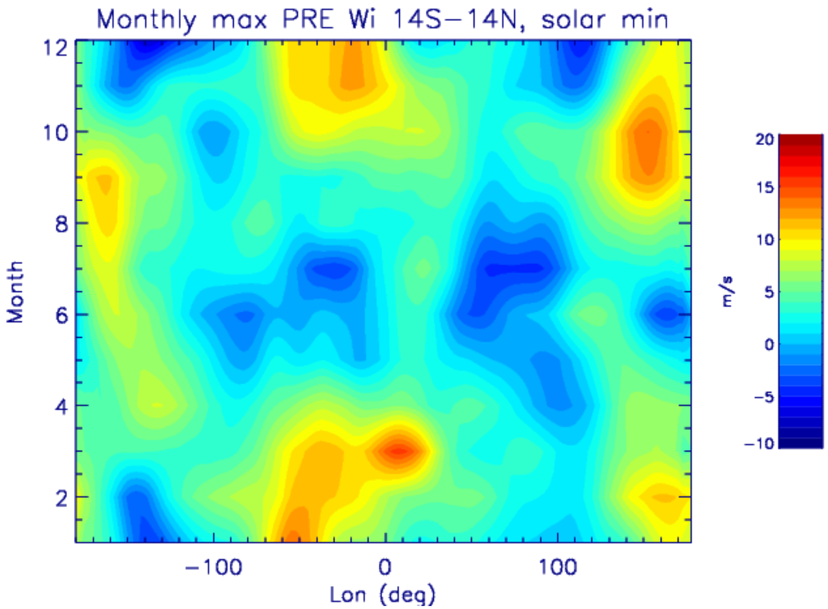
Monthly Mean PRE Peak

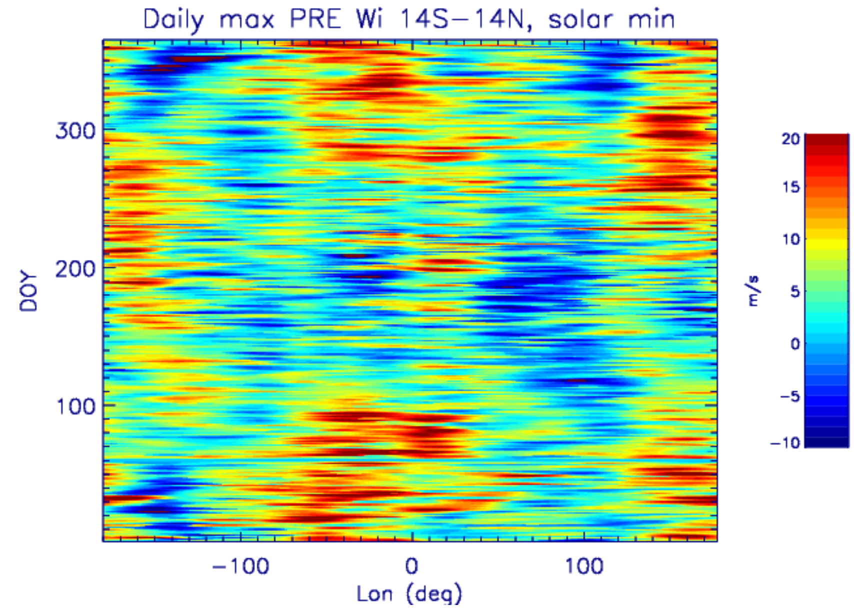


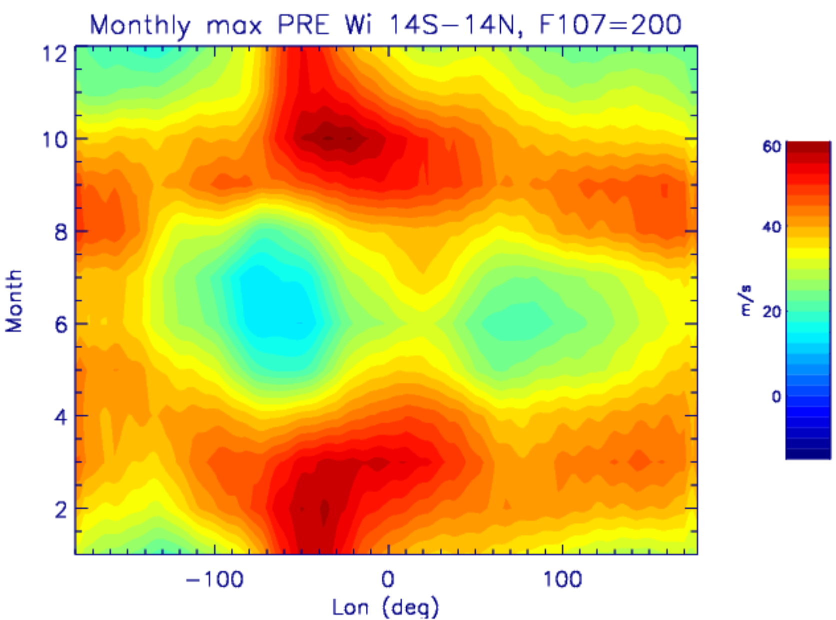


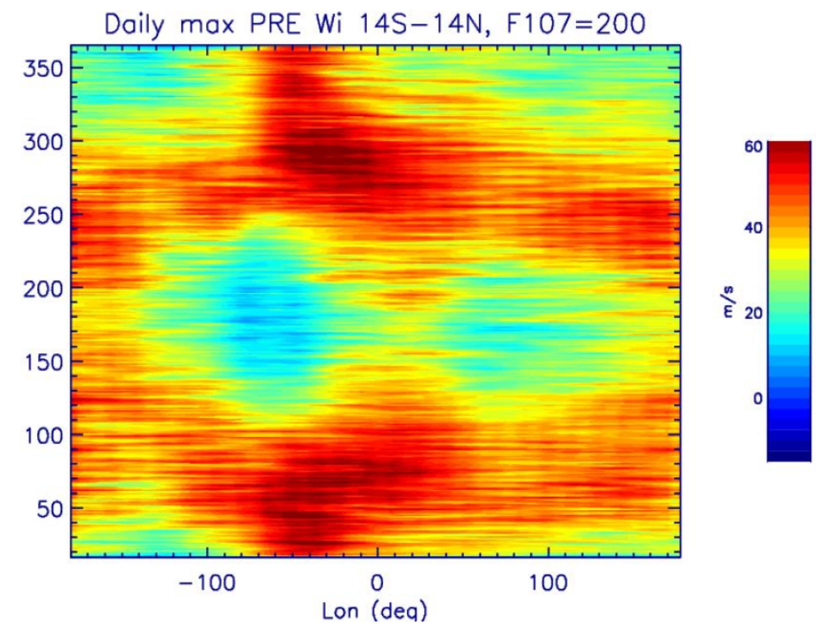
Huang and Hairston, 2015

Monthly vs Daily Variability

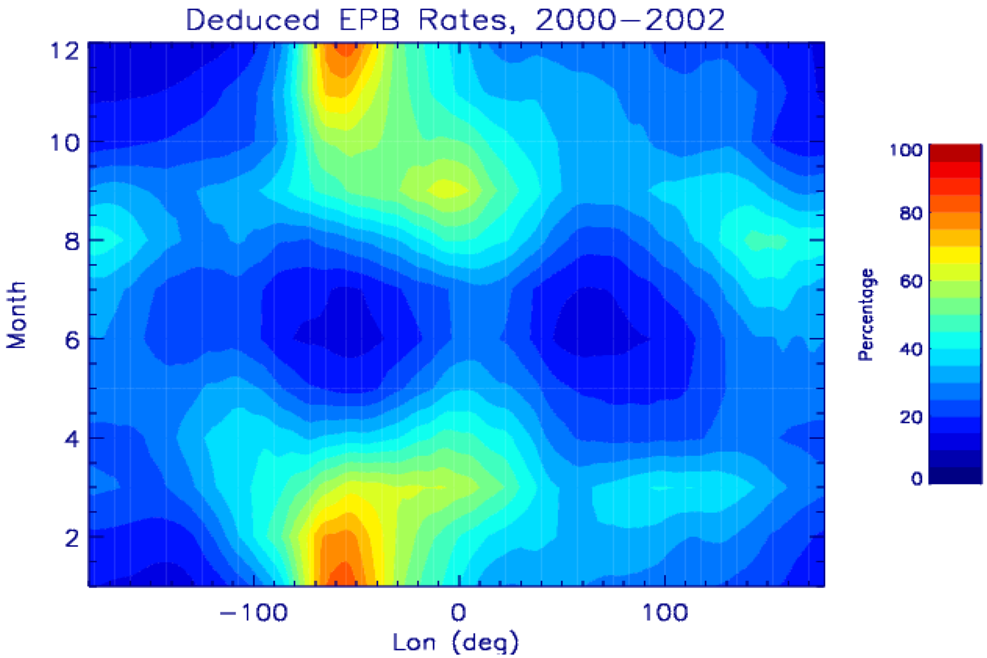


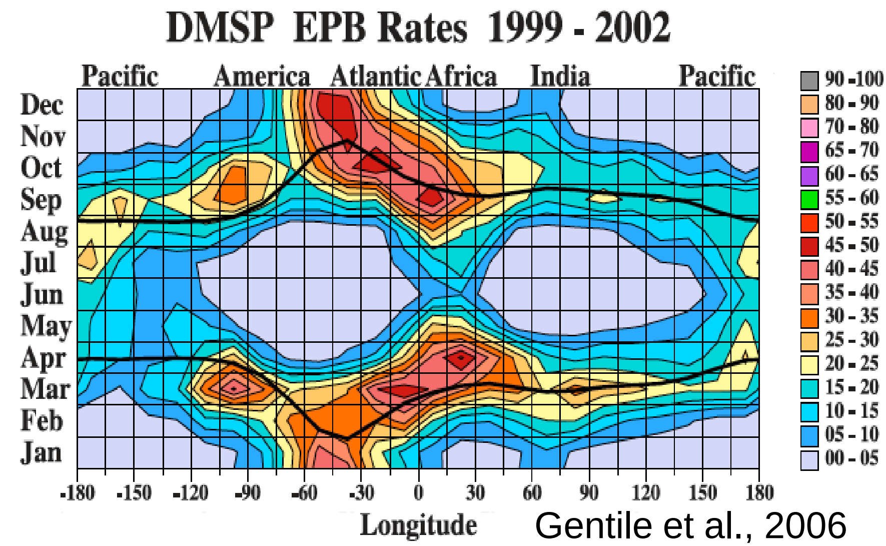




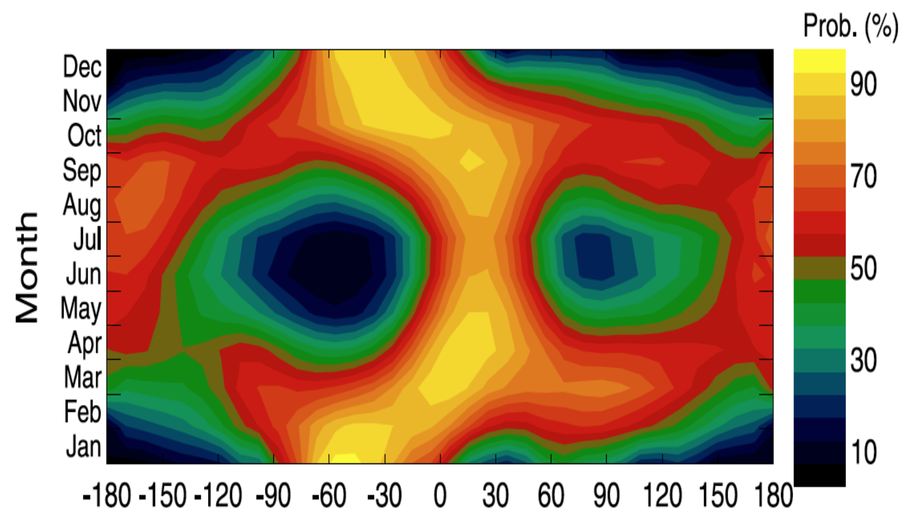


Occurrence Frequency of Equatorial Plasma Bubbles





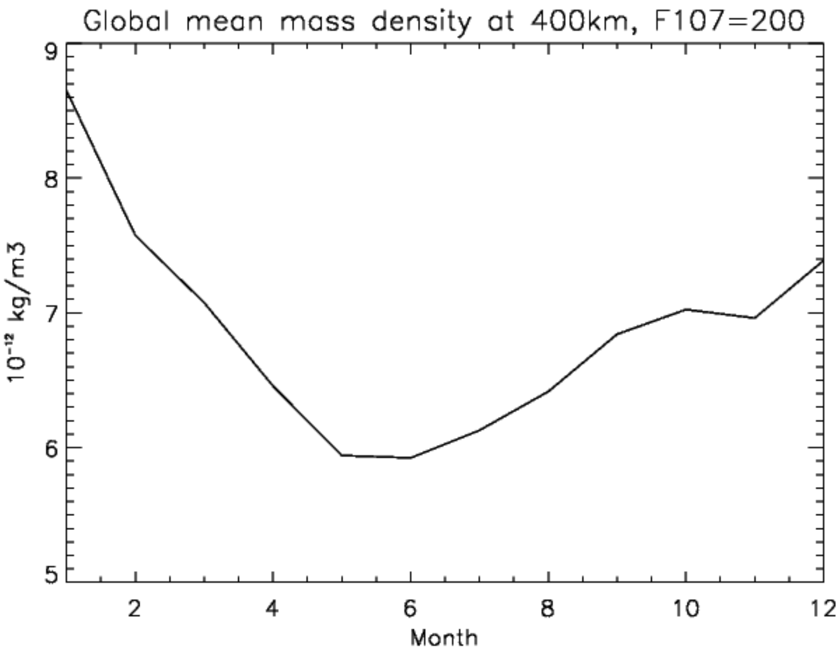
Gentile et al., 2006

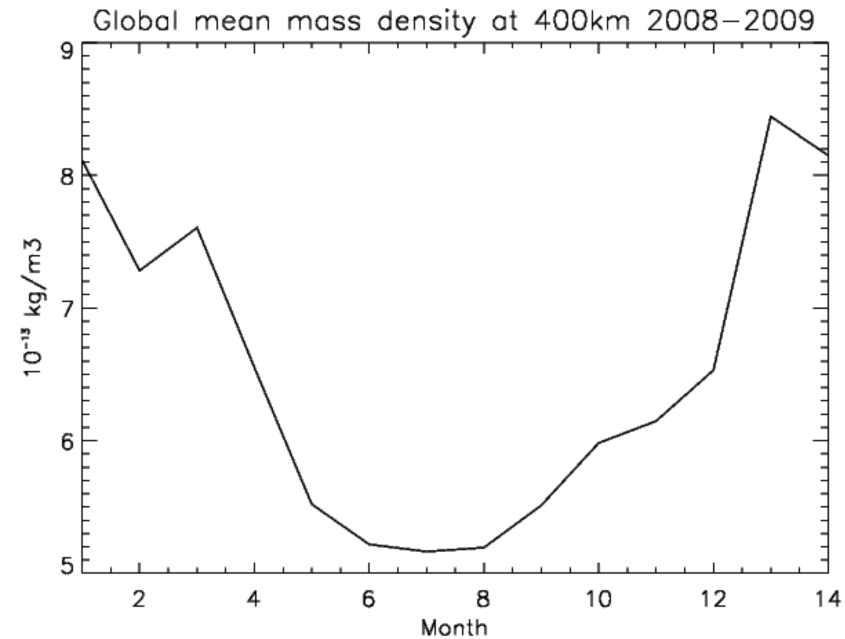


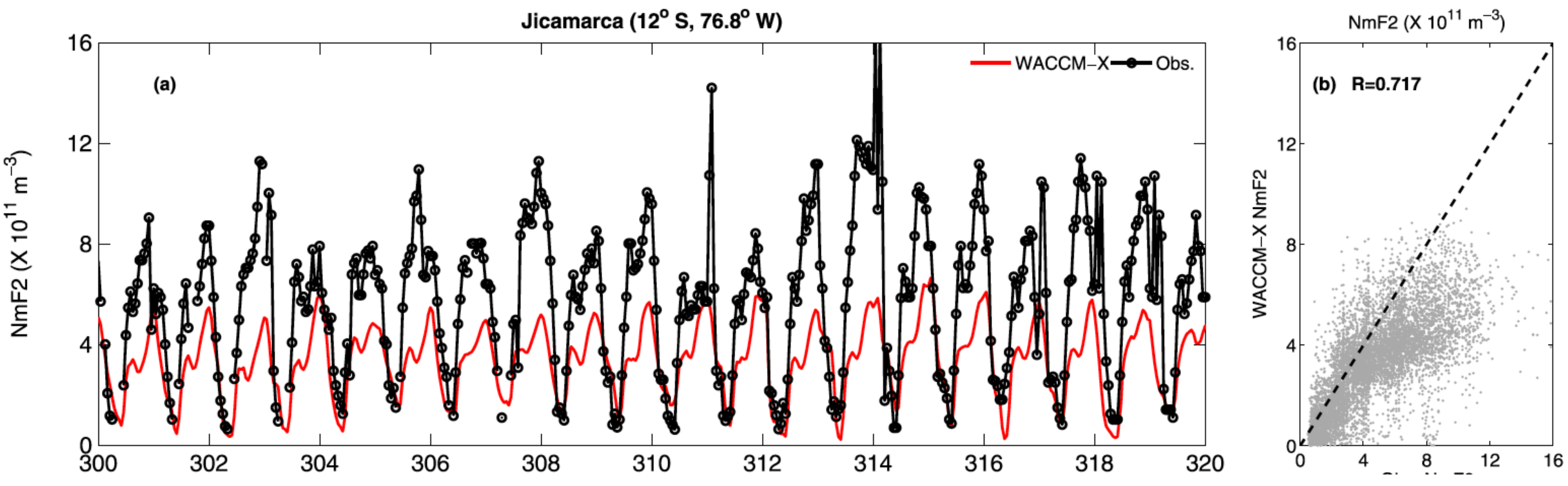
Kil et al., 2009

- The agreement between deduced EPB rates and the observed rates suggest
  - Large-scale dynamics and electrodynamics play a key role in preconditioning EPB
  - Feasibility for probabilistic forecast of EPB—an outlook/warning (analogous to tornado forecast).
- Resolving EPB requires high-resolution capability.

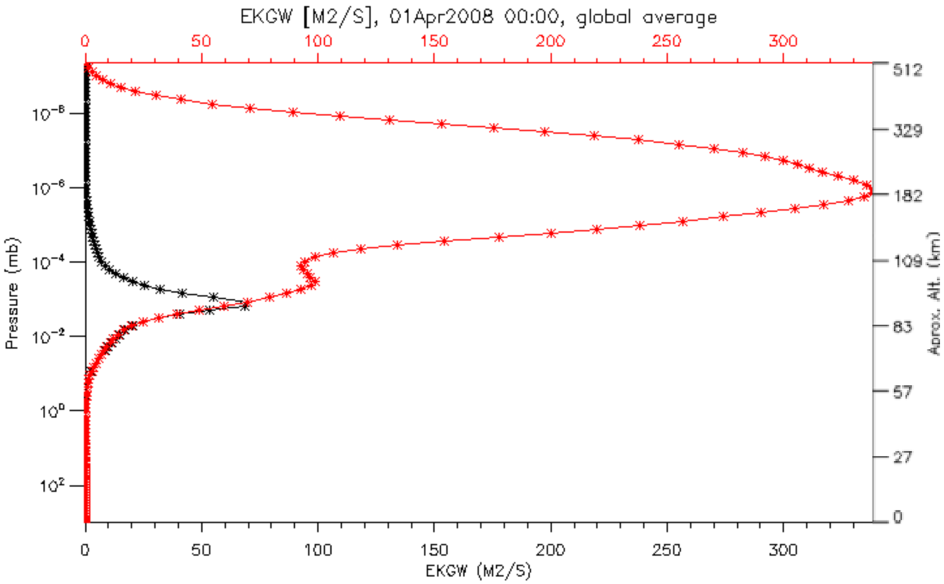
Model Biases and Uncertainties

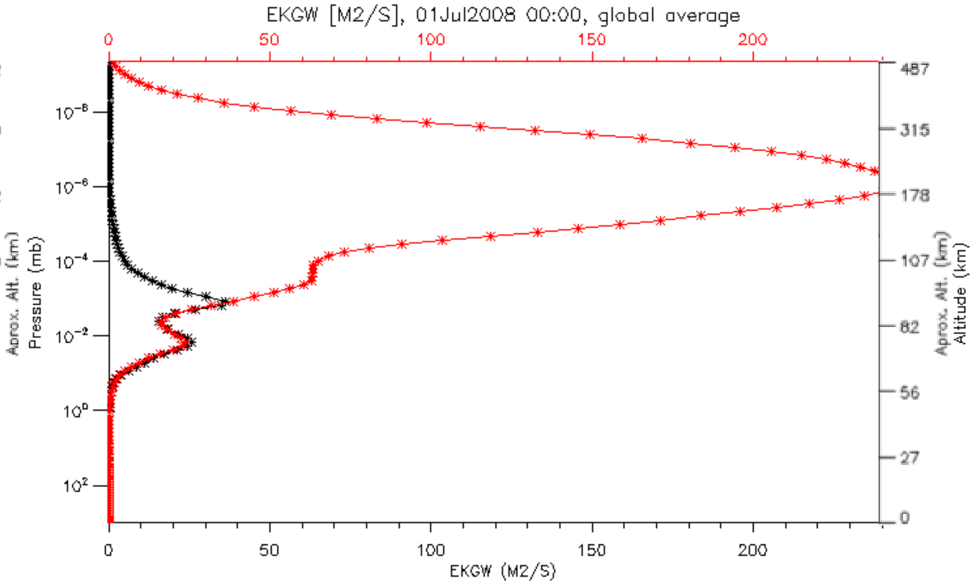


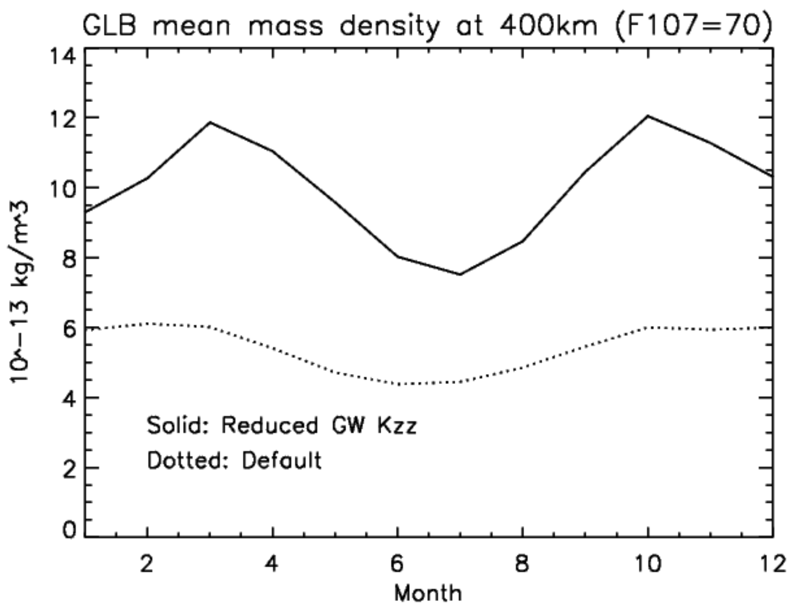


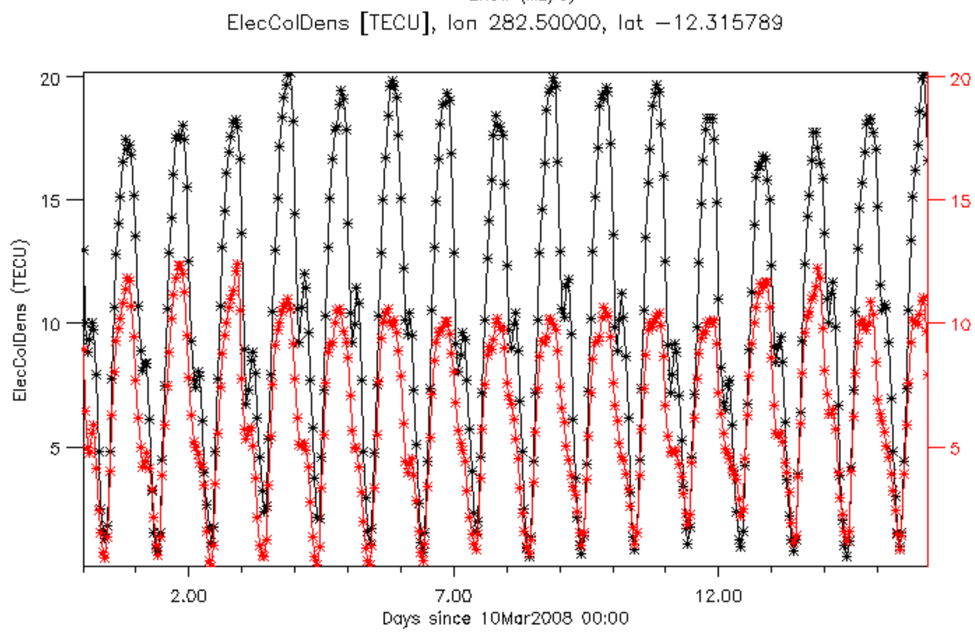


Global Mean Thermosphere: Mass Density, O, and Column O/N2









Summary: Model Requirements

- Consideration of variable species, and along with it variable specific heats and mean molecular mass.
  - Exner function can't be used as vertical coordinate.
  - Solve temperature, rather than potential temperature, for thermal equation.
- Conservative and efficient transport of large number of species.
- Efficient (parallel) 3D mapping between dycore grid and geomagnetic grid.
- Subcycling/supercycling capability to accommodate needs for fast processes (short time step, large horizontal diffusion, storm time simulation).

Summary

- Key WACCM-X capabilities have been developed, and validated against thermospheric and ionospheric observations for climatology, variability during geomagnetic quiet and disturbed conditions, and long-term space climate chage.
  - Simulated PRE, an important quantity for the formation of EPB, shows longitudinal and seasonal variation similar to observations.
  - Simulated PRE varies significantly from day-to-day. Deduced EPB rate is similar to observations.
- Model biases in mesosphere, thermosphere and ionosphere can be caused by issues with gravity wave parameterization (both drag and mixing).